COASTAL GEOMORPHOLOGY AND QUATERNARY GEOLOGY OF THE PORT STEPHENS-MYALL LAKES AREA



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Cover photographs courtesy of Stuart Chape and Patrick Hesp:
Front top: Seal Rocks embayment; *Front bottom*: Transgressive dunefield, northern Fens embayment; *Back top*: Port Stephens (left) and southern Fens embayment; *Back middle*: Blowout and nested parabolic dune, southern Seal Rocks embayment; *Back bottom*: massive long-walled transgressive dune ridge abutting Myall Lake and swamps, Seal Rocks embayment.

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Preface

The prime objective of this monograph is to provide a regional study of the geomorphology and stratigraphy of Quaternary deposits of a part of the New South Wales (N.S.W.) coast. Although the emphasis is on sand deposits of eolian and marine origin, associated sediments from estuarine and fluvial environments of deposition have been investigated in selected areas within the region.

The region selected for study is referred to as the Port Stephens-Myall Lakes area. It occurs between Newcastle in the south (Lat. 32°53′) and Seal Rocks in the north (Lat. 32°26′). There is little doubt that this is an area of considerable morphologic and stratigraphic diversity and richness. This point, together with the region's accessibility and availability of background information on surface and sub-surface conditions, has provided us with an opportunity to describe and explain a wide range of Quaternary landforms and depositional sequences.

The study was initiated in 1960 with a BA (Hons.) thesis by Thom, in the Department of Geography, University of Sydney. Primarily, this was a regional evaluation of landforms although some use was made of Hunter District Water Board drill logs in constructing the stratigraphy (see Thom, 1965). This study formed part of a broader regional analysis of sand deposits along the N.S.W. coast (Langford-Smith and Thom, 1969). In the late '60s, Shepherd undertook a PhD thesis under the supervision of Trevor Langford-Smith on the dunes, beach ridges, fluvial and lakeshore features north of Port Stephens (Shepherd, 1970, 1974). Ly, working at the University of Newcastle, studied the sediments and stratigraphy of Newcastle Bight as a PhD thesis (Ly, 1976, 1978a,b). This thesis was supervised by Thom and S. Warne. Use was made of part of the area (Fens) by Bowman (1979) in his PhD study of podzol development on coastal barriers in eastern Australia (see also Thompson and Bowman, 1984). Hesp undertook doctoral studies on foredune dynamics and sedimentation (Hesp, 1984); a large part of his field work was conducted in the Fens embayment and was part supervised by Thom.

In the '70s both Thom and Roy undertook separate but interrelated drilling projects in the area. As part of a study by the Geological Survey of N.S.W. of heavy mineral potential of estuaries in N.S.W., shallow marine seismic reflection surveys and reversed circulation drilling was carried out in Port Stephens and Fullerton Cove to determine sediment distribution and stratigraphy (Roy, 1980). This work was extended offshore into Newcastle Bight in a joint study with the Public Works Department (P.W.D.) on the sediments and nearshore dynamics of that embayment (Roy and Crawford, 1980). Whilst at the Australian National University then later at the Faculty of Military Studies, University of N.S.W., Duntroon, a further attempt was made to unravel the stratigraphy and age structure of Quaternary sand deposits along the east Australian coast (Thom, 1974). This work has continued to the present and has included research in the Port Stephens-Myall Lakes area (Thom, 1978, 1984; Thom and Roy, 1981; Thom et al., 1978, 1981a,b,c).

All these studies have involved the assistance, co-operation and advice of numerous individuals and organizations. Most of these are acknowledged in the various theses, reports and papers which have been published to date. However, we would like to make reference to some whose invaluable help have made this monograph possible. Professor T. Langford-Smith and Dr J. Jennings provided the initial guidance and encouragement during the early days of research of some of us. The late Peter McKenzie was a source of inspiration to B.G. Thom.

The Hunter District Water Board (H.D.W.B.) and three sand mining companies (Associated Minerals, Mineral Deposits, and Rutile and Zircon) have freely supplied us with information on request. We are indebted to their help. There has also been the support of colleagues who are botanists (A. Martin, R. Carolin, P. Myerscough), engineers (A. Gordon, L. Nielsen), and geomorphologists/geologists (J. Davies, L.D. Wright, A. Short, J. Chappell, D. Simonett, R. Galloway and C. Peat).

We would like to thank the staff of three geography departments who have over the years been extremely helpful and patient in their endeavours to produce this monograph. In particular, we are grateful to Keith Fitchett and Jim Caldwell of the Department of Biogeography and

Geomorphology at A.N.U. for their laboratory assistance. Marcia Murphy has been able to sustain the numerous typists who have worked on the project. Also at the A.N.U., the efforts of the Radiocarbon Laboratory under the directorship of Henry Polach are greatly appreciated. At the University of Sydney, the use of radiocarbon facilities involving Richard Temple, Richard Gillespie and Mike Barbetti provided further support to understanding the age structure of the various sand deposits. At Duntroon, Paul Ballard patiently worked on the maps and diagrams up to 1984 and since then John Roberts and Peter Johnson at Sydney University have maintained the cartographic side of the project.

One individual above all others must be thanked for his role in the project. He is the unsung hero of many Quaternary investigations in Australia in the '70s and '80s. We refer to Karl Shaw, our driller. Over the years he has provided a tower of strength to all those who needed to know more about the subsurface. We dedicate this monograph to him.

The monograph can be considered in three parts. The first part (Chapters 1 to 3) consists of a general description of the study area plus a general account of the geomorphology and sedimentology. The first two chapters are based mostly on the work of Thom and Shepherd, but the third involves thesis research by both Ly and Shepherd plus work of Thom and Roy. The second part contains regional descriptions of the six segments of the coast (chapters 4 to 9). Newcastle Bight was studied mainly by Ly, Thom and Roy. Tomaree Hill dunes is the work of Thom, but involves data collected by the H.D.W.B. and Geological Survey of N.S.W. The Port Stephens section is largely based on unpublished work of Roy (see also Peat and Roy, 1975, and Roy, 1984). The chapter on Fens involves thesis research by Shepherd, Bowman and Hesp and drill studies by Thom. Both Thom and Shepherd were involved in Upper Myall-Broadwater and Eurunderee chapters supplemented by soils studied by Bowman. The Seal Rocks area has been mainly studied by Thom. The third and final part of the study (Chapter 10) is an attempt to bring together these regional descriptions and histories into a coherent framework using various techniques of correlation and chronology.

It is important to stress that this publication contains only a portion of the data collected over the years. Space and cost of publication prohibited more elaborate documentation (for instance, a description of all drill logs used in the study). However, we believe that the information presented here does represent our collective understanding at this stage. The area is rich in material for future Quaternarists to study. It has been difficult to know when to stop collecting data and write up the results because there is so much more to do. For instance, new dating techniques such as amino acid racemization and thermoluminescence are clarifying certain chronological problems (see Epilogue). We hope that this monograph will guide others to a further quest for knowledge, treating this study as no more than a "progress report" on the path to a more comprehensive understanding of not only the region's Quaternary depositional history, but also the processes and products of environmental changes in the coastal zone.

1

Regional Setting

1.1 GENERAL TOPOGRAPHY

In presenting a regional study of the geomorphology and Quaternary geology it is important to provide a general account of the environmental setting. The first chapter of this monograph is directed towards this purpose. Reference is made to the considerable literature on the Port Stephens-Myall Lakes area in this chapter, in order to provide readers with a reasonably comprehensive bibliographic source for future studies.

The coastal environment of central N.S.W., including the Port Stephens-Myall Lakes region, is characterized by:

(i) comparatively steep and narrow inner continental shelf and nearshore zones (Wright, 1976; Davies, 1979; Roy and Thom, 1981)
(ii) a tendency for rocky headlands to alternate with embayed sandy beaches and barriers to form pronounced coastal compartments (Langford-Smith and Thom, 1969; Davies, 1974; Roy et al., 1980)
(iii) a meagre present-day supply of river sand (Roy, 1977; Roy and Crawford, 1977); and
(iv) a mild, humid climate which encourages the growth of sclerophyll forests and woodlands on sandy deposits.

Irregularity in bedrock topography provides the basic framework for the Quaternary morphologic and stratigraphic variability of the central

N.S.W. coast. The topography is such that there are considerable local variations in exposure, nearshore and estuarine gradients and sediment abundance. These factors influence the degree to which oceanographic processes mobilize coastal sediments.

Coastal bedrock topography and continental shelf bathymetry (see Table 1-1 for relevant maps and charts) reflect the geological and geomorphological evolution of the Eastern Highlands and adjacent regions. Episodes of continental uplift (mostly early Tertiary in age) and sea-level change have punctuated long-continued sub-aerial erosion and outer shelf deposition (Andrews, 1916; Bird, 1971, p. 278; Wellman, 1972; Ringis, 1973; Roy and Thom, 1981; Ollier, 1982). The meridional trend of the coast has truncated the structural alignment of Palaeozoic rocks. As is evident in the Port Stephens-Myall Lakes region, the influence of bedrock structure on coastal topography is striking; denudation since deformation has produced ridges and valleys along a NW-SE structural trend. Typically, the ridges are composed of steeply dipping, highly resistant rocks and now form strike promontories and offshore islands, many of which are tied to the mainland by sand deposits.

More specifically, the bedrock topography and the drainage pattern in the study area between Newcastle and Seal Rocks (Sugarloaf Point) are controlled by a fold pattern which trends from N to N 40 degrees W and by associated faults (Engel, 1962). This pattern is shown in Figure 1.1. The resistant strike ridges rise to over 300 m and decline in altitude towards the coast. They are separated by valleys in which the bedrock floor may extend below present sea-level. These valleys are drained by rivers such as the Karuah and Upper Myall, whose headwaters lie on the seaward flank of the Eastern Highlands. Erosion of bedrock promontories at times of lower sea-level has left a complex of rocky hills and ridges. Near the entrance of Port Stephens dissected strike ridges form towering conical-shaped hills up to 300 m above sea-level. These hills are in part enveloped and connected by deposits of Quaternary sand. However, other rock outcrops remain isolated from the mainland by the sea (e.g. Cabbage Tree Island, Broughton Island). Sea-level fluctuations in Quaternary times have led to alternate exposure and drowning of the bedrock topography and the accumulation of sediments from various sources (Davies, 1979; Roy and Thom, 1981).

At the present time of high sea-level, the strike valleys, where they open towards the Pacific Ocean, form an embayed morphology. Rocky headlands alternate with bays of widths varying from a few hundred metres to 30 km. These bays may incorporate bayhead beaches, multiple sand barriers, complex dune fields, lagoons, estuaries and fluvial flood plains. Some of the embayments are amongst the broadest and deepest in N.S.W. They contain sections of relatively unconsolidated sediment extending to depths of 50-100 m below present sea-level. Ocean shorelines form long, gently curved bays, which in plan resemble a zeta-curve (Langford-Smith and Thom, 1969). Sand barriers within these bays may enclose water bodies whose basic configuration is to a large extent determined by the drowned bedrock topography. With the exception of the Hunter River, coastal streams debouch directly into these water-bodies which vary in type from an extensive open estuary (Port Stephens) to a shallow series of irregularly shaped lagoons (Myall Lakes system). Many swamps and portions of flood plains were formerly infilled coastal water-bodies which were open water in the mid-Holocene*.

TABLE 1-1 Selected Published Maps Covering the Port Stephens-Myall Lakes Area

1:25,000 CENTRAL MAPPING AUTHORITY - NSW

Newcastle	9232-II-S	1977	°
Wallsend	9232-III-S	1977	°
Beresfield	9232-III-N	1977	°
Williamtown	9232-II-N	1977	°
Morna Point	9332-III-N	1976	
Port Stephens	9332-IV-S	1976	
Karuah	9232-I-S	1976	
Maitland	9232-IV-S	1976	
Bombah Point	9332-I-N	1976	
The Branch	9332-IV-N	1976	
Clarencetown	9232-I-N	1985	
Paterson	9232-IV-N	1984	
Seal Rocks	9433-III-S	1981	
Myall Lakes	9333-II-S	1983	
Bulahdelah	9333-III-S	1984	
Dungog	9233-II-S	1984	
Wootton	9333-II-N	1984	
Markwell	9333-III-N	1976	

° Orthophoto Background

1:50,000 ROYAL AUSTRALIAN SURVEY CORPS

Port Stephens	9332-IV	1978
Morna Point	9332-III	1977

1:63,360 ROYAL AUSTRALIAN SURVEY CORPS

Newcastle	369	1952	*
Morna Point	397	1941	*
Paterson	388	1941	*
Port Stephens	389	1941	*
Bulahdelah	380	1940	*
Seal Rocks	381	1942	*

* Out of Print

1:100,000 DIVISION OF NATIONAL MAPPING (NATMAP)

Forster	9433	1974
Bulahdelah	9333	1984
Port Stephens	9332	1984
Newcastle	9232	1983

1:250,000 DIVISION OF NATIONAL MAPPING (NATMAP)

Newcastle	SI 56-2	1983

1:250,000 BATHYMETRIC (NATMAP)

Port Stephens	SI 56-2 & 3	1976

1:250,000 GEOLOGIC

Newcastle	SI 56-2	1966

LAND CAPABILITY SERIES 1:100,000 - SOIL CONSERVATION SERVICE OF NSW

Buladelah	9333	1983
Port Stephens	9332	1984

AUSTRALIAN CHARTS HYDROGRAPHIC SERVICES RAN

Aus. 209M Port Stephens 1:25,000	1977
Aus. 207M Approaches to Newcastle 1:25,000	1972
Aus. 809M Port Jackson to Port Stephens 1:150,000	1977
Aus. 810M Port Stephens to Crowdy Head 1:150,000	1960

BRITISH ADMIRALTY CHARTS MINISTRY OF DEFENCE, HYDROGRAPHIC DEPARTMENT

1027 Norah Head to Crowdy Head 1:300,000	1965

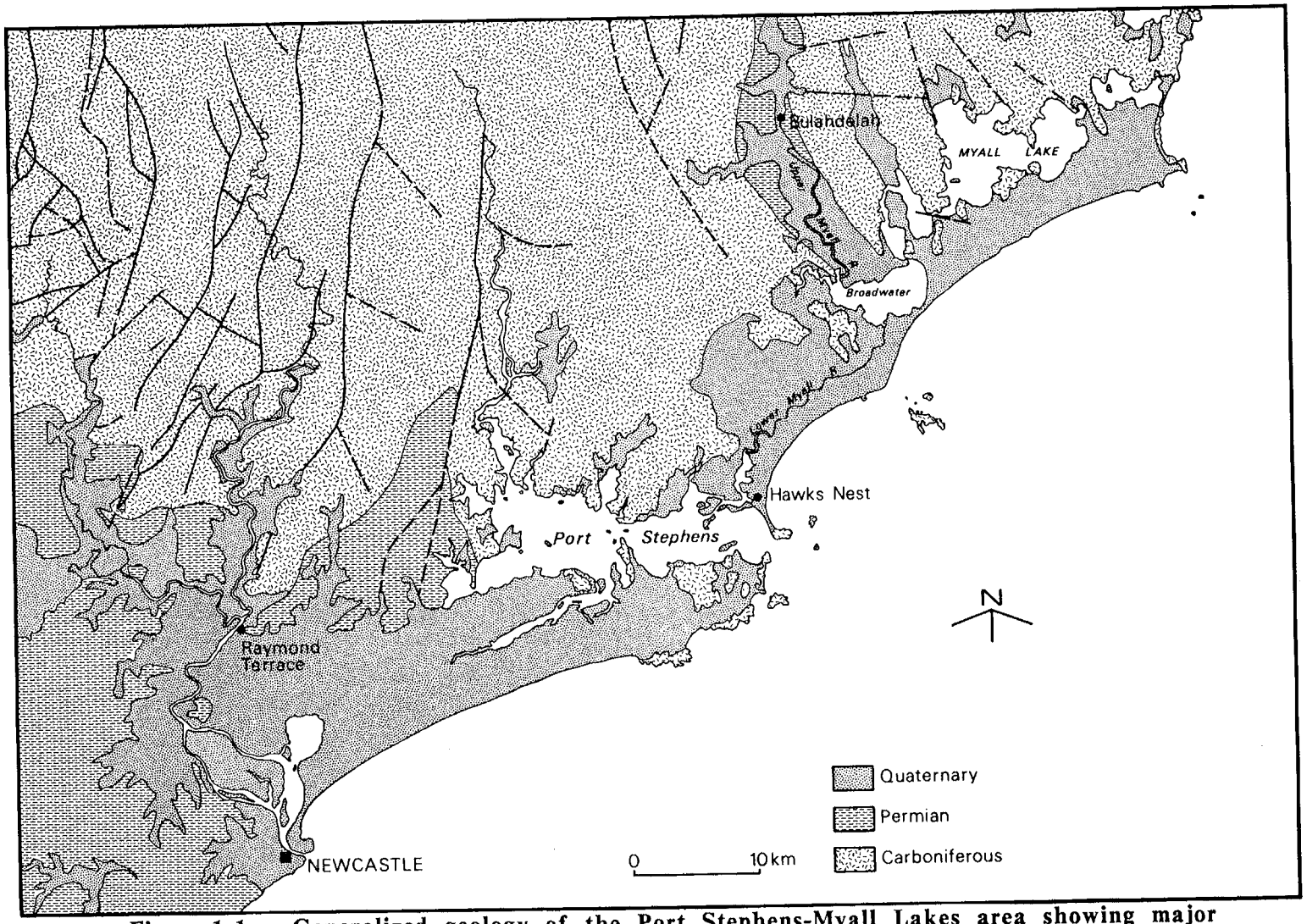

Figure 1-1: Generalized geology of the Port Stephens-Myall Lakes area showing major structural lineaments.

1.2 BEDROCK GEOLOGY

Geological research in the area extends back to 1850s when a survey of Carboniferous strata was undertaken on behalf of the Australian Agricultural Company (for a review of geological literature, see Engel, 1966). Obvious economic interest in the Permian coal measures in the lower Hunter Valley stimulated research, such as the epic memoir of David (1907), and many subsequent studies (e.g. McKenzie, 1969). In the Port Stephens area, the focus of attention has been the stratigraphy of the Carboniferous (Sussmilch and Clarke, 1928; Engel, 1962). Nashar and Catlin (1959) have studied the basaltic dykes of presumed Tertiary age which occur in the headlands flanking Port Stephens; these dykes strongly influence the morphology of bedrock cliffs where erosion has produced steep-sided clefts. Much less stratigraphic work has been undertaken in the vicinity of the Myall Lakes: two papers should be noted, one by Carey (1934) based on general reconnaissance mapping and a more detailed study by Engel (1962), the source work for the summary presented below and Figure 1-1. (See also Newcastle 1:250,000 Geological Series Sheet S1/56.2 and accompanying notes).

The study area is predominantly within the New England fold belt. The sequence is mostly of Carboniferous age. These rocks are felsic arenites together with lesser amounts of conglomerate and indurated mudstones (Engel, 1962). The sequence also includes inter-bedded volcanics, which vary in composition from rhyolite to basalt. The main structural features are shown in Figure 1-1. Subsequent faulting has disrupted the fold pattern in places. Some Permian formations apparently conformable with the upper Carboniferous strata are preserved in the Myall Syncline near Bulahdelah. In the southwestern part of the study area the "Hunter thrust system" separates the fold belt from the structural unit referred to by Bembrick et al. (1973) as the "Hunter Valley dome belt", a subdivision of the Sydney-Bowen basin.

In the lower Hunter Valley, Permian rocks outcrop or are concealed beneath Cainozoic strata, south and east of Paterson (Fig. 1-1). The Permian sequence consists of alternate marine and continental rock units, the latter being characterized by coal seams. Evidence of glaciation and vulcanism, contemporaneous with Permian sedimentation has been observed (Engel, 1966; McKenzie, 1969). The Permian sequence has been weakly folded (Medowie Syncline) and faulted. In the study area, these rocks are predominantly siltstones and are lithologically less resistant than certain units of Carboniferous age (e.g. Alum Mountain Volcanics, Nerong Volcanics). As a result, topography developed on the Permian in the

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* "Holocene" as used here is the time interval spanning the last 10,000 years. This follows internationally accepted division of the Quaternary Period. It is a different usage from that employed by Langford-Smith and Thom (1969) - 17,000 BP to present - which we still maintain is a more logical division from a coastal stratigraphic point of view coinciding with the full period of the Postglacial Marine Transgression. In this report we will use early-Holocene = 10,000 to 6000 BP; mid-Holocene = 6000 - 3000 BP; and late-Holocene = 3000 years to the present (time is measured in radiocarbon years before 1950, except where otherwise stated). Postglacial Marine Transgression is abbreviated P.M.T.

south part of the study area is subdued, in contrast to the bold ridge and valley relief to the northeast where structural trends are approximately at right angles to the coastline (Fig. 1-1). Furthermore, fine-grained sediments near Medowie have been deeply weathered, presumably in the Tertiary. Deep mottled and pallid zones have been noted in a number of quarries just above present sea-level. Although there is no doubt that this weathering has occurred in Permian rocks, there is also the possibility that Tertiary clastic deposition has occurred here and also been deeply weathered (D. Nicholson, N.S.W. Geological Survey, pers. comm., 1974).

1.3 BATHYMETRY

The continental shelf east of the study area is reasonably typical of the east Australian continental margin south of the Great Barrier Reef. This margin is characterised by a narrow shelf and a steep continental slope (Jones and Kudrass, 1982). Figure 1-2a shows the general bathymetry whilst Figure 1-2b depicts three cross-sections between Sugarloaf Point and Newcastle.

The rifted margin of eastern Australia is covered by a thin wedge of sediment (Jones, et al., 1975; Davies, 1979; Roy and Thom, 1981).

> ...the Cainozoic sequence underlying the outer shelf is thin, and furthermore has been extensively eroded; it is the relief of the buried Mesozoic or Palaeozoic basement, rather than low sea-level episodes, which provides the basic control to the gross morphology of the outermost shelf and determines the depth of the shelf break (Jones and Kudrass, 1982, p. 57).

Nevertheless, the Quaternary has left its mark on shelf morphology. Several authors have identified terraces, notches, nick points, beaches, estuarine/lagoonal surfaces and other shoreline features (e.g. Phipps, 1966; Boyd, 1974; Jones and Davies, 1979; Davies, 1979; Roy and Thom, 1981; Jones and Kudrass, 1982).

The continental shelf east of the study area can be subdivided into four zones: nearshore, inner shelf, mid to outer shelf and shelf break. The nearshore zone is quite concave in profile and descends from the surfzone to water depths of 20 to 25 m (see Ch. 3). It is often quite modified off rocky headlands such as south of the entrance to Port Stephens (Fig.1-2a). In comparison, the inner shelf possesses a lesser gradient to depths of 60 to 75 m. Kudrass and Jones (1982) identify a steepening of the outer margin of this zone (termed the inner shelf apron by these authors) with a pronounced change of slope at about 75 m. The mid to outer shelf has long been recognized as a sub-horizontal plain gently sloping seawards. Figure 1-2 shows in plan and sections the relatively broad nature of this plain. Relict shoreline features forming undulations have been identified in this zone. Between Newcastle and Sugarloaf Point (Seal Rocks), the shelf break occurs between 140 and 160 m. The sharp nature of the break is shown in Figures 1-2a and 1-2b.

Details of the morphology, sediments, surficial stratigraphy based on vibro coring, and seismic stratigraphy have been recently summarized in various papers in the cruise report of the SONNE (SO - 15, see von Stackelberg, editor, 1982). Earlier studies by Shepherd (1970), Boyd

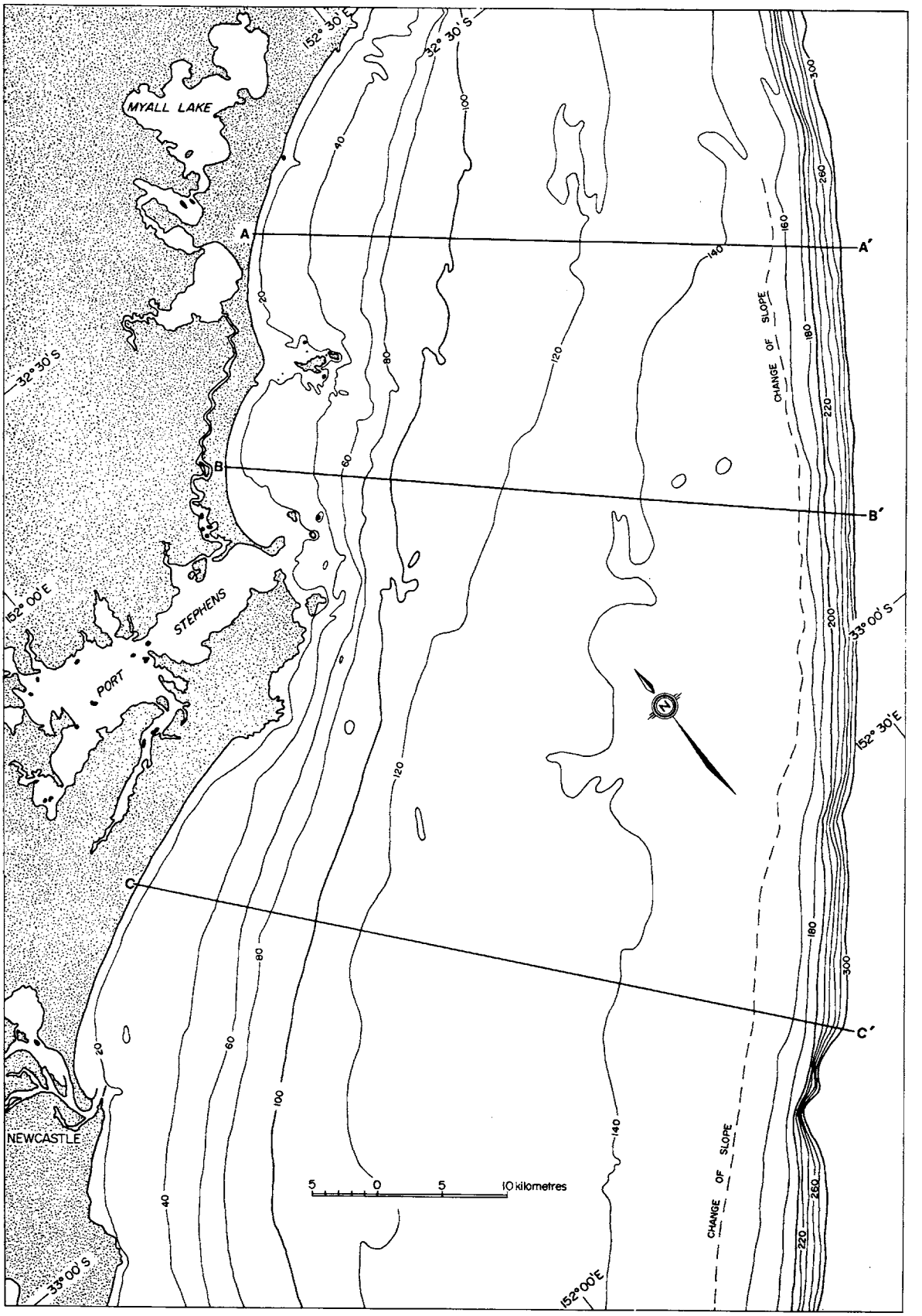

Figure 1-2a: Generalized bathymetry of the continental shelf between Newcastle and Seal Rocks (depths in metres) showing location of cross-sections depicted in Figure 1-2b.

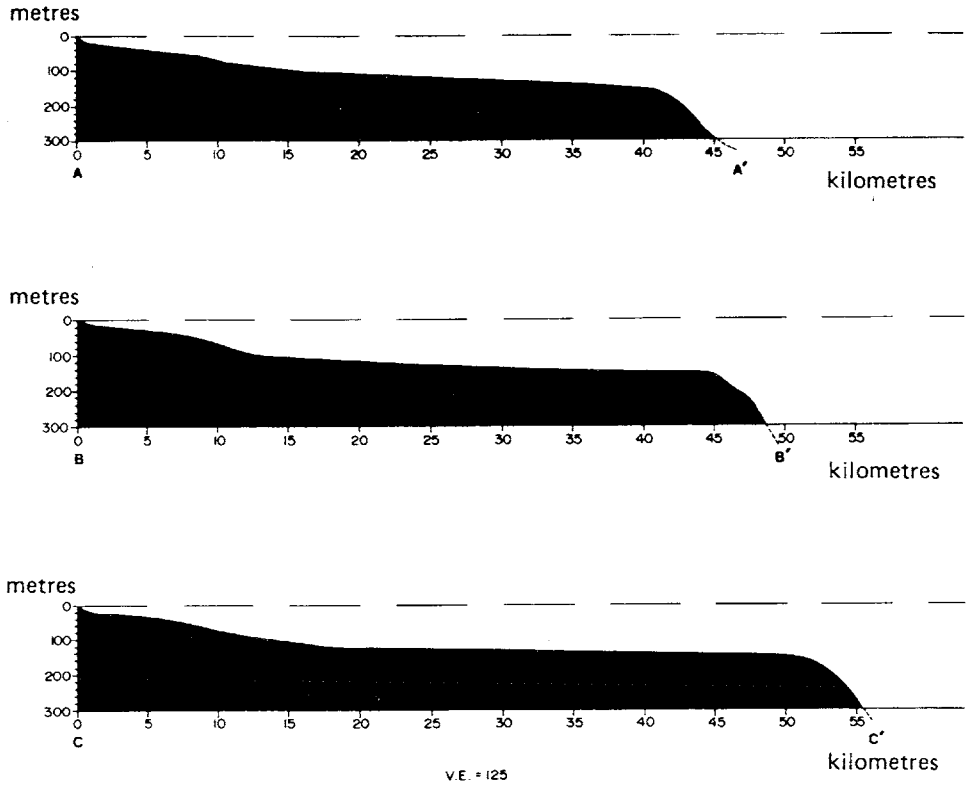

Figure 1-2b: Three cross-sections of the continental shelf: A-A' offshore from Eurunderee embayment; B-B' offshore from Fens embayment; and C-C' offshore from Newcastle Bight.

(1974) and Roy and Crawford (1980) contain useful information on the shelf off the Port Stephens-Myall Lakes coast. This area now represents one of the most well known parts of the east Australian continental shelf. Any understanding of coastal plain deposition in relation to sea-level movements in the Quaternary must take cognisance of shelf geology and morphology. Although the shelf is not the subject of this monograph, an attempt is made in Chapter 10 to integrate shelf history with coastal barrier formation.

1.4 CLIMATE

1.4.1 General Character

The area has a humid temperate climate (Koppen: Cfa). In common with much of SE Australia, it is influenced by a variety of air masses and pressure patterns of varying intensity, seasonal incidence and duration. These are discussed in more detail by Tweedie (1963) and Gentilli (1971). The following brief summary is relevant because changes in weather patterns as well as climatic change are considered significant in the evaluation of sand dune genesis (see also Climatological Atlas, Hunter Valley, 1985).

In winter, this coastal stretch is strongly influenced by southern maritime air masses. Depending on the travelling pressure systems in relation to the trend of the N.S.W. coast, the area may be influenced by one of three weather types (Tweedie, 1963). Southern maritime air masses that cross the coast before reaching the Hunter Valley are relatively dry and cold, and are accompanied by strong westerly winds. This weather type predominated during autumn and winter of 1960. However, there are travelling depressions which produce onshore streams of maritime air; these depressions are often associated with rainfall on the coast and adjacent highlands and strong southerly winds (e.g. in the winter of 1962). A third weather type, which is generally less frequent but may be especially important in some years, perhaps in response to warmer sea surface temperatures, involves the formation of depressions of extra-tropical cyclones off the N.S.W. coast (Thom, 1978). Strong winds, relatively warm air, and high rainfall are the product of such depressions. In 1950, 1967 and 1974 the third type predominated resulting in extensive coastal erosion (see Foster et al., 1975; Thom, 1974, 1978; Thom et al., 1973; McLean and Thom, 1975).

In summer, weather sequences normally progress from cool and relatively stable southern air masses, through "indifferent" air masses frequently accompanied by northeast sea breezes and occasional thunderstorms, to the inflow of moist warm air of tropical maritime origin associated with locally heavy rain (Tweedie, 1963). Heat wave conditions involving a strong flow of hot dry air from the NW are infrequently experienced in summer. Tropical cyclones very rarely extend this far south, and their direct influence upon coastal landforms in the study area is not apparent. However, they do modify the summer wave regime (see below). The passage of a sharply defined trough yields the "Southerly Buster", a frequent summer weather event to the south of Newcastle, but incidence in the study area is perhaps less significant.

1.4.2 Temperature and Precipitation

Table 1-2 summarizes the temperature and precipitation characteristics for Newcastle. The weather station for this centre is located on the coast at Nobbys Signal Station. Although slightly higher summer temperatures may be experienced at inland sites such as Bulahdelah and Raymond Terrace, the area within 30 km of the coast possesses a relatively uniform temperature regime. In winter, frosts are rare so that plant growth is not inhibited by this factor. Summer temperatures are markedly tempered by sea breezes in comparison with inland stations, such as Maitland (Tweedie, 1963).

There is no marked seasonality in the distribution of precipitation though a late autumn-early winter maximum with a secondary maximum in December has been noted (Tweedie, 1963). Spring is the dry season; at Seal Rocks the rainfall averages less than 76 mm (3") only in November (Mineral Deposits Ltd., 1973). Variation in distribution of rainfall for three stations, Newcastle, Port Stephens, Seal Rocks, for the period 1915 to 1959 is shown in Figure 1-3. In spite of general uniformity of seasonal precipitation, over a given period rainfall can be highly variable from month to month and year to year (Fig. 1-3). Monthly variability is highest in late autumn - early winter, perhaps reflecting the irregularity of cyclogenesis during this period in the Tasman Sea. Heaviest rainfall comes from depressions developed off the east coast;

during periods of strong SE winds daily totals may reach 200 mm (8"). The most intense rainfalls are associated with summer thunderstorms. Given generally adequate temperatures for plant growth, variability in the rainfall regime appears to be an important factor in controlling the rate of plant growth.

1.4.3 Evaporation

Evaporation is poorly documented, especially in relation to variations in topography, soil type and plant cover. Table 1-2 lists water balance statistics for Newcastle. These figures suggest that the most likely period of moisture deficit is from November to January. It has been suggested by Tweedie (1963) that growth will be most active in spring when plants are able to use water stored over winter and in summer and autumn when sporadic rains are combined with high temperatures. In permeable sandy soils, however, moisture deficiency may build up rapidly, and given the regions variability in seasonal and annual precipitation, it is likely that the soil moisture reservoir is periodically depleted. The effect of such stress on plant growth depends on moisture-storing capacities of individual species growing in sandy environments. For instance, Carolin (1971) has shown that during dry periods one species of Banksia will have a competitive advantage over another. It is likely that there will be no reduction of plant cover of dunes because of reduced precipitation. However, this point deserves further study.

TABLE 1-2 Climate Statistics, Newcastle, N.S.W.

	Jan	Feb	Mar	Apr	May	Jun	Jul
Rainfall mm	76	75	98	135	118	93	113
Variability %	53	65	54	60	61	71	51
Number of Wet Days	12	11	11	13	12	12	11
Rain Per Wet Day mm	6	7	9	10	10	8	10
Maximum Temperature °C	25.4	25.4	24.5	22.3	19.5	17.2	16.3
Minimum Temperature °C	19.2	19.5	18.2	15.3	12.1	9.7	8.7
Mean Temperature °C	22.3	22.4	21.2	18.8	15.8	13.4	12.6
Mean Relative Humidity %	74	76	76	74	74	71	70

	Aug	Sept	Oct	Nov	Dec	Year
Rainfall mm	59	75	64	56	88	1050
Variability %	45	54	65	57	56	16
Number of Wet Days	10	7	8	10	11	128
Rain Per Wet Day mm	6	11	8	6	8	8.3
Maximum Temperture °C	17.8	20.1	21.8	23.3	24.4	21.3
Minimum Temperature °C	9.3	11.4	14.0	16.3	17.9	14.3
Mean Temperature °C	13.6	15.8	17.9	19.8	21.2	17.9
Mean Relative Humidity %	68	67	69	71	75	73

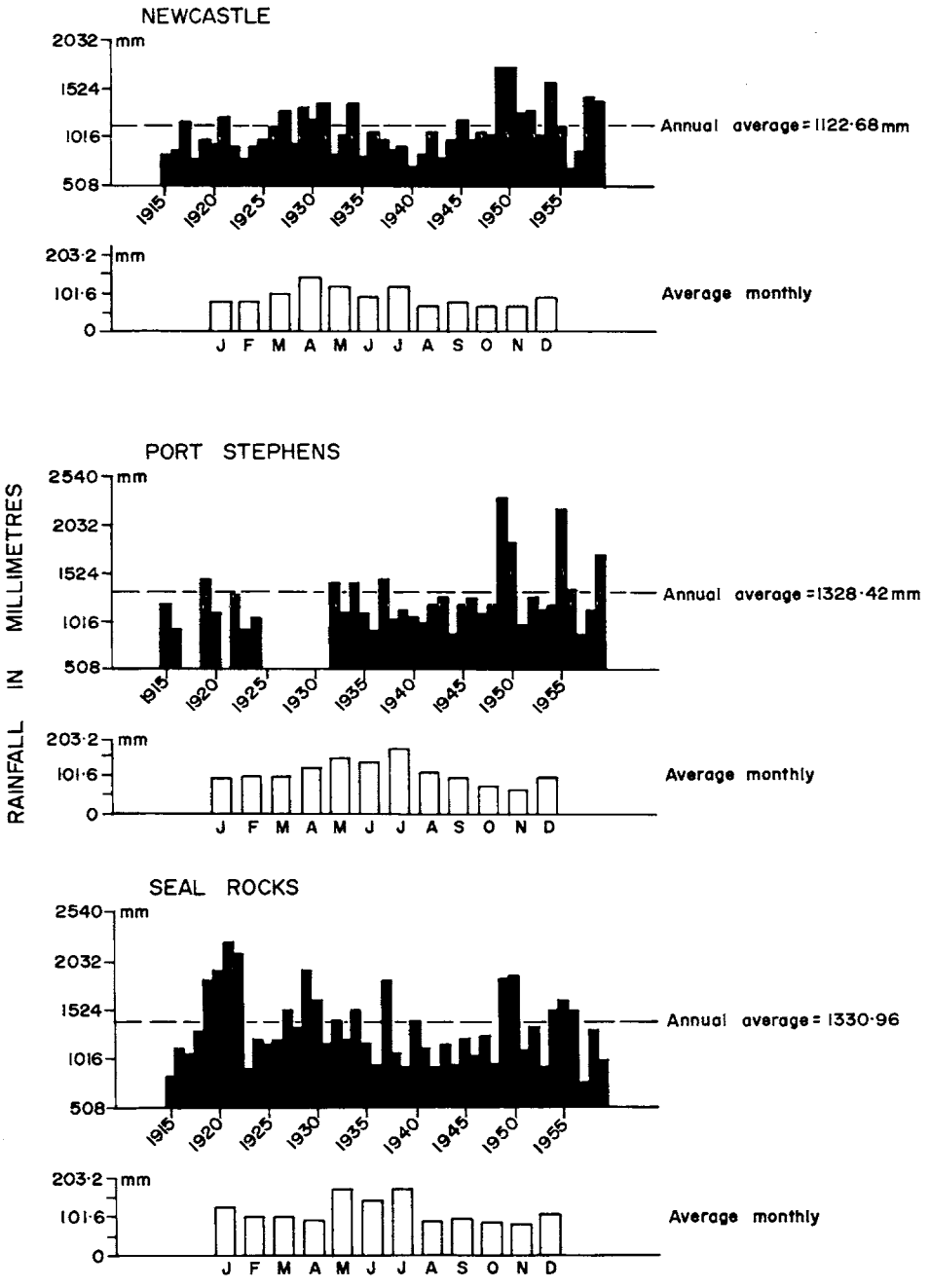

Figure 1-3: **Rainfall patterns from Newcastle, Port Stephens and Seal Rocks showing annual variability and average monthly precipitation. Variability between stations from year to year along a coastal stretch of 100 km is quite noticeable.**

1.4.4 Wind Regime

Two recording stations are operating in the study area: Newcastle at Nobbys and the Williamtown R.A.A.F. base. The later is located 13 km to the north of Nobbys and is 5 km from the sea. Records for Williamtown date back to 1943 and are more complete than those from Nobbys. Wind data from both stations have been studied in detail by Public Works Department (P.W.D., 1977), Bridgman (1978, 1979), Kwok and Bridgman (1979) and Hesp (1982).

The major components of the wind regime can be summarized as follows:

(a) westerlies blow mainly in winter and are associated with moving anticyclones across southern Australia;
(b) southerly to easterly winds resulting from the passage of mid-latitude cyclonic depressions, especially in winter, and depressions which form in the Tasman Sea (chiefly but not exclusively an autumn-early winter phenomenon);
(c) rare tropical cyclones in summer resulting in strong winds from north through east to south;
(d) onshore sea breezes of spring, summer and early autumn attaining moderate velocities in mid-afternoon.

Analysis of the climatological wind situation at Nobbys by Bridgman (1978) indicates that the annual wind regime can be divided into four sections:

(i) December through March when winds from the southeastern quadrant are dominant;
(ii) April, a transition month;
(iii) May through September when winds from the northwestern quadrant are dominant; and
(iv) October-November, a transition period (see Fig. 7 in Bridgman, 1978, p. 6).

In some years the winter wind regime may show greater duration and velocity of east to southeast winds over westerlies. As demonstrated by Karelsky (1954) this may be the product of a more southerly track of anticyclones combined with increased cyclogenesis in the Tasman Sea (see also Thom, 1978). The effect of such variability on the stability and morphology of mobile dune sheets will be discussed below. Similarly, variation in the incidence of southerly winds during summer, as noted by several writers (e.g. Gentilli, 1971), in comparison with the strength of sea breezes is manifest in the pattern of sand movement.

The annual wind regime for the two stations is shown in Figure 1-4. These wind roses have been prepared by P.W.D., (1977, Figs. 7-1 and 7-2) based on data provided by the Department of Defence. The percent frequency of winds above the threshold velocity of sand transport is indicated in these roses. A greater frequency of calm periods is reported for Williamtown.

In Figure 1-5 the Bagnold-Landsberg method for determining the resultant direction of sand transport has been used. This method only employs wind velocities capable of transporting sand where the rate of

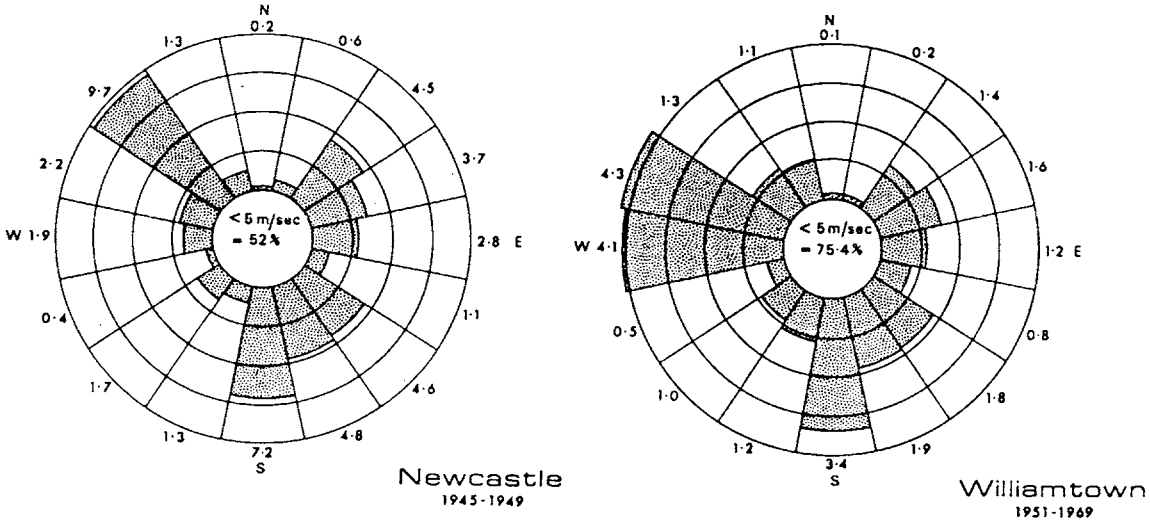

Figure 1-4: **Annual wind regimes for Newcastle (Nobbys Signal Station) and Williamtown RAAF base from data assembled by the Public Works Department for two different time periods (see PWD, 1977).**

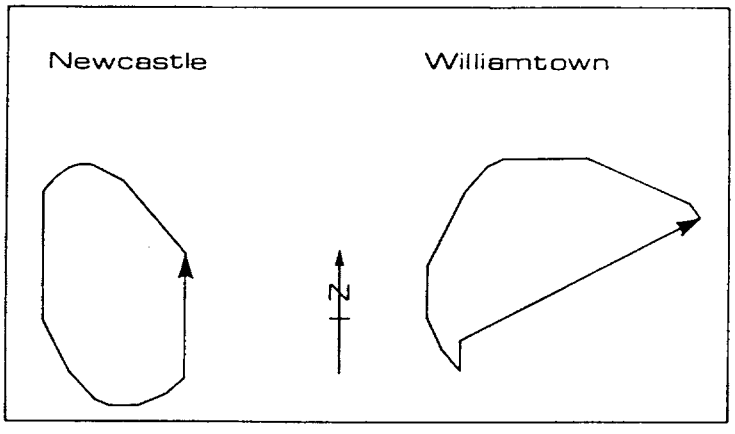

Figure 1-5: **Resultant directions of sand transport for Newcastle and Williamtown calculated by using velocities which exceed the threshold value of sand transport by wind (see Landsberg, 1956). Wind data used in the computation cover the period 1944-1949 for both stations.**

sand movement is proportional to the cube of wind speed (Bagnold, 1941; Landsberg, 1956; Thom, 1960, Appendix 4; Shepherd, 1970, Appendix II; P.W.D., 1977). The data covers the period 1944-49. Williamtown shows a stronger westerly influence than Newcastle. It is possible that during this period the area experienced more than normal NW-WNW winds (Mr. Moss, State Climatologist, Sydney Weather Bureau, pers. comm., 1960). Winds between SW-W are said to be more typical. However, a comparison with data for two other periods 1951-57, 1961-65 shows only minor variations in wind regime between the three periods. The Newcastle station reflects its more maritime position, and is considered more representative of coastal dune sites even though it is located at the extreme south of the study area. Onshore E-NE winds are more apparent at Newcastle than Williamtown (Fig. 1-5). The resultant wind direction for Nobbys is 175 degrees compared to 252 degrees for Williamtown. The effect of winds on the transport of sand on the Newcastle Bight dune sheet will be discussed in Chapter 4.

1.5 WAVE CLIMATE

1.5.1 General Character

Whereas the local wind regime determines eolian sand movement and the properties of waves within coastal lagoons, ocean waves may also be generated by climatic conditions prevailing more than a thousand kilometres away. In the past decade there have been a number of papers which have stressed the importance of swell waves produced by the passage of cyclonic depressions south of Australia (Davies, 1958, 1972; Bird, 1961). As these waves move across the narrow continental shelf they are refracted, so that predominate wave direction in coastal waters is southeasterly. Nevertheless, they remain strong enough to produce moderate to high wave energy conditions on the New South Wales coast (Wright, 1976).

Many refraction diagrams have been constructed for different sections of the coast and they show in general an adjustment between plan form of sandy shorelines and refracted northeast swell (10-12 second period) (see above references, plus Hails, 1964; Wright, 1970).

Until 1968, wave data in eastern Australia were obtained from either shipboard/lighthouse observations or by hindcasting (e.g. Hogben and Lumb, 1967). In hindcasting wave characteristics for the Sydney region from weather maps by the S.M.B. method, Stone and Foster (1967) showed about half the waves over 1 m or so in height arrive from the south, the remainder from the southeast and east. They recognized that the technique underestimated waves generated by sea breezes. They estimated the median wave height of 2 ft. (0.6 m).

The use of "Waverider" buoys off the Gold Coast since 1968, off Botany Bay since 1971, off Port Kembla since 1974, and off Newcastle since 1976, has produced a new dimension in the analysis of wave climate (Delft, 1970; McGrath and Paterson, 1973; Abernethy and Lawson, 1973; Lawson and Abernethy, 1975; Thom et al., 1973; Wright, 1976; Lawson and Youll, 1977; Short and Wright, 1981). We certainly know more today about deep-water wave height and period off the central N.S.W. coast and some of the atmospheric disturbances responsible for wave conditions than we did a decade ago. Wave direction is not nearly as well known. This

new information can be summarized as follows:

(a) Estimates of significant wave height by the hindcasting technique are low compared with "Waverider" data.
(b) Distinction should be made between background swell generated from southern latitudes and wind-driven storm waves produced within the Tasman Sea by a variety of types of atmospheric disturbances.
(c) Wright (1976) has shown that 90 percent or more of deep-water wave energy is dissipated within one kilometre of the shoreline along the N.S.W. coast.

1.5.2 Seasonal Wave Regime

In the study area, wave conditions are generally comparable with those off Sydney, except that the more E-W orientation of the coast strengthens the influence of waves from the south. As winds from the southerly quadrant (SE-SW) are more likely to be accompanied by squalls and storms than winds from any other direction, then higher energy conditions may prevail along sections of the coast between Newcastle and Sugarloaf Point than along any other portion of the N.S.W. coast. This view is supported by the statement in the R.A.A.F. Manual (1944) based on an analysis of weather records, 1929-1944, that "gales are perhaps more frequent along the central coast of N.S.W. than further north or south" (p. 26).

Swell waves generated to the south and southeast of the continent, beat against the Newcastle-Sugarloaf Point coastline all year round. The majority of swell energy arrives from the southeast and south although the coast receives swell from all offshore directions. It is possible that swell waves are of greater magnitude in winter months, and if this is the case, their occurrence at times of offshore winds can explain periods of beach accretion which sometimes takes place in the winter half of the year (Thom, 1974). This interaction of wave, wind and beach conditions has been observed in the Sydney area and on the South Coast of N.S.W. (Thom *et al.*, 1973). Deepwater swell waves are long-crested, sinusoidal in form and have periods ranging from 6 to 14 seconds.

There are many winters which are characterized by frequent cyclonic disturbances either associated with frontal passages, or developed as cut-off depressions in the Tasman Sea. In these winters, westerly winds are subordinate in magnitude if not frequency to southeasterly winds. High energy sea conditions have been observed during such winters and beach-dune erosion often results (Thom *et al.*, 1973; McLean and Thom, 1975; Foster *et al.*, 1975). Weather systems associated with various beach morphologic responses have been described by Thom *et al.* (1973) (see also Short and Wright, 1981). Evidence exists for periods of 6 to 18 months duration when coastal storms are much more frequent and intense than "normal". Such periods recur irregularly along the central N.S.W. coast based on historical records (Thom, 1974; Chapman *et al.*, 1982). That stormy periods are associated with warmer than normal sea surface temperature conditions has been postulated by Thom (1978).

The summer half of the year is characterized by afternoon sea breezes generating steep but low amplitude waves (1-2 m) superimposed on the low background swell. As noted by McKenzie (1958) sea-breeze waves can be associated with local and minor beach erosion, but more commonly beach fill. Trough disturbances and associated waves from south to east

also occur in summer, although they are generally less intense than in the winter. Cyclones of tropical origin infrequently move down the N.S.W. coast or into the southern Tasman Sea in late summer, giving rise to moderate to rough seas from the easterly quadrant. They can produce waves along the central coast as high if not higher than extra-tropical cyclones developed within the Tasman Sea in winter.

Figure 1-6 is a wave-height exceedance diagram based on "Waverider" data from Newcastle. Analyses of "Waverider" records from here and from Sydney and Botany Bay indicate that storm waves may attain significant wave heights (the height of the highest 1/3 of the waves in a spectrum) of 10 m or more (Lawson and Abernethy, 1975; Foster et al., 1975). During the storms of May, 1974, peak wave heights of over 9 m accompanied a period of 16 seconds (Foster et al., 1975). Three years of "Waverider" records at Sydney reveal that the highest storm waves have the shortest duration. However, storm wave height in excess of 2.5 m may be expected to persist for over 24 hours (Lawson and Abernethy, 1975; Lawson and Youll, 1977; Short and Wright, 1981).

Data collected by the N.S.W. Maritime Services Board from its "Waverider" stations are now of sufficient duration to further define the wave climate of the central coast (see Lawson and Abernethy, 1975; Lawson and Youll, 1977). A tabulation of probability of occurrence of waves from varying durations is presented in Table 1-3 (from Lawson and

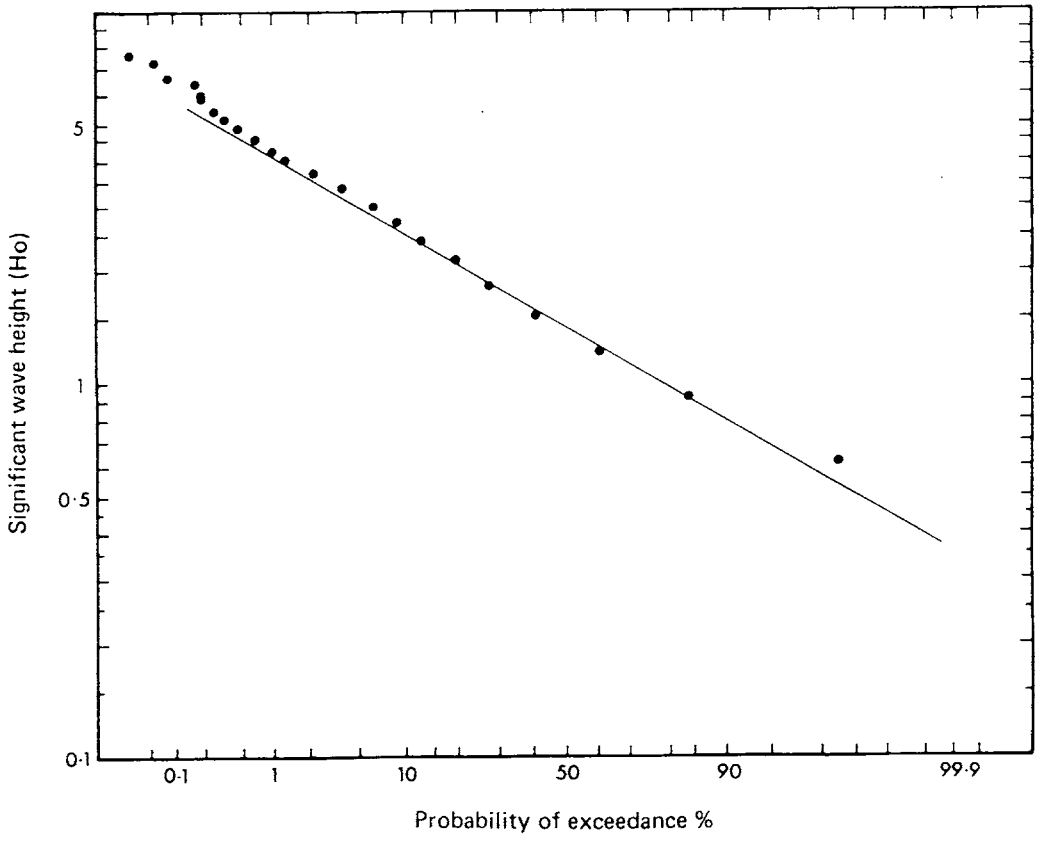

Figure 1-6 **Wave-height exceedance curve based on observations and analysis of "Waverider" records from a deep-water (76 m) site off Newcastle (information supplied by Maritime Services Board of NSW).**

TABLE 1-3 Wave Conditions, Sydney, N.S.W. (from Lawson and Abernethy, 1975)

(a) Seasonal Variations - Direction (%)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
N	-	-	-	-	-	-	1.1	-	-	0.2	0.2	0.4
NNE	2.6	1.5	-	1.8	-	-	0.7	-	5.6	7.0	2.3	3.6
NE	22.6	17.4	21.0	20.2	4.1	3.5	7.5	2.8	17.9	20.0	8.2	14.0
ENE	18.6	21.5	13.3	14.3	9.0	4.0	5.9	9.2	11.1	20.5	10.3	16.7
E	16.6	18.7	14.0	7.2	9.1	11.8	6.7	7.5	8.4	9.2	9.7	17.0
ESE	10.0	15.9	12.2	9.1	9.9	11.0	7.3	6.2	9.5	7.2	9.1	14.8
SE	14.5	10.0	11.4	9.8	11.1	15.1	11.2	23.2	23.1	7.5	19.8	12.0
SSE	9.6	9.9	11.4	10.0	27.0	22.5	23.0	13.4	12.2	8.3	19.7	9.2
S	5.5	5.1	16.7	27.6	28.0	28.0	34.2	33.1	12.2	20.1	21.7	12.3
OTHER	-	-	-	-	1.8	4.1	2.4	4.6	-	-	-	-
P	1.0	1.0	1.0	1.0	.982	.959	.976	.954	1.0	1.0	1.0	1.0

(b) Seasonal Variations - Wave-Heights

	Jan	Feb	Mar	Apr	May	June	Jul	Aug	Sep	Oct	Nov	Dec
H (m)	2.49	2.65	3.16	2.27	2.62	2.69	2.73	2.52	2.12	2.27	2.81	2.2
H (m)	0.69	1.01	1.04	.78	.79	.78	.81	.73	.77	.92	.95	.86

(c) Directional Data (included all periods)

Direction	H (m)	H (m)	P
N	-	-	.002
NNE	2.17	0.83	.021
NE	1.87	0.83	.131
ENE	2.04	0.83	.129
E	2.14	0.84	.112
ESE	2.76	0.87	.100
SE	2.76	0.93	.141
SSE	2.96	0.89	.147
S	3.05	0.89	.206
ALL (N-S)	2.58	0.85	.989

Abernethy, 1975). Although based on Botany Bay data, the same frequencies have been assumed for waves offshore at Newcastle (P.W.D., 1977). Waves from the south and southeast are most frequent in winter months whereas waves from the northeast are most common in summer. The highest waves are, on the average, those which arrive from the south and southeast. Figure 1-6, the exceedance diagram, designates the probability of any given significant wave height being exceeded. For Newcastle significant wave height exceeds 1 m about 80 percent of the time and exceeds 4 m for 1 percent of the time.

1.5.3 Wave Refraction Patterns

Wave refraction diagrams have been constructed by Shepherd (1970, see Appendix Ib) for the coast between Port Stephens and Sugarloaf Point using the method of Wiegel (1964). Some of these are reproduced here in Figure 1-7a,b. Where complicated refraction patterns are caused by offshore islands near the entrance to Port Stephens and shoals off Sugarloaf Point, the resulting confused pattern has been omitted from the diagrams. The patterns show:

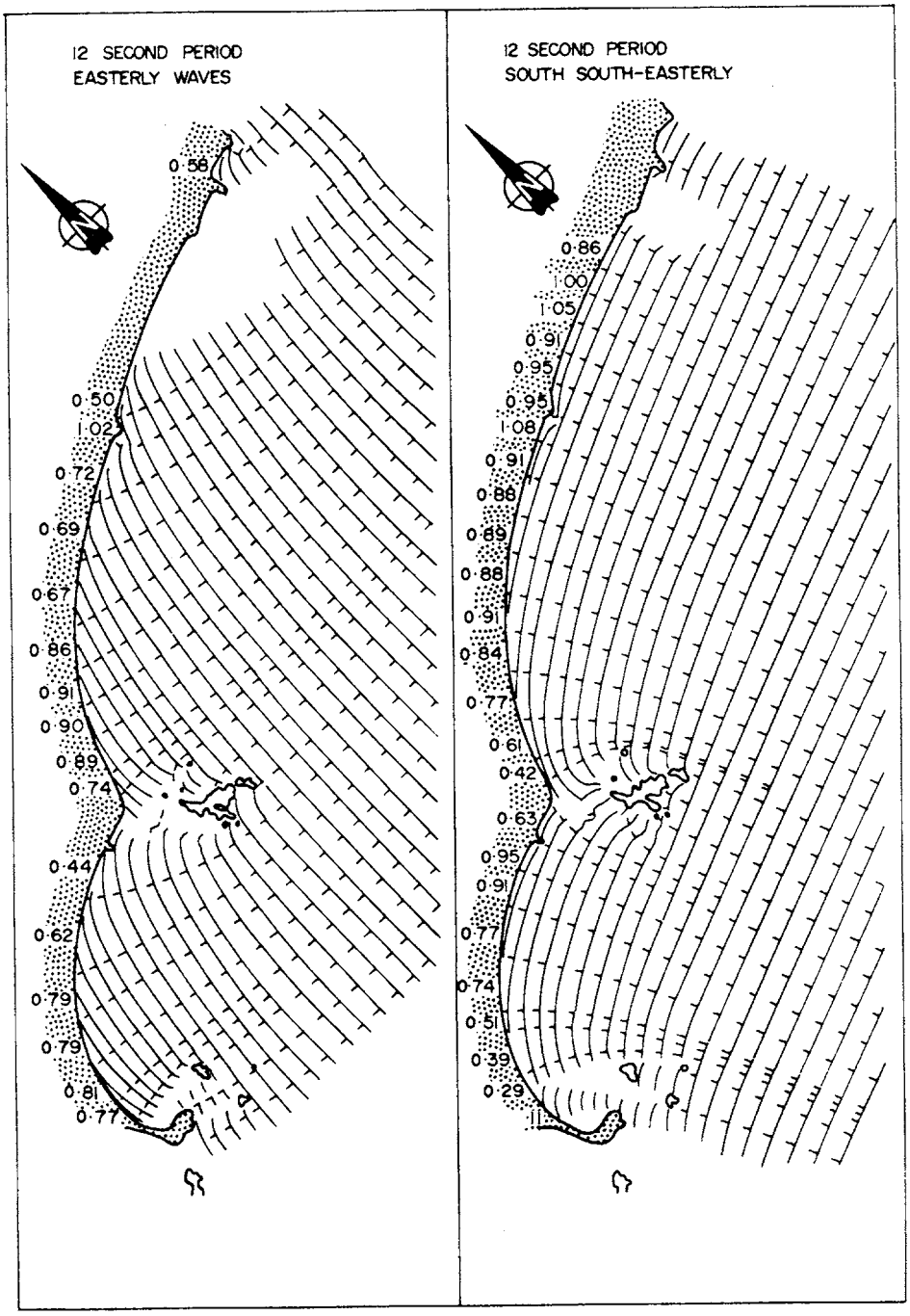

Figure 1-7a: Wave refraction diagrams for the stretch of coast between Port Stephens and Seal Rocks for 12 second swell waves from E to SSE directions (from Shepherd, 1970).

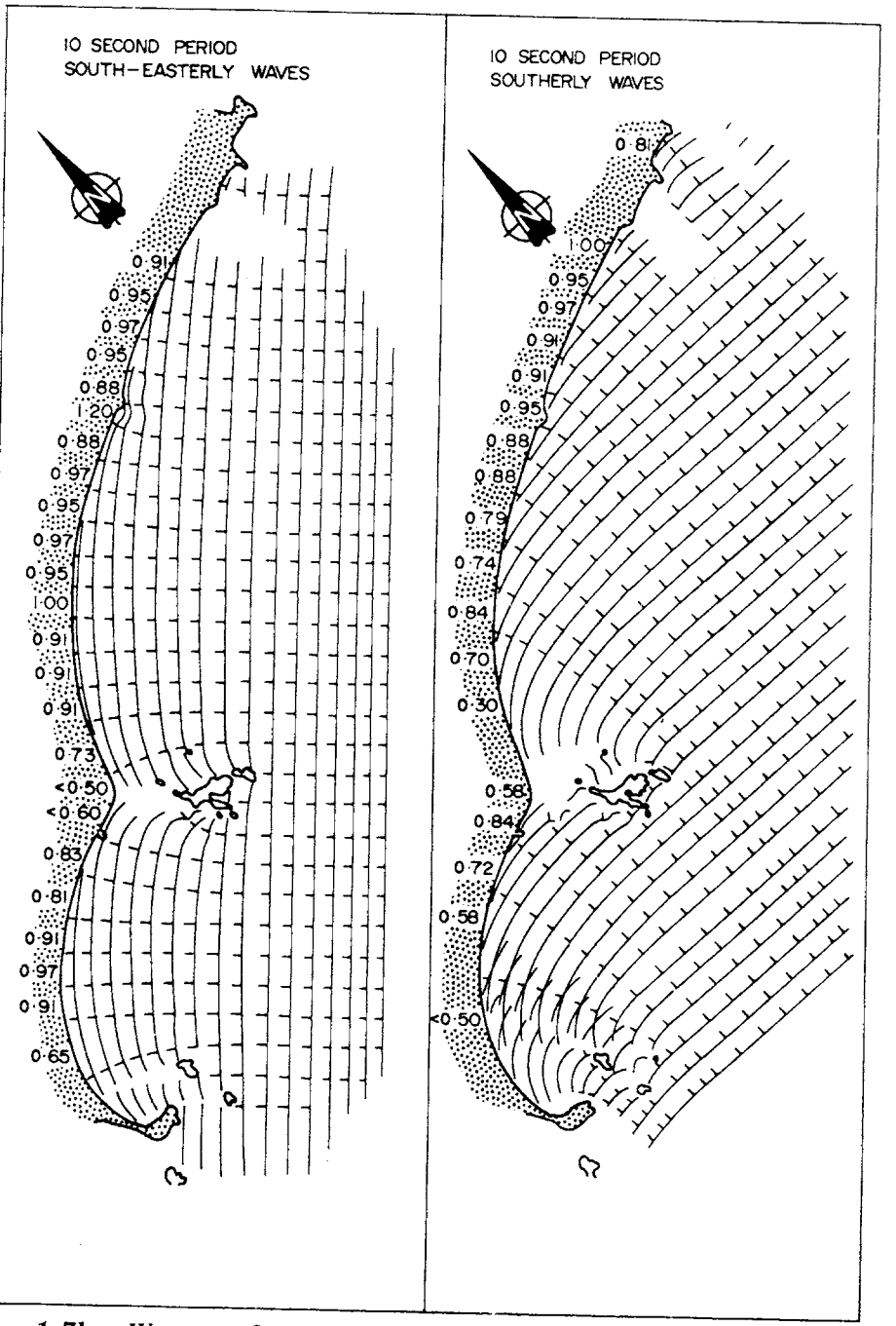

Figure 1-7b: Wave refraction diagrams for the stretch of coast between Port Stephens and Seal Rocks for 10 second swell waves from SE and S directions (from Shepherd, 1970).

(a) Refracted southeasterly and south-southeasterly waves best "fit" the beach plan, the fit for longer period waves (+10 seconds) being better than that of shorter period waves (Fig. 1-7a,b).
(b) Easterly and southerly waves and all waves with periods of 8 seconds or less are not concordant with the plan outline of beaches (Fig. 1-7c).
(c) Sandy Point is a cuspate foreland aligned to southeasterly and south-southeasterly waves which converge after being refracted around Broughton Island.
(d) Fens beach is partially protected by headlands and islands from the full effects of southerly waves which account for 60 percent of wave energy. Consequently the southern end of the beach is aligned to refracted easterly waves, the central section to refracted southeasterly waves and the exposed northern section to south-southeasterly waves.
(e) To the south of Seal Rocks, where the beach is exposed to both southeasterly and south-southeasterly refracted waves, it is the south-southeasterly waves which best "fit" the beach.
(f) The northeastern end of Newcastle Bight is apparently aligned to a wave approach from the direction of 150 - 170 degrees N. Analysis by P.W.D. (1977) of gross sand movement due to longshore energy flux derived from wave refraction analysis shows that the quantity of net littoral drift is small (<10 percent of gross littoral drift). This is because the beach is well aligned to the predominant wave direction.

Beaches along the N.S.W. coast are not perfectly adjusted to the resultant direction of highest wave energy. This has been shown by vector analysis of Stone and Foster (1967) data to be 160 degrees (Shepherd, 1970). The north-northeasterly/south-southwesterly trend of the coast reduces the exposure to the full effects of southerly waves. However, in the study area the more easterly trend of the coast, dictated by the alignment of bedrock headlands and offshore islands, creates conditions not only of higher inshore wave energy, but also for adjustment to more south-southeasterly waves.

It is considered likely that zeta-shaped bays may not result from a simple adjustment of plan form to a particular wave type from a given direction; instead we have to consider the total spectra of wave heights, periods and directions of varying magnitudes and frequencies. The equilibrium plan of the zeta-shaped bay represents an adjustment between sand-transporting capacity of waves, the structural trend of the coast and the bathymetry. The long-term tendency is for wave energy to be dissipated in a direction normal to the beach, but in the short-term frequent shifts in wave properties, including directions, results in a continual adjustment to the plan and profile of the beach and nearshore zones (see P.W.D., 1977, evaluation of Newcastle Bight). However, the existence of prominent headlands (e.g. Morna Point) somewhat inhibits the exchange of sediment between embayments. When sea-level was lowered to the level of shelf plain, a more or less continuous coastal plain 10-15 km seaward of the present shoreline would have offered few obstacles to littoral drift (Roy and Thom, 1981).

1.5.4 Storm Surges and Set-up

In addition to wind-generated ocean waves and swell, strong winds and migrating low-pressure systems can create lower frequency rises in mean water level (see Foster et al., 1975; Wright et al., 1979). In many cases these rises in the water surface are far more destructive to beaches and property than the storm waves themselves. There are two general types of storm-related water level rise:

(i) storm surges (or meteorological tides) generated by the combined influence of shoreward wind stress and low barometric pressure; and

(ii) wave set-up induced by the shoreward mass-transport of water in steep, high waves which causes a piling up of water against the shore. Both types have important effects on the New South Wales coast.

Surges on the New South Wales coast are normally much less than 1 m in height. Wave-induced set-up may produce water level rises of as much as 10 to 20 percent of the wave height (Foster et al., 1975). Analyses of tide records taken during the severe storm of May, 1974 (Foster et al., 1975), revealed a storm surge of 0.23 m. Wave set-up appears to be more significant than surge, at least along the open coast. Foster (1974) estimated the set-up accompanying the May 1974 storm to be of the order of 1.5 to 2.5 m.

1.6 CURRENTS AND TIDES

1.6.1 Ocean Currents

The East Australian Coast current flows southward along the Australian coast from the region of Fraser Island in Queensland to past Cape Howe (Australian Pilot, 1960). This current was believed to form the western side of the general counter-clockwise circulation of the South Pacific Ocean (ibid, p.7). The chief source of water for the East Australian Coast current is the South Sub-Tropical Current which is characterized by a south-westerly flow of warm, nutrient-rich water in the Coral Sea. Various features of this large-scale system have been discussed by Hamon (1965), Nilsson et al. (1977) and by Godfrey et al. (1980).

Off the central N.S.W. coast the current occupies a belt from about 30 to 100 km from land. Its greatest strength is near the 100 fathom (183 m) line, and lies between 30 and 40 km from the shore in the area studied. Current velocity varies between 1 and 4 knots, but may reverse direction when strong southerly winds are blowing. There are considerable seasonal variations; the southerly-setting currents are strongest from December to March, but during winter the southerly currents weaken and northerly flows become more frequent (Australian Pilot, 1960, Fig. 3). As the majority of the northerly currents do not frequently exceed one knot, the net flow of water is still to the south in winter.

In recent years detailed studies have been undertaken on the East Australian current. No longer is it considered, as shown in some atlases (eg. British Admiralty, 1960), a continuous and unidirectional current (Hamon, 1965) and Nilsson et al. (1977) have documented the existence

of anticyclonic eddies apparently shed from the East Australian current. Warm core, closed, mesoscale eddies have been repeatedly observed off the southern coast of Australia. One eddy was observed to form around latitude 35 degrees S during the period February-March 1975. This eddy was resurveyed seven weeks later, having moved only about 45 km westward. It had then assumed a more circular and stable shape. The principal feature of the eddy was a subsurface lens-shaped core of warm isothermal water which formed in less than 10 days (Nilsson et al., 1977, p.659). The inner edges of such eddies exhibit north to south flow. However, flow is south to north further offshore (see Godfrey et al., 1980, for further data on flow patterns).

Surface currents over the inner shelf are dominated by the landward edges of these eddies. The Australian Pilot (1960) noted that just south of Port Stephens, the current sometimes sets towards the land (i.e. to the south-west). Inshore of the southerly set and close to the land in large bights (e.g. Newcastle Bight), there is commonly an eddy to the north with a velocity up to 1 knot. Northwesterly flow in these eddies may occur in spite of strong northeasterly winds and swell (Shepherd, 1970, p. 16). Also observed east of Port Stephens is a flow of water off the East Australian Coast current to the east and east-north-easterly at a rate up to 2 knots. The persistence of these more localized currents is not known. Northward flowing countercurrents occur at depths beneath the southerly flows, particularly over the deeper outer portions of the shelf (Highley, 1967). Cresswell (1974) reports deep northerly set currents with velocities of 20-50 cm/sec. These values are much less than those at the surface (Hamon, 1965). Velocities in water depths of 50 to 69 m rarely exceed 20-30 cm/sec. Data on currents at depth are slowly accumulating, although the value of such data for predicting bottom sediment motion is not known (see Wright et al., 1980, for a review of this problem). Recent work by one of us (P.R.) partly in conjunction with P.W.D. suggests that ocean currents are quite effective in transporting sand near prominent headlands such as Cape Byron and Seal Rocks.

1.6.2 Astronomical Tides

The tide regime of the Sydney-Newcastle region is described by Easton (1970) as microtidal semidiurnal with a diurnal inequality (secular changes in tidal levels of Newcastle are noted in Thom and Roy, 1985). The tide range is less than 2 m. There are 2 high tides and 2 low tides per day, and there is a once-daily inequality in tide range arising from the superimposition of the diurnal tidal constituents. On the open coast the tide regime is remarkably uniform along the entire N.S.W. coast. Throughout the region the major semidiurnal tide occurs almost simultaneously and with approximately the same amplitude. Absolute tide levels within the region also exhibit minimum variation between stations. Table 1-4 gives the amplitudes of major tidal constituents for Newcastle.

Shorelines facing the open areas experience a mean spring tidal range of about 1.2 m which is slightly lower than the range within parts of estuaries. For instance, the mean spring range near the mouth of Port Stephens is 1.26 m, but at Karuah, 22 km to the west near the head of the estuary, the range is 1.45 m (aspects of estuarine hydrology of Port Stephens are discussed by Rochford, 1959, Figs. 37 and 39).

TABLE 1-4 Tide Levels at Newcastle, N.S.W.
(Lat 32°56'S; Long 151°47'E)

Highest Astronomical Tide	+ 2.0 metres
Mean Higher High Water	+ 1.6 metres
Mean Lower High Water	+ 1.3 metres
Mean Sea Level	+ 0.9 metres
Mean High Low Water	+ 0.5 metres
Mean Lower Low Water	+ 0.4 metres
Lowest Astronomical Tide	0.0 metres

In general, tides create rotary or bidirectional currents in nearshore waters. Tidal currents on open coasts are normally most pronounced over flat, relatively shallow submarine profiles, but are generally rather weak over steep profiles like that which borders the N.S.W. coast (Wright et al., 1982). However, strong tidal currents are observed in and immediately seaward of estuary entrances. P.W.D. investigations (1973) indicate reversing tidal currents with speeds of 1 to 2 knots at the entrance to Port Stephens.

1.6.3 Wind and Wave-induced Nearshore and Inshore Currents

Coastal winds blowing over the surface of coastal waters induce local, short-term circulation patterns which are added to the wave-induced circulations (Wright et al., 1979). Detailed documentation of wind-generated nearshore currents on the eastern Australia coast is lacking; however, undoubtedly they play a significant role in nearshore sediment transport (Wright et al., 1979, 1980, 1982). In the coastal zone local wind stress induces surface currents which flow approximately in the direction from which the wind is blowing. This surface flow is commonly accompanied by a return flow (i.e. in the opposite direction) near the bottom to maintain continuity. Return flows are particularly well developed in shallow water. Prolonged conditions of this type can enhance shoreline erosion by causing seaward migration of sand. On the other hand, strong westerlies which cause seaward-flowing surface currents commonly generate landward flows near the bottom which augment beach accretion.

Waves breaking near the shore induce currents at various scales, intensities, and direction. The simplest and best known nearshore currents are generated by waves breaking oblique to the shore. These currents are well developed within the surf zone and are responsible for transporting sand parallel to the shore (Komar, 1975). The direction of the longshore currents varies depending on direction of wave incidence. Longshore drift on the N.S.W. coast is normally from south to north when southerly and southeasterly waves dominate and from north to south when the summer northeasterly sea breezes prevail. Over the long term, the net drift direction appears to be from south to north, especially in the northern part of the state (Delft, 1970). The south to southeasterly

aspect of Newcastle Bight minimizes the obliquity of south to southeasterly wave incidence but enhances the obliquity of easterly and northeasterly waves, and this could produce a net north to south littoral drift. However, such an effect would probably be of minor or secondary importance, owing to the dominance of southerly and southeasterly waves (P.W.D., 1977). There is a greater capacity for south to north sand transport in the Fens, Eurunderee and Seal Rocks embayments.

In general, longshore currents (and associated littoral drift) on the central N.S.W. coast are discontinuous and poorly developed owing to frequent interruption by the rocky headlands which alternate with sandy embayments (Roy and Thom, 1981). The result is that nearshore circulation and sediment transport tend to be compartmented within embayments. In the study area the actual extent of sediment by-passing around headlands and sand promontories such as Sandy Point and Seal Rocks is an important problem demanding future field investigation.

The most obvious and intense forms of wave-induced nearshore circulation are the rip cells generated by the radiation stress associated with energy dissipation in the surf zone. Nearshore rip circulations on N.S.W. beaches were first described by McKenzie (1958) and have been discussed more recently by Eliot (1973) and Wright et al. (1979). The circulation pattern is generally characterized by weak shoreward flow over shoal regions. Near the beach this flow intensifies somewhat within alongshore feeder currents. When wave incidence is normal to the beach, feeder currents may flow in alternate directions; oblique wave incidence tends to produce unidirectional longshore flows. Eventually flows converge and turn seaward as still more intense rip currents. These rip currents are effective in transporting beach sand beyond the breaker zone. In some cases rip positions may migrate along the beach; however, on many N.S.W. beaches larger rips commonly occupy certain preferred locations. It has been generally observed that rips become fewer in number but larger and much more intense as wave energy increases. Consequently, storm waves may produce huge powerful rips which transport sand seaward of the breaker zone. Recent data on process-form interaction in nearshore systems along the central N.S.W. coast are discussed in Wright et al. (1979).

1.7 FLUVIAL INPUTS

The coastal region from Newcastle to Sugarloaf Point is influenced by one major river, the Hunter, two smaller rivers, the Karuah and Myall, and a number of creeks (e.g. Boolambayte). The Hunter has formed an extensive deltaic plain within a broad, almost completely filled bay near Newcastle (Fig. 1-1). Fullerton Cove is the main relic of this bay (see Ch. 4). Other rivers and creeks debouch into water bodies trapped behind coastal deposits of Quaternary age (Fig. 1-1). The Karuah has formed a branching delta into Port Stephens, whereas the Myall River flows both into (Upper Myall) and out of (Lower Myall) the Broadwater Lake.

Of the three rivers the Hunter has the highest discharge (Bell and Edwards, 1980). It is the fifth largest river in N.S.W. with an average

discharge at Raymond Terrace of 2000 cusecs (information supplied by Water Resources Commission). The port for Newcastle lies at the mouth of the Hunter River. Breakwaters and port facilities have been constructed, and the lower estuary has been dredged since 1905 to reclaim land and improve navigation (P.W.D., 1969). Consequently much of the river bed in the port area and the delta surface itself reflect human interference. The river is tidal for a distance of c. 55 km from its present mouth (Roy, 1977; see P.W.D., 1969, Figure 2 for details on tidal limits and tidal gradients). The Hunter branches at Hexham into two "arms" or distributaries separated by interdistributary "islands" or tidal flats. The North Arm carries 80 percent of tidal flow while the South Arm carries the rest (P.W.D., 1969). Approximately 45 percent of flood discharge passes down North Arm, 35 percent down the South Arm and 20 percent over the islands. Observed surface velocities at the entrance of Newcastle Harbour during a flood are as high as 2.5 m per second (P.W.D., 1969, p. 2). A study of the sediment types in the Hunter delta shows "marine" quartz sand filling the lower 9.5 km of the Hunter estuary with lithic river sand occurring upstream (Roy, 1977; see also Ly, 1976). Minor amounts of very fine river sand are admixed with coarser marine sand in the lower estuary along with superficial deposits of terrestrial mud. Roy believes that very fine river sediment is periodically flushed out to sea by floods and is deposited in deeper water offshore.

The Karuah River flows into western Port Stephens. No information exists on its sediment load. Water discharge data show considerable variation in discharge. It is considered that sediment discharge is also highly variable in response to periodic floods. The predominance of muddy over sandy sediments in the delta area of western Port Stephens indicates that the sediment load of the lower Karuah is mainly composed of sandy silts and clays. Sandy sediments are confined to channels. The Karuah is tidal in its lower reaches; the mean spring range at Karuah Bridge is 1.45 m and the Indian Spring range is 2.09 m. These values exceed those at the entrance of Port Stephens by 0.19 and 0.3 m respectively. Other creeks which flow into Port Stephens appear to have negligible influence on estuarine sedimentation except for some minor shallowing at their mouths. This includes the Lower Myall River. The influence of these creeks on the salinity structure of Port Stephens is also probably quite limited, but this point requires field testing.

The Upper Myall River, with its major tributary the Crawford River, enters Broadwater Lake. Boolambayte Creek, the other stream draining into the Myall Lake complex, drains a much smaller area (see Bell and Edwards, 1980, for more details on drainage characteristics of the estuaries and coastal lagoons of the region). No information is available on the sediment discharge of these two streams. They both carry a lithic sand bed load, but at the mouth there is an abrupt change to muds of the lake bottom. Tidal exchange does not take place in these two rivers. However, river levels may be raised periodically due to retention of flood waters within the Myall Lakes complex.

The Lower Myall River drains the waters of the Myall Lakes system via the interbarrier depression of the Fens embayment. Figure 1-1 shows the entrance of the Lower Myall to be on the south side of Broadwater. This river carries no lithic sand to Port Stephens as is shown by the dominance of marine sand derived from the enclosing sand barriers in its bed (see Ch. 6). Only limited data exist on the flow regime of the Lower Myall River (Shepherd, 1970).

1.8 BIOLOGICAL ACTIVITY

1.8.1 Terrestrial Vegetation

The role of plants in the construction and stabilization of coastal dunes is well-documented overseas (see Cooper, 1958, p. 66, and references). It is necessary to describe the basic elements of plant communities present in the study area; in the chapter discussing the systematic geomorphology (Ch. 2) and in the chapters dealing with particular regions within the study area, further aspects of vegetation in relation to the development of the geomorphology will be discussed. Five basic vegetation types are prominent in coastal environments north of Newcastle (Story et al., 1963):

(i) dry sclerophyll woodland and forest,
(ii) foredune trees, shrubs, grasses and mat plants,
(iii) heath,
(iv) fen (= freshwater swamp), and
(v) mangrove - salt marsh.

Osborn and Robertson (1939), Sim Committee (1967), Carolin (1969, 1971), Anderson (1973), McDonald (1971, 1973), Lewis (1973, 1978) and Fox (1981) discuss aspects of the vegetation of the study area. Reference should also be made to the pioneering work of Pidgeon (1940). No attempt will be made in this monograph to describe vegetation on bedrock surfaces (see Osborn and Robertson, 1939). Rock and sand dune areas in the vicinity of the Myall Lakes have recently been the subject of a detailed floristic and ecological study by Myerscough and Carolin (1986; see their accompanying map at scale 1:25000 for distribution of 17 plant communities)

Dry sclerophyll forests and woodlands on sand surfaces are commonly dominated by Eucalyptus pilularis, E. gummifera, and Angophora costata. Each species may dominate or they may occur together in relatively equal proportion. They constitute the taller elements (up to 20 m) of a layered forest, which also contains scattered smaller trees (chiefly Banksia serrata), and a 1-3 m shrub layer consisting of Leptospermum sp., Acacia sp., Dillwynia sp. and many other plants (see Osborn and Robertson, 1939, and Myerscough and Carolin, 1986, for species lists). The distinctive white-trunked Eucalyptus signata locally grows in more open woodlands on deeply leached soil. Bracken, Pteridium aquilinum, is very common in woodlands particularly after an area has been fired. Occasional plants of Macrozamia occur, but grasses, except Imperata cylindrica, are scarce or absent (Osborn and Robertson, 1939, p. 285).

The foredune community consists of a variety of sand-binding grasses (e.g. Spinifex hirsutus, Festuca littoralis), succulents and mat plants. Acacia longifolia var. sophorae often grows as a dense sprawling low shrub on sand ridges behind open ocean beaches. Dense foliage on foredunes may contain low trees, including Banksia integrifolia and Leptospermum laevigatum. McDonald (1971, 1973) has made a study of plant communities at Anna Bay. Nine zones were identified:

(1) Bare sands to high water mark
(2) Berm area or Spinifex zone
(3) Foredune face, or Lomandra zone

(4) Foredune top, or Acacia zone
(5) Hind dune or Leptospermum zone
(6) Banksia/Angophora woodland
(7) Swamp border or Casuarina zone
(8) Swamp or Melaleuca zone
(9) Climax open forest or Eucalyptus pilularis zone.

(Note: zones 7 and 8 are anomalous in that there are many places where zone 6 grades directly into zone 9; McDonald, 1971, p. 125, see also 1973, Fig. 2).

Heath vegetation occurs on sandy soil associated with unfavourable water relations (Story et al., 1963). On extensive level sandy plains, locally known as "moors", a considerable number of shrubs and herbs characterize the flora. Few shrubs exceed 2 m in height, but locally low trees protrude through the dense scrub cover. Carolin (1971) showed that within the heath vegetation type the spatial arrangement of plants can be quite complex; there is very little overlapping of the distribution of the species of the same genus in most cases. Myerscough and Carolin (1986) recognize two heath and two heath forest communities which occur on Pleistocene sand surfaces.

Characteristic trees and shrubs of fen (freshwater swamp) vegetation are Melaleuca quinquinervia, Casuarina glauca, Eucalyptus robusta, Livistona australis and Leptospermum sp. This community has many components in common with the freshwater swamps of dune depressions (deflation hollows) found within the sclerophyll forest.

Around shores of lakes, Casuarina typically forms a fringing forest amidst which waves are reworking sand (see Myerscough and Carolin, 1986, pp. 431-432). A community of reeds consisting of Scirpus, Phragmites and Typha sp. occurs lakeward of the trees in more sheltered localities, and together they constitute an "encroachment succession" using a term employed by Bird (1978) in his study of Gippsland Lakes area. Characteristics of the successional sequence around the Myall Lakes have been described by Osborn and Robertson (1939, pp. 286-289), although there has been little attempt to relate plant species and habitat preference to the dynamics of lakeshore geomorphology as undertaken by Bird in Gippsland.

On silt-clay flats bordering coastal sand deposits, or on poorly drained alluvial-colluvial deposits of river valleys, Melaleuca, Livistona and Eucalyptus robusta grow in some abundance. In the Upper Myall Valley, occasional trees of E. saligna are left as indicators of a former magnificent forest (Osborn and Robertson, 1939, p. 288).

Low-lying terrain in the Hunter Delta, bordering Port Stephens and along the Lower Myall River is colonized by a mixture of mangrove and salt marsh species. The banks of numerous tidal creeks are fringed with low Avicennia and Aegiceras trees, and adjacent tidal flats form some of the most extensive salt marshes in eastern Australia. Plant relationships appear to be very similar to those described by Clarke and Hannon (1967) for the Sydney area.

1.8.2 Marine, Estuarine and Aquatic Environments

The role of marine biota on sedimentation in nearshore oceanic areas is little studied in N.S.W. Sediment sampling and SCUBA diving to depths of 20 m in the study area and elsewhere have shown that the bottom molluscan fauna outside the breaker zone is dominated by the so-called banded kelp shell, Bankivia fasciata. This gastropod inhabits in its millions the rippled sand bottom of the nearshore environment to depths of at least -20 m. It may be a filter-feeding mollusc (W. Ponder, pers. comm., 1974). Near the Hunter River and offshore from Port Stephens transported estuarine shells (e.g. Pyrazus), sometimes occupied by hermit crabs, have been noted. Plebidonax deltoides is prolific on exposed sandy beaches, and the colourful bivalve Veletuceta flammea is often washed up on beaches. Richer molluscan fauna inhabit rocky shores and get concentrated as carbonate detritus in beach or nearshore sand deposits, particularly in pocket beaches.

The fauna and flora of Port Stephens play important roles in sedimentation. Peat and Roy (1975) have discussed the remarkable bioherms, composed primarily of the large mud oyster, Ostrea angasi, which occur in the estuary (see Ch. 5). Other molluscs, such as Anadara trapezia, Pyrazus ebeninus, Crassostrea commercialis (cultivated on extensive oyster farms today), Proxichione chemnitsi and Trichomya hirsuta, in either living or dead form, are frequently evident in the sediments. Sponges and bryozoans are locally plentiful, the latter forming extensive "meadows" in deep turbid channels near Soldiers Point. Burrowing organisms, especially various crustaceans and polychaetes, disturb the bedding in more sheltered environments. Burrowing of the banks of tidal creeks by crabs seems to facilitate their erosion by currents. Zostera and Posidonia weed beds also occur in Port Stephens, and probably assist sedimentation by their baffling effect on transport and autocthonous decomposition.

In the fresh to brackish Myall Lakes, molluscan fauna appear to be of little significance to sedimentation, although a rich fauna existed in Broadwater Lake before it was denied direct access to the sea (see Ch. 7). The bottom of the lake is covered with submerged vegetation (Osborn and Robertson, 1939, p. 286). Chara and Naias predominate, although both die back in winter and as a result of increased salinity during droughts. Other genera such as Ruppia and Myriophyllum are abundant locally at shallow depths. Shepherd (1970) believes that these aquatic plants are major contributors to the highly organic lake floor sediment.

1.9 INFLUENCE OF MAN

The spread of human settlement to sandy coastal regions in many parts of the world often leads to the modification of the landscape (for a general discussion of this problem, see Cooper, 1958, pp. 22-23). Human disturbance of stabilized coastal dunes in the study area has resulted from many activities, including fire, grazing, excessive foot or vehicle traffic, etc., some of which have been in operation ever since man entered the region in prehistorical times.

1.9.1 Prehistory

A systematic prehistory has not been written for this part of the N.S.W. coast. It is believed the Aborigines were occupying the N.S.W. coast at least 20,000 years ago (Lampert, 1971). Their presence on the continental shelf at times of lower sea-level is inferred by Bowdler (1977). Cook observed "several smooks" on the 11th May, 1770, while sailing past Port Stephens, which he named (Hakluyt Society ed., Voyage of Endeavour, 1955, p. 314). These he speculated to be from the shores of lagoons.

When John Oxley travelled overland from Seal Rocks to Port Stephens in 1818, he observed the area to be fairly densely populated with Aborigines, some of whom attacked his party (Oxley, 1820).

> The natives are extremely numerous along this part of the coast; these extensive lakes, which abound in fish, being extremely favourable to their very easy inheritance; large troops of them appear on the beaches, whilst their canoes on the lakes are equally numerous. In the morning their fires are to be observed in every direction (ibid., p. 346).

Published prehistory studies in this area have been limited to cataloging of artifact types (Hall, 1928). There are also some ethnographic reports (Enright, 1899, 1900). In a recent "ethnohistory" of the "Worimi", a linguistic group occupying the coastal tracts in the early 19th century, Sokoloff (1973) cites various sources in his discussion of the "horde" territories.

Maiangel:	Newcastle Bight and Tomaree
Garuagal:	Tomago and inland
Gaingal:	North side Port Stephens and Fens
Garawerigal:	part of Fens, Eurunderee and Seal Rocks.

He has mapped the distribution of shell middens, artifacts and burial sites near Port Stephens (p. 151), but did not attempt to distinguish shell midden types, nor does his map contain all known sites. More field work is required.

Two types of middens can be distinguished: one containing shells predominantly derived from ocean beaches, especially Plebidonax, the other containing estuarine shells (Anadara, Pyrazus, Ostrea). The ocean type is located amidst frontal ridges (see Sullivan, 1982, who has described middens from Newcastle Bight). Extensive middens have been noted on headlands such as those described by Hall (1928) near Morna Point. Sites close to or on rock outcrops contain a greater variety of shell species. Middens composed of estuarine shells occur either in sheltered high dunes which overlook salt marshes and mud flats (e.g. near Bobs Farm), or along the backshores of the many small beaches which flank Port Stephens. It is of interest that middens are rare around the shores of Myall Lakes.

Ethnograhic accounts are of interest in any attempt to establish the role of Aborigines in disturbing the dune landscape. Scott (1929) in his recollections of 25 years with the "Gringdi" tribe near Carrington,

describes the method of lighting fires for cooking purposes; apparently game was so plentiful on the north side of Port Stephens that it could be obtained by tracking and/or use of "beaters", a method without recourse to fire (ibid, p. 18). Whether other groups in the area deliberately fired the vegetation is not known.

1.9.2 European Occupance

To our knowledge there has been no collation of historical records on the settlement of this region (a brief account for Newcastle Bight can be found in Robson et al., 1986). A few cedar-cutters had reached the area by the 1820s, but the first organized settlement began in 1826 after the Australian Agricultural Company had been granted a million acres adjacent to Port Stephens. Settlers employed by the Company were engaged to graze sheep on the local bedrock hills and in the Karuah Valley (Harris, 1849). No reference is made to the possibilities of utilizing coastal sand terrain in the early accounts, even though the Company held title to the land west of the Lower Myall River. The area proved unsuitable for sheep grazing, but the Company continued here until the 1860s, grazing some sheep and permitting tenant farmers to grow wheat.

By the middle of the last century squatters and freehold farmers were taking up land on low-lying alluvial flats on the Upper Myall River, around the bedrock shores of the Myall Lakes, on the sandy terrain east of the Lower Myall River, and to the south of Port Stephens. At this stage beef and dairy cattle were introduced to vegetated sand dunes. Cattle relish the sand-binding plant Spinifex hirsutus and this factor plus frequent burning of scrub to promote the growth of succulent green shoots, points to the likelihood of grazing as a cause of dune instability. This seems to have been the case east of Williamtown where even today cattle graze in the dunes, especially during wet weather.

Exploitation of the forests for timber has continued in the region since the days of Oxley. Cedar cutting was well advanced when Dawson visited a timber camp on the (Upper?) Myall River in 1825 (Dawson, 1835). However, their activities were mostly confined to bedrock terrain. Timber was transported by barge or paddle-wheel boat to Port Stephens. Blackbutt (Eucalyptus pilularis) was logged on the high dunes near Seal Rocks for over 70 years. The extraction of this tree has been highly selective, because many large trees have suffered sufficiently from insect infestation to have rendered them useless for logging in the past. Much of the logging was undertaken in winter when access to bedrock sites was often difficult. There is no sign that such extraction has created dune instability at any point in the high dune area.

In more recent years, the sand dune landscape has been utilized by other activities even though much of the area has remained as Crown Land. The first involved the ravages of the military, particularly east of Williamtown. World War II exercises were conducted in these dunes. Aerial bombing continued until the mid-1960s. Sand deposits have been extensively used as a source of ground-water by the Hunter District Water Board, particularly south of Port Stephens in the Tomago area (Corlette, 1942). Australian Pines and Paper Products in the 1930s planted pines on the low-relief sand ridges west of the Lower Myall River. This project

was not very successful and the company is now concentrating its efforts on bedrock terrain. The region in recent years has been discovered by the tourist industry. Port Stephens, in particular, is a growing recreation area, and there is much interest in boosting tourism around the Myall Lakes. Geomorphologically, the trampling effect of people walking across dunes can create many problems. Perhaps more damaging is the impact of bikes and dune buggies on fragile foredune plants. Finally, since the early 1960s three mining companies have been active in the search for rutile, ilmenite and zircon. Their use of the area has been contested from many points of view (Sim Committee, 1967; Bunning Commission, 1974, and Piper, 1980). Although they have devastated large tracts of sand heath, dune woodland and foredune vegetation, these companies have gone to great lengths to restore native vegetation. Mining in this area commenced after stringent regulations were introduced in N.S.W. to ensure no post-mining dune mobility. It is unlikely that this activity has or will create areas of dune erosion. Although their excavations reveal much to the stratigrapher, the geomorphologist and ecologist finds his "natural" landscape eradicated forever. As scientists, we benefit and suffer at the same time from heavy mineral mining (see Ch. 9).

Increasing population pressure in the N.S.W. coastal zone requires a greater effort on the part of planners and decision-makers to develop a better understanding of physical, economic and social factors involved in landscape change. The Port Stephens-Myall Lakes area is no exception. A variety of authorities have been interested in fostering future development including those referred to above in relation to conflicts over mining and park use of the dune landscape. In more settled areas such as Tomaree Peninsula, the National Trust recently commissioned a landscape study to assist local and state governments in making "decisive planning decisions" (Gardner, et al., 1986). It is our view that a better understanding of the Quaternary history of the area's landscape will provide a better appreciation of the natural heritage of this stretch of coast and thus enhance the decision-making process.

2

Systematic Geomorphology

2.1 LANDFORM TYPES

Within bedrock embayments between Newcastle and Seal Rocks several types of depositional landforms can be recognized. These are the product of a variety of interacting processes which have operated with varying magnitude and frequency during the late Quaternary period. In this monograph, it is convenient to separate landforms which are primarily the result of fluvial, lagoonal, estuarine and paludal processes from those due to marine-eolian action. The latter will receive most attention in the following discussion.

2.1.1 Fluvial-Estuarine-Paludal Landforms

Depositional processes have led to the development of an array of fluvial landforms in the river valleys which drain into the study area. No attempt will be made here to review these features in detail. They consist of contemporary flood-plain landforms of the Lower Hunter, Paterson, Williams, Karuah, Upper Myall and Boolambayte Rivers. Ranging in width from a few hundred metres to c. 5 km these flood plains possess a flat to very gently undulating relief composed of active and abandoned levees, active and abandoned channels, depressions partly filled with water, and low-lying backswamps. Crevasse splays are particularly prominent on the Lower Hunter downstream from Maitland. Large tracts of the silty-clay surface of the flood plains have been extensively cultivated.

As noted by Story et al. (1963), flood plains of large and small rivers are commonly flanked by alluvial and colluvial terraces. In the lower reaches of the rivers these terraces are composed of sand, silt, and clay, rarely gravel. Locally they may occupy most of the valley floor, but often form discontinuous benches which merge almost imperceptibly into bedrock and colluvial slopes. Their surface is gently undulating, and locally dissected; they often contain swampy hollows and sandy levee-like features.

Fluvial deposits both overlie and grade into estuarine sediment complexes. Estuarine landforms are dominated by the occurrence of tidal creeks and flats, either in the deltas of large rivers such as the Hunter and Karuah, or in drainage basins which receive relatively little freshwater discharge (e.g. Pipeclay Creek). In the Hunter Valley, Story et al. (1963) delineate fluvial from estuarine landforms when they distinguish the Hunter, Hexham and Avicennia land systems. The Hunter L.S. consists of two parts:

(i) freshwater swamps or alluvial material near sea-level, ponds, and drier levee sites; and

(ii) brackish swamps occasionally covered by high spring tides and crossed by tidal creeks.

The Avicennia L.S. occupies low relief mudflats at the mouth of the delta. These flats are either covered by dense Avicennia trees and scrub, or where relief is slightly higher, by salt marsh plants with mangroves fringing tidal creeks. The land system is densely laced by branching tidal creeks (see Story et al., 1963, Table 1, also pp. 22, 35 and 36).

Around the shores of the water-bodies fully or partly enclosed by sand deposits, two distinctive processes are in operation. One involves the conversion of open-water into vegetated mudflats, peaty swamps or bogs, whilst the other involves reworking of sediment by wave action. Plants fringing relatively freshwater lagoons appear to develop a swamp encroachment succession in a manner not unlike that described by Bird (1978). Depending on width and depth of lagoons, and on exposure to wave action, swamp encroachment appears to have advanced to varying stages. Interbarrier depressions (see Table 2-1 for definition) may now contain little or no open water as in the Eurunderee embayment (Ch. 8).

In sheltered parts of Port Stephens and along interbarrier depressions still influenced by tidal processes, the deposition of fine-grained sediment has facilitated the development of mudflats. As in the river deltas, these mudflats have been colonized by halophytic plants. However, there is evidence that such plants have been succeeded by freshwater swamp species including Casuarina and Melaleuca, converting the mudflats into areas of organic-rich mud or peat. Such changes have occurred within the interbarrier depressions of Newcastle Bight and Fens embayment (see below, Chs. 4 and 6).

Beaches of various types (pocket, delta, bayhead) occur within the enclosed water bodies of the study area. They have been discussed in detail by Shepherd (1970) for Myall Lakes together with adjacent submarine bars and sand shoals. Some aspects of these features will be discussed below in the regional chapters.

2.1.2 Marine-Eolian Landforms

Of prime interest in this study are those landforms which are the product of the interaction of four elements of the coastal environment: sand, wind, ocean waves and plants. The Port Stephens-Myall Lakes region possesses a rich variety of such landforms, and it is our intention to describe their major morphological characteristics (this chapter), to evaluate their sedimentary properties (Ch. 3), to discuss their distributional and stratigraphical relations (Chs. 4 - 9), and to generalize on their origin and history (Ch. 10).

Table 2-1 represents an attempt to define depositional forms common to this part of the central N.S.W. coast. Only landforms which have developed either along or inland from an oceanic shoreline are depicted in this list. The usage of terms in Table 2-1 differs somewhat from that contained in standard references (e.g. King, 1972; Zenkovich, 1967), and in places new terms are employed. The generalized distribution of many of these landforms within the study area is shown in Figure 2-1.

Along the N.S.W. coast numerous bedrock embayments have been partially or completely enclosed by sand barriers (Langford-Smith and Thom, 1969). Coastal lagoons and swamps, which are typical of all sectors of the coast, have been formed behind these bay barriers. In the sector between Newcastle and Seal Rocks, two quite separate barrier systems have been identified, and have been termed the Inner Barrier System and the Outer Barrier System (Thom, 1965). These dual barriers are pronounced in the Newcastle Bight, Fens and Eurunderee embayments whilst a well-developed Inner Barrier occurs in the Upper Myall Valley, and Outer Barriers are present in the small embayments of the Tomaree Hills sector and across the mouth of Broadwater Lake (Fig. 2-1). The barrier systems may be represented by a single foredune, or by a wide series of beach ridges trending parallel to the shoreline, or by highly varied and complex dune morphology (e.g. Seal Rocks sector, Fig. 2-1; see also Thom, 1974, Thom et al., 1978). Field studies of geomorphology, sediments and soils, and stratigraphic relations of sediment units have shown the barriers to be partly wave-built and partly eolian in origin. The two systems with their component beach ridges and dunes represent two separate periods of deposition (Ch. 10).

2.2 OUTER BARRIER SYSTEM

2.2.1 Outer Barrier Types

Sand barriers of the Outer Barrier system mainly occupy bay-mouth positions within embayments of the study area. They completely or partly enclose lagoons or swamps which generally form linear interbarrier depressions arranged parallel to the shoreline (e.g. in Newcastle Bight, Fens, Eurunderee, see Fig. 2-1). Irregularly shaped water bodies whose configuration is determined for the most part by drowned bedrock valleys are also blocked by Outer Barriers (e.g. Broadwater Lake, Fig. 2-1).

Thom (1974) has recognized four basic types of Outer Barrier along the N.S.W. coast on the basis of their morphology and stratigraphy (see Thom et al., 1978, for a more elaborate classification). These types all occur in the study area.

1. Prograded barriers composed primarily of multiple beach ridges.
2. Stationary barriers composed of a high and often complex foredune ridge containing buried soils; parts of the ridge may be dissected by blowouts.
3. Receded barriers composed of a foredune ridge migrating over lagoonal or backbarrier sand deposits which are at present sea-level (may also be dissected by blowouts).
4. Episodic transgressive dune barriers where the morphology and stratigraphy are dominated by wind-transported sands which have been deposited in discrete episodes in the Holocene.

Types 1 and 4 constitute the larger and most prominent Outer Barriers in the study area. There are localities where both are found in juxtaposition, thus forming a composite barrier of two or more types (Thom et al. 1978, Fig. 2).

Outer Barriers are composed of stabilized sand masses which, in common with dunes on the "outer barrier" of Gippsland Lakes (Bird, 1978), retain a vigour and freshness of relief which suggest little change in their morphology since fixation by vegetation. Beach ridges and transgressive dunes both possess this sharper topographic appearance relative to their counterparts on Inner Barriers. Soil profiles in the predominantly quartz sands of Outer Barriers are usually well developed away from foredunes, but hardpans are rarely present (Bowman, 1979). Vegetation varies from grasses, which colonize freshly deposited sand, to scrub, woodland and forest on leached sands of ridges and swales. Heath vegetation is only locally present (fire-induced?). Swales within the Outer Barrier system are seldom swampy, except in some relict deflation hollows in stabilized dunes.

For purposes of further description, it is convenient to discuss those parts of barrier systems dominated by progradational morphology (sections 2.2.2 and 2.2.3) separately from those dominated by transgressive dunes (sections 2.4 and 2.5).

2.2.2 Beaches and Foredunes

Oceanic beaches in the study area are either composed of sand or rounded boulders. The latter form numerous pocket beaches within narrow bedrock embayments carved into the Nerong Volcanics of the Tomaree Hills sector (Ch. 5). They also occur near Seal Rocks and at Yacaaba (Oak, 1981, 1984). The upper part of many boulder beaches appears to be relict (see Sussmilch and Clarke, 1928).

Sand beaches and bars flank all Outer Barriers in the study area. In common with most beaches on the N.S.W. coast facing east to south, they experience changes in morphology depending on the magnitude and frequency of storms off the east coast (Thom et al., 1973; Wright et al., 1979). Hesp (1982) has studied beach profile changes over a 3.5 year period in the Fens embayment. Moreover, striking changes in the morphology of nearshore bars are apparent on aerial photographs taken at different times. Well-developed rhythmic bars, crescentic in plan, often occur in the Fens and Eurunderee embayments (Wright et al., 1979;Short and Hesp, 1982). Beach profiles are concave after periods of beach erosion, but convex profiles characterized by one or more berms occur during periods of beach accretion. Shepherd (1970) has shown that swash

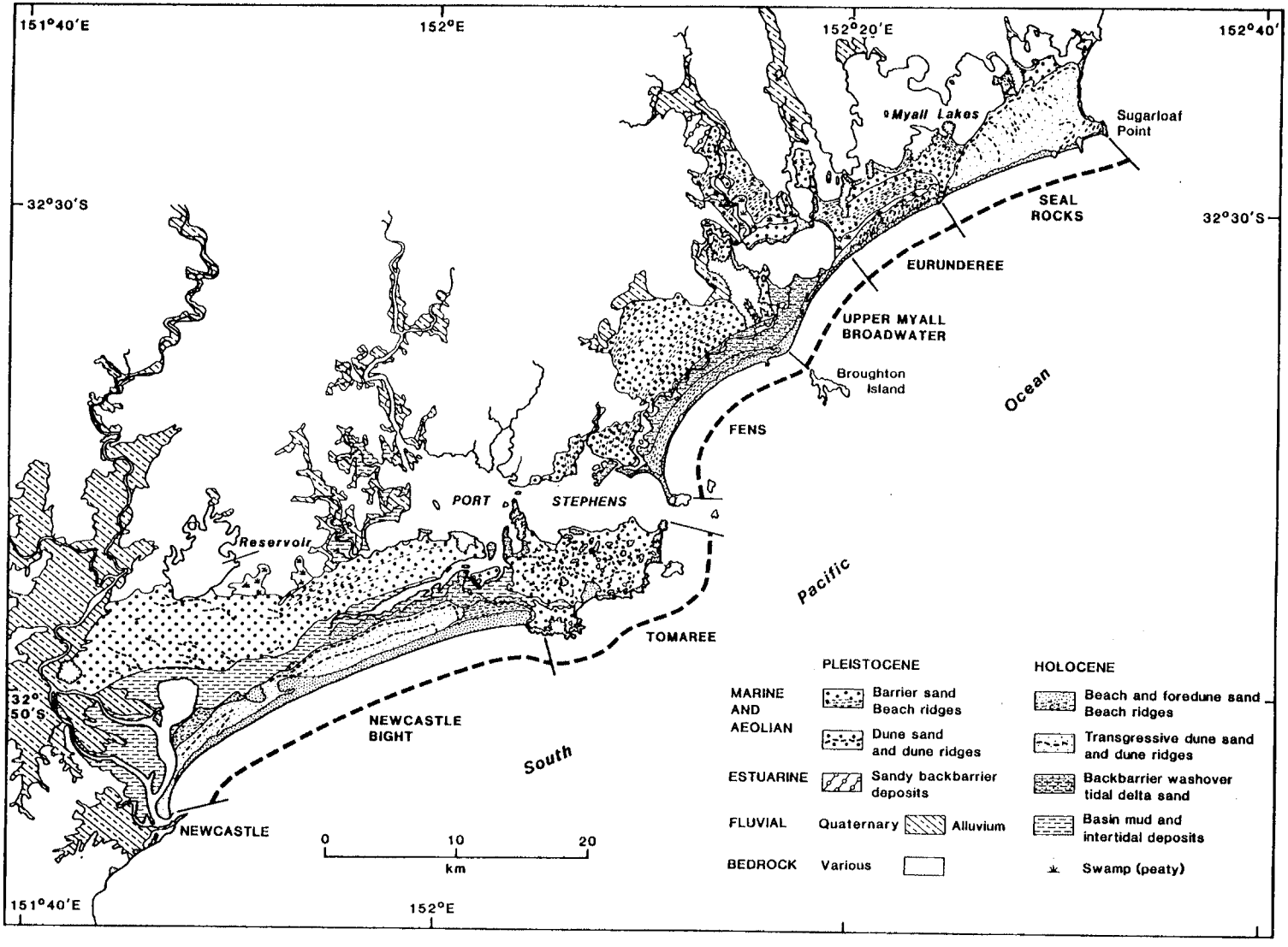

Figure 2-1: Generalized morphological patterns in the Port Stephens-Myall Lakes region. The study area is divided into six segments as indicated on this map.

activity leading to sand deposition on the upper part of beach slopes may vary from 2 to 4 m above MSL depending on degree of exposure to high energy waves and grain size of beach sands.

During periods when the beach is restored to its full-beach or bermed condition, wave activity is progressively denied access to upper parts of the beach. Aggressive sand-binding plants, especially Spinifex hirsutus colonize this backshore zone. The plants may extend out from the base of an eroded established foredune as noted by McKenzie (1958), or may colonize the berm, leaving a sparsely vegetated area behind (Bird, 1960; Hesp, 1984b). Sand moved landward by onshore winds accumulates around these plants leading to the development of a seaward sloping hummocky terrace on the one hand, or a hummocky ridge parallel to beach. The plants have the capacity to grow vertically as accretion continues. We refer to this type of partially vegetated frontal dune as "incipient foredune" (Table 2-1). Hesp (1982; Hesp, 1984a,b) has recently documented many characteristics of incipient foredune development in this area.

Rates of incipient foredune development along the N.S.W. coast have been documented by Andrews (1916), McKenzie (1958), Wright (1970), Thom (1974), McLean and Thom (1975) and Hesp (1982). In the study area over the past 25 years episodes of incipient foredune destruction by waves, either total or partial, have been reported in winter 1950 (general), 1958 (Fens embayment), 1962 (Fingal Bay, in Tomaree Hills sector), November 1966 (Fens embayment), winter 1967 (general), and autumn-winter 1974 (general). Specific rates of growth have been documented by Hesp (1982) in the Fens embayment since 1977. In those areas where established foredunes are absent and mobile dunes occur landwards of the beach, the presence or absence of an incipient foredune is critical in determining the degree of sand exchange between the beach and the mobile dune system. During periods of incipient foredune construction sand is occasionally supplied to the vegetated ridge from the mobile dune sheet by offshore winds.

The "established foredune" is a more permanent type of frontal ridge landward of the incipient foredune. It is generally a relatively massive feature in the broad embayments of the study area, often attaining 20-30 m in height, particularly at the northern end of embayments (Short and Hesp, 1982), where exposure to southerly onshore wind is at a maximum (Hesp, 1982, Fig. 6-8). In contrast, the southern portion of foredunes rarely exceeds 6-8 m in height above MSL. Typically, the established foredune is more densely vegetated than the incipient foredune, and its plant species are regarded as reflecting a more advanced stage of plant succession (Osborn and Robertson, 1939). In addition to the grasses of the incipient foredune, the vegetation includes mat plants such as Scaevola calendulacea, Carpobrotus sp., Hibbertia scandens and Senecio spathulatus, and low woody shrubs such as Correa alba, Leucopogon sp., and Acacia longifolia var. sophorae. Small trees, including Banksia integrifolia and Leptospermum laevigatum, may appear in more sheltered depressions within the hillocky foredune and on its inland-facing flank (McDonald, 1971, 1973). In many localities the abundant root system of this diverse plant community acts as an effective stabilizer of the foredune ridge. Depending on the rate of accession of wind-blown sand and age of the structure, soils in foredunes vary from unleached sand to well-defined podzol profiles. Localized instability can impart a mosaic pattern to vegetation on established foredunes, especially in more

exposed localities. The more mobile parts of the foredune may be dominated by sand-binding grasses whereas more stable areas close by are rich in Acacia and other shrubs.

The seaward face of the established foredune frequently shows signs of wave erosion forming a poorly vegetated bluff. This cliff is only undercut when the incipient foredune has been removed. Periodic trimming of the foredune appears to be a frequent phenomenon in eastern Australia (Thom, 1974). The foredune has been dissected by blowouts within several embayments of the study area (see also Hesp, 1982). Buried soils often rich in charcoal and wood fragments as well as primary bedding are sometimes exposed along the scoured walls of these gaps. Scour of the walls results in the lateral expansion of blowouts leaving, as a remnant of the established foredune, a row of butte-like knobs or "remanie" dunes. It is possible to infer a pattern of relative erosion of established foredunes, along an exposure gradient, ranging from non-dissected, smooth-crested ridges in relatively sheltered localities, through increasing blowout development to "remanie" knobs and finally complete removal with extensive mobile dune sheets landward of the beach being the end point of the sequence. Similar sequences have been observed in Europe (Steers, 1937; Schou, 1949), Oregon-Washington (Cooper, 1958) and elsewhere in N.S.W. (Sless, 1957).

2.2.3 Beach Ridges

The extensive sand beach ridge systems of south-eastern Australia have been the subject of considerable discussion in recent years (Sprigg, 1952; Burges and Drover, 1953; Davies, 1957, 1972; McKenzie, 1958; Bird, 1960, 1984; Thom, 1964, 1965; Langford-Smith and Thom, 1969; Jenkin, 1968; Shepherd, 1970; Hails, 1972; Bowman, 1979; Hesp, 1984b). Considerable uncertainty and divergence of opinion exist as to their exact nature and origin (Davies, 1957). Such a state of affairs is the result of the fact that most, if not all, systems in southern Australia are relict. However, since Davies presented his synthesis and theory in 1957, many systems have been studied in some detail, including those which occur in the Port Stephens-Myall Lakes region (see Thom, 1960, 1965; Shepherd, 1970; Ly, 1976; Bowman, 1979; and Hesp, 1982, 1984a,b).

Before describing the character of beach ridges in the study area, it is relevant to discuss their terminology. The literature is very confusing on this issue. Several points of view, derived from assumed genesis of the feature, are employed by different writers. There are those who see these sand ridges as dune features ("dune ridges": Beal and Shepard, 1956, McKenzie; 1958, or "foredune ridges": Jennings, 1959). Emphasis is placed on their inherited foredune morphology and sediment characteristics; they are believed to be a series of relict foredunes left stranded as the shoreline progrades (see also Short, 1987). Bird has argued that:

> Continued growth of the new foredune gradually cuts off the supply of sand to its predecessor, which becomes relatively stable, and the dune grasses are then invaded and replaced by scrub vegetation....If the shoreline progradation continues, alternating episodes of cut and fill lead to the formation of a series of parallel dunes, separated by swales (Bird, 1968, pp. 131-133).

Bigarella (1972) distinguishes between "foredune features" and "beach-dune ridges" using sedimentary structures. There are those who have emphasized the beach derivation of the ridge, the nucleus of each ridge being provided by a beach berm (Davies, 1957).

> ...the initiation of a sand beach ridge requires a shallowing of the offshore zone, normally by an extensive accumulation of sand by arrested longshore movement. The berm or incipient ridge is built by calm weather waves and its continued existence depends upon the subsequent occurrence or non-occurrence of steep storm waves which will tend to destroy it (ibid., p. 107).

Hesp has recently presented detailed morphologic, photographic and stratigraphic data on the genesis, dynamics and ecology of incipient foredunes (Hesp, 1982, 1984a,b). He has shown that 'beach ridges' (as used in the Australian literature) are analogous to incipient foredunes. They are initiated by eolian sand deposition within pioneer plant communities in the backshore zone of beaches. As the shoreline progrades, with or without berm formation, a new incipient foredune may form isolating the former dune ridge to landward.

As used in this monograph a beach ridge associated with an oceanic shoreline is synonymous with a relict foredune. Every beach ridge parallel to an oceanic shoreline is expected to contain a certain amount of wind-blown sand. The final form of the ridge is a function of many interacting factors (Hesp, 1982). We make no attempt to distinguish between beach ridges and frontal dunes in the manner of Davies (1957, p. 198; 1972, p. 154, Fig. 109). As Davies (1957, p. 108) admits, "no clear cut dividing line can be drawn"; therefore, we prefer to distinguish low amplitude from high amplitude beach ridges, especially as a single ridge or complex of ridges, may grade from a low rounded form at one end of an embayment to a high, hillocky feature at the other.

Beach ridges occur on only two Outer Barriers in the study area: Newcastle Bight and Fens (Fig. 2-1). Owing to the destruction and burial by more recent mobile dunes, the seaward portion of Outer Barrier beach ridges can no longer be studied. Minimum modification has occurred at the south end of the Fens embayment, but in the Newcastle Bight sector, only a very limited area of beach ridges remains intact (Fig. 2-1). The ridges are generally parallel to the present beach and to each other, particularly in the centre of bays, but occasionally they merge or diverge. There is no tendency for individual ridges to recurve in a manner characteristic of spits; they therefore can be considered to be swash-aligned features (Davies, 1972, p. 123). Innermost ridges are somewhat less regular in form than those to seaward, a phenomenon which will be shown later to be the product of transgressive dune development and backbarrier deposition during barrier initiation. Spacing between ridges can be quite variable, ranging from 20 to 100 m. However, ridges average 40-60 m in distance apart. Ridges tend to increase in height toward the north where onshore wind energy increases (see Ch. 6). Ridge amplitudes in Outer Barriers average between 1-2 m, but it is frequent to find amplitudes exceeding 3 m, especially at northern or eastern ends of embayments (Chs. 4 and 6). When either ridge heights or swale heights are correlated with distance seawards from the crest of the innermost ridge, no statistically significant tilt of the transverse series is detected (Ch. 6). Invariably, where intact, the present foredune is

higher than any Outer Barrier beach ridge, whereas the oldest ridge is broad compared with the other ridges. More detail on beach-ridge morphology is contained in appropriate regional chapters.

Soils of beach ridges on the Outer Barrier have been podzolized to varying degrees (Bowman, 1979). In the Fens embayment, the present foredune shows little or no soil profile differentiation, but the seawardmost beach ridges exhibit an incipient B horizon overlain by a leached grey A2 horizon less than 1 m thick. The A2 horizon thickens inland and the Bh horizon becomes more pronounced, until at innermost ridge sites the profile consists of a leached A2 horizon up to 2 m thick overlying a Bh horizon, mottled dark brown, with semi-indurated humic-impregnated nodules. Locally, a thin organic-rich pan may occur in the sand at the water-table at the rear of the Outer Barrier. Whilst the soil profile shows marked changes across the barrier, pH values are relatively uniform: 5.5-6.7 at 1 m depth in beach ridges, 7.0-8.0 in foredunes. This soil sequence has been studied by Bowman (1979) and is summarized in Chapter 6.

Figure 2-2 depicts the general pattern of vegetation communities across beach ridges based on information from the Fens Outer Barrier. It is difficult to find areas with a complete sequence as shown in this figure because large tracts of ridges have been destroyed by transgressive dunes, or the vegetation has been disturbed by fire and human impact. Nevertheless, it appears that ridges immediately behind the foredune are usually characterized by a Leptospermum-Banksia thicket. This community gives way inland to a Banksia woodland in which two species of Banksia are intermixed (B. integrifolia, B. serrata), plus Angophora costata and occasionally Eucalyptus pilularis. Trees in this zone may reach 10 m in height. A different assemblage of shrubs makes its appearance in the Banksia woodland: species include Persoonia lanceolata, Acacia suaveolens, Eriostemon lanceolatus, Hibbertia fasciculata, Xanthosia pilosa, Monotoca elliptica, Pomax umbellata, and

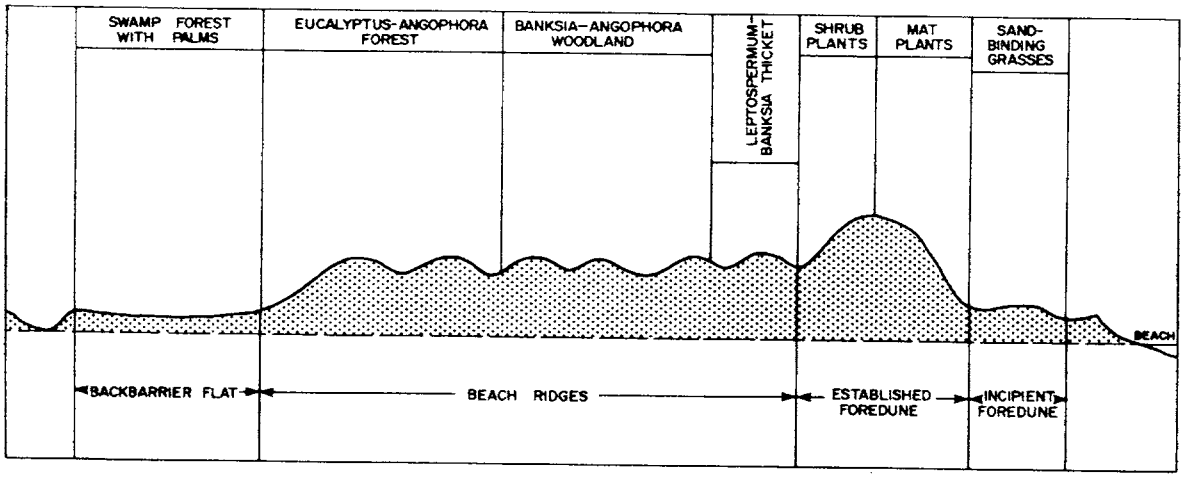

Figure 2-2: Schematic section across an Outer Barrier (eg Fens Embayment) showing association of landform and vegetation types.

Opercularia varia. Innermost ridges are colonized by a well-developed dry sclerophyll forest composed of Eucalyptus pilularis, E. gummifera, Angophora costata and Banksia serrata with a lower and varied shrub layer. This vegetation zonation is similar to that described for the more restricted foredune-hind dune sequence at Anna Bay (see 1.8.1 and McDonald, 1971, 1973).

It is usual for one or more of these communities to be either absent or poorly developed. There is rarely longitudinal continuity of vegetation zones along the ridges (except for foredune or innermost ridge), nor is there a clear association between degree of soil development and vegetation type (Bowman, 1979). Two processes strongly influence the vegetation pattern, fire incidence and salt spray during severe storms. The vegetation pattern on Outer Barriers appears to be composed of a number of competing communities in an environment characterized by infrequent events of great stress. These events are related to phases of dune instability. Die-back in upper branches of eucalyptus trees located behind the foredune or mobile dune sheet is an expression of these processes.

2.3 INNER BARRIER SYSTEM

Sand barriers of the Inner Barrier type occupy bay-head and mid-bay positions in the study area, but never occur in bay-mouths. Unlike Outer Barriers which are separated from older sand or bedrock surfaces by an intervening parallel tract of lagoon or swamp, Inner Barriers commonly abut the bedrock margin of embayments (Fig. 2-1). In western Port Stephens and Myall Lake they enclose extensive water bodies, but elsewhere they block narrow drowned valleys, such as Grahamstown Swamp and Moffats Swamp in Newcastle Bight (Ch. 4). The Upper Myall Valley has been partly enclosed by an Inner Barrier (Ch. 7).

Newcastle Bight, Fens, Upper Myall and Eurunderee embayments all contain Inner Barriers with well-developed multiple beach ridges (Fig. 2-1). The Inner Barrier in the Eurunderee embayment is composite in character, possessing an inner set of transgressive dunes to which has been welded a series of beach ridges (Ch. 8). In the Tomaree Hills, dune sands which will be shown to have been deposited at various stages in the late Pleistocene link bedrock outcrops below and above present sea-level (Ch. 5). The linking together of these rocky hills effectively has extended the Inner Barrier across eastern Port Stephens, thereby enlarging this complex barrier lagoon. An Inner Barrier is presumably buried beneath younger transgressive sands in the Seal Rocks area (Ch. 9). Parts of the Inner Barrier surface have been reworked by post-depositional eolian activity at Newcastle Bight and Eurunderee; this reworking reflects changing environmental conditions in the late Quaternary (Ch. 10).

2.3.1 Beach Ridges

Beach ridges of the Inner Barrier system are characteristically of subdued relief (Thom, 1965, p. 27, Fig. 4D; Shepherd, 1970). Topographic features are not readily discernible in places. Osborn and Robertson (1939), who apparently did not have access to aerial photos, on inspection of the Eurunderee Inner Barrier, concluded:

> The origin of the extensive level sandy plains, locally called "moors", but which we have termed heaths, is difficult to explain, except as the sandy bottoms of former lake beds (p. 289).

From the air a marked ridge-swale pattern is obvious (Thom, 1965, Fig. 3). The pattern closely parallels the present coastline with individual ridges often extending across the entire width of an embayment, a distance of five or more kilometres. There is no evidence of recurvature or marked alignment changes in ridge pattern except at the south end of the Fens Inner Barrier (Ch. 6).

The innermost, or first-formed, ridge may stand 1-5 m above the rest of the ridge series. This ridge is characterized by a broad rounded form. Other ridges, especially in Newcastle Bight, Fens and Eurunderee, stand 0.3-1.5 m above adjacent swales. Ridge amplitude sometimes increases toward the north or east ends of embayments. The crests are flat or very gently rounded. Where a ridge-swale lineation is distinguishable on aerial photographs, individual ridges can be shown to vary in width from 30 to 450 m. Variation in width is limited within any given area. Greatest widths occur in the Upper Myall Valley (Ch. 7). In contrast to beach ridges on the Outer Barrier, the spacing of beach ridges on the Inner Barrier shows considerable variation. Ridge spacing varies from c. 100-200m (Thom, 1965). However, most of the wide beach ridges on Inner Barriers are probably composite features (see below 2.3.2). Shepherd (1970) indicates that in some localities the spacing is comparable with that of the Outer Barrier. Single Inner Barrier beach ridges may grade laterally into two or more narrow but discrete ridges.

Inner Barrier beach ridges are composed of leached quartz sand, varying in depth from 1 to 4 m. This sand is typically light grey in colour and overlies a dark brown to black sand heavily impregnated with organic colloids (see Ch. 3). The degree of impregnation varies from place to place (one to five percent by weight), and locally can give rise to an impermeable hardpan. The water table usually coincides with the top of the organic-stained sand, which is regarded as the upper B horizon of a giant ground-water podzol (Thom, 1965). Characteristically, pH values in the soils are very low, 3.5-4.5; other aspects of Inner Barrier sandy soils have been described by Maze (1942). Swales are mostly wet and boggy, some with slightly less than 1m of standing water. Parts of the Eurunderee barrier have been shown to contain up to 1 to 2 m of detrital organic sand or peat in the swales.

The higher and better drained ridges are often covered by a low woodland which rarely exceeds 8 m in height. Eucalyptus gummifera is the most abundant tree along with E. signata, Angophora costata and Banksia sp. Carolin (1971) has distinguished a number of communities within the low relief ridge and swale terrain of the Eurunderee Inner Barrier. It is apparent that the linear ridge-swale pattern has strongly influenced the habitats of plants in this area and thus exerted a control on plant distribution (see Myerscough and Carolin, 1986). Of importance to the process of swale infilling, is the scanty nature of low stratum vegetation on ridge crests and slopes, especially after fire.

2.3.2 Modification Morphology

The term "modification morphology" refers to landforms derived from primary depositional terrain by processes which lead to the moulding of that terrain subsequent to deposition (Thom, 1975). Inner Barriers of the study area have been modified to varying degrees since they were first formed. At least three processes are responsible for surface change: stream dissection, slope degradation, and eolian reworking of barrier-sand. The impact of each process will be considered in more detail in appropriate regional chapters, and only the basic aspects of modification will be outlined here.

One of the distinguishing traits of Inner Barriers as compared to Outer Barriers is that they have been dissected by streams. Fluvial dissection appears to have been in operation in the past to base levels lower than present sea-level. There is no tendency for barriers to be incised by streams at present, although both Outer and Inner Barriers are locally subject to lateral erosion of meandering streams (e.g. along Lower and Upper Myall Rivers). Gullies or valleys carved into Inner Barriers are now partly infilled with fine-grained and/or organic sediment during a period of "alluvial drowning". Entrenchment has been most dramatic in the Upper Myall Valley where not only the beach ridge sequence has been incised and truncated, but also swales have been gullied (Ch. 7). Grahamstown Swamp appears to have maintained an outlet to the Hunter River via Windeyers Creek during periods of lower base level (Ch. 4). Remarkably, few other parts of Inner Barriers in the study area show the effects of dissection.

Two types of slope degradation have influenced the morphology of beach ridges on Inner Barriers. The first involves removal of sand and organic material of ridge crests and swales. Rain impact and surface runoff on the ridge surface appear primarily responsible for the degradation of the morphology. Wind erosion may also be important, but the lack of blowouts within a ridge sequence suggests this process to be of minor importance. These slope processes appear responsible for the "cannibalism" of certain swales giving rise to a greater wave length in the ridge-swale pattern than was originally the case (Shepherd, 1970).

Another type of slope process involves movement of weathered sand, silt and clay off bedrock slopes over adjacent beach-ridge surfaces. A maximum of 2 to 3 m of this colluvial material buries barrier sand, the thickness depending on height and lithology of the bedrock slope. This slope mantle gradually diminishes in thickness from the hillside. It is best demonstrated at the rear of the Fens embayment where it merges with paludal sediments behind a relatively high beach ridge (Shepherd, 1970).

The third process of surface modification involves the complete or partial removal of the vegetation cover on beach ridges and the formation of "terrestrial" dunes. This type of reworking by wind has occurred in two areas: on the western portion of the Inner Barrier in the Newcastle Bight sector, and on the southern part of the Eurunderee barrier (Fig. 2-1). In both cases the dunes today are covered by a Eucalyptus woodland with swampy depressions between ridges. Well-developed podzol soils have formed on these surfaces. It is considered that these dunes were formed when sea-level was at a lower level than it is now, under the influence of a dominant westerly wind regime (Ch. 10).

2.4 TRANSGRESSIVE DUNES

In this monograph, dunes whether active or not, which can be shown to have moved inland over surfaces composed of forest, swamp, marsh, scrub, or bedrock, or into lagoons, are collectively referred to as "transgressive dunes". In a well-vegetated coastal district there is a strong contrast between moving sand and other types of surface being buried. Such contrasts are not as distinctive in semi-arid or arid environments so the generic term "transgressive dunes" is appropriate in humid regions such as the study area. Buried soils, peat or stumps exposed in sections or on deflated windward slopes indicate the occurrence of dune transgression *. As shown in Table 2-1, the term embraces features referred to as blowouts, parabolic dunes, long-walled transgressive dunes, wrap-around dunes and cliff-top dunes. Although Davies does not include Cooper's "precipitation ridge" in transgressive dune category (1972, p. 152), he recognised the transitional nature of the form (p. 153). We consider it most appropriate to place its homologue, the long-walled transgressive dune, in the transgressive dune class. Furthermore, we do not agree with the inclusion by Davies of longitudinal dunes in this class as these dunes appear to have developed on a mobile sand sheet. However, this is a matter of some dispute, depending largely on whether such dunes have formed as "blown-through" parabolics; thus, for convenience, longitudinal dunes have been placed in a separate category (2.6).

2.4.1 Blow-out Dunes

Blow-out dunes are currently active dunes which involve the dissection of vegetated sand masses. In the study area they are mostly derived from the erosion of frontal dunes, particularly foredunes. However, there are cases where these dunes have been initiated in parabolic dunes (Eurunderee Outer Barrier) or on a stabilized long-walled transgressive ridge (Newcastle Bight Outer Barrier). The continuity of the established foredune is frequently interrupted by non-vegetated gaps through which sand is channelled inland from the beach. These "blowouts" vary in width from 10 to 100 m and may extend 100-300 m inland. Buried soils are sometimes exposed along the scoured walls of these gaps. The transported sand forms steep (30-35 degrees) slopes at the leeward end of the blowouts and along side walls. As the slipface advances over the beach-ridge woodland, buried trees become exhumed on the windward slope. Scour of the walls results in the lateral expansion of blowouts leaving as a remnant of the foredune a row of butte-like knobs or "remanie" dunes. On the Fens Outer Barrier the foredune is progressively modified northward being continuous in the south, then becoming broken by blowouts. At the north end "remanie" dunes as observed in 1961, but poorly preserved in 1978, attested to the near final stage of foredune destruction by blowout expansion (see Short and Hesp, 1982, Fig. 9). However, there are cases where the gaps between knobs have been infilled with sand freshly vegetated by Spinifex grass. The result is a reformed foredune (Hesp, 1982). The trough shape of individual blowouts which cut into foredunes, is best developed in the relatively more sheltered bays (e.g. Fingal Bay and Anna Bay in the Tomaree Hills area).

* Transgressive dune is a term used widely in Australian coastal literature. It appears to have gained acceptance following its introduction by Gardner (1955).

Those blowouts which cut into high stabilized transgressive dunes in the study area reach considerable dimensions. They may exceed 1 km in length and over 100 m in width. These features are discussed and illustrated in more detail in Chapter 8 where it is shown that the active sand mass widens downwind, and that onshore winds are driving these lobes of sand over high Eucalyptus forest of the Eurunderee Outer Barrier.

On the Outer Barrier near Williamtown in the Newcastle Bight sector, there is a large saucer-shaped blowout which lacks connection to the sea. Steep slipface slopes surround the blowout. This feature was probably initiated by careless land-use practices in the last century (see Ch. 4).

2.4.2 Parabolic Dunes

A common form of fixed or partially fixed elongate blowout found in this area is the parabolic dune. Other terms have been used to describe the same type including bow-shaped, horseshoe-shaped, upsiloidal, elongate, wind drift, U-dune and parabola (see Smith, 1949). The parabolic shape is defined by the outline of the lateral arms and the terminal wall. In this region the open or up-wind side of the Holocene parabolic faces seaward suggesting that these dunes have been initiated by onshore winds. Parabolics of Pleistocene age may open seaward or may face the west depending on age of formation and dominant wind (see Ch. 10).

Parabolic dunes on the Inner Barriers are low, subdued features with lateral arms less than 500 to 600 m long. An example is the series of imperfect crescents behind beach ridges in the Eurunderee embayment (Ch. 8). Here soils are well podzolized and troughs are filled with shallow peat. In contrast, Outer Barrier parabolics possess strong relief with ridge crests locally attaining heights of 30 m or more above adjacent ground. Wooded slopes on lee sides may exceed 25 degrees. Windward slopes are generally, but not always, less steep than lee slopes. Their lateral arms may extend for 2000 m although 300 to 1200 m is more common. Particularly in the Eurunderee area younger and smaller parabolics nest within larger dunes. Ephemeral ponds have been noted in the troughs of these parabolics, but peat fill typical of Inner Barrier sites is not present. Parabolics may occur singly (in Fingal Bay) or in a group (southwest end Newcastle Bight, Anna Bay, and Eurunderee). At these localities the assemblage of these dunes imparts a rake-like plan form (dunes de rateau) (see Fig. 2-1 and Ch. 8). Some terminal walls are U-shaped and others are more sharply pointed like a V. Orientation of parabolic dunes or sets will be discussed in the appropriate regional chapter. Jennings (1957) has discussed the general relationship between parabolic dune alignment and the direction of "effective" (resultant) winds.

2.4.3 Long-walled Transgressive Dunes

Sand ridges of this type are distinct from parabolics in plan and magnitude of relief, but both have the common property of advancing downwind over surfaces other than mobile sand. In the study area long-walled transgressive ridges form the inland migrating fronts of broad sand sheets. These ridges are elongated roughly parallel to the coast. They appear to result from the complete destruction of vegetated dunes behind the beach (Ch. 9).

Active transgressive ridges of the long-walled type are sometimes termed wandering or migrating dunes. Along the Oregon coast Cooper (1958) describes similar features invading tall coniferous forests. He refers to them as "precipitation ridges", and in private communication with one of us (B.G.T., 1961), suggested that this term be confined to such a situation. Between Newcastle and Seal Rocks dune sheets transgress marsh, scrub and water as well as forests without any apparent difference in the morphology of the advancing ridge. Therefore, the more generally applicable term will be used in this paper. The term "transgressive frontal dune", employed by Bird (1968, Fig. 56) for dune ridges of the long-walled type on Stradbroke Island, Queensland, cannot be invoked here because of confusion with foredune (Table 2-1).

Both active and stabilized long-walled transgressive ridges have been recognized in the study area. Where frontal dune ridges have been completely, or almost completely, destroyed and are replaced by mobile sand sheets bare of vegetation, the landward edge of the dune sheet forms a massive ridge towering over the invaded surface. The advancing edge is a steep slipface down which sand avalanches into forest, scrub, etc. (Fig. 2-3). This front may be 20 to 30 m in height and be more or less continuous for up to 20 km (e.g. in Newcastle Bight). As with blowouts, forests are buried by the advancing sand only to be exhumed as ghostly remnants on the gentle windward flank as the ridge moves farther inland. The long-walled ridge roughly parallels the shoreline, but in detail it is composed of lobate projections. Rates of encroachment vary from place to place and over time depending on the incidence of onshore winds from the southerly quadrant. Estimates in Newcastle Bight based on photograph measurements indicate rates as high as 5 to 10 m/yr (P.W.D., 1977).

Stabilized vegetated ridges of the long-walled type vary from 10 to 30 km in length and from 10 to 100 m in height (Fig. 2-4). They may trend parallel (e.g. in Newcastle Bight) or slightly oblique to the shoreline (e.g. at Seal Rocks). Those long-walled ridges which have been interpreted as vegetated outer margins of former dune sheets differ morphologically in four respects from the ridge fronts of active dune sheets.

(i) The windward slope is steeper in the case of the stabilized type, which frequently ranges between 15 and 25 degrees. The comparable windward side of an active ridge is often not clearly distinguished from other features on the mobile sand surface.

(ii) Lee slopes of the fixed ridge vary from 23 to 29 degrees compared with the slipface angle of repose (30 to 35 degrees) for the active ridge.

(iii) Currently mobile ridges seldom exceed 20 m height on their leeward side. Stabilized ridges may exceed 50 m, especially at Seal Rocks.

(iv) Micro-relief of the stabilized ridge is more intricate and diversified than that of the active dune. The former is composed of conical-shaped hillocks sharply separated by cols 5-15 m below hillock summits.

Irregular-shaped hummocks and hollows are also characteristic of the stabilized form. Terracettes with risers less that 1 m high may occur on

steep slopes. Leeward bulges of the lobes are more pronounced in the case of the vegetated type. Between these lobes are steep-sided reentrants through which no surface water flows.

2.4.4 Wrap-around Dunes

The wrap-around dune type is dependent on a pre-existing form which possesses a relatively high order of relief. In the study area dune hillocks and bedrock outcrops provide such prominences. In the Seal Rocks sector, steep-sided dune ridges generally symmetrical in section are wrapped around the windward slopes of large hillocks which constitute part of the massive long-walled transgressive ridge of that area (Ch. 9). Enclosed depressions separate the hillock from the wrap-around dune. A remarkable pattern of "ring dunes" was observed at the eastern end of a long-walled ridge of the Newcastle Bight embayment. Three hillocks on the windward side of this ridge are almost completely encircled by sharp crested ridges, 2 to 4 m high. Their morphological character suggests a climbing series of three or four ridges, which have advanced from the south and embraced a stabilized or semi-stabilized hillock at successively lower elevations. These appear similar to "echo dunes" of Tsoar (1983).

Isolated outcrops of Carboniferous rocks over 100 m in elevation dominate the Tomaree Hills area south of the entrance to Port Stephens. Unconsolidated sediment, largely sand dunes, link these outcrops, with outcrops of bedrock being restricted to the summits of hills and to rocky shores between narrow pocket beaches (Ch. 5). Large stabilized sand ridges, some of which are 20 m high and 1500 m long, occur in the Tomaree area. Their arms, although distorted by the rock outcrops, open toward the southwest. Many of the bedrock hills are flanked by partially encircling ridges. In some cases the bases of the depressions are occupied by swamps 30-50 m above sea-level. It appears that the dunes have migrated into the bedrock terrain from sand plains to the west and southwest, and have wrapped themselves around the windward faces of the hills. They provide interesting examples of the deformation of a wind field by bedrock hills.

2.4.5 Cliff-top Dunes

Jennings (1967) has noted that coastal dunes sometimes occur on the tops of cliffs in positions which make their emplacement problematic. On the N.S.W. coast, fixed and highly podzolized cliff-top dunes have been discussed by Langford-Smith and Thom (1969). Between Newcastle and Seal Rocks cliff-top dunes are confined to a few localities. Tomaree Hills and Seal Rocks sectors are two areas where low-relief mounds of sand mantle bedrock surfaces near the coast (Fig. 2-1). Locally, the mounds may possess a vague parabolic morphology. In both areas the sands are stabilized by dune woodland. These sands appear to be derived from masses of sand which form the transgressive dunes to windward.

2.5 MOBILE DUNES

In this monograph mobile dunes refer to the free-moving sand masses which are unimpeded by vegetation or other obstacles (Table 2-1). They are only found on sand sheets bare of vegetation. These sand sheets typically occur behind a beach where established foredune ridges have



Figure 2-3: Active slipface of a free-moving dune sheet transgressing Eucalyptus forest in the Newcastle Bight Embayment.

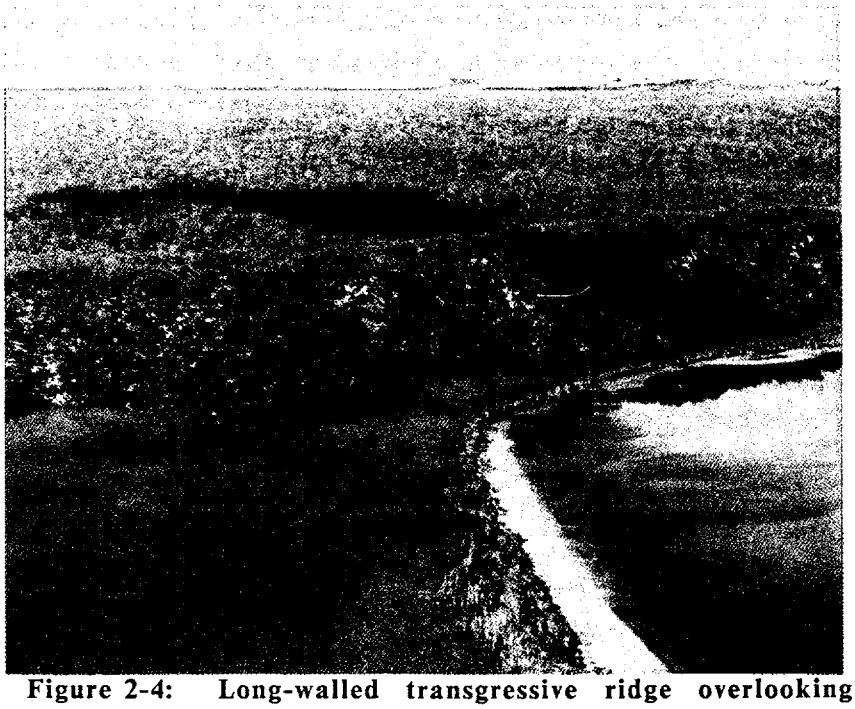

Figure 2-4: Long-walled transgressive ridge overlooking Myall Lake and adjacent swamps. This ridge rises to c.100m above sea level, but varies in height along its crest. The ridge is covered by dry sclerophyll forest dominated by Eucalyptus pilularis.

been removed. Incipient foredunes may redevelop from time to time between the beach and the sand sheet, as has been observed in the study area since 1950.

Mobile sand sheets are located in Newcastle Bight, at the northern end of Anna Bay (Tomaree Hills sector), and in the Fens and Seal Rocks areas. Mobile sand sheets may exceed 20 m in elevation. Highest points are on transgressive ridges near the inland edge. There is a general slope seaward to a flat, partly water-logged sand surface behind the beach. This is a deflation surface eroded to the water-table. Under conditions of strong winds from a constant direction the sand on these sheets is arranged into spectacular transverse and barchanoid dune ridges (Fig. 2-5).

The transverse dune, as defined by Cooper (1958, p. 1), is a ridge essentially normal to the wind and moving with it; it is asymmetric in profile with a gentle windward slope and a steep leeward slope (slipface). Figure 2-5 clearly demonstrates the wave-like pattern of transverse ridges as viewed toward the slipface. This pattern was produced by westerly winds during the late autumn and winter of 1960. Ridge heights of the lee side may exceed 10 m, but the crest line is usually undulating. The ridge is slightly sinuous in plan and attains lengths varying from less than 100 to over 600 m. Lee projections (Cooper, 1958, p. 44) frequently develop in the transverse dune field. Spacing between ridges is often quite regular varying between 100 and 200 m.



Figure 2-5: Transverse dune field in Newcastle Bight in June 1960, after a period of strong westerly winds (view is to the west).

A regular seasonal construction and destruction of transverse dunes was observed by Cooper (1958) along the Oregon coast, USA. In the study area, the details of the dune pattern depend on the incidence of high-velocity winds from a particular direction. Here there is a marked seasonal reversal of slipface orientation. The ridges are aligned north-south at right angles to effective east and west winds. In winter, westerly winds prevail and the steep slipface on the lee side of the ridge is oriented to the east. Under the influence of east to northeast winds in summer, the direction from which sea breezes blow along this stretch of coast, the slipface reverses itself. There is no seasonal destruction of the transverse dune field as observed in Oregon. Thus the transverse dunes in the study area are perhaps better described as "reversing dunes" (see Harding King, 1918; Bigarella, 1972, p.22; McKee and Bigarella, 1972). Further details on their morphology, rates of movement, relation to wind field, including the impact of southerlies, are discussed in Chapter 4.

In two areas, Newcastle Bight and Seal Rocks, transverse-like dune ridges occur under dune forest. Cooper (1958) has argued that the transverse pattern is destroyed during stabilization: "the characteristic forms are apparently gradually transformed into those determined by a plant cover in conjunction with wind and water" (p. 65). However, in both areas in N.S.W. a regular set of near-parallel ridges generally asymmetrical in section lies on a sand plain seaward of a stabilized long-walled transgressive dune. Their specific characteristics will be discussed in Chapters 4 and 9.

Transverse ridges in this area often acquire a "barchanoid" form. This may happen on those parts of the moving dune area where the sand supply is limited by proximity to the relatively immobile, water-saturated, deflation surface. As noted above, this surface lies behind the beach seaward of the great bulk of moving sand. The dunes are barchanoid in the sense that they are crescentic in shape with the slipface on the concave or lee side. However, it is rare for the horns to be perfectly parallel with the effective wind direction. Westerly winds produce the longest slipfaces with much shorter lee slopes and horns being characteristic of summer months under the influence of east to northeast winds. Southerly winds were noted to remove sand from the narrow deflation strip behind the beach and add it to the transverse ridge system. A large barchan dune has been observed on the "tombolo" linking Yacaaba headland to the Fens Outer Barrier (Ch. 6).

2.6 LONGITUDINAL DUNES

In the Williamtown-Tomago area of the Inner Barrier in Newcastle Bight, and in the vicinity of Anna Bay (Tomaree Hills sector), there exist a number of elongate sand ridges aligned west-east. At the eastern end of the Inner Barrier these ridges cut obliquely across and obscure the beach ridges (Fig. 2-1 and Fig. 4-4). Many of the ridges form individual dunes 1 to 2 km in length. They attain elevations of up to 50 m above sea-level. These ridges possess a plan form resembling a string of beads with gently rounded hillocks often symmetrical in section joined together by a low ridge. In places adjacent ridges join to produce a "Y" junction open to the west; some ridges appear to be V-shaped parabolics or blown-through parabolics. All of the ridges are currently stabilized, and where not cleared for farming or home sites are vegetated by a dune woodland dominated by Eucalyptus pilularis,

E. signata, Banksia serrata and Angophora costata. Soils are deeply podzolized (see Maze, 1942). This dune type, here referred to as "longitudinal", will be discussed in more detail in Chapters 4 and 5.

2.7 SUMMARY

The area between Newcastle and Seal Rocks embraces a wide variety of wave and wind deposited landforms. In this chapter we have attempted to describe this diverse morphological array concentrating especially on those found on the bay barriers of late Pleistocene and Holocene age. It is deemed significant that many sand dune types are relict, being preserved under a cover of eucalyptus woodland. These relict landforms may be the product of different environmental conditions from those which prevail today. Yet there are currently active dunes which are similar in many respects to those which are now well vegetated. In the next chapter the sedimentological characteristics of the various environments of deposition will be discussed as a prelude to a more detailed examination of regional diversity in morphostratigraphy and depositional history. These discussions will assist further in our understanding of environmental conditions and processes responsible for the evolution of such a diverse, segmented coastal landscape (Ch. 10).

TABLE 2-1 Nomenclature of Sand Depositional Forms Associated with Oceanic Conditions in the Port Stephens-Myall Lakes Region.

Bay Barrier: a general term to describe sand deposits within or across the mouths of bedrock embayments, extending roughly parallel to the coast, and which wholly of partly encloses a lagoon or swamp (relict lagoon). Today most of the barrier lies above the level of highest wave action and is vegetated, although part may contain large tracts of mobile dune sand.

Inner Barrier: barriers characterised by subdued topography and well-developed soils occupying a bay-head or mid-bay position in the study area.

Outer Barrier: barriers characterised by "fresh" relief and zero to moderate developed soils, occupying a bay-mouth position in this region.

Interbarrier Depression: low relief surface separating Inner from Outer Barrier, often elongate and swampy and containing water-bodies.

Bar: an elongate or crescentic sand ridge which is always submerged at high tide.

Beach: deposit of sand, shingle or boulders extending landward from mean low water line to the line of vegetation or bedrock, and which is subjected to the normal wash of waves during the tidal cycle.

Frontal Ridge: a general term to cover various types of sand deposits derived from and adjacent to the beach as a result of the interaction of waves, wind and vegetation.

Incipient Foredune: ridge of sand parallel to and often adjacent to the beach, colonized by herbaceous vegetation and subject to periodic destruction by wave action (see Hesp, 1982, for more elaborate classification).

Established Foredune: ridges of sand parallel to and sometimes adjacent to the beach if the incipient foredune is absent, and colonised by mixed herbaceous and woody vegetation; usually a more massive structure than the incipient foredune and may contain buried soils (see Hesp, 1982, for more elaborate classification).

Beach Ridge: vegetated ridge of sand more or less parallel to the beach and landward of the foredune; usually occurs as a series of regularly spaced parallel to sub-parallel ridges of varying amplitude and wave-length (also termed relict foredune or foredune ridge). A series of ridges forms a beach-ridge or strand plain.

Dune Platform: vegetated terrace of sand lacking pronounced topographic form usually found between the beach and bedrock in small embayments (after Davies, 1972).

Remanie Dune: eroded remnant of frontal ridge, usually the foredune, breached by wind and waves.

Transgressive Dune: a general term to cover various types of sand deposit moved in the direction of the effective wind over surfaces other than mobile sand.

Blow-out Dune: hollow or trough cut into vegetated sand deposits, usually with a steep mobile sand ridge downwind.

Parabolic Dune: vegetated or partly vegetated accurate ridge which opens towards the wind (may occur singly or in groups).

Long-Walled Transgressive Dune: Elongate ridge of mobile sand forming the inland migrating front of a sand sheet; also occurs as a stabilized form.

Wrap-Around Dunes: near concentric ridge or ridges partly encircling bedrock or stabilized dune hillocks (occurs as a stabilized form at present).

Cliff-Top Dunes: low mounds of sand mantling bedrock surfaces near the coast (occurs as a stabilized form at present).

Mobile Dune: a general term to cover various types of free-moving sand ridges superimposed on a sand sheet bare of vegetation.

Barchan: crescentic ridge with steep slipface on lee side, and lateral arms trailing downwind.

Transverse Dunes: elongate ridge of dune sand oriented normal to effective wind, and asymmetrical in section with steep lee slope and gentle windward slope (stabilized form may be more symmetrical and sinuous); in the study area transverse and barchan dunes typically "reverse" their profiles seasonally and thus may be referred to as "reversing dunes" (after Bigarella, 1972).

Longitudinal Dune: sand ridge oriented parallel to the effective wind direction; these ridges are often beaded in plan, symmetrical in section and taper downwind. This type is stabilized at present.

3

Sedimentary Facies

3.1 NOMENCLATURE AND CLASSIFICATION

A sedimentary facies can be defined as a mass of sedimentary material which is distinguished from others by certain characteristic properties, such as its geometry, lithology, depositional structures, paleocurrent pattern and fossil content (Selley, 1970). The recurrence in space and time of units of sedimentary material which possess many of these characteristics in common facilitates the recognition of facies units, the summation of which equals the entire mass of sediment present within an area. A sedimentary facies is the product of a depositional sedimentary environment, that "complex of physical, chemical and biological conditions under which a sediment accumulates" (Krumbein and Sloss, 1963, p. 234). These conditions influence not only the characteristics of sediments being deposited, but also the nature and circulation of ground waters, which in turn influence diagenetic change within a sediment unit after burial or stabilisation by vegetation. These changes modify the original depositional properties, particularly the faunal and organic contents and give rise to a distinctive sedimentary unit.

In modern sediments, it is generally possible to associate a depositional environment and its product, a sedimentary facies. Processes operating within a depositional environment can be either directly observed or readily inferred. Consequently, a facies may be

qualified by an environmental term which expresses some distinctive attribute of the unit (e.g. nearshore shelly sands).

Knowledge of the properties of facies units forming today obviously enhances the interpretation of a region's stratigraphy. However, there exists in the Newcastle-Myall Lakes area a number of sediment units which are relict. The environment of deposition of such units can be inferred from their sediment properties, and our understanding of processes responsible for similar units today.

In the previous two chapters some of the characteristics of depositional environments have already been discussed. In general, three major environments can be recognized in the area between Newcastle and Seal Rocks: open ocean, estuarine-coastal lagoon, and terrestrial. Most attention will be focussed on sediments which accumulated under the influence of open-ocean conditions, either on or seaward of coastal sand barriers. The estuarine-coastal lagoon environment incorporates semi-enclosed water bodies which have varying access to the open ocean so are subject to some tidal exchange and periodic dilution with freshwater derived from the land. A number of sub-environments can be recognized each with a distinctive facies product. In this study bottom sediments from Port Stephens are examined, and are used in the reconstruction of Quaternary paleoenvironments. The terrestrial environment embraces either those areas where river drainage from the bedrock hinterland dominates depositional processes, or where organic deposits are accumulating under freshwater conditions. It has not been subjected to any extensive study as yet, although our surface and sub-surface investigations have yielded some information on resulting facies in three areas: Hunter River delta, Karuah River and Upper Myall River.

In this chapter, certain symbols are introduced which designate facies type and time period. Capital letters (M, E and T) are used for major environments of deposition, whilst lower case letters refer to various facies. Numbers 1 to 6 relate to six time periods in the late Quaternary (see Ch. 10). In the following chapters, these symbols are used on diagrams and maps.

3.2 MODERN ENVIRONMENTS OF DEPOSITION

3.2.1 Open-ocean Environment (M)

In Chapter 2 the open-ocean environment was considered to embrace those areas of the coast where wave and wind processes generated seaward of the shoreline over the open ocean initiate sediment transport and accumulation. Sediments deposited in this environment can be classified into four types (types A-D in Table 3-1). Each type corresponds to a morphological zone, the basic characteristics of which have already been described (Ch. 2). Exposure to waves and winds and position relative to sea-level determine many of the characteristics of the sediment types or facies units which occur within the open-ocean environment. However, local variation in the nature of depositional processes does produce certain distinctive patterns of sediment accumulation within each unit which must be characterized.

3.2.1.1 Nearshore marine sand facies (n)

Nearshore (or shoreface) marine sands at present are being actively reworked seaward of the beach zone to depths of 15-20 m below mean sea-level. It is possible that sediment transport occurs below this depth, but the extent and frequency of movement is inadequately documented at this time (Wright et al., 1980, 1982). The inner part of the nearshore zone is strongly influenced by the passage of broken waves and longshore currents, whereas the outer part (depths greater than c. 5 to 10 m depending on exposure) is predominantly affected by oscillatory motion induced by shoaling waves. The morphology of the inner zone is characterized by bars, shoals and troughs which are constantly changing their shape and size in adjustment to the wave regime. The outer zone possesses a gently inclined slope of varying gradient depending on exposure and sediment abundance.

Sands on the bed of the nearshore zone are all unconsolidated and free to move under the influence of currents. There is no cementation or consolidation by a mud matrix. Short (1983) has examined internal structures from beaches and nearshore zones within the dissipative to reflective range including Myall Lakes beaches. The structures range from parallel low angle cross-bedding on the beach face, to complex, higher angle small-scale cross-bedding in nearshore areas formed by the interaction of shore-normal and shore-parallel currents and wave motions (see also Clifton et al., 1971).

Nearshore and inner shelf sands are quite varied in grain size. Analysis of 90 samples collected in Newcastle bight from just below LWM to -60 m on the inner shelf shows that mean grain size ranges from 1.0 Figure 3-1 is a plot of mean grain size against depth for these samples; phi to 2.5 phi. they include samples analysed using a settling tube by Boyd (1974) and by sieving (Ly, 1976)*. Sands in Newcastle Bight tend to fine offshore to c. -15 m after which they become coarser. The inner shelf sand zone is characterized by a more poorly sorted sand type which extends to c. -60 m. At this depth the sediments become muddy (Boyd, 1974; Roy and Crawford, 1980). Similar, but less well documented patterns, have been found within Eurunderee and Fens embayments (Shepherd, 1970).

Grain size distributions of nearshore marine sands (non-carbonate fraction) are illustrated in Figure 3-2(see Roy and Crawford, 1980, Fig.11 and Fig. 14 for more detail in Newcastle Bight). The method of plotting follows Visher (1969). They all show three or four populations: one rolling, one or two saltation and one suspension. Higher amounts of rolling population are usually observed in the inner nearshore zone where they can be up to 20 to 25 percent at the bar. In this high energy zone the amounts of the suspension population are low and always less than one percent, whereas in the quieter outer nearshore zone they can reach 20 percent. The nearshore marine samples are well to moderately sorted with phi standard deviation varying from 0.38 to 0.81. Best sorted samples are transported by saltation. The addition of a coarse rolling population at the bar zone or of a fine suspension population in the

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* Techniques used in this study for calculating grain size statistics are described in detail in Shepherd (1970), Boyd, (1974), Ly (1976), and Bowman (1979).

TABLE 3-1 General Characteristics of the open-ocean facies units in the Newcastle-Myall Lakes area (Modified after Ly, 1976).

Type	Environment	Sedimentary Structures	Grain Size			
			Mean (ϕ unit)	Sorting (ϕ unit)	Skewness (ϕ unit)	Size Distribution
A	Outer nearshore Marine (20 - 40 m)	No core data but symmetrical ripples common on sand bed	Fine sand $M\phi$ = 2.00-2.50	Well to moderately sorted $c\phi$ = 0.40-0.80	Generally positively skewed	Increase in amount of suspension population which can be up to 20 per cent.
	Inner nearshore Marine (0-20 m)	No core data but variety of bedforms observed within and approaching bar-trough inshore zone	Medium sand $M\phi$ = 1.20-1.90		Generally negatively skewed	Mainly rolling and saltation populations with less than one per cent suspension population
B	Subaerial Beach	Parallel stratification gently dipping seaward are most typical	Coarse to fine sand $M\phi$ = 0.60-2.20	Very well sorted $c\phi$ = 0.20-0.50	Generally negatively skewed	One or two saltation populations truncated with or without saltation population. Rolling population occurs in coarse sands
C	Frontal ridge	Short, steeply dipping cross bedding, and low angle dipping, discontinuous laminae. interrupted by roots.	Medium to fine sand $M\phi$ = 1.40-2.30	Very well sorted $c\phi$ = 0.25-0.45	Generally negatively skewed	Two saltation populations and a suspension population Small amounts of rolling population
D	Transgressive dune	Combination of steeply (leeward) and gently (windward) dipping laminae (multi-directional forests reflecting variable wind regime)	Medium to fine sand $M\phi$ = 1.30-2.30	Usually very well sorted $c\phi$ = 0.20-0.40	Generally positively skewed	A single saltation population. Very small amounts or often absence of rolling population.

outer nearshore zone makes the samples more poorly sorted. The sign of skewness depends on the relative abundance of the coarser and finer ends of grain size distribution. In the inner nearshore zone where the coarse rolling population is higher, the samples appear to be negatively skewed whereas in the outer nearshore zone where the fine suspension population predominates over the coarser end, the samples become positively skewed (Ly, 1976).

Nearshore marine samples are mainly quartzose. In the Newcastle Bight samples, the rock fragment and feldspar content ranges from 3 to 12 percent. Feldspars constitute a maximum of 9.5 percent (Ly, 1976). Although the heavy mineral suite is composed of 80-90 percent rutile, zircon, tourmaline, opaques (e.g. leucoxene and magnetite) and garnet, less stable minerals such as pyroxene, hornblende and epidote are occasionally found in the samples from the outer nearshore zone. The content of heavy minerals in the nearshore marine sands is usually less than 2 percent.

The quartz grains vary greatly in roundness from well rounded to very angular. Values of average roundness as determined from the Newcastle Bight samples range from 0.21 to 0.37 (Powers scale). Detailed analysis of the fraction between 1.75 and 2.75 phi showed that the amounts of angular and very angular quartz grains were usually higher in the samples from the outer nearshore zone than in those from shallower depths.

Small amounts of organic carbon are contained in sediments of the nearshore zone, especially the outer part. The SCUBA diver may encounter

Roundness R = average roundness n = % angular grains	Composition			Organic content	Surface Textures by SEM
	Rock Fragments %	Feldspars %	Heavy Minerals		
Subrounded to very angular grains R=0.21-0.25 n=35-75%	3.5-12.0	5-9.5	Contents = 1-2% Rutile, Zircon opaques, pyroxene, hornblende epidote, tourmaline, garnet	Grey colour of sand possibly due to organic fraction (<2%) - see some charcole & wood fragments	- chemical features (etch cavities)
Rounded to sub-angular grains R=0.30-0.37 n=20-35%			Content = 1-2% Rutile, Zircon, tourmaline opaques, garnet	Low (<1%)	- mechanical features (V - shaped pits)
Well rounded to angular grains R=0.29-0.44 n=7-55%	3.5-13.6	0.9-7.6	Content = 0.1 - 1.25%. Usually rutile, zircon, opaques, tourmaline, garnet. Local concentrations of pyroxine, hornblende and epidote near volcanic outcrops	Very low	Mechanical features predominate over chemical features (V-shaped pits, straight or curved grooves, conchoidal breakage blocks)
Well rounded to subangular grains R=0.35-0.38 n=19-27%	2-8	3-4.2	Content = 0.1 - 0.7%. Usually rutile, zircon, opaques, tourmaline, garnet with local centrations of pyroxine, hornblende and epidote	Abundant roots from grasses and woody shrubs	Mainly mechanical features (V-shaped pits, straight or curved grooves conchoidal breakage blocks)
Very well rounded to subangular grains R=0.30-0.46 n=4-17%	0.7-4.3	0.5-9.5	Content = 1.1 - 6.4% Usually rutile, zircon, opaques, tourmaline,	Very low	Mechanical features superimposed by chemical action

the odd water-saturated log. Finely divided plant fragments are segregated by oscillatory wave motion and deposited as thin laminae in the cross-bedded shelly sands. The predominantly grey colour of the outer nearshore zone is presumably due to decaying organic matter.

The nearshore environment possesses a very mobile sand surface. Aquatic plants do not grow in the zone. Molluscs are quite common on the surface as well as buried. The assemblage is dominated by the so-called banded kelp shell, Bankivia fasciata. This colourful gastropod, which reaches up to 2 cm in length, occurs in countless millions on the sand surface (they may suffer a dramatic reduction in population after a period of severe storms). Generally, Bankivia shells cluster together in the troughs of ripples where they move freely under the influence of passing waves. Glycymeris flammea and Amesodesma angusta are two burrowing pelecypods which occur in nearshore sands, but knowledge of their ecology is scanty. Conuber sp. are sometimes quite abundant, but other shell species are not common*. Locally, a variety of detrital shell types may occur in low numbers (Table 3-2). Skeletal carbonate fragments of gravel and sand size range occur in the sediment of the nearshore zone. In the study area, the content of carbonate in the sands is usually less than 20 percent.

Quartz grains from the nearshore marine sand facies are characterized by both chemical etching or dissolution and mechanical features. It is possible that the intensity of mechanical action depends

* No attempt has been made to identify foraminifera and other micro-organisms found in this environment.

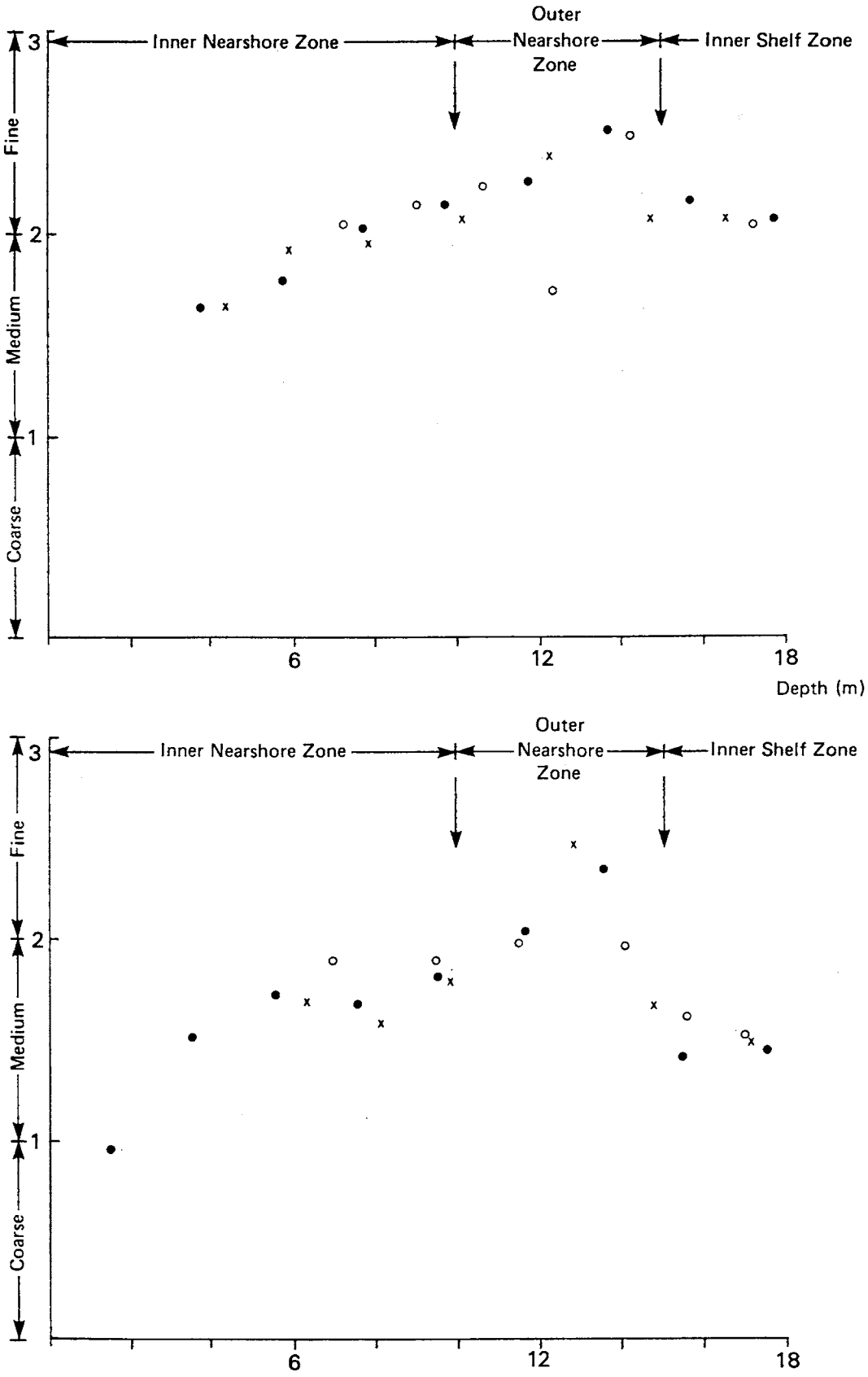

Figure 3-1: **Variation in mean grain size for samples collected from nearshore and inner sediment zones in Newcastle Bight (from PWD, 1977, Figs. 6.4 to 6.7).**

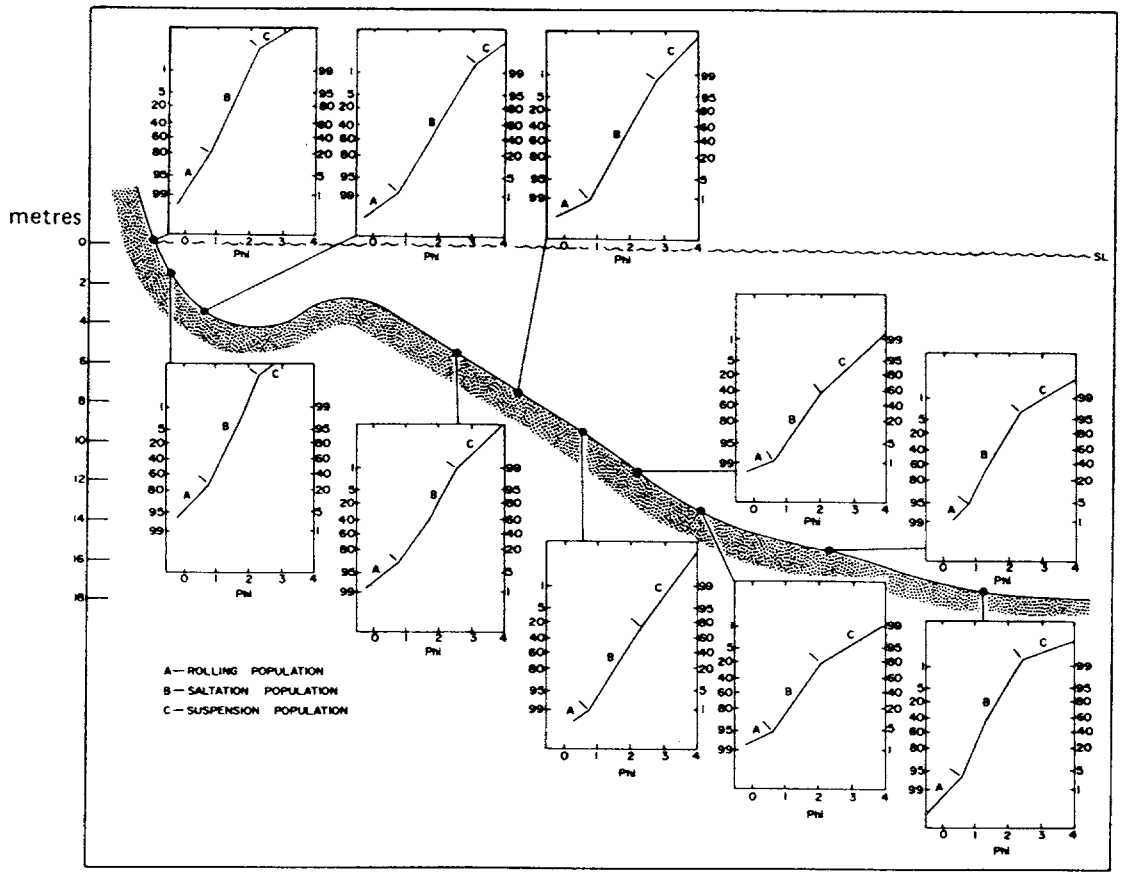

Figure 3-2: Grain size distribution of samples collected from the nearshore environment in Newcastle Bight, and plotted following the method of Visher (1969). This method enables separation of rolling (A), saltation (B) and suspension (C) populations.

on the depth due to the energy variation normal to the shore (Margolis, 1968). An examination of quartz sand grains from 13 to 14 m below mean sea-level in Newcastle Bight showed a predominance of chemical etching features, although mechanical pits are also observed (Fig. 3-3; see also Ly, 1978a). Redeposition of silica can be seen either as small precipitates in the etch cavities or as smooth surfaces in the grain surface depressions. The mechanical features are mainly V-shaped pits. They are smaller than those seen in the high energy beach environment.

3.2.1.2 Beach sand facies (b)

The open-ocean beach is a zone of fluctuating wave energy being affected by both swash and backwash action of broken waves. This zone includes the subaerial beach and overlaps with the adjacent nearshore zone affected by wave bores. As noted in Chapter 1, beaches along this part of the New South Wales coast are subjected to periods of erosion interspersed with periods of deposition. The duration and intensity of each erosional or depositional phase is dependent on the wave climate interacting with nearshore topography. In very general terms, coarser sands often accumulate as lag concentrations during periods of storm-wave erosion, interbedded with layers of fine-grained heavy minerals, while relatively finer sands are deposited at other times.

TABLE 3-2 Holocene Molluscan Associations, Port Stephens - Myall Lakes Area
(common species only; see Iredale and McMichael, 1962 for reference list)

GROUP I = sandy and upper nearshore, sandy

Plebidonax deltoides
Ammesodesma angusta
Glycymeris flammea
Bankivia fasciata
Tawera gallinula
Conuber conica
Anadara sp. (reworked)
Pyrazus sp. (reworked)

(Various reworked limpet species near rock headlands)

GROUP II = lower nearshore, sandy

Bankivia fasciata
Leiopyrga lineolaris
Flycymeris flammea
Numella adamsi
Nannomactra jacksonensis
Ammesodesma angusta

GROUP III = tidal delta or nearshore adjacent to estuary mouth, sandy (mostly reworked from other environments)

Bankivia fasciata
Leiopyrga lineolaris
Glycymeris sp.
Plebidonax deltoides
Conuber conica
Ammesodesma angusta
Nassarius jonasii
Eumarcia fumigata
Anadara trapezia
Cacozeliana granaria
Pyrazus ebeninus
Velacumantus australis
Trichomya hirsuta
Ostrea sp.

GROUP IV = shell bioherm in estuary (see Peat and Roy, 1974)

Proxichione chemnitzi
Ostrea angasi
Acritopaphia transfusa
Crassostrea commercialis
Chlamys asperrima
Trichomya hirsuta
Pecten benedictus-fematus

GROUP V = mud basin in estuary

Notospisula parva
Nassarius sp.
Ostrea angasi

GROUP VI = nearshore estuarine sand-mud

Anadara trapezia
Velacumantus asutralia
Pyrazus ebeninus
Crassostrea commercialis
Ostrea angasi
Nassarius jonasii
Notospisula parva

GROUP VII = nearshore estuarine - weedy sand-banks (shelly sandy bay facies)

Cacozeliana granaria
Prothalotia comtessei
Trichomya hirsuta
Neosolen correctus
Nassarius jonasii
Nassarius burcharddi
Austroginella johnstoni
Conuber conica
Conuber sordida
Pecten fumatus
Eumarcia fumigata
Chlamys lividus
Pexocodakia rugifera
Fulvia tennicostatum
Anadara trapezia

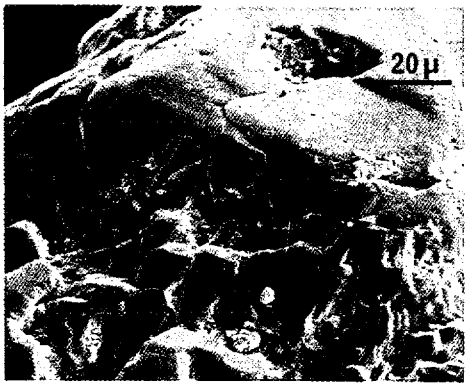

Figure 3-3: **Scanning electron micrograph of surface texture of a sand grain from the nearshore "marine" sand facies collected between -13 to -14m MSL Newcastle Bight.**

The well-established relationship between mean grain size of sediment and beach gradient is observed in the study area with the beach slope tending to be steeper where there is coarser beach material (see Ch. 4). Measurements carried out by Shepherd in winter and summer (October and April, 1969), within Eurunderee and Fens embayments, indicated that the beach slope was also related to the length and steepness of waves affecting the beach; the beaches were steeper in winter than in summer during the period of observation (see also Hesp, 1982).

Bedding characteristics of beaches in the Newcastle-Myall Lakes area have been observed in sand cliffs formed during phases of beach erosion, and in trenches cut during mining operations and in studies by Hesp (1982, 1984a,b). Bedding parallel to the shoreline is commonly horizontal with parallel tabular strata displaying little variation alongshore. The upper beach (backshore) bedding at right angles to the shore is also typically tabular, simple (i.e. depositional), very low angle (<5 degrees), large-scale (>6m), seaward dipping strata. Cross strata on or near the berm crest may be somewhat steeper and occasionally planar (i.e. erosional), wedge-shaped strata. These are similar to beach structures described by Panin (1967) and Wunderlich (1972). Wave deposited logs occur at various elevations (up to 4 m above HWM) and are exposed in cliffs cut into foredunes.

Beach sands are coarse to fine-grained and yellowish in colour. They are free of silt and clay. Size analysis of 69 samples showed that the phi mean grain size varied from 0.63 to 2.23 in Newcastle Bight (Ly, 1976) whereas in Fens and Eurunderee embayments, it ranged from 1.10 to 1.96. Shepherd (1970) demonstrated an increase in grain size north of Hawks Nest to Eurunderee (Fig. 3-4). This longshore variation in grain size may be the response of beach material to exposure to increasing wave energy, but in Newcastle Bight the trend is reversed with coarser samples occurring to the southwest. Figure 3-5 shows the lateral variation in grain size of 13 samples collected from the foreshore at Newcastle Bight (solid lines) in comparison with somewhat finer sands collected from

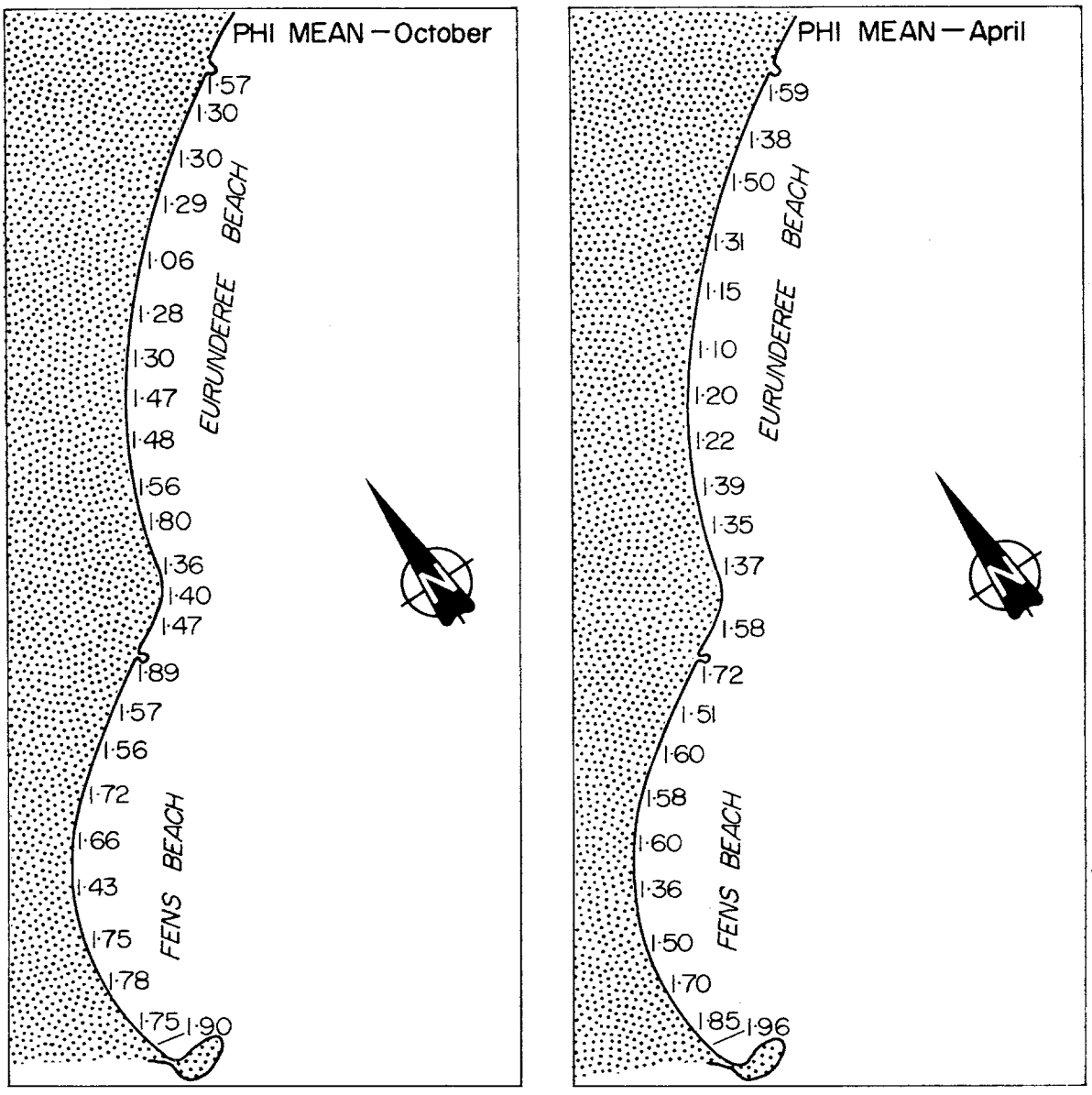

Figure 3-4: Trends in mean grain size for the beach environment in Fens and Eurunderee embayments for two months of the year (from Shepherd, 1970).

adjacent mobile dunes. It is possible that these contrasting distributions reflect different sedimentation histories during periods of lower sea-level. Newcastle Bight embayment is fed by a large river whereas those to the north of Port Stephens may be adjusted to long-term longshore drift from the south.

Visher (1969) indicated that foreshore beach sediments are characterized by three or four populations: suspension, two saltations (probably produced by swash and backwash) and rolling. The grain size populations of the beach samples from Newcastle Bight and Tomaree are characterized by one or two saltation populations which are truncated with or without a small suspension population (always less than one

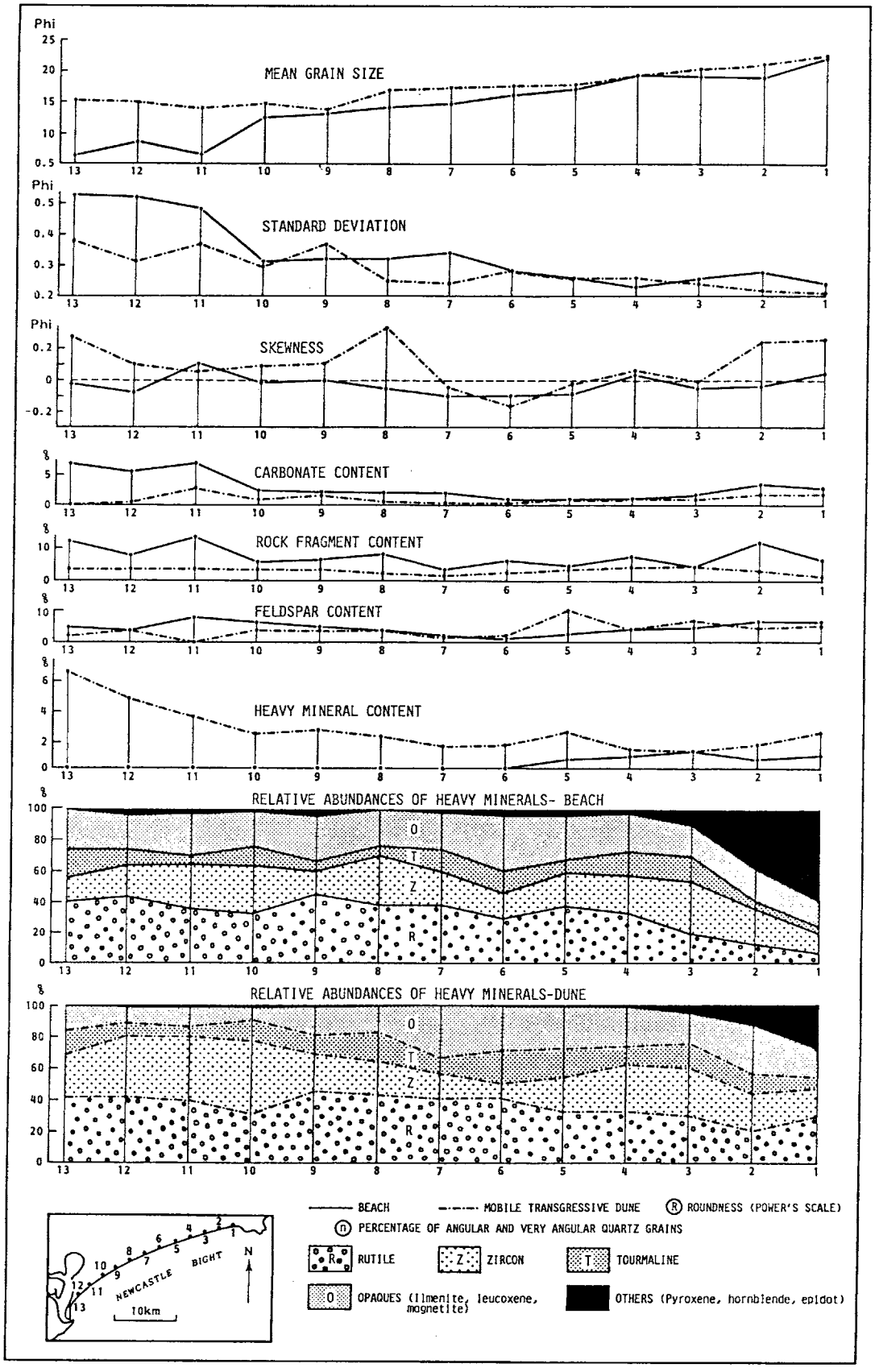

Figure 3-5: Variations in sediment characteristics for beach and mobile transgressive dune environments in Newcastle Bight (from Ly, 1976).

percent). The rolling population usually occurs in the samples containing a coarse mode (e.g. west end Newcastle Bight).

Beach sands are usually very well sorted to well sorted with standard deviations ranging from 0.23 to 0.53 (Ly, 1976). Highest values are found in the sands of the west end of Newcastle Bight (Fig. 3-5). More than 85 percent of beach samples show a negative skewness; the remaining samples are unskewed or slightly positively skewed. Removal of most of the finer fraction from the size distribution due to winnowing action, and the high energy of the beach environment, causes the beach sands to be negatively skewed (Friedman, 1961).

At Fens and Eurunderee samples were taken from the beach at three different localities (low tide mark, mid-swash zone and near the top of the swash zone) from five transects normal to the shoreline (Shepherd, 1970). Size analysis showed that in each individual transect the low tide sample was the most poorly sorted, and, with one exception, the coarsest and most negatively skewed. Low tide samples contained a markedly higher percentage of material coarser than 0.5 phi. There was little difference between size parametres of middle and upper swash zones, although there was a tendency for the upper swash zone to be coarser than the mid-swash zone (see Shepherd, 1970, pp. 77-81).

Beach sands of the study area are predominantly quartzose. The amount of rock fragments and feldspars in beach samples is generally less than 10 percent in each case. When compared to the fluvial sands of Hunter and Karuah rivers, the beach sands are much less lithic and feldspathic (Fig. 3-6). Under moderate to low wave conditions, heavy minerals occur either as thin and discontinuous laminae at the upper part of the beach near the high water mark, or as disseminated particles in the sediment. In stormy conditions, the heavy minerals are deposited in relatively thicker and more continuous layers. The heavy minerals include rutile, zircon, opaques, tourmaline, garnet, pyroxene, hornblende and epidote. The three last minerals mainly occur in relatively higher amounts in the vicinity of the Carboniferous volcanic headlands, the most likely source of these three minerals in the area. Under normal conditions, the content of heavy minerals in the beach sands is generally low and usually varies from 0.1 to 1.25 percent. However, after storms heavy minerals may concentrate as seams in excess of 80 percent.

Beaches have been regarded as the environment where there is active rounding of the quartz sand grains (see Pettijohn, Potter and Siever, 1972, p. 482). Kukal (1971, p. 216) indicated that the rounding of beach sand grains was almost always perfect. However, Beal and Shepard (1956) and Shepard and Young (1961) gave the roundness values of beach sands which indicated that they are subangular to subrounded and are less rounded than dune sands. Determinations of average roundness from 13 samples from Newcastle Bight indicated that the sands were subangular to subrounded with R ranging from 0.29 to 0.44 (Ly, 1976). Except for 2 samples, amounts of angular and very angular grains in quartz fraction are less than 35 percent.

The distribution of detrital carbonate in the study area appears to be a function of wave energy (see Dexter, 1983, for review of beach fauna). As energy and clastic grain size increases, the carbonate content of beach sand decreases. The range of values for carbonate at Newcastle Bight beach is 0.8 to 7 percent, for Fens beach 1.3 to 5

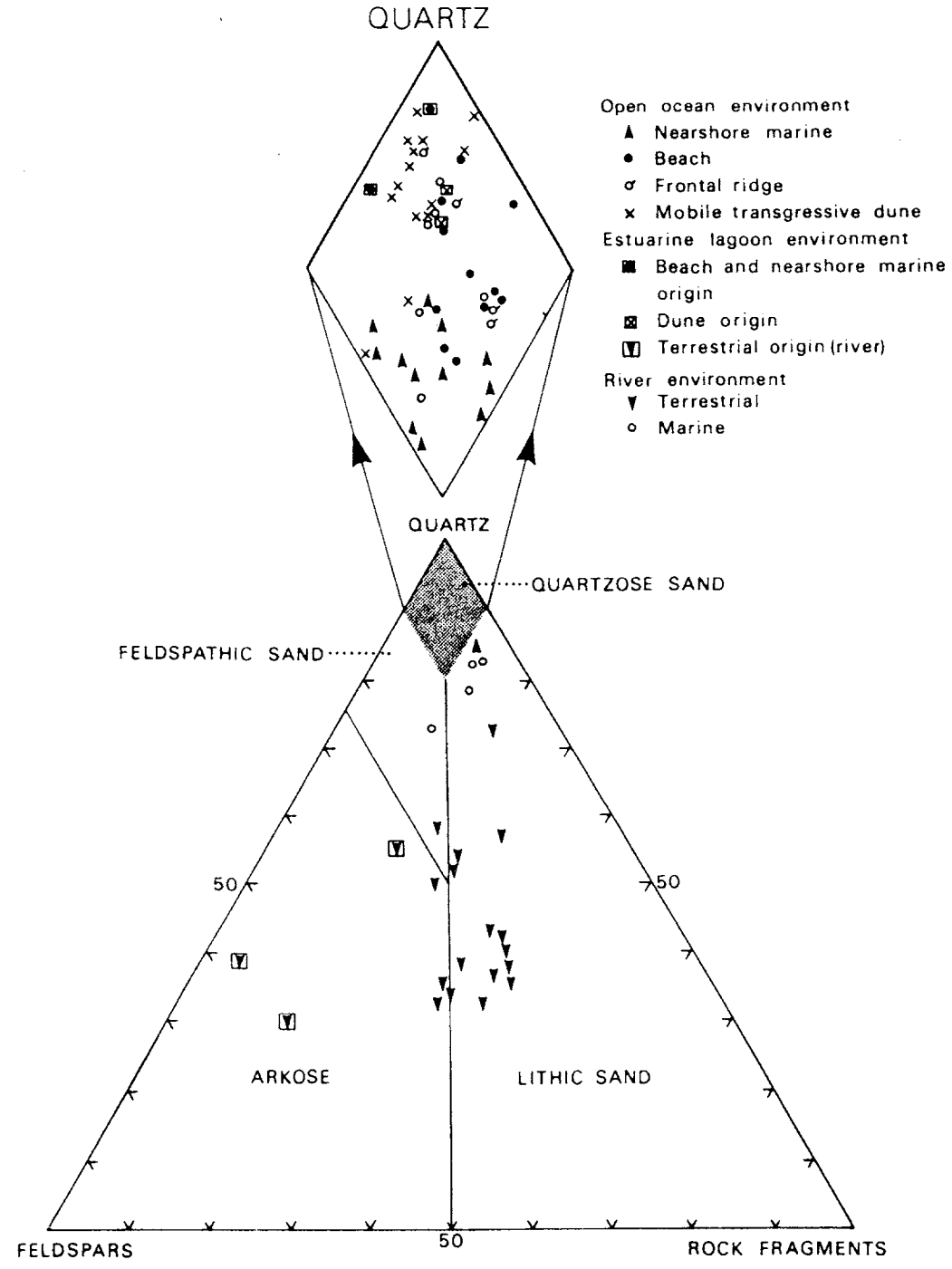

Figure 3-6: Composition of sands from various environments of deposition in the Newcastle Bight/Lower Hunter delta area.

percent, and for Eurunderee beach 0.2 to 4 percent. Highest values are obtained in relatively sheltered localities, e.g. eastern end of Newcastle Bight, southern end of Fens and near Sandy Cape. Most of the carbonate in beach sands is composed of comminuted mollusc fragments, although particles of echinoid spines and crustacean fragments also occur. A variety of molluscs inhabits the beach, the most common being the pelecypod, Plebidonax deltoides. This species can be frequently seen burrowing into the sand as the backwash retreats. Molluscan fragments are sometimes concentrated along swash lines on the beach. They include Amesodesma angusta, and Glycymeris flammea (Table 3-2). Gastropods are not common amidst this assemblage although the conical sand snail, Conuber conicum, has been noted. Bankivia fasciata is sometimes washed ashore in large numbers, particularly during periods of beach berm accretion. Shells from estuarine or rocky sources are also redeposited on open ocean beaches, but they are generally quite worn in appearance.

SEM studies of the surface textures of quartz grains from the beach at Newcastle Bight indicate that beaches are characterized by a predominance of mechanical features which could occupy up to 90-95 percent of the grain surface (Ly, 1976, 1978a). The impact between grains due to the action of aqueous turbulence in the beach environment is believed to be the cause of the formation of these mechanical features (see Krinsley and Doornkamp, 1973). Mechanical features include V-shaped pits, straight or curved grooves and conchoidal breakage patterns (Fig. 3-7). Unaltered V-shaped pits are the most diagnostic features of the beach sands. The size of these pits varies from approximately 0.2 to 3 microns with the most common size around 0.5μ. Straight or curved grooves occur irregularly and are scattered over the grain surface. Their size ranges from a few microns to as much as 15 in length. They are found associated with the V-shaped pits. Close examination of the straight or curved grooves revealed that their formation may have been related to the over-production of V-shaped pits on the grain surface which could accommodate only up to a certain critical number of pits. Conchoidal breakage patterns are usually small microns, and are occasionally observed on the quartz grains from the high energy parts of the beach. Their rarity of occurrence probably indicates that either they require a much higher energy or they may be the relict features from the source material as quartz has a natural conchoidal fracture. Chemical etching features (e.g. solution and/or precipitation) are minor in the sands of Newcastle Bight beach: they represent, however, a significant feature of the beach samples from the Tomaree segment. In this region, various forms of etch holes and precipitation of silica were observed. Reasons for these differences are not readily apparent.

3.2.1.3 Foredune sand facies (ef)

The frontal ridge or foredune complex occurs in a zone landward of and parallel to the beach. It is a morphological zone characterized by hummocky sand ridges vegetated to varying degrees by herbaceous and woody plants. In Chapter 2, two units were described in which sand is currently accumulating: the ephemeral incipient foredune, and the more permanent and more massive established foredune (see Hesp, 1984a,b, for detailed description).

Internal structures are generally well preserved in both incipient and established foredunes. Incipient foredunes are dominated by low

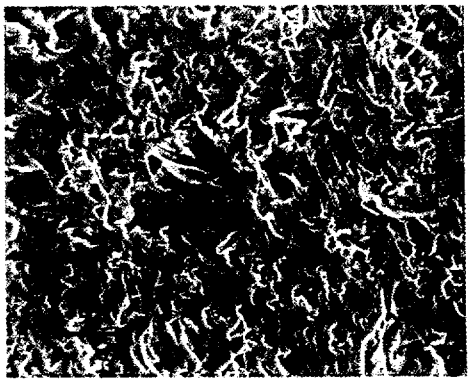

Figure 3-7: Scanning electron micrograph of sand grain surface texture from the beach environment.

angle (<13 degrees), commonly simple, tabular, large-scale (>6m), convex sets of cross-strata. As these dunes are formed at the landward edge of the beach, beach swash and eolian cross-laminae are continuous into the vegetated zone (Hesp, 1984a, b). Where incipient foredunes continue to accrete vertically and horizontally under conditions of minimum erosion and maximum vegetation cover continued eolian sedimentation produces established foredunes characterized by large-scale, convex, low angle, primarily depositional, continuous cross-laminae. As the degree of wave and wind erosion increases, and vegetation cover decreases, more medium-scale planar (i.e. erosional) sets of higher-angle, discontinuous cross-strata are found. Bedding with dips up to 46 degrees may be formed where sand is accreting on vegetated lee slopes (Hesp, 1982). Buried organic horizons infrequently occur as discontinuous lenses attesting to periods of stability of the ridge surface when wind accretion was insignificant.

Foredune sediments are composed of medium to fine sand, yellowish in colour. However, under a stable vegetation the surface becomes enriched in organic matter and the grains turn grey. Size analysis of 32 samples showed that the phi mean grain size varied from 1.42 to 2.32 at Newcastle Bight (Ly, 1976) and from 1.50 to 1.92 at Fens and Eurunderee embayments (Shepherd, 1970). Figure 3-8 illustrates examples of grain size distribution of foredune sands from Newcastle Bight. They are characterized by two saltation populations with a break point at 1.5 phi, and a suspension population. The two saltation populations are inherited from the adjacent beach. A slight increase in the suspension population is probably due to the wind action. In all the samples saltation populations represent about 99 percent of the distribution.

The foredune sands of the Newcastle-Myall Lakes area are very well sorted with phi standard deviation ranging from 0.25 to 0.44. About 80 percent of the samples examined from both the incipient and established foredunes are negatively skewed. This indicates that the foredune is still affected by wave action by which sediment can be transported from the beach to the ridge where it is mixed with eolian sand.

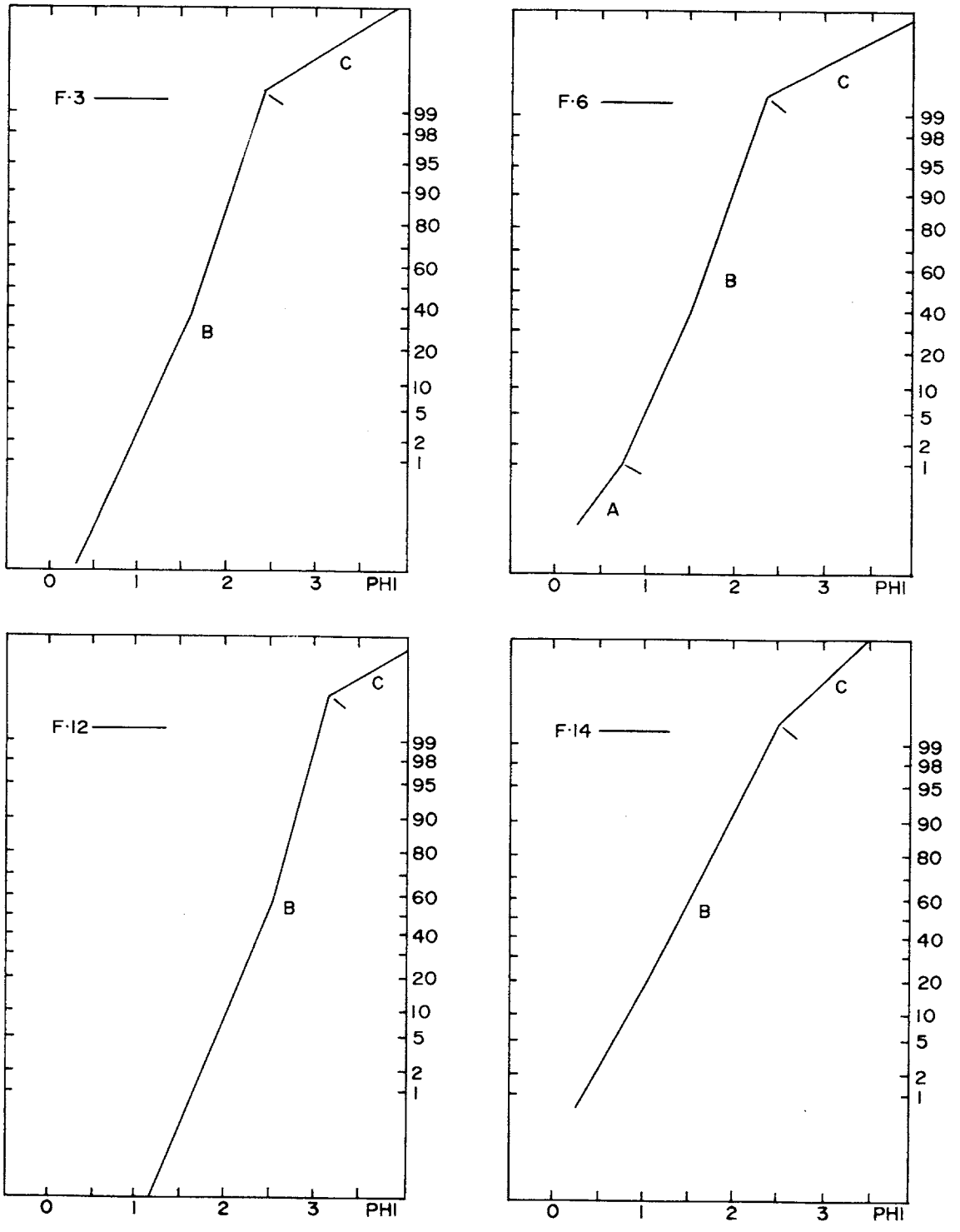

Figure 3-8: **Grain size distribution for four samples from the active foredune ridge from Newcastle Bight plotted following the methods of Visher (1969).**

Quartz dominates the composition of foredune sand with total amount of rock fragments and feldspars being less than 10 percent (Fig. 3-6). Discontinuous patches of heavy mineral layers are found in both seaward and landward facies of the foredune, although the heavy mineral particles are also found disseminated within the ridge. The composition of the heavy minerals in the frontal ridge sand is similar to that in the beach sand but their amounts usually vary from 0.1 to 0.7 percent. The carbonate content rarely exceeds 2 percent and is composed of finely comminuted skeletal fragments.

As in the beach samples, quartz grains in the foredune samples are rounded to angular. Detailed examinations of four samples from Newcastle Bight indicated that the average roundness values, R, are within the range of average roundness for beach samples, although the amounts of angular and very angular quartz grains tended to be lower in foredune samples than in the beach sample (Ly, 1976). Surface textures, similar to those seen on quartz beach sands (i.e. V-shaped pits and straight or curved grooves) were observed on the quartz grains from the incipient foredune of Newcastle Bight.

3.2.1.4 Mobile transgressive dune sand facies (et)

The mobile transgressive dune facies forms the free-moving sand sheet which occurs landward of the frontal ridge. Mobile transgressive dunes can attain 30 m in height and are usually separated from the frontal ridge by a flat, partly water-logged hollow (deflation surface). The dunes are arranged into a variety of free-moving forms including blowouts, long-walled transgressive ridges, "reversing" transverse dunes and barchan dunes (see Ch. 2). The common property possessed by each of these types is that their surface is composed of free-moving sand capable of transportation by saltation or suspension processes. Under such conditions the dunes commonly present a gentle slope to the wind, but their lee slopes are quite steep, often exceeding the angle of repose of sand at which point avalanches occur.

Perhaps the most distinctive sedimentary property of these dune sheets is their internal structure. In common with other areas of coastal dunes of similar type (see Bigarella 1972; Goldsmith, 1978), these sands contain a combination of steeply and gently dipping laminae associated with leeward and windward slopes, respectively. The reversing transverse dunes are dominated by high-angle (commonly 32 degrees) tabular cross-laminae characteristic of advancing slip-faces. The upper 2 metres or so of the dune crests display truncated slip-face cross-strata facing opposing directions. These are alternatively formed by the seasonal and synoptic reversal of wind direction. In contrast, the bedding patterns of advancing lobes of transgressive dunes appear relatively simple. Slipface beds facing north are overlain by thin (less than 1 m) topset beds (Thom et al., 1981b, Fig. 27 from near Belmont). The steeply dipping laminae are sometimes exposed on windward faces following periods of deflation.

Mobile transgressive dune sands are medium to fine-grained, yellowish in colour and free of a silt and clay fraction. A spatial pattern of variation of mean grain size similar to that of the beach sands is observed along Newcastle Bight: these sands are coarser at the western end than at the eastern end (Fig. 4-10). Size analysis of 40

samples showed that the phi mean grain size ranged from 1.36 to 2.28 at Newcastle Bight (Ly, 1976) and from 1.52 to 1.90 at Fens and Eurunderee embayments (Shepherd, 1970). Grain size distributions of the dune sands from Newcastle Bight are illustrated in Figure 4-10. They are characterized by a large single saltation population of up to 99 percent and a small suspension population. The increase in the suspension population from the eastern end to western end appears to be related to wind direction. The samples were collected in summer when easterly winds predominated. During that period, the sand was seen to be carried in suspension up to 0.3-0.4 m in height. The general lack of competence of onshore wind action to move sand particles by rolling is responsible for the very small percentage, or even absence of the coarse population. Scattered shell fragments up to 5 mm long occur on dunes behind beach surfaces (e.g. west end Newcastle Bight); these fragments may be rolled rather than saltated over the sand surface.

As mobile dune sands are usually composed of a single saltation population, they tend to be very well sorted (Fig. 3-5). The phi standard deviation varies from 0.2 to 0.4 for the whole area between Newcastle and Seal Rocks. The relatively high percentage of the finer fraction in the grain size distribution accounts for the tendency of most of the dune samples to become positively skewed. In Newcastle Bight, out of 33 samples collected, only two were negatively skewed and two normal; the remaining samples were positively skewed.

The proportion of rock fragments in the dune samples is usually the lowest of the facies deposited in the open-ocean environment. This suggests that abrasion of soft rock fragments by wind action is significant. If this were not the case and selective sorting was responsible for their absence, then dune sands would have been rich in rock fragments, as the latter are generally well rounded. The content of rock fragments in the dune samples is always lower than 4 percent (see Fig. 3-6). However, wind action appears not to have a significant effect on the feldspar grains; the feldspar content in the mobile transgressive dune samples is similar to that in the beach sands and varies from about 0.5 to 9.5 percent, but is usually less than 5 percent (Ly, 1976). The decrease in rock fragment content but similarity in feldspar content from beach to dune is probably due to differences in resistance between volcanic rock fragments and potassium feldspars; the latter are probably more resistant than the former.

Dark thin layers of heavy minerals are often observed on the lee face of mobile dune ridges and in the troughs of small wind ripples. Heavy minerals are mainly concentrated on the lee face and not on the windward face. A comparison between 13 dune samples and 13 beach samples from Newcastle Bight showed, at the time of sampling, the content of heavy minerals to be significantly higher in dune sands than in beach sands, at 95 percent level of confidence (Ly, 1976). This situation is usually reversed along the N.S.W. coast (see Hails, 1967), and there is no doubt that after storms concentrations of heavy minerals on the beaches of the study area yield heavy mineral contents far in excess of what have been observed on dunes. The heavy mineral suite is generally composed of the stable rutile, zircon, tourmaline and opaques, probably due to the non-durability of the less stable minerals (i.e. pyroxene, hornblende and epidote).

Mobile transgressive dune samples are usually composed of very well



Figure 3-9: **Scanning electron micrograph of sand grain surface texture from the mobile transgressive dune environment.**

rounded to angular grains. Values of average roundness of the quartz fraction determined from the Newcastle Bight samples ranged from 0.30 to 0.46 (subangular to subrounded). Angular and very angular grains in the quartz fraction are usually lower than those for beach samples and vary from 4 to 17 percent (Ly, 1976).

The carbonate content is usually low, varying from 0.1 to 2.8 percent in the Newcastle Bight dunes; it rarely exceeds 0.5 percent in the Fens and Eurunderee dunes. However, in deflation troughs between the bulk of the moving dune mass and the incipient foredune, shell concentrations from washovers or exhumed middens frequently occur.

Mechanical features such as V-shaped pits and straight or curved grooves are still visible on quartz grains using SEM (Fig. 3-9). At low magnifications the grains appear very similar to those from the beach sands. However, at high magnifications (greater than 2000 X) the pits are no longer sharp, and appear slightly modified by silica precipitation. Precipitation of silica appears to smooth out the relief of the grain. Small precipitates of silica are seen in the mechanical pits or depressions which as a result become shallower. Conchoidal breakage patterns appear to be rarer compared to the beach environment, perhaps because they are more difficult to recognize due to silica precipitation. The reason for the silica precipitation is unknown.

3.2.2 Estuarine-Coastal Lagoon Environment (E)

The estuarine-coastal lagoon environment of deposition incorporates those areas which are relatively protected from the influence of open-ocean waves. It includes the beds of Port Stephens and Myall Lakes as well as the flanking beaches, and tidal marshes and swamps. Semi-enclosed water bodies of this area are influenced to varying degrees by tidal forces. Consequently, sub-environments and associated sediment types are mainly controlled by salinity, depth, tidal current action, and exposure to locally generated waves. Seven facies are distinguished in the estuarine-coastal lagoon environment. Sediment types will only be

described in general terms in this chapter. Details on the Port Stephens estuary will be given in Chapter 5.

3.2.2.1 Tidal delta sand facies (d)

Broad sand banks occur at the entrance of Port Stephens. These shoals form a morphological transition zone between the oceanic, wave-dominated, nearshore zone and the sheltered basins within Port Stephens. The sand surface of this flood tidal delta is subjected to frequent movement by tidal currents and periodic disturbance by large ocean waves which enter Port Stephens from the east. Fluvial processes do not appear to directly influence the tidal delta, although major floods of the Lower Myall River in conjunction with high tides and storm waves in eastern Port Stephens may modify the sand bodies around Winda Woppa spit (see Ch. 5).

Although no cores were examined for internal structures, the presence of large megaripples and ripples, and the profusion of channels, implies that this sand facies is extensively cross-bedded with large-scale scour and fill structures. Reinson (1977) has documented many of the bedform and structural characteristics of a tidal delta at Mallacoota Inlet in north-eastern Victoria, and similar bedform features exist at the entrance of Port Stephens, albeit on a larger scale.

Tidal delta sands vary in size grading from coarse to fine. They are generally well to moderately sorted and free of mud. Quartz dominates the mineralogy of the sands with less than 10 percent lithic and feldspathic fragments. The quartz grains are typically rounded to subangular and light grey to fawn in colour.

The carbonate content is quite variable (0-30 percent) consisting of whole shells and shell fragments. However, values of 4 to 6 percent seem characteristic of the facies. Open-ocean and estuarine species are intermixed in this sediment type. Most specimens have the appearance of being transported into the tidal delta from adjacent nearshore beach, rock and estuary areas, although it is likely that live molluscs (e.g. Bankivia) are also present. Locally, stands of seagrass (Posidonia, Zostera) grow on the sand surface and grazing gastropods (e.g. Cacozeliana, Protholathia) populate the fronds. Little ecological research has been undertaken in this area although elsewhere in N.S.W. the ecology of Posidonia and Zostera communities in tidal delta habitats has been extensively studied (e.g. Higginson, 1965; Larkum, 1976, 1977).

Mud mixes with quartz sand to produce a muddy quartzose sand lithofacies along the steeply sloping western or prograding side of the tidal delta. The distribution of this sub-unit reflects the influence of locally dominant flood and ebb tidal currents (Ch. 5). The relatively powerful flood current in the southern channel of the tidal delta carries quartz sand beyond the edge of the bank into adjacent deep water (+10 m) where it mixes with mud to form a westward protruding lobe. In contrast, the stronger ebb current of a channel to the north supplies mud which is mixed with sand to form a lobe of muddy sand extending eastwards.

3.2.2.2 Estuarine shoreline sand facies (sh)

Fringing Port Stephens for most of its length is a sediment unit which includes the active estuarine beach and adjacent sub-littoral

platform or terrace. Sands, shelly sands and muddy sands are common in this facies with both lithic and quartzose compositions being present in different places depending on variations in source material.

In the southwest part of Port Stephens adjacent to the Inner Barrier, quartzose sands predominate along the estuary shoreline. These clean sands form the beach in Tanilba Bay and also occur as small, isolated, cuspate sand sheets in the nearshore. The proportion of mud in these nearshore sands increases with water depth producing sub-parallel zones of sand, muddy sand and sandy muds. The shell content is often quite high as this unit is the habitat of Pyrazus and Anadara species, two of the most common estuary molluscs (Table 3-2).

Along the northern rocky shoreline of western Port Stephens, beach and nearshore sands form narrow, discontinuous bands. This area is solely a lithic province. The hinterland is hilly and the sediment is supplied by fluvial and wave erosion of bedrock and hillslope colluvium. The sands are relatively poorly sorted and quite angular. Phi standard deviation for 3 samples on the northern shore ranged from 0.7 to 0.9 whereas five sand samples collected from estuarine beaches derived from Pleistocene dunes ranged from 0.2 to 0.5.

Shoreline sediments in eastern Port Stephens are mainly quartzose in character having been derived through erosion of Pleistocene dunes or from beaches adjacent to the tidal delta. Clean, very well to well sorted sand forms the beach and sub-littoral terrace, although on the outer parts of the terrace (c. 2-4 m deep) the sands tend to be more muddy. The fine-grained fraction increases with greater water depth and in more protected sites (e.g. Duckhole Bay). The terrace surface is often colonized by extensive seagrass meadows (Posidonia, Zostera). Anadara is frequently observed as swash concentrates on these sand beaches.

3.2.2.3 Estuarine shelly mud facies (m)

In central and western Port Stephens vast areas of the bottom are blanketed by a cover of black to dark grey soft mud (physical and chemical properties of mud deposited in similar environments are described by Baas Becking, 1959, and Reinson, 1977). This mud is accumulating from the supply of suspended sediment discharged into Port Stephens primarily by the Karuah River. Deposition of mud only occurs where the hydrodynamic energy level is sufficiently low to allow silt and clay to settle from suspension. These quiet conditions are achieved where water depths are greater than wave base, although it is possibly promoted by baffling action on tidal currents induced by bottom growths of bryozoa and seagrasses in some areas (e.g. around Middle Island).

Mud deposition is occurring today on broad, gently sloping to flat surfaces ranging in water depth from less than 1 m to 18 m. The distribution of estuarine muds is discussed in Chapter 5. At shallow depths, the depositional sites are typically protected bays with restricted fetch (e.g. Cromartys Bay). In western Port Stephens it is possible that wave base (c. 3-5 m) controls the depth at which mud accumulates, but in central Port Stephens, between Soldiers Point and the tidal delta, the depth to the mud surface generally exceeds 10 m. These greater depths are believed to reflect a combination of lower rates of

sediment supply and deeper basal Pleistocene surface.

Basin muds are a mixture of clay, silt and sand (Fig. 3-10). Generally less than 10 percent of the sediment is sand. The sand component decreases with increasing distance from bedrock and sand barrier shores, the tidal delta, and the fluvial delta of Karuah River. The sand fraction is dominantly quartzose close to the tidal delta and the sand barriers and dunes of southern Port Stephens. Elsewhere it contains a high lithic fraction including rock fragments and feldspar grains. Clastic grains are noticeably angular in the mud facies except in areas where the sand has been derived from marine-eolian sources.

The sediment surface of basin muds is smooth although signs of active burrowing are always apparent. This bioturbated mud contains abundant shell carbonate either whole or in fragments (see Roy, 1981). Values range from less than 1 percent to 70 percent. The high values pertain to mounds of shells or bioherms (see 3.3.3). The high degree of shell fragmentation is believed to be the product of scavenging organisms which live in the sediment. Articulated shells of Notospisula parva, the dominant pelecypod of the basin mud facies, were rarely observed. Species collected in this facies are listed in Table 3-2. The greatest variety of shells was observed close to the bioherms. Foraminifera, bryozoa and sponge spicules also occur in the mud.

Quite consistently, samples of mud assayed for organic carbon yielded values of 1 to 2.5 percent (Table 3-3). Partly decayed wood and fibrous plant fragments were observed on the mud surface. Table 3-3 also lists values of total iron, manganese, phosphorus, and strontium and mobile aluminium determined on selected mud samples. These samples were noticeably rich in sulphide indicating the reduced nature of this environment of deposition.

Mineralogically, the muds are dominated by kaolinite with lesser amounts of illite or montmorillonite (Fig. 3-11; Table 3-3). Authigenic minerals are also present. Glauconite forms a minor component of the coarse fraction. It is a soft, amorphous, light green mineral and often infills foraminifera tests. Sometimes it occurs as dark green, rounded, hard grains. An early stage of glauconization with the coating of organic-rich clay aggregrates or faecal pellets has been noted.

3.2.2.4 Tidal flat mud facies (t)

Actively forming tidal flats in Newcastle - Port Stephens area occur in four main areas (for locations see Chs. 4 and 5):

(i) In the delta of the Hunter River, particularly downstream from Hexham and along the margin of Fullerton Cove.
(ii) Along the shores of drowned river valleys, where tidal and fluvial processes intermix and where wave action is minimal (e.g. lower Karuah Valley, North Arm Cove, Duckhole Bay, Little Swan Bay).
(iii) In depressions formed behind coastal sand barriers and adjacent to sand islands (e.g. marginal to Tilligerry Creek, Lower Myall River, Big Swan Bay, Pipeclay Creek).
(iv) In the lee of ephemeral sand barriers such as Corrie Island.

In all areas mangroves and salt marsh plants colonize the surface of stable or accreting flats (e.g. north side of Fullerton Cove) and the

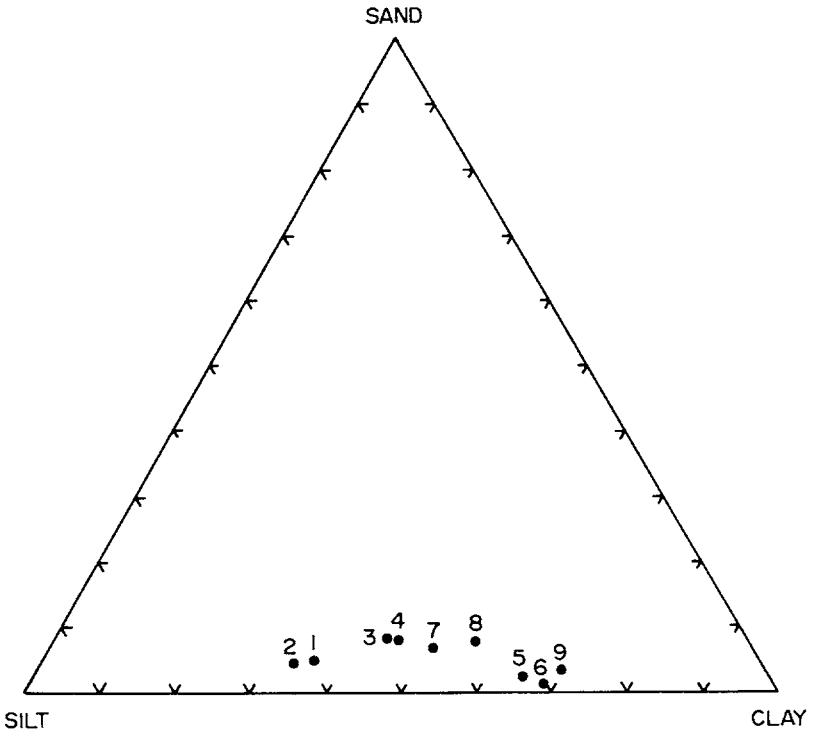

Figure 3-10: Percentage sand, silt clay for nine samples collected from the mud basin environment in Port Stephens.

margins of tidal creeks and gullies. Clarke and Hannon (1967) have described the halophytic flora of the Sydney area which is basically similar to that of the Newcastle-Port Stephens region. Avicennia marina and Aegiceras corniculatum are the two mangrove species present, whilst Sporobolus sp., Arthrocnemum sp., Juncus maritima, Casuarina glauca and Scirpus nodosus are other important elements in the plant community.

In Port Stephens, two basic types of tidal flats have been recognized. The first approximates mean sea-level in elevation, and is extensively covered by Avicennia with well-developed pneumatophores. These flats are restricted to areas of active mud and sand accretion (e.g. parts of Karuah delta, Corrie Island). Tidal creek development in this type is minimal. Commonly, the surface is soft mud which is perennially wet, being flooded at each high tide. Shell life is abundant with Pyrazus being dominant. The muds are rich in sand and organic detritus, including flood debris trapped by the roots and trunks.

The second type of flat rises to just above HWOST and is dissected by tidal creeks. "Elevated" tidal flats, in common with many tidal flats in areas of one metre or more tidal range (e.g. Shark Bay, W.A., see Logan et al., 1970), can be subdivided into a number of morphological and ecological zones. The extent of each zone depends largely on the gradient of the surface. Zones recognized in the study area include:

(i) Supratidal, characterized by a dense vegetation of mixed trees (Casuarina), shrubs and herbaceous plants.
(ii) Higher intertidal, inundated by spring tides and only partially

TABLE 3-3 Chemical Analyses Estuarine Fine-Grained Fraction (J. Caldwell Analyst)

Ref No	Modern Environments	$CaCO_3$%	C%	Fe%	M ppm	P_2O_5ppm	Sr ppm	Al%	Clay Mineral		
									Mont	Kaol	Illite
107	Fluvial delta sand	10.5	1.49	2.23	111	660			minor	major	v. minor
9	Beach lithic sand		0.31	0.73					major	major	v. minor
89	Beach lithic sand		0.67	0.95							
33	Beach quartzose sand		0.93	0.68					minor	major	v. minor
118	Beach quartzose sand		0.39	0.31							
337	Tidal delta sand	4.1	0.11	0.046	3	240			major	minor	v. minor
363	Tidal delta sand	4.4	0.05	0.070	4	95					
163	Reworked eolian sand	0.02	0.45	0.55					minor	major	v. minor
180	Reworked eolian sand	17.6	0.25	0.47			152				
125	Reworked fluvial sand	11.7	0.86	1.56	10	690			minor	major	minor
133	Reworked fluvial land	0.01	1.16	1.29	110	450					
6	Mud basin	0.6	2.00	3.47	166	750		1.38	minor	major	v. minor
23	Mud basin	73.4	0.93	0.87	224	1100	820	0.68	major	major	v. minor
80	Mud basin	0.01	2.29	2.36	142	860					
93	Mud basin	0.01	2.42	3.66	153	1290					
425	Tidal flat mud	0.01	1.46	3.16	4	1240			minor	major	minor
426	Tidal flat mud	0.01	2.20	3.47	72	1290			minor	major	minor
427	Tidal flat mud		1.88	2.71							
428	Tidal flat mud		2.20	2.84					minor	major	trace
415	Tidal flat mud	0.01	0.31	0.39	12	20		0.60	major	major	nil
417	Tidal flat mud	nil	0.21	0.50	7	25					
418	Tidal flat mud		3.77	0.97	14			0.75			
420	Tidal flat mud		0.18	5.38					minor	major	nil
423	Tidal flat mud		0.18	2.63							
Core No	Drill Hole										
19-33	Pleistocene clay	nil	3.26	1.67	143	480		0.88	minor	major	minor
19-34	Pleistocene clay	nil	2.58	2.84	184	380		0.74			
22-7	Holocene mud	2.4	1.63	2.84	82	1220					
22-9	Holocene mud	0.6	1.19	1.14	102	1450			minor	major	minor
23-14	Pleistocene clay	nil	0.15	3.67	41	87					

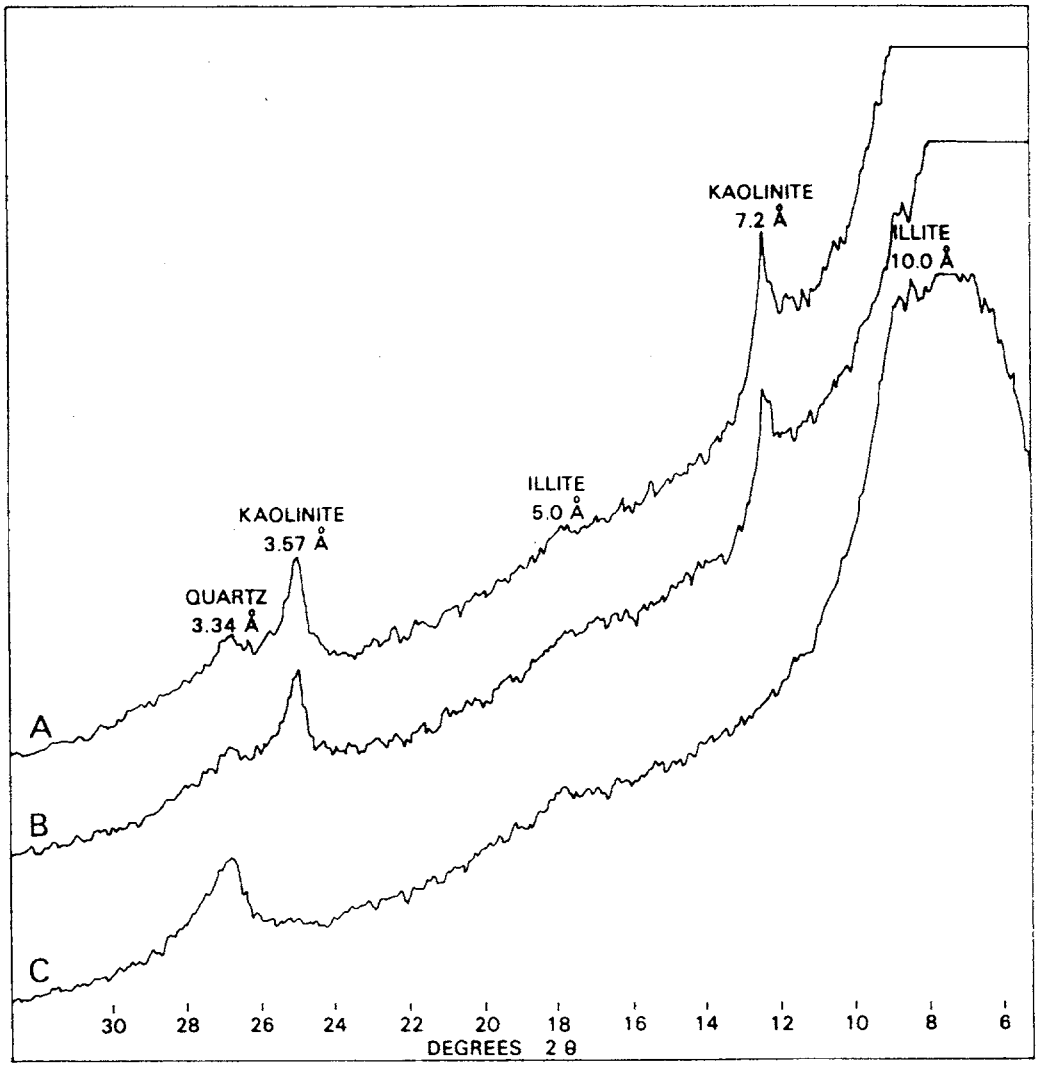

Figure 3-11: XRD analysis of three mud samples from Port Stephens mud basin environment of deposition.

vegetated by algal mats, Avicennia, Arthrocnemum and the grass Sporobolus.

(iii) Middle intertidal and channel levee, inundated by spring tides and higher neap tides and covered by a mixed mangrove woodland (two species present) and Sporobolus.

(iv) Lower intertidal, containing areas of bare, soft mud, especially below mean sea-level.

Generally, tidal flat sediments of both mud flat types are fine-grained. Where wet the muds constitute a grey to brownish grey, greasy but firm surface. Crab burrowing is active in zones (iii) and (iv), particularly in the cut banks of tidal creeks. In the higher intertidal zone (ii) away from tidal creeks, the mud surface frequently dries out. At approximately HWOST level the surface is partially covered by a grey, often suncracked crust. The exact composition of the crust has not been determined, but it contains thin films of blue-green algae.

Mineralogically and chemically, muds of the tidal flats have many properties in common with the estuarine shelly mud facies (Table 3-3), Kaolinite is the dominant clay mineral with minor amounts of illite and montmorillonite. Total iron approximates 2 to 4 percent, probably in an oxidized form and forms red and brown mottles in the shallow sub-surface beneath the surface of zones (i) and (ii). Amounts of organic carbon are approximately the same, but carbonate content is quite low on the "elevated" tidal flat mud facies. Shells are rare on the higher surfaces of zones (i) and (ii).

3.2.2.5 Lagoon organic mud facies (l)

The Myall Lakes, comprising Broadwater Lake, West and East Boolambayte Lakes and Myall Lake itself, are predominantly brackish to freshwater coastal lagoons (Atkinson et al., 1981). Astronomical tides are very small (<20 cm) to negligible in these lakes. Salinity varies with the input of freshwater from the catchment of Upper Myall River and Boolambayte Creek (see Ch. 1). The two largest lakes, Broadwater and Myall, contain broad flat bottoms seldom more than 4-5 m below the lake surface. In these basins organic mud is actively accumulating over large areas.

The mud floor of Myall Lake is densely covered by submerged aquatic vegetation (see Ch. 8). The muds are organic-rich with a gelatinous appearance. They could be described as a gyttja. The surface is highly mobile and is easily stirred by lake waves even when covered by vigorously growing vegetation. It appears that Myall Lake muds contain a higher organic fraction than Broadwater Lake muds. The terrigenous content of the former rarely exceeds 20 percent (Shepherd, 1970). Analysis of two mud samples from Broadwater (from 3.5 m and 4.5 m deep) after removal of organics yielded 60 and 75 percent clay, 28 and 16 percent silt, and 10 and 9 percent sand.

The floors of the constricted Boolambayte Lakes are locally scoured by flood currents. Sediments are poorly sorted in deeper water in the vicinity of the delta of Boolambayte Creek with approximately equal amounts of sand, silt and clay. Elsewhere at depths greater than 3 m the sediment contains less sand and is highly organic.

3.2.2.6 Lagoon shoreline sand and mud facies (lsm)

As noted in Chapter 1 (see 1.8.2), the Myall Lakes are bordered by subaqueous sand shoals. These shoals occur in shallow water usually less than 2 m deep. Their surface is subjected to frequent reworking by wave-induced bottom currents. In the sub-aerial lake-shore zone the sands form swash bars amidst fringing reeds and Casuarina and Melaleuca trees (see Ch. 7).

Generally, lake sands are grey to greyish white in colour. Locally, the aquatic plant Myriophyllum brusiliensis grows on the sand surface. In environments more protected from local waves, the reed fringe is particularly dense, and silts and clays are deposited from suspension. Low relief swampy surfaces rich in organic matter develop under these conditions. An encroachment succession of plants is apparent in these localities (e.g. Russells Bay).

Sand shoals within the Myall Lake often form distinctive cuspate bars. Nine samples from the surface of a bar showed extremely uniform size and sorting with the phi mean varying from 1.49 to 1.59 and phi deviation from 0.35 to 0.38 (Shepherd, 1970). Eleven samples from bars elsewhere in the lakes possess similar characteristics (see Shepherd, 1970, Addendum to Ch. 5). The sands are mostly composed of quartz grains and appear to be derived from the high dunes which border the lakes, or from the reworking of Pleistocene backbarrier flats. The local occurrence of coarser sands of slightly more diverse mineralogy suggests a fluvial origin for some sands, especially in Broadwater Lake, the "sink" for coarse sediment transported down the Upper Myall River. Rounded gravels reworked from Carboniferous conglomerate form small beaches and spits on the west side of Myall Lake (Thom, 1965; Shepherd, 1970; see also Ch. 8).

3.2.3 Terrestrial Environment (T)

3.2.3.1 Channel sand facies (c)

Sediment sampling in the channel of the Lower Hunter River was undertaken to determine if this major river influences the sediment characteristics of the coastal region. Analysis of grain size and mineralogy showed the presence of "marine" sand similar to that of the tidal delta or nearshore marine sand facies in the lower reaches (see Roy, 1977, Fig. 1 for bottom sampling locations). The sand is medium to fine-grained, quartzose, very well sorted to well sorted and is composed mainly of well rounded to subrounded grains. A medium to fine-grained, lithic and angular "fluvial" sand occurs upstream of the quartz-rich "marine" sand (Roy, 1977; Roy and Crawford, 1977; Roy et al., 1980). Surficial deposits of terrestrial muds also occur in those parts of the lower estuary that have been dredged.

Grain size distributions of 8 of the 47 fluvial and marine sand samples are illustrated in Figure 3-12. Fluvial sands (HR 2,5,14,15 in Fig. 3-12) are characterized by: (i) a well-developed suspension population which usually comprises 5 to 10 percent of the distribution; (ii) more than two saltation populations; and (iii) generally a rolling population. The saltation population of the marine sands (HR 41 and HR 47 in Fig. 3-12) is typically better sorted than that of the fluvial sands. Samples 18 and 22 have mixed characteristics (Fig. 3-12, see also Figs. 3-14, 15) and contain a relatively high proportion of sediment finer than 4 phi.

Size grading of channel sands collected from the Hunter River indicated that they vary markedly from coarse to very fine sands with phi means ranging from 1.20 to 3.80. They are very well sorted to poorly sorted with phi standard deviation from 0.24 to 1.20 (Fig. 3-13). When compared to the fluvial sands, the marine sands are generally better sorted. The fluvial sands are either positively or negatively skewed.

The Hunter fluvial sands are quite rich in lithic and feldspathic grains with the amounts of rock fragments and feldspar grains always exceeding 15 and 20 percent, respectively (Fig. 3-6). Figure 3-14 depicts the downstream variation in mineralogy. The heavy mineral suite of the fluvial samples is composed mainly of pyroxene, hornblende and

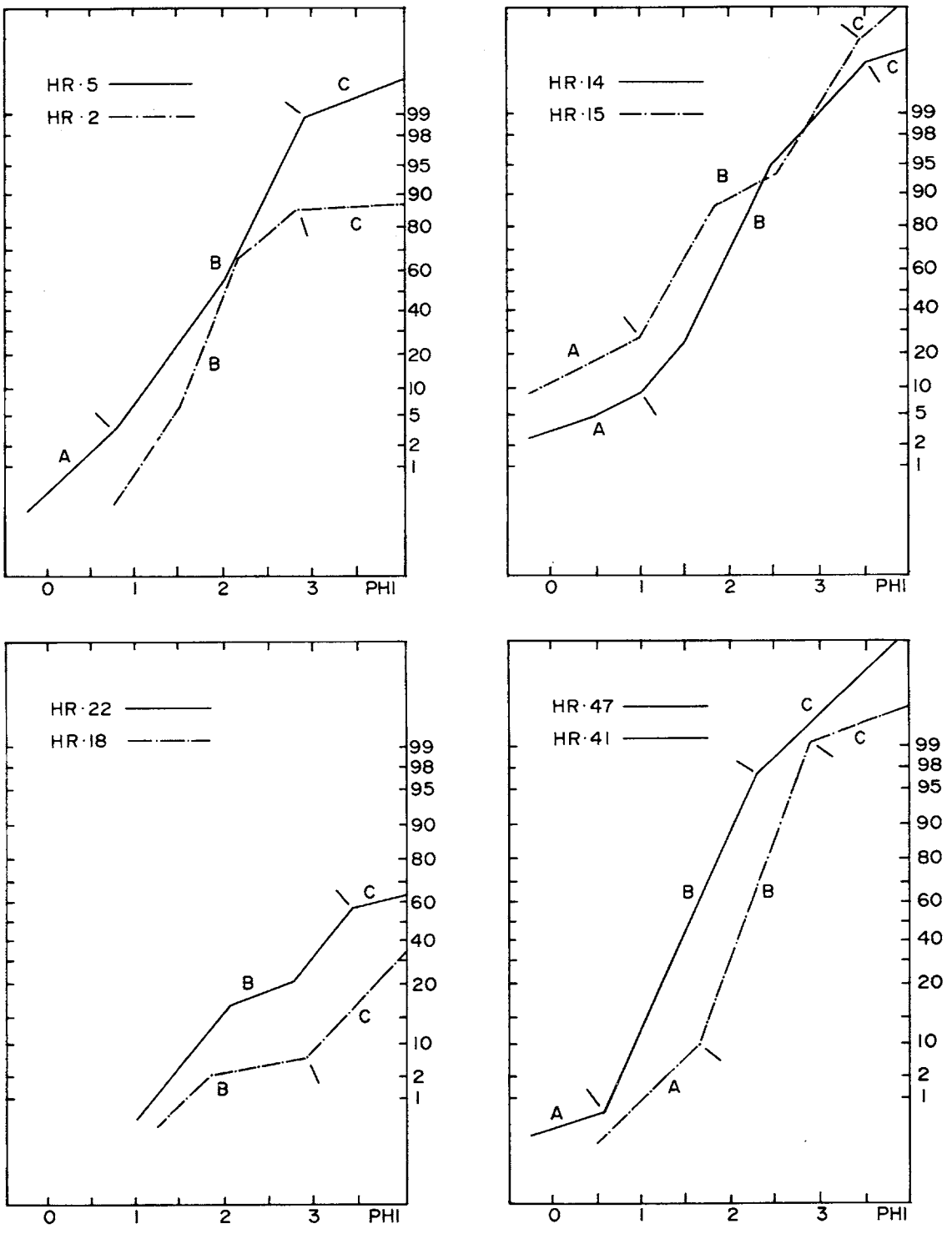

Figure 3-12: Grainsize distributions for eight samples collected in the Hunter River channel (see Fig. 3-14 for location).

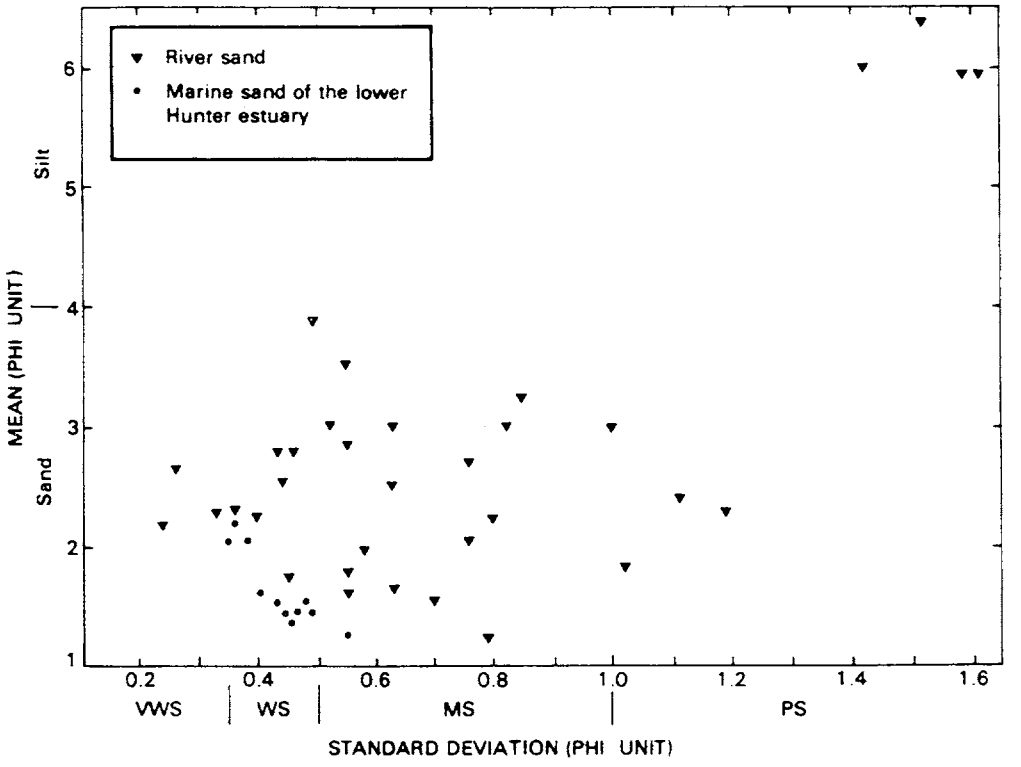

Figure 3-13: Comparison of mean grain size and sorting for "fluvial" sand and "marine" sand found in the Hunter River estuary.

opaque minerals, and a small proportion of angular grains of zircon, rutile and tourmaline. The content of heavy minerals in the fluvial sands usually varies from 0.4 to 3.0 percent.

The quartz fraction of the fluvial sand samples is composed primarily of angular and very angular grains which always exceeds 50 percent in the total fraction. The average roundness values of quartz fraction ranges from 0.21 to 0.29. Downstream variability, indicating the two different sand types and the mixed zone, is illustrated in Figure 3-15. South Arm samples are clearly more marine in character on the basis of roundness, and this reflects the lower discharge regime of this distributary compared to the North Arm.

Surface textures of quartz sand grains from the fluvial environment are characterised by large conchoidal fractures and imbricated breakage blocks (Fig. 3-16). However, a sample collected from the mixed zone showed not only these features, but also traces of chemical etching or weathering and some mechanical action superimposed. More work is needed on surface textures in such estuarine environments.

Roy and Crawford (1977) have demonstrated that the distinction between "fluvial" and "marine" sands can be applied to most northern N.S.W. rivers. The contrast is also apparent in the Karuah-Port Stephens and Upper Myall-Broadwater areas (Chs. 5 and 7). However, in the lower

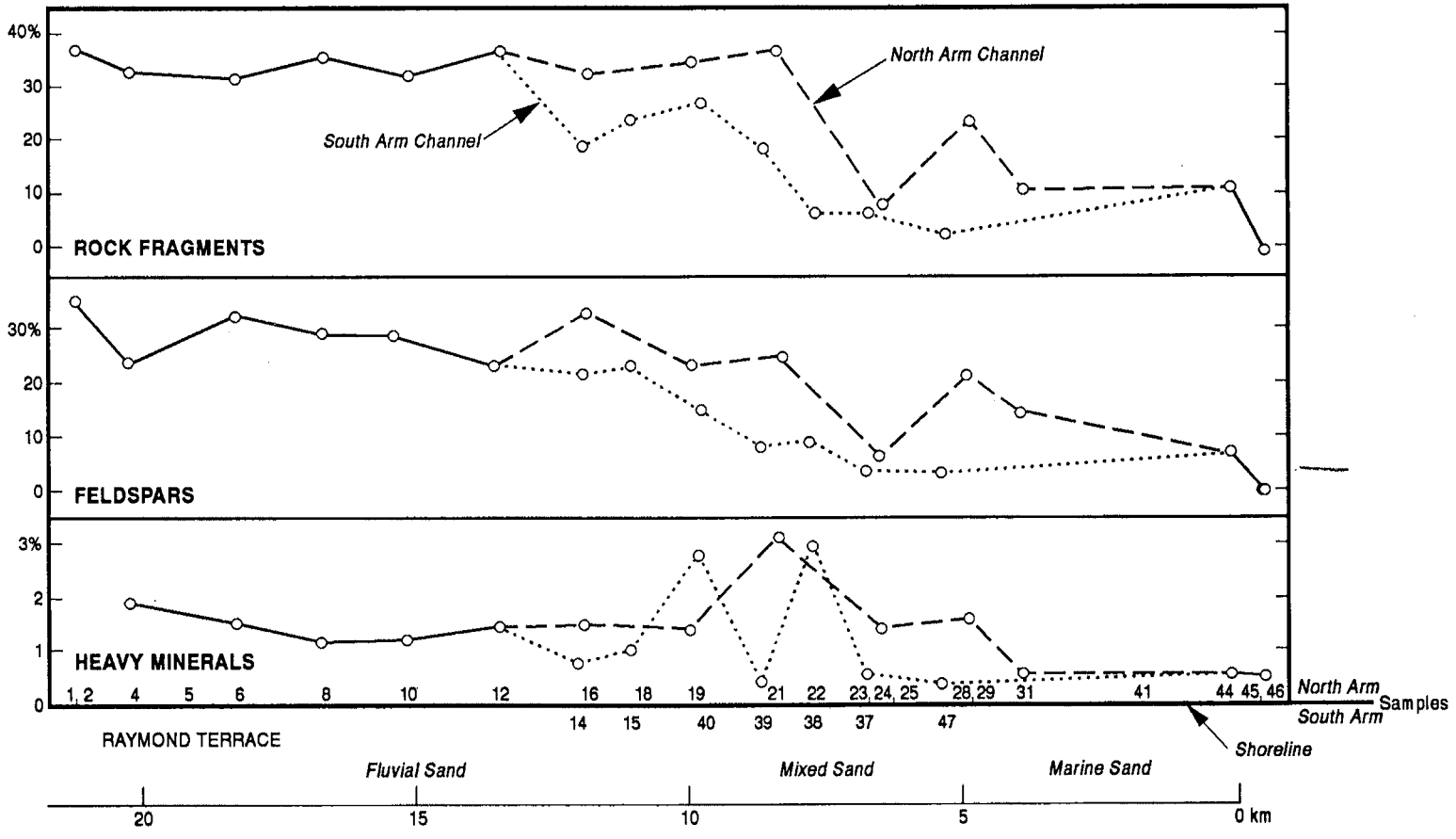

Figure 3-14: Changes in sand grain composition along both North Arm and South Arm of Hunter River downstream from Raymond Terrace.

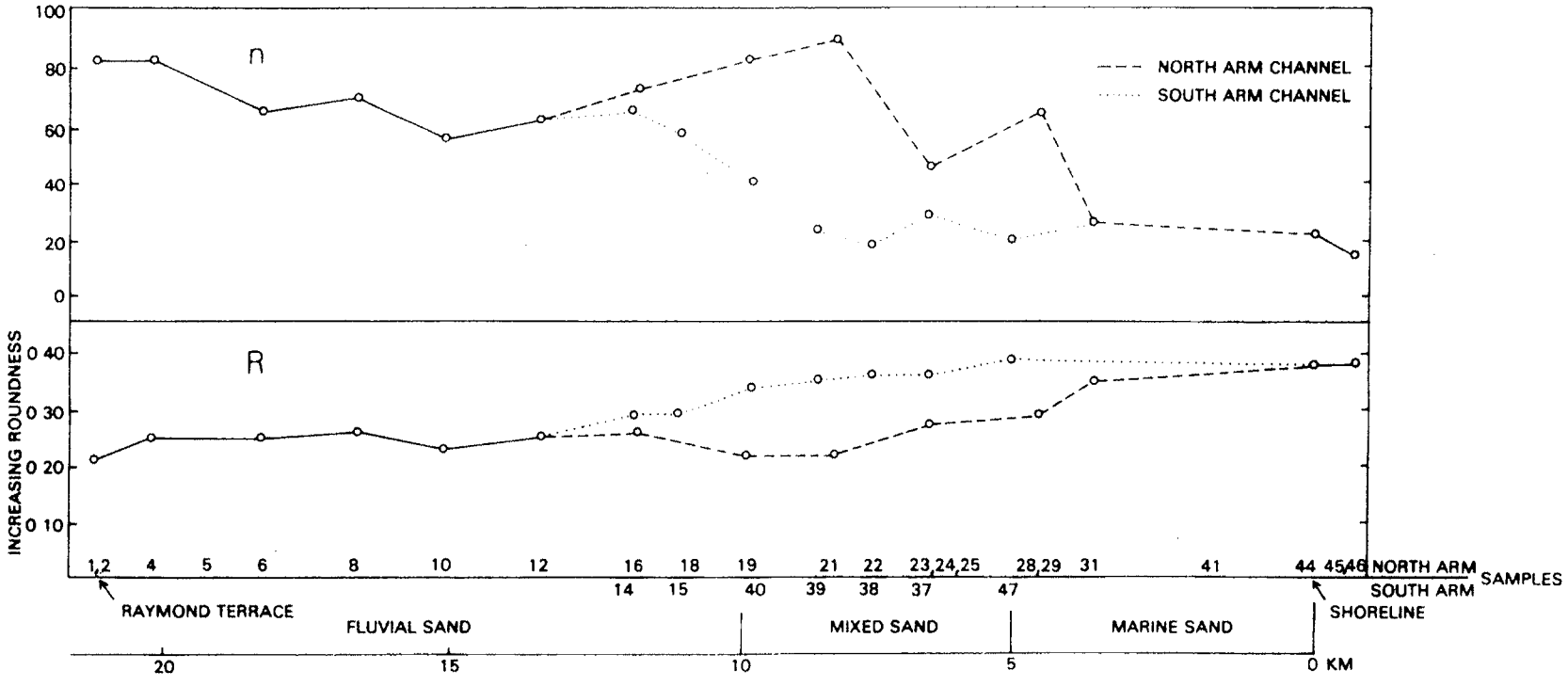

Figure 3-15: **Changes in roundness properties of sand grains along both North Arm and South Arm of Hunter River downstream from Raymond Terrace. Two measures of roundness are used: n is a measure of percentages of angular grains in the quartz fraction and R is the average roundness value (Powers Scale).**

Karuah River "fluvial" sands are mixed with estuarine shells so that the facies is more estuarine in character (cf. lower Hawkesbury, Georges Rivers - Roy et al., 1980). The conclusion is that at present sea-level coastal rivers such as the Hunter are not effectively contributing sand to open-ocean beaches. There are, however, some exceptions (e.g. Shoalhaven, Thom et al., 1981b).

3.2.3.2 Deltaic sand and mud facies (dsm)

At the mouth of the Karuah River the bottom sediments are composed of poorly sorted muddy sands or sandy muds mixed with estuarine shell fragments. The sand fraction is angular and quite lithic, and is of fluvial origin. Two distributary channels enter Port Stephens. The most active channel possesses a coarser bed of muddy sands, whereas the bed of the less active channel is mostly fine sandy mud. The mud fraction increases in a seaward direction as river discharge spreads into the estuary. Local concentrations of more sandy sediments on the surface of the delta, which is generally composed of sandy mud, may reflect the action of wave reworking in very shallow water, or the development of submarine levees during floods.

3.2.3.3 Floodplain silt facies (f)

In the lower Hunter Valley, three rivers (Hunter, Williams and Paterson) have combined to produce an extensive deltaic plain. The plain is composed of predominantly brown silts. The silt unit rarely exceeds more than 4 m in thickness; near river levees and at sites of crevasse splays (e.g. near Maitland), the unit thickens and coarsens. Following extensive flooding in 1955 large sheets of "lithic" sand were spread over the alluvial flats north of Maitland.

The floodplain silt facies abruptly overlies an estuarine shelly mud facies. The thickness of the latter is quite variable. Intact Notospisula shells collected from the Eskdale swamp beneath the silt facies were dated at 5900 + 145 ^{14}C yrs BP (0 - 1844).* Here the silt facies was 3 to 4 m thick. This facies thins eastward; it is suggested that the unit represents a prograding wedge of fluvial sediment which is encroaching upon and burying the estuarine mud and mangrove flats of the Hunter estuary (Story et al., 1963).

3.2.3.4 Freshwater swamp facies (o)

The accumulation of autochthonous organic detritus under a vegetation cover takes place at a number of sites in the Newcastle-Myall Lakes area. One site is the swales of beach-ridge plains on Inner Barriers. Such swamps are dominated by either a wet woody heath or reed

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* All radiocarbon (^{14}C) dates in the monograph are expressed in radiocarbon years before present (BP), and are corrected for both isotopic fractionation (all samples) and ocean reservoir effect (shell samples only) following Thom et al. (1978). These are shown as ^{14}C yrs BP. However, in the case of 0-1844 no isotopic fractionation is believed to have been undertaken, and as the two effects more or less cancel each other out, then the date remains as reported by the now extinct Humble Oil Company Laboratory.



Figure 3-16: Scanning electron micrograph of sand grain surface texture from the fluvial channel environment of the Hunter River.

swamp flora, sometimes with Melaleuca trees. They often contain thin peats less than 1 m thick. The deposits form surficial lenses parallel to the shoreline overlying sand. In the Upper Myall Valley the swales have been enlarged by dissection during periods of lower sea-level (Ch. 7 and Martin, 1987). Peats, up to 3 to 4 m thick, have accumulated over estuarine mud during the Postglacial Marine Transgression. The organic sequence has been documented by A.R.H. Martin at Bombah Bog (see Ch. 7 and Martin, 1987).

Interbarrier depressions are another site of swamp organic sedimentation. The elongate depression separating Inner and Outer Barriers in the Eurunderee embayment is a good example (Ch. 8). Very little open water persists in this area; it is mostly a sedge fen with less than 1 metre of water. Organic sediments are rarely more than 3 m thick in this depression.

A third site occurs in basins within dune fields. Water tables have been perched by either underlying bedrock or the development of an organic hardpan (humate) in the dune sand. Melaleuca frequently dominates the flora. Typically, the peats are quite thin (less than 1 m). Some of these sites may be quite high above sea-level (e.g. in Tomaree Hills, see Ch. 5).

Finally, there are organic-filled depressions enclosed by sand barriers. These depressions may be former river valleys, drowned by rising sea-level. Moffats Swamp is an excellent example in the Newcastle Bight embayment. Former lagoons blocked by barrier construction between rocky headlands are often irregular in shape and again contain peat no more than 2 to 3 m thick over sand or clay. Tomaree Hills contains several good examples (e.g. north end of One Mile Beach, Fingal Bay). Small Blechnum bogs occur behind lakeshore sand ridges fringing the Myall Lakes.

Generally, the freshwater peats are quite soft, but are still rich in plant fibres and roots. They all seem to contain well-preserved pollen and sometimes seeds. Available radiocarbon dates show the basal age of swamp sediments, which are still accumulating today, to be Late Pleistocene in age in some cases (e.g. Bombah Bog).

3.3 RELICT ENVIRONMENTS OF DEPOSITION

3.3.1 Humate-impregnated Sand Facies (hu)

Inner Barrier sand deposits are characteristically impregnated with humate, an organic gel as defined by Swanson and Palacas (1964). Various studies suggest that the accumulation of the organic fraction is a diagenetic phenomenon involving the translocation of organic material through porous sands under low pH conditions in either colloidal or soluble form (Swanson and Palacas, 1964; Thom, 1965). Its occurrence in many New South Wales coastal deposits which resemble the Inner Barrier of the study area is quite well documented (Langford-Smith and Thom, 1969; Polach and Thom, 1973). In places, the sand becomes solidly cemented to form "coastal sandrock" (Coaldrake, 1955; McGarity, 1956). The cemented portion is also referred to as "indurated sand", "coffee rock", "Waterloo rock" or "Wooloomooloo". The last mentioned term is used in the Tomago area of Newcastle Bight. However, it is important to recognize that there exist non-cemented sands which also contain humate. For this reason the facies will be referred to as the "humate-impregnated sand facies".

Numerous drill holes in parts of the study area, particularly near Tomago, have provided unique opportunities to investigate the chemistry, sedimentology, stratigraphy and spatial distribution of the humate-impregnated sand facies. In a study commissioned by the Hunter District Water Board (Soil Mechanics Ltd., 1970), four units were recognized in this facies:

1. Upper light coloured sand (ULS), generally 1.5 to 5 m thick, but locally much greater in high dune areas; it is a medium to fine sand; colour variations include white, light yellow and light grey layers, but it is predominantly light brown.
2. Dark coloured sand (DS), generally 1 to 10 m thick, but reaching as much as 20 m thick in places; it is a dark brown to black medium sand with some fine sand, occasionally cemented ("Wooloomooloo").
3. Lower light coloured sand (LLS), generally 1.5 to 8 m thick, medium sand, with some fine and coarse sand.
4. Light grey, non-impregnated sand (GS) which may contain shell fragments; the occurrence of Bankivia in this sand suggests a nearshore environment of deposition.

The four units are not always present, but the vertical sequence is repeated sufficiently to permit correlation between drill holes (Soil Mechanics Ltd., 1970). The nature of contacts between the units as well as their lateral extent strongly suggest that they represent a giant ground-water podzol developed during the Late Pleistocene (Thom, 1965). Radiocarbon dates on the organic colloids support this view (Ch. 4).

The upper light coloured sand (ULS) occupies a unit of varying thickness part of which lies above the water table. It is composed of loose quartz sand, containing less than 1 percent of organic carbon. However, the organic-rich sands are often arranged in layers or lenses indicating zones of preferential concentration within the unit. In this case the water table lies close to the surface, and probably fluctuates seasonally through a large part of the ULS sub-facies. In areas of high dune relief, loose sand may exceed 20 m in thickness, most of which is above the water table. Here a well-developed B-horizon possessing

organic-rich sand columns up to 6 m in length, underlies a leached A-horizon rarely more than 2 m thick. Specific characteristics of this soil type will be discussed in more detail in Chapters 4 and 5. Maze (1942) has described various attributes of the surface soils (see Ch. 4).

The dark coloured sand (DS) and lower light coloured sand (LLS) units occur below the water-table reaching average depths of 10-12 m below present sea-level (see Ch. 4). Organic content is greatest in the dark coloured sand unit. Permeability is reduced in layers with high organic content (Soil Mechanics Ltd., 1970, Fig. 13).

The lower light coloured sand (LLS) grades downward into the light grey sand unit (GS) indicating gradual dilution of humate. The organic fraction becomes progressively enriched in fulvic acid with depth. Humic acids are concentrated in the upper parts of the unit. Variations with depth in these components are discussed in Chapter 4 for samples from one hole (SK3523, see Table 4-2).

3.3.2 Estuarine Clay Facies (mm)

Drilling beneath the coastal barriers and the Port Stephens estuary, as well as inspection of outcrops along some tidal creeks (e.g. Pipeclay Creek) has established the existence of compact, stiff, partly de-watered clays of considerable areal extent and thickness. The light grey, non-impregnated sand unit of the Inner Barrier (GS) abruptly overlies the clay which is unoxidized and possesses a smooth contact with overlying sands. However, beneath the estuary the surface is quite dissected and the clays frequently possess prominent yellow and red mottles. These mottles probably represent the imprint of sub-aerial weathering as observed along Pipeclay Creek, where a clay unit is overlapped by Holocene tidal flat muds up to the level of present HWS. Above this level the clay outcrops to an elevation of +5 to 6 m. Deep drilling by the Joint Coal Board has established that the clay thickens seawards to a maximum of 60-70 m. The clays overlie weathered bedrock or basal fluvial sands and gravels (see Ch. 10 for discussion).

Generally, the clay unit contains less than 10 percent sand. Layers of sand up to several metres thick are interbedded with the clay. The sand fraction is of variable mineralogy being comparable to modern estuarine sands. Shells, foraminifera and sponge spicules are also locally present, especially in unweathered clays beneath barrier sands. However, few samples as yet are available for compilation of a fauna list. Wood fragments are sometimes found in dark grey to black clays.

In common with the estuarine mud facies, the estuarine clays are dominated by the clay mineral, kaolinite (Fig. 3-17). Minor amounts of montmorillonite and illite are present. Weathered, authigenic iron oxide has developed in irregular bands. The grey clays quickly oxidize on exposure to the atmosphere. Black, stiff clays also occur where the organic carbon content exceeds c. 3 percent. Table 3-3 lists some of the chemical properties of this facies. It is noticeable that a similar range in values exists for both clay and mud facies for organic carbon, total iron, and manganese. The carbonate content is much lower in weathered samples, as is the phosphorous content. However, only a few samples have been analyzed so that caution must be exercised in regarding these values as representative of the units.

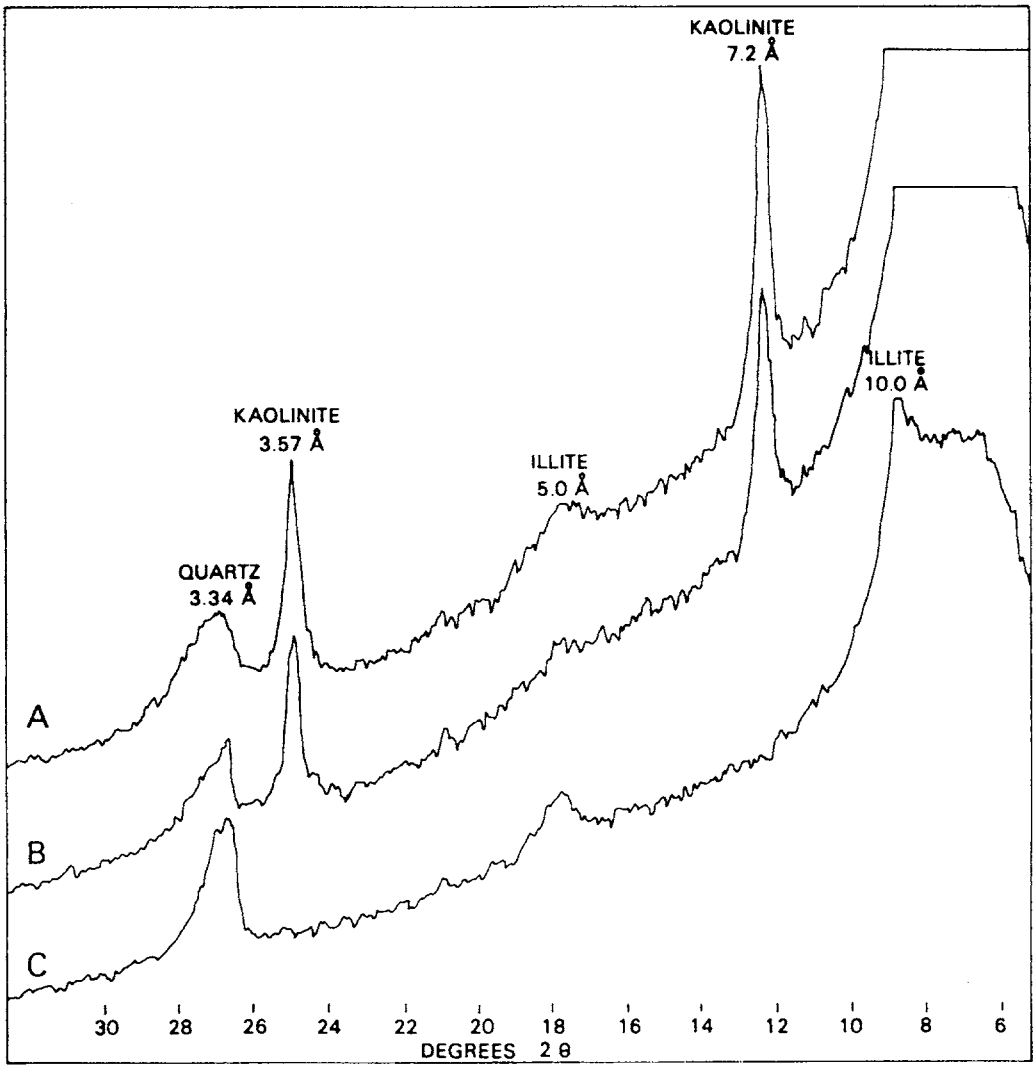


Figure 3-17: XRD analysis of three clay samples from Pleistocene estuarine clay facies showing dominant kaolinite peaks.

Several authigenic minerals have been recognized in the clay facies beneath Port Stephens. These minerals are not characteristic of the younger estuarine mud facies. Red, yellow and orange ironstone "grit" is the dominant authigenic mineral in the clay. In some places it may represent up to 90 percent of the sand fraction. It occurs as irregular aggregates of silt or fine sand cemented by goethite and hematite. Occasionally, it is found enveloping rootlets or worm tubes. A minor amount of pyrite also occurs as fine, crystalline, irregular aggregrates, often in association with wood (i.e. in darker grey or black clays). Gypsum is also present in minor amounts, as is siderite. The latter may represent 30 percent of the sand fraction in some samples and takes the form of yellow-brown coloured, fine-grained, rounded nodules or spherulites. An interesting discovery by J. Caldwell (analyst, Dept. Biogeography and Geomorphology, A.N.U.) was the occurrence of yellow

scales of carphosiderite (ASTM 18-653) in drill hole PS 19 (Sample 34). This mineral is a basic ferric sulphate hydrate. The mineral may have formed by oxidation after the sample was collected. Most unweathered clay samples appear to be rich in sulphides, the smell of H_2S being quite common.

The environment of deposition of this thick clay unit is believed to be in sheltered estuarine basins. Four attributes strongly suggest clay accumulation behind a coastal sand barrier during a marine transgression:

(i) Clays contain shells and foraminifera, not inconsistent with an estuarine environment.
(ii) Clay minerals are similar to those of modern estuarine muds.
(iii) The upper surface of the clay facies may be conformable with the overlying barrier sands (Inner Barrier).
(iv) The clay unit thickens seaward and is interbedded with, as well as overlying, coarse-grained sediments presumably derived from a fluvial source, which fill valleys cut into bedrock. The possible composite or polycyclic origin of the clay unit will be discussed in Chapter 10.

3.3.3 Bioherm Shell Facies (s)

Peat and Roy (1975) have described thick accumulations of shells in Port Stephens. These deposits occur within the estuarine shelly mud facies, but because of their distinctive composition and geometry they are treated as a separate facies unit. There is no evidence that they are growing today. The shell beds have been extensively explored by BHP and the Sulphide Corporation for possible commercial exploitation, and by the N.S.W. Geological Survey. In these surveys they were drilled, surface sampled by SCUBA divers, and investigated by seismic profiling.

The deposits are primarily composed of shell containing less than 50 percent sand and mud. Table 3-2 lists the mollusc species collected from several of the shell banks. Ostrea angasi, the mud oyster, is overwhelmingly the major component of the deposits. Other species mainly occur on the surface of the deposits.

The shell facies forms massive, inactive biohermal reefs which vary in known thickness from 0.3 m to 8.3 m, but probably attain 20 m thick in certain localities (e.g. West Bank). Their distribution is discussed in Chapter 5. They form "banks" veneered with mud or muddy calcareous sand. Seagrasses are often extensive on their upper slopes and flat tops, and bryozoa and sponges may be locally abundant on the flanks. An example is West Bank, which forms a prominent topographic peak or mound rising out of the relatively flat mud-covered floor of central Port Stephens. At depths below 21 m few shells are seen in the soft mud, but on the flanks of the bank, densely packed dead oyster shells occur under a thin cover of mud (Peat and Roy, 1975).

Seismic profiles and drilling show that there is a marked coincidence between the position of topographic highs on the eroded clay subsurface and the biohermal shell banks. Shell deposits are mostly confined to the plateau-like tops of the eroded Pleistocene surface generally at depths of 5-10 m below present sea-level and do not appear to extend below -21 m.

The shell facies is contained wholly within sediments of Holocene age. They do not transgress the Holocene-Pleistocene boundary. A single radiocarbon date on shell just beneath the surface of West Bank gave an environmentally corrected age of 1620 ± 100 ^{14}C yrs BP (SUA-366). Peat and Roy (1975) has postulated that the reefs commenced development on the tops of bathymetric highs during the Postglacial Marine Transgression. With continued submergence the deposits grew vertically, faster than the rate of mud accumulation in adjacent areas. The uniform depth of the tops of the bioherms (c. 2 m) suggests some control by wave action generated within the estuary. The cause of cessation of growth is not clear. The process of self-silting by the oysters (see Lund, 1957), which probably enhanced the vertical growth of the deposits during the transgression, possibly became detrimental to the colonies when sea-level remained static (Peat and Roy, 1975). During the last few thousand years the surface of the oyster deposits has been colonized by other molluscs, bryozoa, sponges and sea-grasses, and partly covered by mud and/or sand.

3.3.4 Backbarrier Sand Facies and Shelly Sandy Bay Facies (bb and sbb)

These two facies are no longer active in the study area. High foredunes and broad beach-ridge plains inhibit the deposition of sand as washover fans at the present time along the N.S.W. coast. During severe storms waves rarely breach the foredunes. However, most Outer Barriers and some Inner Barriers possess low relief sand flats landward of the innermost beach ridge or foredune ridge. These sand flats are vegetated by a swamp tree flora (e.g. Melaleuca, Casuarina) and are patchily covered by a thin woody peat layer usually less than 50 cm thick. The flats dip toward the muddy interbarrier depression; in fact they generally form the eastern side of the depression. They appear to be a relict of a period near the termination of a marine transgression just prior to the seaward and vertical growth of the sand barriers (Thom et al., 1978). The sedimentary properties of the backbarrier sand facies will be described in the appropriate regional chapters in association with the stratigraphy of the sequence (see Chs. 4, 6 and 7). However, it should be noted that two sediment types exist, an upper type which is positively skewed and probably has been reworked by the wind, and a lower type which is negatively skewed. Both types contain very small amounts of silt and clay (less than 0.5 percent).

Shelly sand bay facies also have been discovered by dredging and drilling at the southern end of Newcastle Bight (Hunter River estuary) and southern half of Fens embayments. The richness of the fauna of this facies is indicated by Group VII in Table 3-2. Sediment and stratigraphic properties are discussed in Chapters 4 and 6. Generally, they underlie backbarrier sands. They resemble the shelly sand and muddy sand facies of estuarine channels described by Roy (1980; see 4.3.3.4).

3.3.5 Terrestrial Dune Sand Facies (e)

The study area contains extensive sand sheets and dune ridges of pre-Holocene age which are covered by Eucalyptus-dominated woodland (see 2.6). Well developed podzol soils are found in the sands (Maze, 1942; Appendix A) and bedding features are rarely observed. Characteristically, the sands have been reworked from Inner Barrier surfaces into parabolic (see 7.2.4) or longitudinal ridges (see Tomago dune sheet, 4.2.2.2). In addition, there exist sand ridges which envelop bedrock hills as in the Tomaree segment (see Ch. 5) and mantle bedrock

surfaces even as a cliff-top sand cover. It is argued in Chapter 10 that these are terrestrial dunes, and are largely the product of vegetation destruction, eolian reworking and subsequent vegetative colonization during the Last Glacial period.

Table 3-4 lists moment measure statistics on 119 samples of terrestrial dune sand reworked on the Inner Barrier in the Tomago-Williamtown area. These samples were collected in 1962 by D. Simonett from dune crests, sideslopes and at the toe of dune slopes. Various statistical analyses revealed no distinctive patterns between and within dunes, although some dunes (eg, the Grahamstown Ridge) tend to be coarser than others. The sand of the ridges are medium, well sorted and symmetrical in size distribution; those of the sand plain collected at various localities are slightly less well sorted.

3.4 COMPARISON OF SEDIMENTARY PROPERTIES FOR DIFFERENT ENVIRONMENTS

The various properties of the modern sediments of the Newcastle-Myall Lakes region have been described in this chapter. A comparison of these properties for the different environments should assist in the environmental interpretation of subsurface deposits of the area (Table 3-1). Attention is focussed on the sand facies of the open-ocean and fluvial environments.

3.4.1 Grain Size

Differences in grain size properties between sands from the outer and inner nearshore marine zones, beach and frontal ridge are shown in Figure 3-18. Frontal ridge or foredune samples tend to be slightly better sorted than the other two facies. However, the samples from the outer nearshore marine zone can be differentiated from those of the beach, frontal ridge and inner nearshore marine zone by an increase of suspension population. The outer nearshore zone is finer and generally more poorly sorted than the other units (Fig. 3-18).

Differences in grain size exist between dune sand and beach sand. The former is usually finer and better sorted than the latter (Fig. 3-18). The most striking difference in this area is the sign of skewness; the dune samples are generally positively skewed whereas the beach samples are essentially negatively skewed (Fig. 3-19). Kurtosis is not environmentally sensitive. Inner and outer nearshore sands are not as clearly differentiated in this plot, although outer nearshore sands tend to be more positively skewed (Fig. 3-19).

The most typical grain size characteristic of the river sands is the "multi-population" character of the saltation population. More than two saltation populations are usually observed (Ly, 1976).

3.4.2 Roundness

Figure 3-20 demonstrates that the samples from the nearshore marine zone and fluvial environment are generally more angular than those from the beach (including inner nearshore), frontal ridge and mobile transgressive dune. There is no difference in average roundness (denoted by R in Fig. 3-20 using Powers scale), between the beach, frontal ridge and dune samples (Ly, 1976). However, the detailed analysis of the

TABLE 3-4 Moment Measure Grain Size Statistics on Samples from the Tomago-Williamtown Dunefield

Ridge No.	Grid Ref.	No. Samples	Mean	Max.	Min.	Mean Standard Deviation
II	936695	4	1.96	2.06	1.91	.41
III	033753	4	2.19	2.24	2.15	.36
IV	004748	13	2.02	2.14	1.90	.37
V	888737	2	1.78	1.80	1.76	.44
VI	948724	3	1.84	1.91	1.81	.40
VII	945724	12	1.81	1.90	1.74	.43
VIII	836684	19	1.68	1.80	1.53	.44
X	847686	5	1.60	1.66	1.48	.41
XI	864686	15	1.65	1.86	1.44	.45
Masonite	823710	5	1.53	1.61	1.44	.44
Duckhole	895728	25	1.68	1.86	1.53	.43
Grahamtown	886736	4	1.51	1.58	1.34	.43
Sand Plain	(various)	8	1.56	1.80	1.36	.55

Note: Moment measures are in phi values. The samples were sieved at 0.25 phi intervals. Grid references are approximate and from Williamtown (9232-II-N) and Beresfield (9232-III-N) Orthophotomaps (1:25,000).

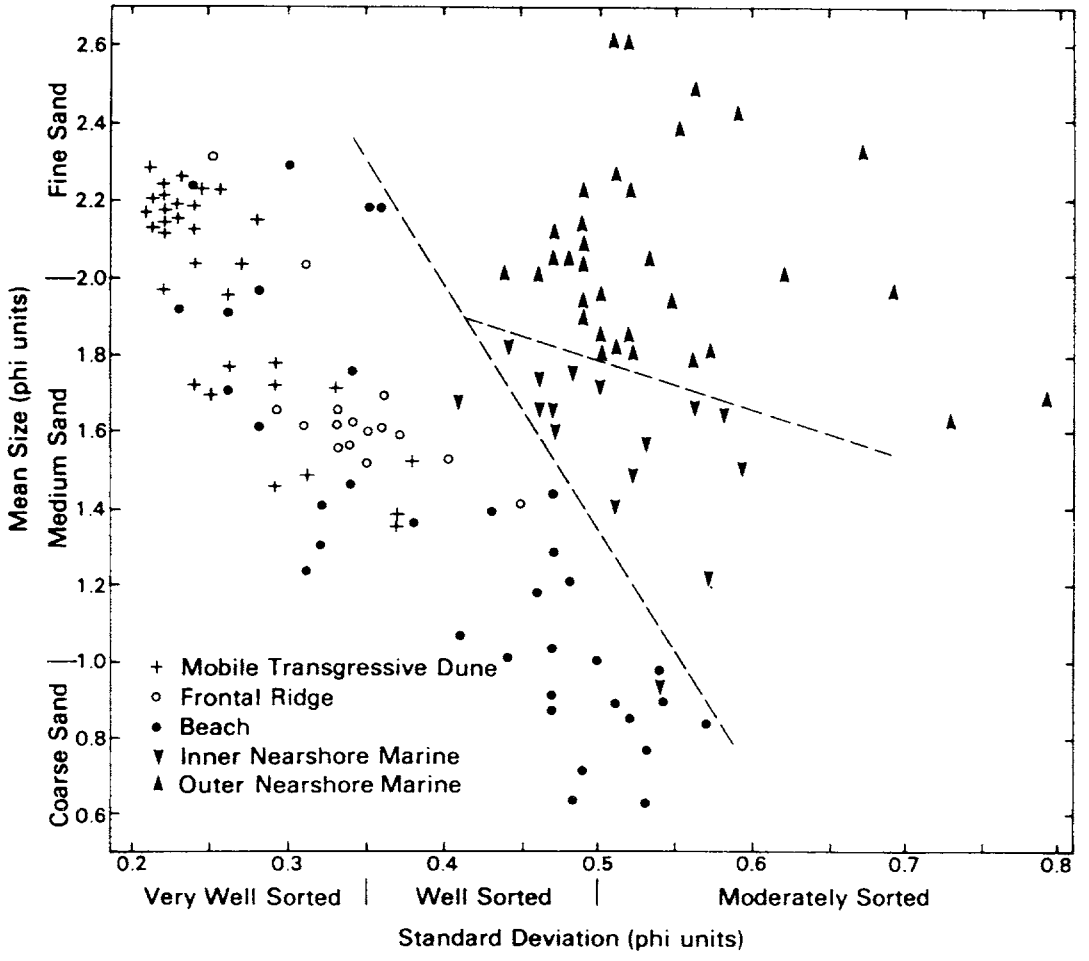


Figure 3-18: Differentiation of modern environments of deposition on the basis of mean grain size and sorting.

quartz fraction showed that the amounts of angular and very angular grains (denoted by n in Fig. 3-20) were usually lower in the dune samples than in the beach, frontal ridge and nearshore marine samples, probably due to the selective action by wind. Figure 3-20 also shows that the river sands are more angular than most of the types of sands from the open-ocean environment, and the average roundness, R, can be successfully used to differentiate between the river sands and the marine sands. The amounts of angular and very angular grains in the quartz fraction of the river sands are usually higher than 50 percent.

3.4.3 Mineralogic Composition

In the open-ocean environment, there are only minor differences in mineralogy between the different types of facies, although the dune sands tend to be less lithic than the beach, frontal ridge and nearshore marine sands (Fig. 3-6). Open-ocean sands contain usually less than 15 percent rock fragments and feldspars. However, Figure 3-6 clearly shows a striking difference in composition between river sands (Hunter River) and open-ocean sands; the former are much more lithic and feldspathic than the latter (cf. Roy, 1977).

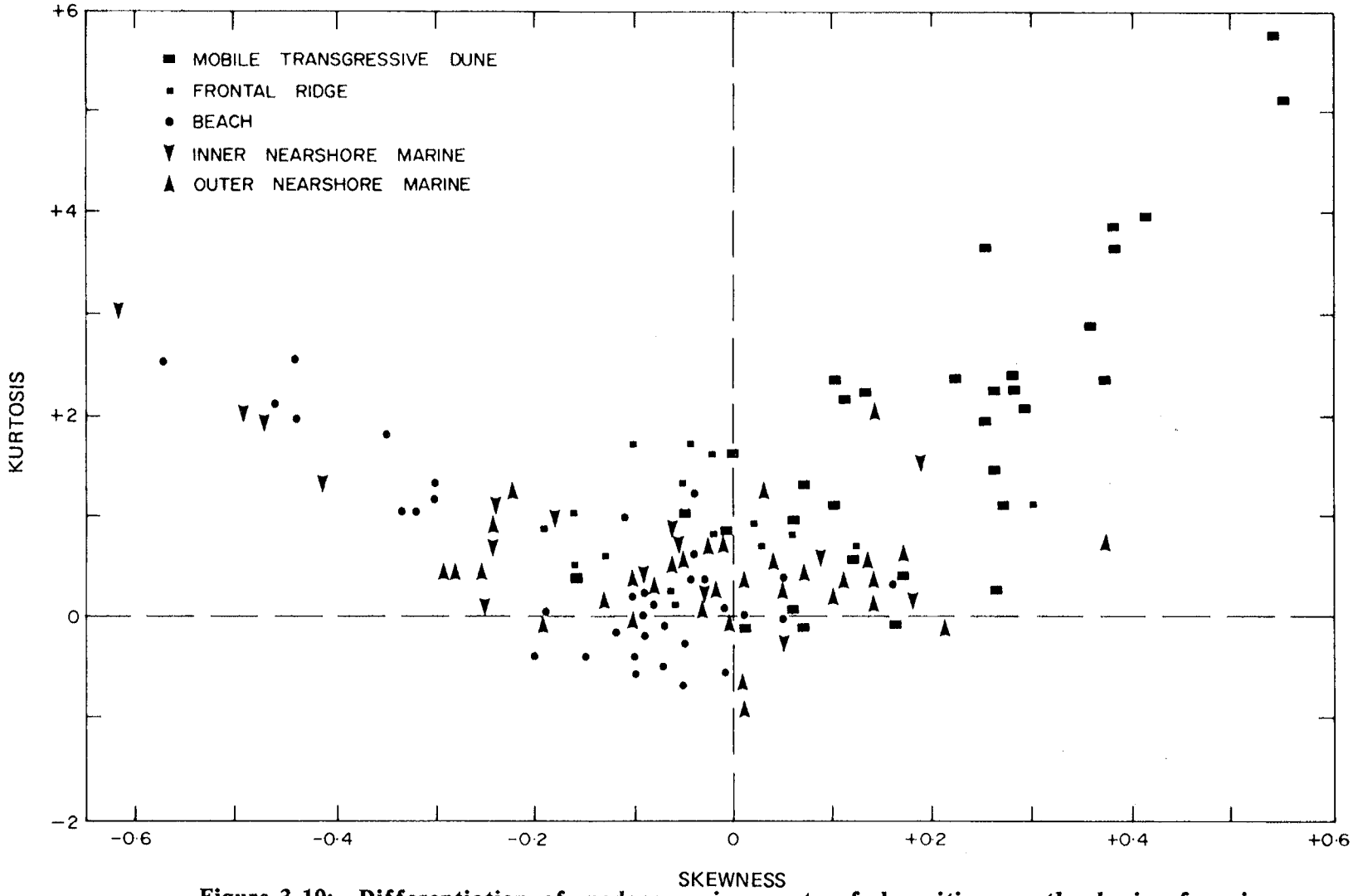
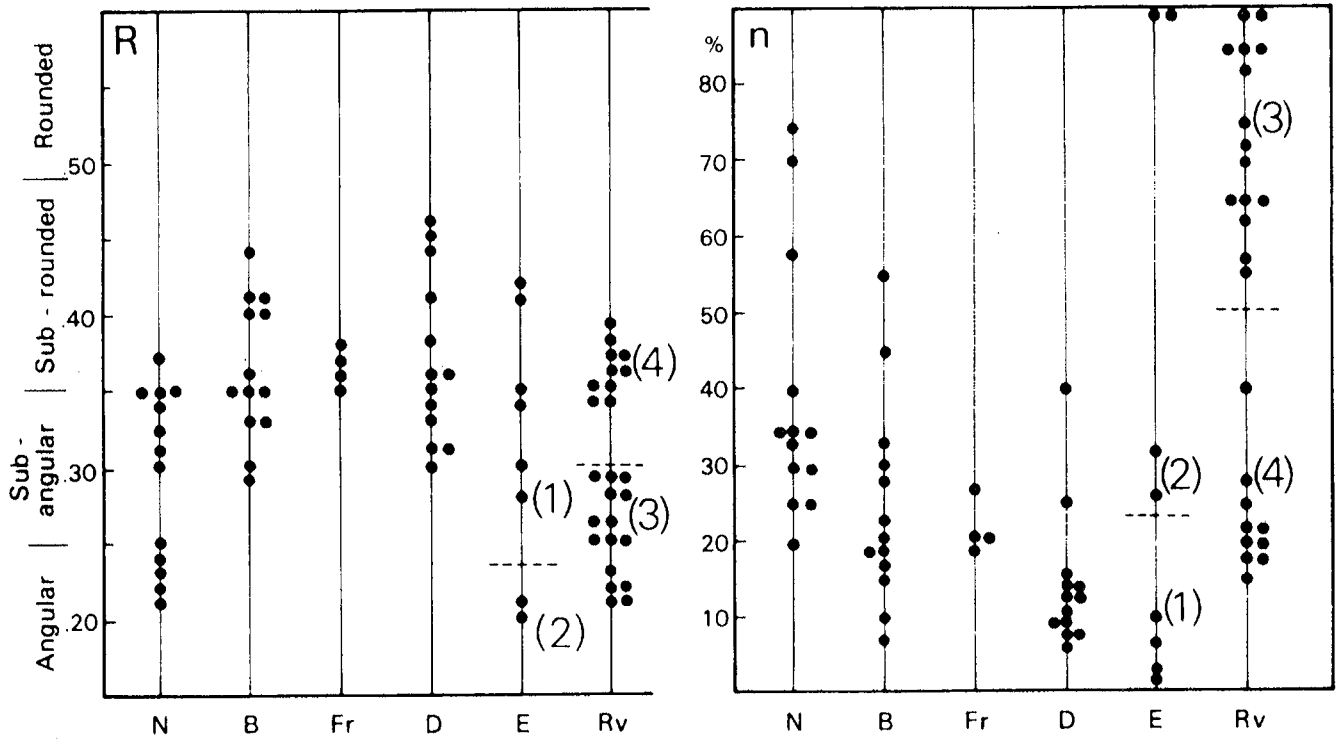


Figure 3-19: **Differentiation of modern environments of deposition on the basis of grain skewness and kurtosis. Transgressive dune sands are clearly the more positively skewed of the samples analyzed in the Newcastle Bight area.**



N — Nearshore marine B — Beach Fr — Frontal Ridge D — Mobile transgressive dune

E — Estuarine lagoon (1) marine and dune origin Rv — River (3) terrestrial

(2) terrestrial origin (4) marine

R — Average roundness value (Power Scale)

n — Percentage of angular and very angular grains in quartz fraction

Figure 3-20: Differentiation of modern environments of deposition using two measures of quartz grain roundness.

Differences are also reflected in the heavy mineral suite (Fig. 3-21). Sands from the inner nearshore marine zone, beach, frontal ridge and mobile dune are primarily characterized by the stable zircon, rutile, tourmaline and opaques, although the samples from the outer nearshore marine zone contain relatively higher amounts of the less stable pyroxene, hornblende and epidote. In contrast to the open ocean sands, the heavy mineral suite of the river sands (Hunter River) is dominated by pyroxene, hornblende and epidote. This analysis suggests that some river sand is bypassing high energy inshore environments and being deposited in the outer nearshore zone.

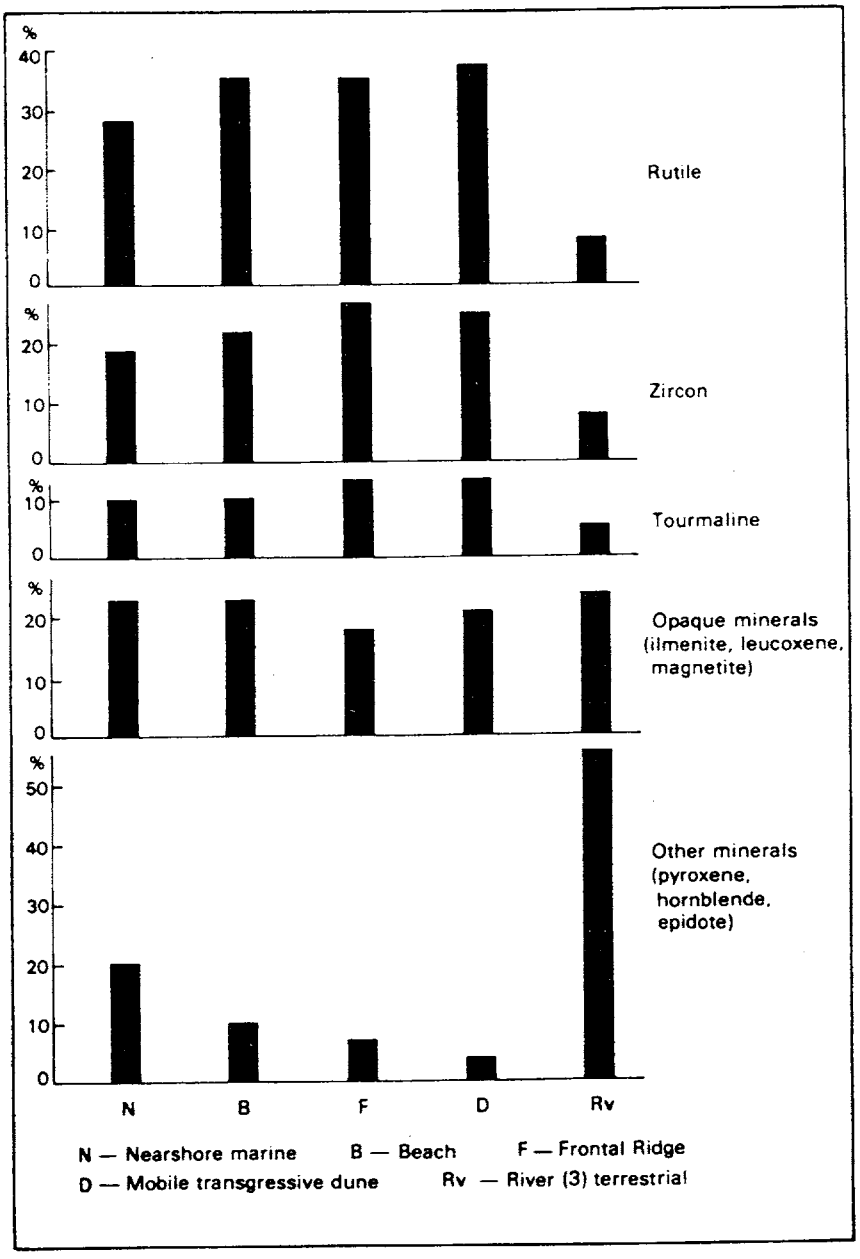


Figure 3-21: Variation in heavy mineral composition for five modern environments of deposition in the Newcastle Bight embayment.

3.4.4 Grain Surface Textures

Examination of the surface features of quartz grains from different environments of the Newcastle-Myall Lakes region by Scanning Electron Microscopy has shown differences in grain surface textures between the different types of sand facies (Ly, 1978a). In the beach and inner nearshore marine zone where the energy is high, mechanical features are predominant (Fig. 3-7). In the outer nearshore marine zone or on low energy beaches where the turbulent movement is less, chemical action is apparently more important and quartz grains are affected by chemical etching with some traces of precipitation (Fig. 3-3). Grains from the frontal ridge exhibit features similar to those seen on the beach sand grains. Mechanical features are rare on grains from the mobile transgressive dune facies. Chemical precipitation and etching features were noted (Fig. 3-9), but the extent to which these surface textures are inherited from other environments is unknown. River sands are characterized by large conchoidal fractures (Fig. 3-16; see Ly, 1976, 1978a, for more detailed discussion).

3.4.5 Faunal Composition

In this study only molluscan assemblages associated with different environments of deposition have been studied. Micro-organisms await further research. The ecology of many shell species is little understood, but there is no doubt that certain species have preferred habitats which relate to hydrodynamic and other environmental conditions. Table 3-2 lists the characteristic species for each environment. The groups do provide a basis for distinguishing some relict sediment types. For instance, Bankivia is absent in backbarrier and sandy bay faunas and occurs as part of a very mixed assemblage in tidal delta deposits. However, open-ocean sand facies are extremely rich in this species; whole shells are most noticeable in water depths greater than 5 m.

3.4.6 Sedimentary Structures

As drilling was mostly by augering, it was not possible to recover samples from below water table for analysis of primary sedimentary structures. Therefore, this parameter has been of little use in deciphering most environments of deposition. Characteristic bedding patterns have been noted in some facies (e.g. dunes) and others will be referred to below (e.g. backbarrier flat at Fens, Ch. 6).

3.4.7 Geometry of Facies Units

Drilling and surface mapping of sediment units make possible the delineation of the geometry of facies units including those buried below sea-level. Shallow auger drilling has been used to define the geometry of most major geomorphic features (e.g. beach ridges, transgressive dunes, interbarrier depressions). Only a few sediment units lack surface expression. In some cases drilling has indicated the shape of the sub-surface unit, but there are problem features (e.g. possible tidal inlets through the inner part of the Newcastle Bight Outer Barrier, Ch. 4). General geometric characteristics are listed in Table 3-1.

3.5 SUMMARY

The aim of this chapter has been to describe sediment properties associated with different environments of deposition identified in the study area. A number of facies units has been recognized in active environments. The properties of these units will be used in the identification and interpretation of stratigraphic sequences (Chs. 4 to 9). Emphasis has been on sediment properties from Newcastle Bight which is the best studied portion of the study area. In the next chapter further details of the sediments, geomorphology and geologic history of Newcastle Bight will be presented and discussed.

4

Newcastle Bight

4.1 REGIONAL SETTING

4.1.1 Division of the Study Area

For purposes of describing morphological and stratigraphical characteristics of the area between Newcastle and Seal Rocks, the coast has been divided into six segments. The location of each segment is shown in Figure 2-1. Each segment has been named by either a local geographical feature (e.g. Newcastle Bight, Upper Myall or Seal Rocks), or by the local parish (e.g. Tomaree, Fens, Eurunderee).

The general disposition of bedrock topography as discussed in Chapter 1 makes possible the division of this coastal stretch into segments. The boundaries of each segment are usually bedrock promontories (strike ridges) or water bodies (e.g. Port Stephens). The presence of bedrock ridges has served to compartmentalize sediment distribution within each coastal segment. In particular, patterns of wave refraction have been controlled by the configuration of these ridges, so that constructional sand features, such as beach ridges, have been tied to the bedrock divides.

The segmentation of the study area is useful not only for purposes of description, but also for understanding past and present morphodynamics. The evolution of sand deposits in the late Quaternary

has been influenced by the configuration of bedrock outcrops along the coast by compartmentalizing sand movement. As shown by Davies (1974), the coastal sediment compartment or littoral cell constitutes a morphological unit with discrete boundaries in which "we can monitor what is happening, do our sums and calculate energy and sediment budgets" (p. 149). Furthermore, histories of Quaternary sedimentation should be based on the sequence within each compartment:

> The compartment also helps to emphasize the time factor because it may be possible to show that different compartments are at a somewhat different point in a sediment budget cycle triggered by Quaternary sea-level swings (ibid., p. 150).

4.1.2 Bedrock Properties of the Newcastle Bight Segment

The southwest boundary of Newcastle Bight (also known as Stockton Bight) is the Hunter River which more or less abuts sedimentary rocks of Permian age (Newcastle Coal Measures and Tomago Coal Measures, see Fig. 1-1 and Newcastle 1:250,000 Geological Series Sheet S1/56-2). That the river has not always been in this position at times of lower sea-level will be shown in 4.3.1.

On the south side of the river mouth near Stockton, there exists a small bedrock outcrop of Permian sandstone known as Nobbys Head (Fig. 4-1a). This cliffed headland forms the southern limit of the Newcastle Bight embayment. The narrow Stockton portion of the Outer Barrier approximates a logarithmic spiral or "zeta-curve" in a thwarted attempt to join the headland. South of Nobbys Head are a number of short bay-mouth barriers and bay-head beaches linking bedrock headlands (see Galloway, 1965, Fig. 3).

The northern margin of the Newcastle Bight embayment is formed by sedimentary rocks of the Tomago Coal Measures, the Mulbring Siltstone and the Branxton Formation. In this area, Permian rocks are contained within a low amplitude fold in the Carboniferous sequence known as the Medowie Syncline (Engel, 1966; see also Newcastle 1:250,000 Geological Series Sheet S1/56-2). To a large extent these rocks are fine grained and deeply weathered. To the east of the Grahamstown Reservoir a borrow pit exhibits a well-developed lateritic profile at an elevation of between 15 and 20 m above sea-level in what is believed to be the Mulbring Siltstone. This weathered profile extends at least to and perhaps below present sea-level. Galloway (1965) in his reconstruction of bedrock contours shows an embayment more than -30 m MSL deep beneath Grahamstown Swamp (now a water-storage reservoir). Camp Vale Swamp and Moffats Swamp also appear to be alluvially drowned bedrock valleys. However, the seaward projecting spurs of these old valleys have been buried by marine and eolian deposits of the Inner Barrier. Low degraded cliffs have been cut into the bedrock margin (Galloway, 1965, Fig. 1). Little is known of the depth to which the cliffs extend below the bedrock-sediment contact (see Fig. 4-1a for location of place names).

At the eastern end, the embayment's inner margin coincides with the bedrock shoreline of western Port Stephens. Here Carboniferous rocks striking north-south plunge beneath the waters of Big Swan Bay and Little Swan Bay. An outcrop of the Nerong Volcanics of Carboniferous age at Lemon Tree Passage provides the northeastern limit of the embayment.

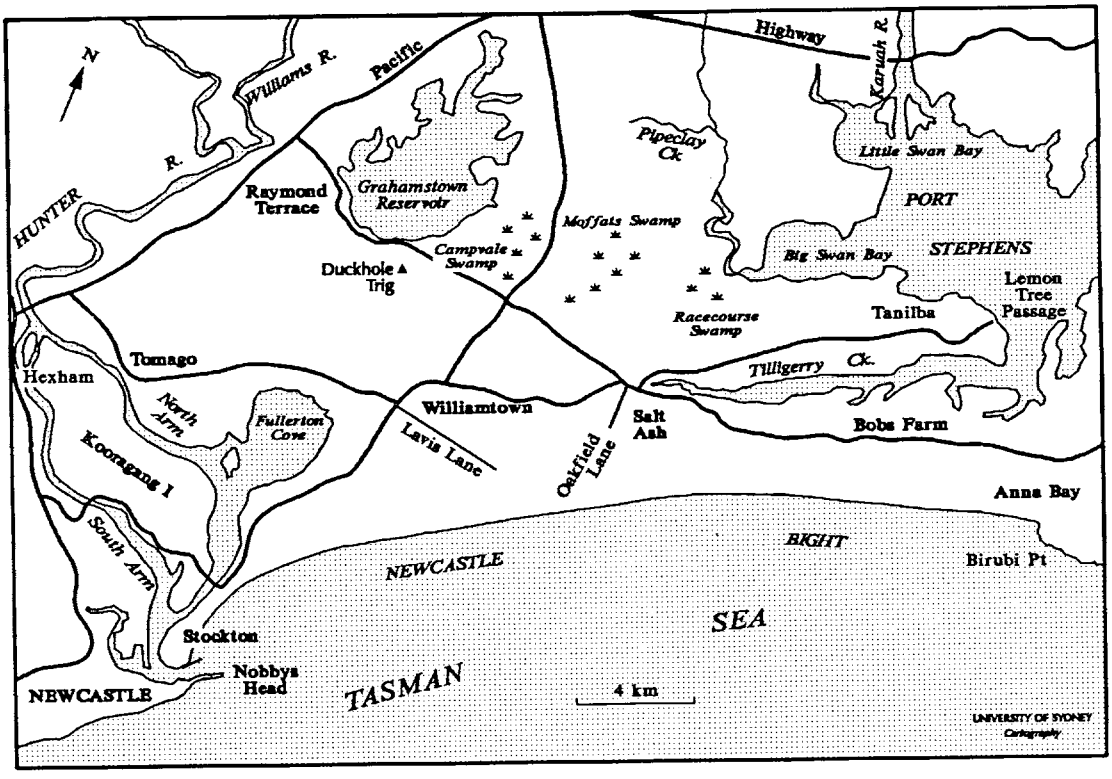


Figure 4-1a: Location map of Newcastle Bight embayment.

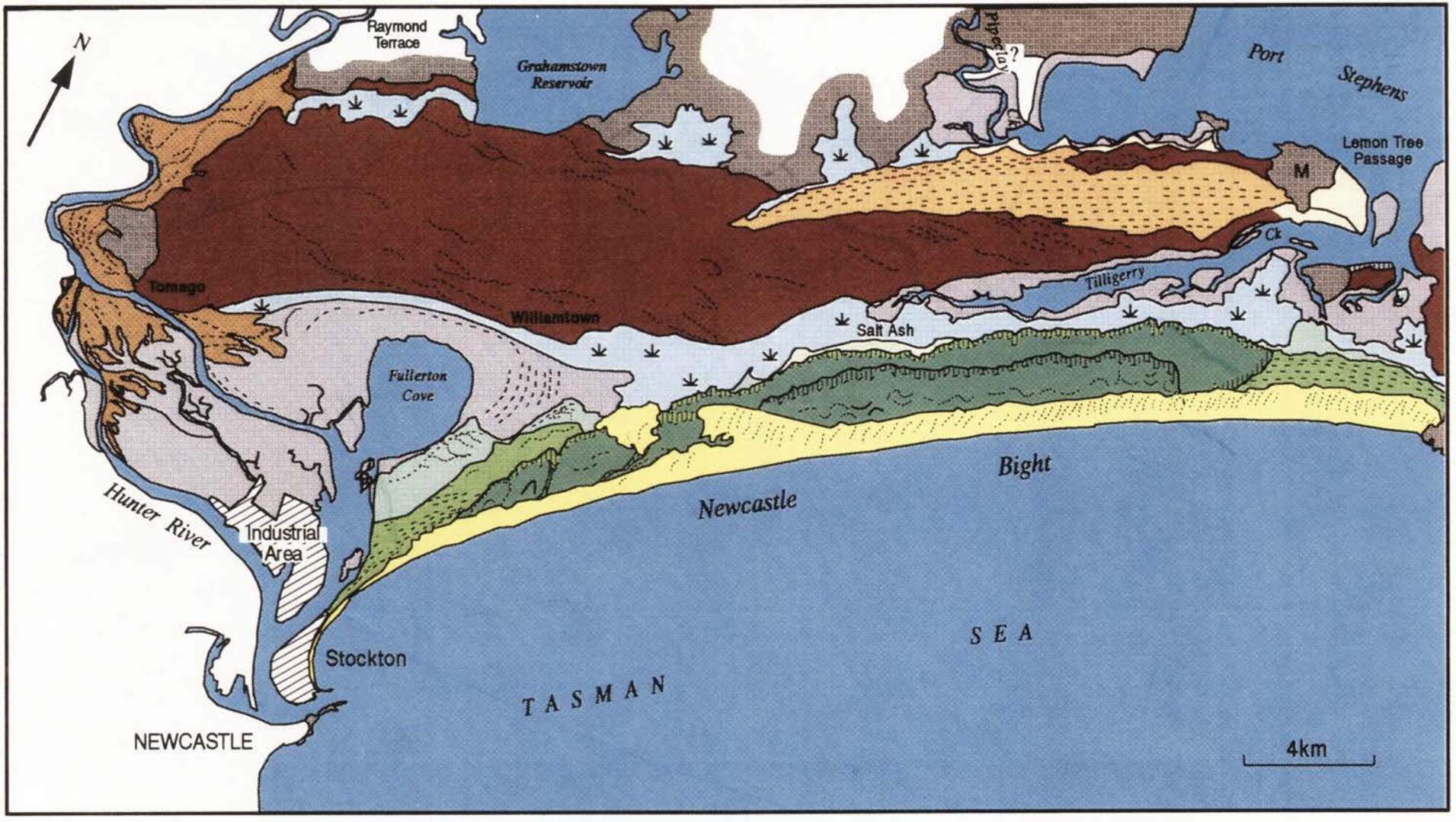


Figure 4-1b: Generalized morphological map of the Newcastle Bight embayment (see Fig. 4-1c for general legend).

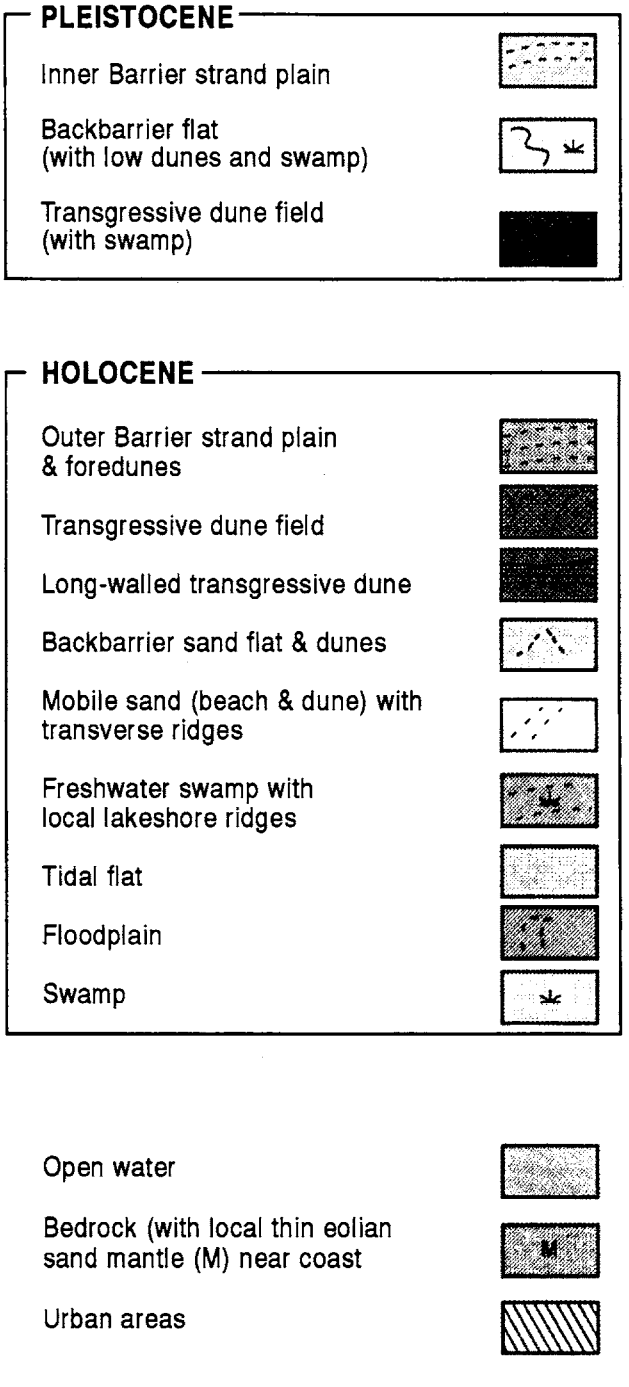


Figure 4-1c: General legend used in morphological maps of individual segments of coast between Newcastle and Seal Rocks.

This low bedrock hill formed the eastern "headland" of a marine embayment at the time the Inner Barrier was being constructed (i.e. the Inner Barrier is "tied" to this rock outcrop).

An outcrop of Nerong Volcanics forms the eastern bedrock headland of Newcastle Bight. This headland is sometimes known as Morna Point, the southern tip of which is called Birubi Point (or Cemetary Point). Figure 4-1a shows the village of Anna Bay behind this headland. Sand deposits of the Outer Barrier are "tied" to this headland. Figure 4-1b shows a narrow interbarrier depression between the Lemon Tree Passage outcrop and Morna Point. This depression opens via Tilligerry Creek into Port Stephens, but is blocked from direct entry into the sea by Holocene dunes which form a sand barrier at Anna Bay (see Ch. 5). The northeastern side of the depression abuts a morphologically complex area of dune ridges and swamps of Pleistocene age, which in turn envelops the bedrock hills of the Tomaree segment (Fig. 2-1).

4.2 MORPHOLOGICAL CHARACTERISTICS

4.2.1 Major Morphological Features

Newcastle Bight is a broad embayment open to the south-southeast. It is the largest sedimentary "basin" of Quaternary age in the study area. This area includes Holocene deposits of the Hunter delta, the filled valleys east of Raymond Terrace and the barrier sand deposits. The area of sand deposition of marine or eolian origin is c. 113 km . The maximum length of the embayment where sand has been deposited is c. 32 km measured along the east-west axis of the Inner Barrier. The maximum width across the sand barriers normal to the coast is 14 km. Sediment thickness below MSL in the Newcastle Bight segment is well established, and from drill records up to 100 m of what is believed to be Quaternary fill has been recorded. To this should be added the accumulation of dune sands which locally extends to 30-40 m above sea-level on both Inner and Outer Barriers.

There are six major depositional features in the Newcastle Bight segment: Hunter delta; Inner Barrier (area 80 km^2); alluvial "drowned" valleys behind the Inner Barrier; western Port Stephens including Pipeclay Creek; interbarrier depression including Fullerton Cove and Tilligerry Creek; and the Outer Barrier (area 33 km^2). The distribution of these morphological units is shown in Figure 4-1b. It is not our intention in this monograph to discuss the Hunter delta (see Story et al., 1963), or the drowned valleys. Western Port Stephens is briefly described in Chapter 5.

4.2.2 Inner Barrier

The Inner Barrier of the Newcastle Bight embayment occupies both a bay-head and mid-bay position. It is in a bay-head position where it abuts the Permian rocks east of Raymond Terrace. Here it blocks the mouths of the three freshwater swamps (Grahamstown, Moffats and Camp Vale), and the tidal swamps of Pipeclay Creek. However, towards Tanilba, the barrier extends across Big Swan Bay as a mid-bay feature. The linkage of bedrock outcrops at Tanilba Point and Mallabula Point by the Inner Barrier constitutes the eastern extension of the barrier where it partially blocks off western Port Stephens as a barrier "lagoon".

The barrier attains a maximum length of 32 km measured from its western tip where it is tied to a Permian "headland" near Hexham to the Lemon Tree Passage outcrop of Carboniferous volcanics in the east. In width, the barrier ranges from 5-6 km in the western or Tomago section to 3-4 km in the eastern or Salt Ash section. The general orientation of the barrier is 070 degrees, i.e. at right angles to wind and wave forces from the south-southeast (see Ch. 1). The general elevation of much of the Inner Barrier is c. +10m MSL. However, there is considerable variation in relief. Duckhole Trig Station on an elongate dune ridge is the highest point on the barrier at 59.2 m. On the southern margin bordering the interbarrier depression, the Inner Barrier merges almost imperceptibly with the flat surface of the former Holocene barrier lagoon. In the western section dune ridges frequently rise 15 to 20 m above the surface of the barrier. Figure 4-2 is a series of generalized topographic sections derived from data in the Soil Mechanics Report Ltd. (1970, Fig. 5). These sections depict changes in relative relief across the barrier from the relatively flat beach-ridge plain in the east to the Tomago-Williamtown dune field farther west (see also Figs. 4-1b and 4-3).

4.2.2.1 Beach ridges

At its eastern end, the barrier is characterized by a beach-ridge plain. The location and trend of ridges is shown in Figure 4-1b. The maximum length of the ridge pattern is 15 km. In width, the plain nowhere exceeds 3.5 km. Ridge orientation varies from 060 degrees in the west to 090 degrees where the ridges are attached to the Lemon Tree Passage bedrock "headland". This slight curvature is largely confined to the eastern 5 km, and is expressed by all ridges visible on aerial photographs. It is also apparent that the trend of the ridges generally parallels the present coast. The beach-ridge pattern to the west is obscured by east-west trending dunes, which post-date beach-ridge formation (see 4.2.2.2). This is evident in vertical airphotos (Fig. 4-3). However, extrapolation of beach-ridge orientation to the west at 060 degrees, suggests that their alignment would not parallel the barrier as a whole (070 degrees). Therefore, unless there is a change in orientation of ridges towards a more east-west trend (perhaps dictated by a subsurface bedrock high), then beach ridge and barrier orientation may not coincide, a phenomenon which would be quite rare on the N.S.W. coast. The extrapolated beach trends are confirmed by an examination of plans of heavy mineral concentration in an area mined by Rutile and Zircon Mines. Mineral seams are interpreted as having accumulated on a beachface by storm-wave swash action. The area concerned lies in the western section near Tomago. Mineral values frequently exceed 5 percent and are concentrated in bands aligned 050 to 060 degrees.

The beach-ridge plain slopes seaward at an approximate gradient of 1:400 (Fig. 4-2). In the field this gradient is not perceptible, and it is also very difficult to discern micro-relief of ridges and swales. Generally, the relative relief is less than 1 metre. Subtle changes in vegetation type help delineate the ridge-swale pattern (Fig. 4-3). Soils of the swales are composed of wet peaty sands. The ecology of the area has been disturbed by military activities (RAAF bombing and parachute drop zones). However, it is considered that the vegetation pattern was once similar to that of the Eurunderee Inner Barrier (see Ch. 8).

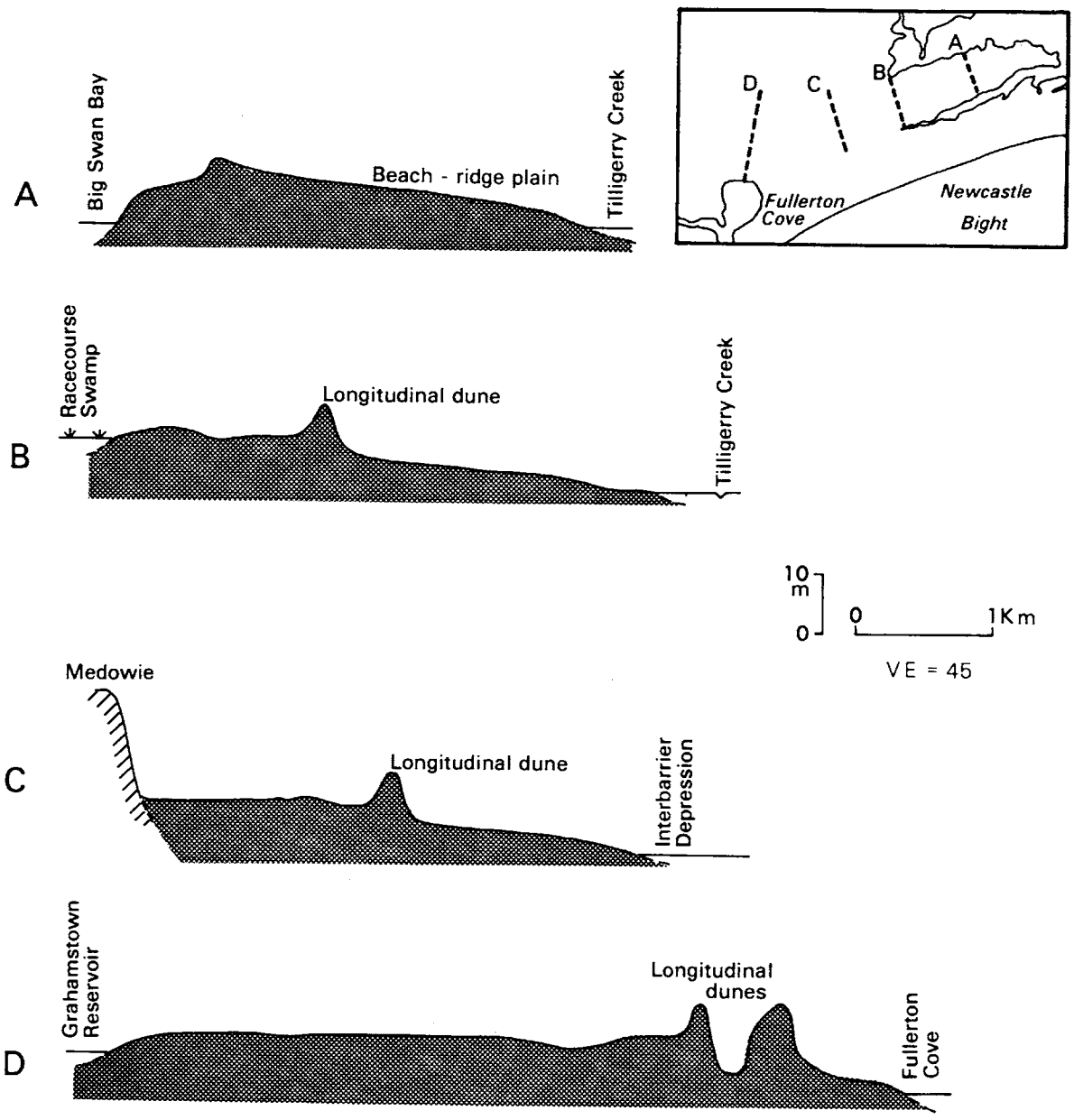


Figure 4-2: **Topographic sections across the Inner Barrier of Newcastle Bight (see inset map for locations). Section A traverses the beach-ridge (or strand) plain at the eastern end of the barrier (see Fig. 4-3). Sections B, C and D intersect west-east trending longitudinal dunes.**

The landward-most ridge which extends across the mouth of Moffats Swamp and the tidal flats adjacent to Pipeclay Creek, as well as blocking off Big Swan Bay and Tanilba Bay, is strikingly different in many ways from the beach ridges to seaward. It is a feature of high, hummocky relief attaining an elevation of +10 m MSL. The ridge tends to be symmetrical in cross-section and is interpreted as a large, relict established foredune. It has been mined by Associated Minerals Ltd. for heavy mineral (see Winward, 1974, for maps of mined areas).

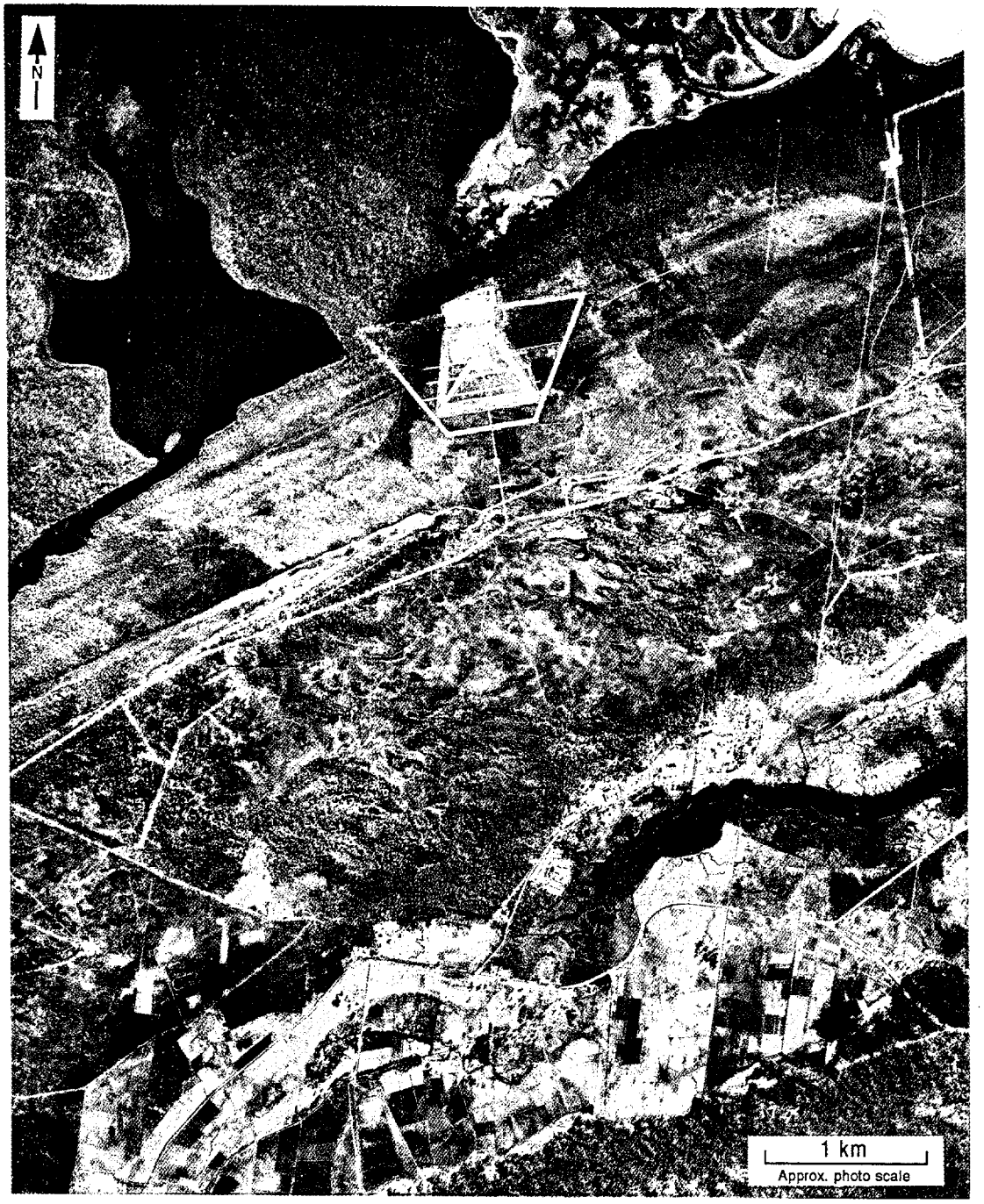


Figure 4-3: **Low relief terrain composed predominantly of beach ridges (relict foredunes) at the eastern end of the Inner Barrier at Newcastle Bight. The aerial photo shows the Parachute Drop Zone on the beach ridges. Eolian reworking of the barrier is manifested by west-east trending dune ridges. The Inner Barrier is separated from the Outer Barrier by cultivated flats of the Interbarrier Depression bordering Tilligerry Creek (NSW 1464, 5140, 14/8/66).**

Ridge and swale micro-relief is partially obscured by subsequent eolian reworking (Fig. 4-3). At first appearance, the ridge-swale spacing seems to be broad, between 100-200 m. However, faint traces of lineations at intervals of less than 100 m can be detected on air photos suggesting an initial close spacing at the time of deposition which has been abstracted to some degree by "modification processes" (Thom, 1975). The secondary longitudinal and parabolic dunes, described in the next section, constitute one type of surface modification since the beach ridges were formed. At some stage parts of the ridges have been subjected to eolian deflation. Another process involves swale infilling by peat accumulation. A third phenomenon, discernible only on aerial photographs, is the shallow dissection of ridge crests into rectangular "blocks". Although not as well developed here as in the Eurunderee segment, the "block" pattern is still apparent. It is typical of the micro-topography of beach ridges on the Inner Barrier: the spacing between "blocks" varies from 50-300 m. Therefore it is possible that all three modification processes (eolian reworking, peat infill of swales, and cross-dissection perhaps involving sheet flow) are responsible for ridge abstraction.

4.2.2.2 Longitudinal and parabolic dunes

At the western or Tomago end, the Inner Barrier of the Newcastle Bight segment is characterized by hummocky ridges of sand. These ridges are covered by a dune woodland community which is typical of well-drained, highly podzolized soils. In the last three decades, this part of the barrier has been subjected to increased intensity of land use: as a reservoir for water (Tomago Sandbeds, see Corlette, 1944), as a site for heavy industry (e.g. aluminium refinery), for market gardening, for home sites on large blocks, and for heavy mineral sand mining (Soil Mechanics Ltd. 1970). However, the H.D.W.B. has maintained a major proportion of the area under natural vegetation cover as part of their management of the "Sandbeds" water catchment.

The barrier surface at the western end is an eolian reworked sand plain initially formed by beach-ridge progradation. Although beach-ridge morphology is not visible on the ground or on aerial photographs, the alignment of heavy mineral seams as noted above confirms the beach-ridge progradation origin of the western part of this Inner Barrier.

Sand ridges on the Tomago surface of the Inner Barrier form a series of elongated dunes trending east-west for the most part, although there are some at the extreme western end which trend more northwest-southeast (Fig. 4-4). They occur mainly on the periphery of the western part of the Inner Barrier and cut across the northeast-southwest trend of beach ridges where the latter can still be seen at the eastern end (Fig. 4-3). A broad, slightly undulating sand plain occurs between the dunes in the centre of the barrier.

A study of the morphology of 26 elongated dunes has shown that most exceed 3 m in height and range from 500 m to 3000 m in length. Smaller undulations also trend east-west and impart a distinct grain to the photographs (Fig. 4-3). The mean height of ridge crest above base of slope is 8 m, the mean slope facing south is 12.7 degrees, while the mean slope facing north is 7.7 degrees (these averages are based on 80 observations). Steepest slopes are on the southern side of the barrier bordering the interbarrier depression, with maximum slope of 25-28°.

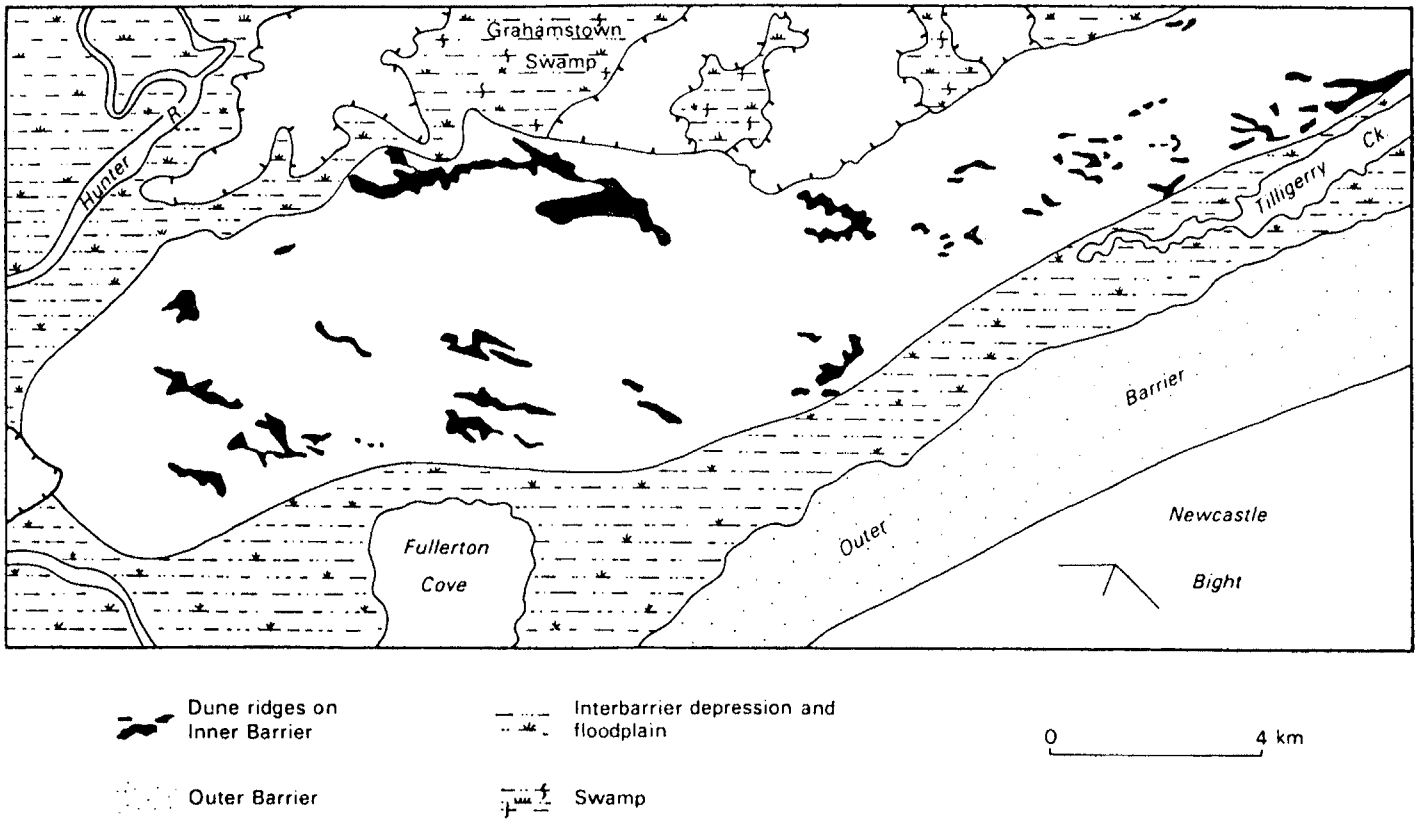


Figure 4-4: **Pattern of stabilized dune ridges on the Inner Barrier of Newcastle Bight. The ridges have formed as a result of reworking by westerly winds of the strand plain into longitudinal, blown-through parabolic and parabolic dunes. Grahamstown Swamp is now the site of Grahamstown Reservoir.**

The dune ridges taper distinctly from a broad western end to a sharp eastern point. In plan they have the appearance of a string of beads. The crest line rises and falls by as much as 10 m in descending to a low, relatively broad col separating two rounded hillocks. No measurements were made of the interhillock distance, but it appears to be regular along a given ridge and to vary between ridges. The crests are gently rounded although sometimes they may be quite flat. Many ridges are quite linear, but others are clearly shown in Figure 4-4 to possess a more arcuate plan shape. This is particularly so of two large dunes on the north side of the barrier. These features could be regarded as parabolic dunes. The fact that such dunes open to the west is considered to be significant in the interpretation of west to east sand transport believed responsible for dune development during the Last Glacial period (see Ch. 10). Highly podzolized soils are characteristic of these vegetated dune ridges (Type 3 soil in Ch. 10 and Appendix A; see also Maze, 1942).

4.2.3 Outer Barrier

The Outer Barrier of the Newcastle Bight embayment occupies a bay-mouth position between Nobbys Head in the southwest to Birubi Point in the northeast. The barrier is separated from Nobbys Head by the single mouth of the Hunter River. An elongate interbarrier depression stretches between the North Arm of the Hunter River to western Port Stephens, and includes Fullerton Cove and Tilligerry Creek (Fig. 4-1b; see 4.2.4). Nowhere do the Inner and Outer Barriers merge at the surface, but at the northeast end of the embayment the Outer Barrier abuts the complex Pleistocene terrain of the Tomaree Hills segment (see Ch. 5)

The Outer Barrier is 31 km in length. It is the longest continuous Outer Barrier in N.S.W. In width, the barrier ranges from 1.0 to 2.0 km (Fig. 4-1b). The general orientation is 065 degrees, although to the east the barrier trends more 070-080 degrees, whereas to the west it trends 045-055 degrees. In plan there is a slight increase in barrier curvature towards Stockton.

Perhaps one of the most remarkable features of this Outer Barrier compared with others in eastern Australia is the elevation of sand deposits. There exists a range in relief from swampy depressions near sea-level to sand ridges 30 to 40 m above MSL (Fig. 4-5). It will be shown that the high ridges of the Newcastle Bight Outer Barrier have accumulated in the last 6000 years. The variation in relief is depicted in Figure 4-5 by a series of cross-sections. These sections illustrate the existence of beach ridges inland of a high active sand sheet in the northeast, three high ridges which parallel the shoreline in the central part of the embayment, and low relief dune ridges near Stockton. Minor relief features also occur on the Outer Barrier and will be described in the following sections. Soils formed in sand deposits on the Outer Barrier are markedly less well developed than those of the Inner Barrier, and vary in characteristics depending on age of the deposit (Appendix A).

4.2.3.1 Beach ridges

The eastern end of the Outer Barrier, between Bobs Farm and Anna Bay, consists of a set of well-developed beach ridges forming a strand plain (Fig. 4-6). As in the case of the Inner Barrier, these beach ridges do not run the entire length of the barrier (Fig. 4-1b). They are

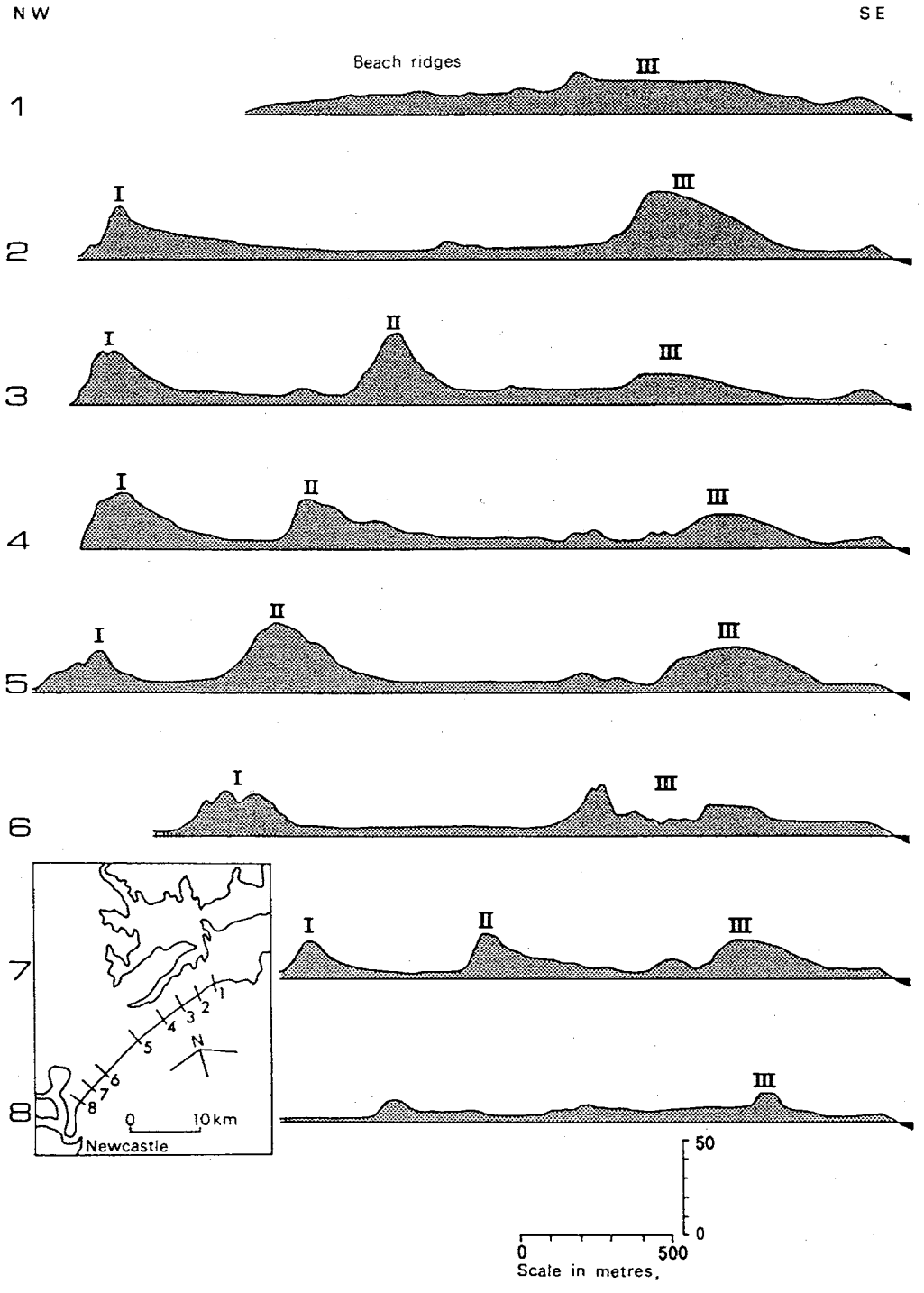


Figure 4-5: **Topographic sections across the Outer Barrier of Newcastle Bight (see inset map for general location of each section). Section 1 traverses the beach-ridge (or strand plain) at the northeast end of the embayment. Roman numerals, I, II, III identify transgressive dune ridges. Ridges I and II are stable but Ridge III is mobile. The sea is on the right.**

consumed by transgressive dunes to the west. The relationship between these different morphological features is clearly shown in Figure 4-6. The maximum length of the beach ridge pattern is 6.6 km, the minimum length being 4.6 km. The width of the ridges is gradually diminishing with time as the mobile dune sheet encroaches upon the vegetated beach ridges from the south. In general, the ridge set is narrowest (600-700 m) in the east where it ties onto Birubi Point, and widest in the west (c. 1000 m) where they are overlain by stabilized transgressive dunes (Fig. 4-6).

The orientation of beach ridges changes slightly from east to west. Near the bedrock headland they curve east-west, but towards the west they gradually assume the general orientation of the barrier. Specific attributes of the beach ridges near Birubi Point include:

(i) General elevation of ridges above mean sea-level of 4-6 m.
(ii) An increase in elevation seawards of both ridges and swales (see Fig. 4-7 for detailed levelled section across beach ridges).
(iii) Elevation of innermost ridges tends to be uniform, but ridges nearest the active sand sheet are quite hummocky along their length. Individual hummocks may stand 3-4 m above the general ridge level.
(iv) Ridge-swale relief increases from 1-1.5 m near the rear of the barrier to 1.5-3 m nearer the sea.
(v) Spacing between ridges varies quite markedly across the set as shown in Figure 4-7.
(vi) Except near the road the vegetation has not been cleared. The dune woodland is dominated by Eucalyptus pilularis and Banksia serrata, and has been regularly fired and grazed. Trees within c. 200 m of the active dune front have suffered extensive die-back.
(vii) Soils on the ridges are well-developed with clear differentiation of horizons; Type 4 soil in Appendix A.

Landward of the beach ridges, bordering the interbarrier depression, is a narrow sand flat, referred to in Chapter 2 as a backbarrier flat. This surface is widest in the west where it is also overlain by stabilized transgressive dunes. At Bobs Farm the backbarrier flat is 400-500 m wide. It slopes imperceptibly towards the mud-filled interbarrier depression. On air photos lobes of sand can be seen extending into the interbarrier depression. To the east, the zone between the depression and the innermost beach ridge is more compressed, and at Anna Bay there is a marked break of slope between these two units. They are separated by a narrow backbarrier sand flat no more than 100 m wide.

4.2.3.2 Stabilized transgressive dunes

The Outer Barrier of Newcastle Bight is dominated by transgressive dunes. Stabilized transgressive dunes occupy c. 80 percent of the Outer Barrier (Fig. 4-1b). They are vegetated for the most part by a dune woodland community (see Ch. 1). In wet sandy depressions between dune ridges, tall Melaleuca trees with a ground cover of sedges commonly occur, but peat development at these sites is either poor (usually less 0.5 m) or non-existent. Although a major road crosses the dunes, there has been little clearing of timber within the dune field. Between Salt Ash and Bobs Farm small-scale farming is expanding. The woodland has



Figure 4-6: **Vertical air photograph of the northeastern end of the Outer Barrier of Newcastle Bight showing beach ridges (or relict foredunes) which form a strand plain. This constitutes the "core" of the barrier and has been overridden by a long-walled transgressive ridge (Ridge I) from the southwest. This ridge has in turn been transgressed by Ridge II. Both I and II are now covered by a Eucalyptus woodland. Ridges I and II and the beach ridges at present are being consumed by a mobile dune sheet, the leading edge of which forms Ridge III. Figure 2-3 depicts the character of the activily transgressing sand slipface of Ridge III.**

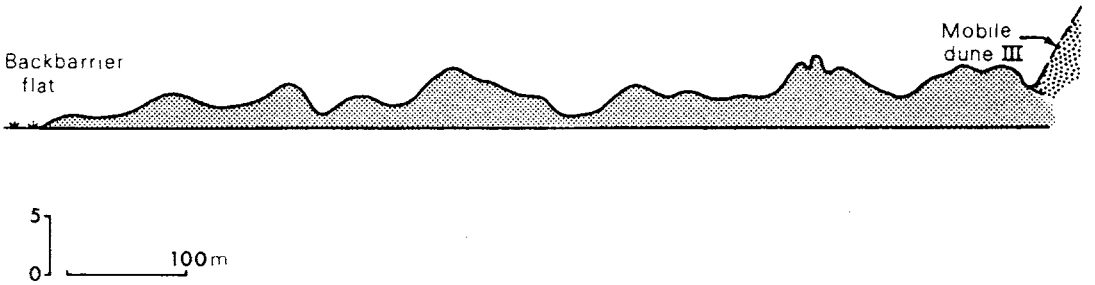


Figure 4-7: Levelled section across beach ridges at Anna Bay (GR 113730 to 114737 on Morna Point topographic map 9332-111-N, 1:25,000).

been used extensively for dry land grazing, some timber cutting, limited mining of sand, and more recently, as a recreational site for trail bikes. Fires are quite common in the area.

Stabilized trangressive dunes extend from North Stockton to Bobs Farm, a distance of 24 km. Two long-walled ridges constitute the major transgressive dunes on the Outer Barrier, referred to as Ridge I (inner) and Ridge II (outer). These discrete ridges parallel the shoreline for most of their length (Fig. 4-1b). At the eastern end they curve seawards (Fig. 4-6). To the west near Fullerton Cove, they converge and overlap (Fig. 4-1b). The two ridges are separated from each other by a low relief sand plain containing shallow Melaleuca swamps and isolated dune hillocks. These hillocks trend sub-parallel to the shoreline and rarely exceed 5 to 7 m in height.

The morphological sequence of stabilized transgressive ridges is most easily interpreted to the east of the saucer blowout near Williamtown (Fig. 4-1b). Here the two ridges are well-preserved, achieving heights in excess of 20 m and are uninterrupted in length for as much as 15 km. Ridge I partially buries backbarrier dune and beach features, the interbarrier depression, and at its eastern extremity, beach ridges (Fig. 4-6). The shore-parallel trend of the ridge is terminated at the eastern end by a well-defined hook curving southwards. The soil properties of Ridge I, sampled near Bobs Farm are described in Appendix A. A and B horizons are clearly differentiated with the concentration of humic colloids and iron oxides in the B horizon (Type 5 in Ch. 10). In comparison, Ridge II, which occurs seaward of Ridge I, has similar geomorphological characteristics, but possesses distinctively less well-developed soils with little sign of profile differentiation except for organic enrichment of the surface 20 to 30 cm (Appendix A; Type 6 in Ch. 10). This ridge has encroached upon the deflation plain of Ridge I. It has a similar "hook" at the eastern end.

Near Williamtown, between the saucer blowout and the western extension of the mobile dune sheet, Ridge I has been partially overwhelmed by Ridge II. Unfortunately, no single exposure has been observed which shows one sand body overlying the other. However, the contrast in soil characteristics (observed in the road cuts beside Lavis Lane) is quite marked with the "older" dune sands of Ridge I occurring at the base of the dune ridge and "younger" sands on the crest.

To the southwest of the saucer blowout the spatial arrangement of stabilized transgressive ridges is more confused (Fig. 4-1b). Three separate ridges have been mapped, but there are also less pronounced ridges with parabolic shapes. The innermost ridge overlooks Fullerton Cove, and on the basis of soils and stratigraphy (see below), may pre-date Ridge I and the beach ridges. The exceedingly well-developed soil characteristic of sand deposits of mid Holocene age compares more with soils of the beach ridges than Ridges I or II. The lateral extension of Ridge I and Ridge II south of the saucer blowout is indicated in Figure 4-1b. These ridges rarely exceed 20 m in height in this area, and their age designation must be regarded as tentative at this stage pending further field mapping and drilling.

Morphological characteristics of long-walled ridges have been summarized in Chapter 2 (see Fig. 2-4). In the Newcastle Bight segment all of these characteristics are well-expressed. Slope angles have not been systematically measured on either ridge, but field observation and detailed 1:4000 topographic maps (unpublished CMA Series) show north-facing slopes to be generally steeper than south-facing slopes. The north-facing slopes would have been lee or avalanche slopes during periods of dune encroachment. As shown in Figure 2-4 the ridges have a crenulated plan form with lobate projections extending northwards. These lobes often contain enclosed depressions on their southern flanks. They are separated on their northern sides by well-defined "constructional gullies". The gullies are quite steep-sided, receive no overland flow of water, and are well-vegetated. Where Ridge I overlies the interbarrier depression, particularly at Bobs Farm, farmers have utilised these relatively sheltered re-entrants as nursery sites for vegetables.

An interesting set of timbered dune ridges occurs seaward of Ridge II in the centre of the Newcastle Bight embayment (Fig. 4-1b). These ridges, to be referred to as "serpentine dunes", occur on an undulating sand plain. They possess crests which are markedly sinuous, with a distinct tendency for many to anastomose. In general, they parallel the shoreline. Closely spaced, they range from 3 to 15 m in height above the swales, and are generally symmetrical in cross-profile. The depressions between ridges are irregular in shape, shallow, and swampy; they are suggestive of small deflation basins. These dunes give the appearance of being migrating dune ridges formed normal to the southerly wind on a mobile sand sheet. The inland edge of such a sheet would be Ridge II to the north (Fig. 4-1b). An east-west alignment can be detected, and their spacing, height and crest length are comparable to active south-wind pattern "transverse dunes". Their symmetry in profile, is, however, quite dissimilar. Locally, small parabolic dunes opening to the south occur.

4.2.3.3 Mobile dunes and foredune

The free-moving sand sheet of the Newcastle Bight Outer Barrier constitutes the largest continuous mobile sand mass in N.S.W. (2,257 hectares, P.W.D., 1977; see also Watt, 1972, Table 2 and Robson et al., 1986). It is composed of three parts, a coast-parallel dune sheet which widens to the northeast, an east-west trending extension which cuts across the stabilized dune sheet near Williamtown, and a saucer-shaped blowout or "bowl" enclosed by vegetated dunes and swamps also near Williamtown (Fig. 4-1b).

The mobile dune sheet extends from North Stockton to Birubi Point, a distance of 29 km. Between North Stockton and the mouth of the Hunter, the dune sheet is broken into blowouts and "remanie" dune hillocks. At present, the dune sheet near North Stockton is 400 to 600 m wide measured from the beach to the transgressive ridge slipface, but 10 km to the north-east, near the saucer blowout, it widens to 700 to 900 m. Figure 4-1b shows that the dune sheet attains a width of 800 to 900 m east of the western blowout extension and, between Bobs Farm and Anna Bay, it achieves its maximum width of 900-1100 m.

The average net encroachment of the mobile dune sheet into the vegetated area is of the order of 5 to 10 m per year (P.W.D., 1977, Figs. 9-3, 9-4). Photographs were obtained by P.W.D. for the years 1938, 1954, 1966, 1972, 1975 and 1976. Seven points were identified on the photographs at approximately equal spacings along the beach. From these fixed points distances were measured to the "leading edge" of the mobile dune sheet and to the waterline. However, the order of accuracy was $\pm$20 m. The area of greatest dune advance is towards the northeast end of the beach (maximum rate measured being c. 80 m in 3 years). Shoreline recession is spatially more variable with no obvious trend existing along the beach. The average recession is of the order of 1 to 5 m per year (P.W.D., 1977, Fig. 9-4). Movements of 40 to 100 m for the entire beach were noted in 1974.

A more recent evaluation of sand drift rates has been undertaken for the Soil Conservation Service by Robson et al., (1986). They conclude:

(i) that the encroachment rate calculated by the P.W.D. (1977) of 5 to 10 m per year is too high; these figures more closely depict the rates that were prevalent in the "storm years" between 1966 and 1974;

(ii) the overall rate of sand drift for the embayment as a whole is 4.1 m per year in a NNW direction;

(iii) over a 29 year period rates varied between -0.7 m to 8.4 m per year;

(iv) over the period a total of 780.1 hectares has been added to the mobile dune sheet;

(v) the rate of sand drift varies from an average of 0.8 m per year in the southwest to 5.2 mm in the northeast;

(vi) rates of movement for all areas in Newcastle Bight fell from April 1975 to rates that were less than those recorded previous to August 1966;

(vii) sand drift in the "bowl" is predominantly in an easterly direction and except for a front of about 100 m does not have "an apparently northerly gross movement" as stated by P.W.D. (1977);

(viii) vegetation is encroaching on the western margin of the "bowl" and "tongue";

(ix) movement of the dune front (Ridge III) at Anna Bay is maintained by sand coming from the west; elsewhere the beach and foredune

complex is still supplying sand to the mobile dune sheet;

(x) the mobile dune sheet contained a greater volume and height per unit of ground surface in 1984 than in 1971.

The "leading edge" of the mobile dune sheet has been referred to in Chapter 2 as an active long-walled transgressive dune (Fig. 2-3). In the context of the Newcastle Bight segment, it forms Ridge III (Fig. 4-5). The mobile sand sheet is encroaching upon either the well-vegetated sand plain seaward of Ridge II, or the vegetated beach ridges (Fig. 4-6). Trees may continue to grow as they are transgressed by sand until most of the foliage is buried. These trees are often exhumed on the windward side of the transgressive ridge as the mass of sand migrates inland. The lee or north-facing slope of Ridge III constitutes a dune slipface at the angle of repose of loose sand. Small-scale avalanches are common on the slope which varies considerably in height from 5 m to over 20 m.

Although Ridge III follows the general alignment of the shoreline of Newcastle Bight, the detailed plan form is quite irregular. However, the pattern is not as crenulate as the stabilized ridges, I and II. Rarely do active sand lobes project more than 50 m in front of the main portion of the transgressive ridge.

The mobile dune sheet is characteristically asymmetrical in cross-profile. Five morphological units are identified on the mobile dune and beach:

(i) Active slipface moving northwards;
(ii) Sand sheet with its "transverse" dunes;
(iii) Deflation plain, partially vegetated and containing freshwater ponds;
(iv) Foredune;
(v) Beach.

The transverse dune morphology is very evident after a period of strong westerly winds. Figure 2-5, taken in July, 1960, depicts the classic west-wind pattern characterized by "rows" of east-facing slipfaces of a highly organized dune "sea". A more complex "cell" morphology develops during periods of prolonged strong southerly winds. During these periods the seaward ends of the dunes swing into the vales between ridges to form the north-facing side of each cell.

The reversing nature of the transverse dunes is evident from a time sequence of two profiles across a dune located just south of the western dune extension. Figure 4-8 depicts the impact of reversal processes over a four-year period, March 1975 to October, 1978. The steep but relatively short lee slope faces west in autumn in response to the summer easterlies; the impact of winter westerlies is seen in the longer lee slopes facing east in September-October profiles. Over the period of survey there was no long-term migration tendency to either east or west. Work by P.W.D. in the western dune extension (or "tongue") near Williamtown suggests a long-term easterly sand motion, but this trend remains to be confirmed (Gordon and Roy, 1977; see also Robson *et al.*, 1986). It is concluded that east and west winds mainly "reverse" dune forms *in situ* on the sand sheet as a seasonal oscillation. The reversing dunes have a "wet core" in which the bulk of the sand comprising the dune is quite moist. The upper boundary of this moist zone lies very near the

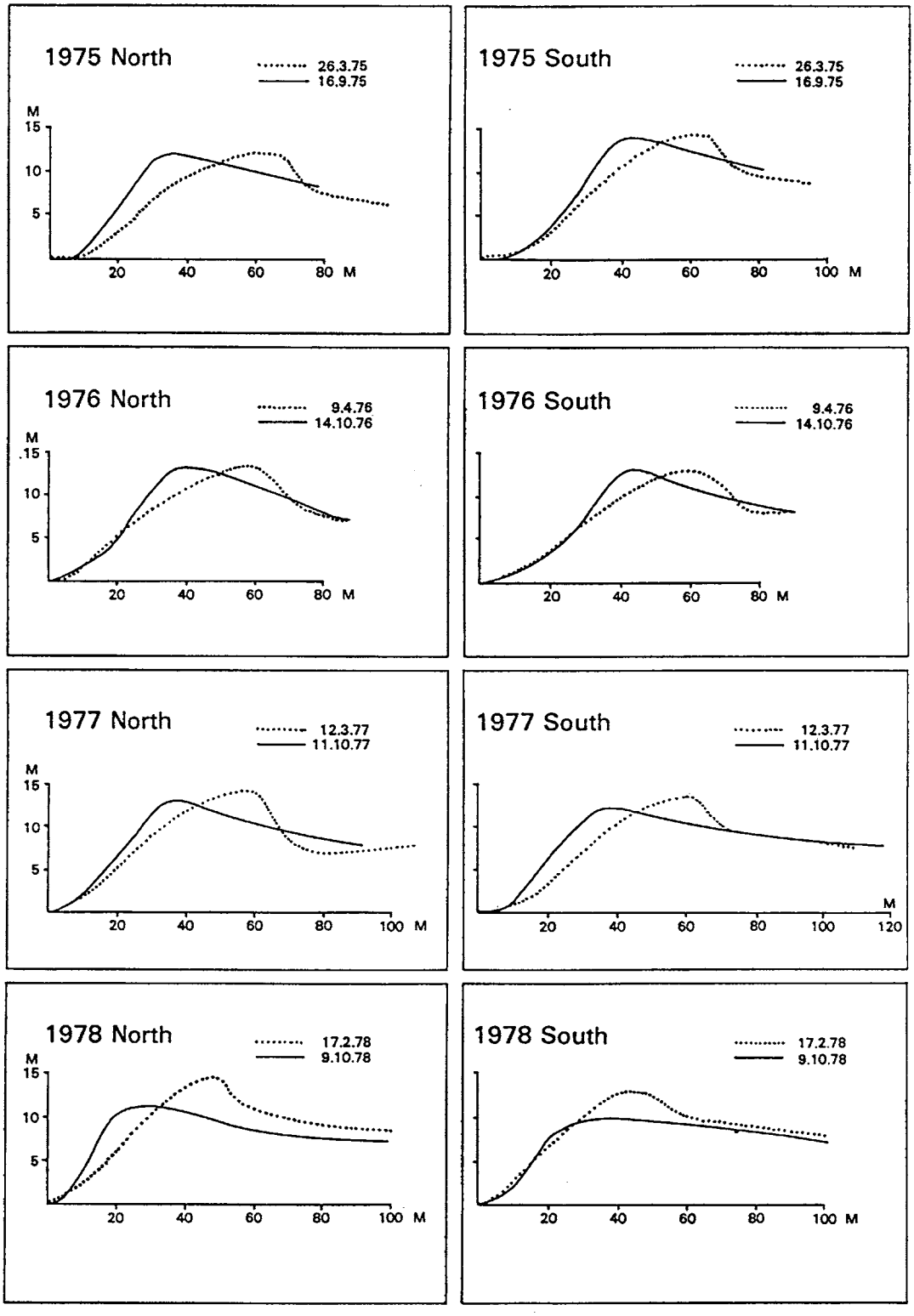


Figure 4-8: Reversing character of a transverse dune located east of Williamtown (GR 946660). Two profiles were surveyed across the slipface twice each year from 1975 to 1978. The profiles are c.100m apart (north profile and south profile) on the same dune ridge (see Fig. 2-5 for general view of transverse dunefield).

dune surface. In summer, incoming solar radiation is much higher than in winter, the "wet core" surface is lower, and when exposed is dried much more rapidly than in winter. Although winter westerly winds are much stronger than the summer easterly winds, as indicated by the Williamtown resultant vector (Fig. 1-5), the summer-winter variation in the rate of "wet core" drying and hence eolian sand transport, explains why there is limited eastward movement of the dunes (Hyde and Wasson, 1983; R. Hyde, pers. comm.). Complex sets of sedimentary structures are exposed on wet eroded surfaces of these dunes after storms (see McKee and Bigarella, 1972, for details on a similar dune field in southern Brazil).

The present foredune in Newcastle Bight is low (<5 m) and hummocky and is vegetated by a variety of pioneer and secondary species. Its simple morphology and poor vegetation richness indicate that it has been formed in recent time (perhaps the last 50-100 years).

4.2.3.4 Beach and nearshore topographies

Variation alongshore in beach profile morphology at Newcastle Bight is shown in Figure 4-9. These three profiles were surveyed in September, 1975; they depict the change in beach slope and form from southwest to east. At this time the beach profile was concave-up at the east end of Newcastle Bight. The incipient foredune eroded during the 1974 storms had not yet healed. In the centre of the bay a double berm profile was noted. The elevation of the upper berm was 2.5 m above MSL. The foredune at this locality had been breached by storm waves in 1974. Towards the southwest the overall beach gradient was even steeper but again two berms were noted. Here the upper berm surface was +3 m above MSL.

In Figure 4-10 the marked change in grain size from southwest to east along the beach at Newcastle Bight is shown. Obviously, the steeper and higher beach profiles are associated with coarser grain size (Fig. 4-9). Temporal variations in beach gradient and grain size have not been studied. The present view is that beach morphologic variability on the one hand is spatially determined by a "fixed" grain size distribution, and on the other by the frequency and magnitude of storm waves. The pattern reflects interaction between changes in wave energy and the morphology of the nearshore zone.

Aerial photographs of different vintage demonstrate major changes in nearshore topographies (see Wright et al., 1979 and Short and Hesp, 1982, for description and discussion of beach/nearshore states which occur in the study area). Newcastle Bight may possess an array of states at any one time (see Roy and Crawford, 1980, Fig. 4). Multiple bars characteristic of dissipative conditions may occur at the northeastern end of the embayment. Linear bar-trough morphology is also common as are rhythmic bars associated with an indented beach. Low energy reflective beach conditions are far less common and only develop towards the southwest end.

In summary, this beach experiences a wide spectrum of wave energy conditions. The general dominance of high energy morphologies with the persistence of a linear bar up to 400 m from shore confirms visual observations and sea state data that the morphology of beach and nearshore zones in Newcastle Bight is dominated by high wave energy

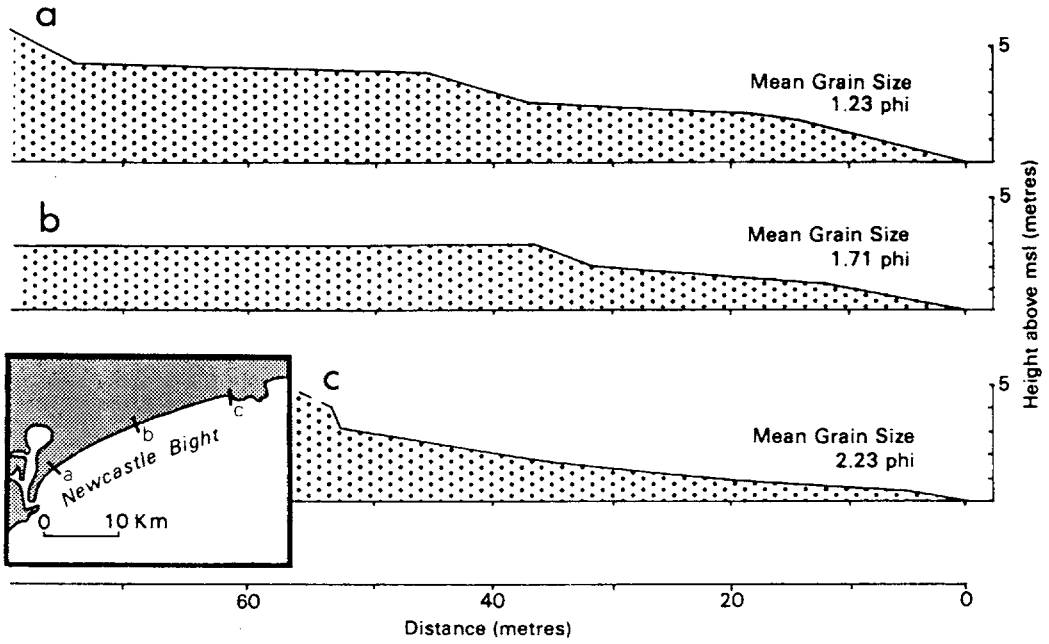


Figure 4-9: Three beach profiles surveyed in September 1975, showing a trend for steeper slopes and more complex berm topography in the coarser sands of the southwest part of Newcastle Bight compared to the area of finer sands in the northeast.

conditions. Nearshore morphologic patterns rarely develop into types which express low energy conditions. Multiple bars occur where grain size is finer, whereas steeper beaches with poor bar development are located at the southwest end where grain size is coarsest (Fig. 4-10).

Figure 4-10 also shows grain size variation in the dune sheet behind the beach. The same trend as on the beach is observed in the mobile dunes, i.e. coarser sands to southwest fining to the northeast. Dune sands are slightly finer at any given site, suggesting that the dunes are derived from eolian reworking of beach deposits (see also Fig. 3-18). Ly (1976) noted similar west to east fining of grain size in other Outer and Inner barrier sediments indicating persistence in lateral trends in grain size properties through time in the Newcastle Bight embayment.

4.2.4 Interbarrier Depression

The interbarrier depression of the Newcastle Bight embayment extends from the Hunter River to Port Stephens. At the south end, the North Arm of the Hunter River opens into Fullerton Cove, a large, shallow mud basin fringed by mangroves (Roy, 1980). The depression narrows to the northeast between the Inner and Outer barriers. Near Salt Ash the depression is drained by Tilligerry Creek which opens into western Port Stephens near Lemon Tree Passage (Fig. 4-1b).

Several features of the depression on both a macro and micro scale, deserve comment in this study. Tidal drainage systems can be traced on

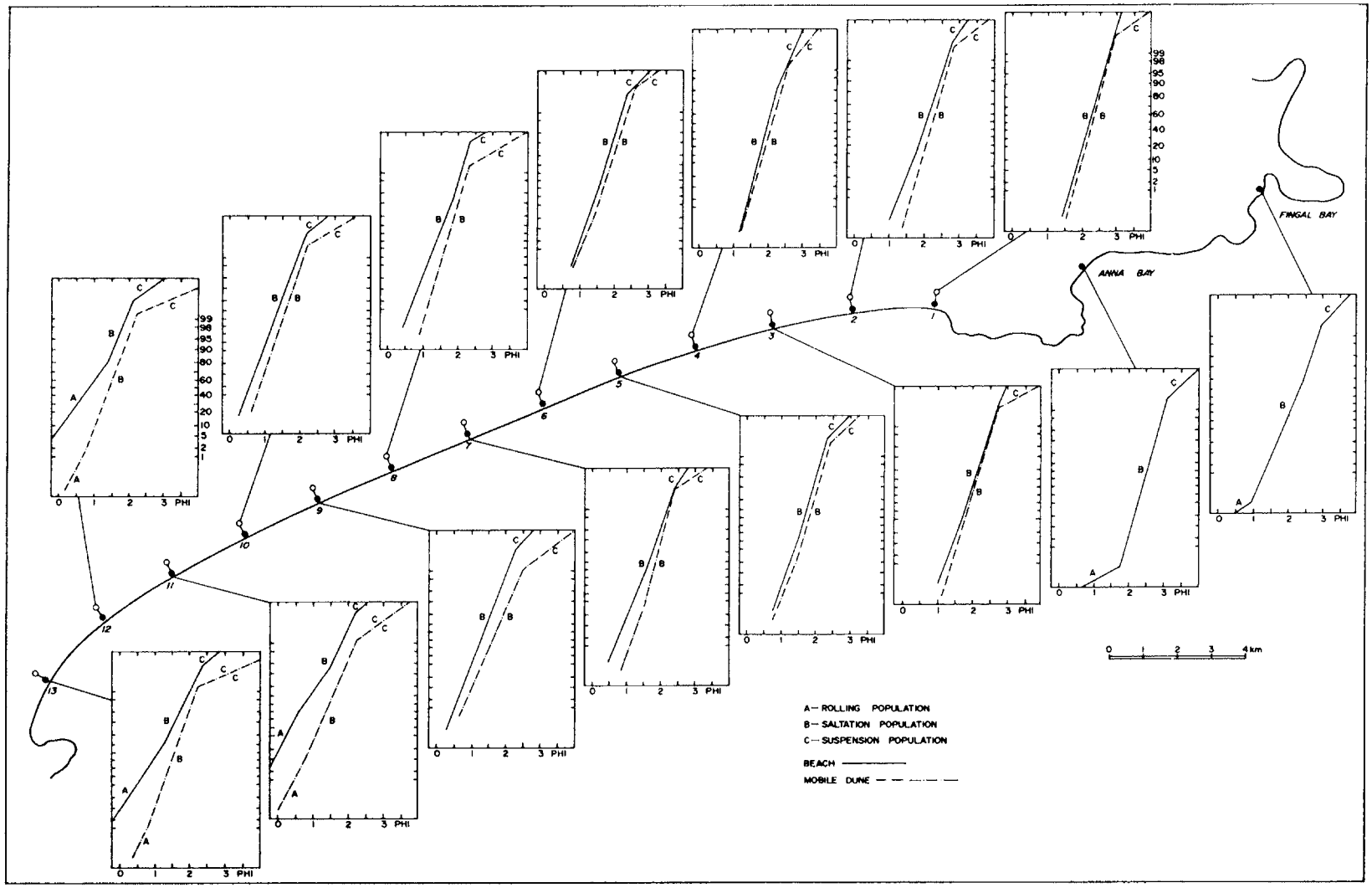


Figure 4-10: Comparison of grain size curves for beach and mobile dune sand samples for Newcastle Bight, Anna Bay and Fingal Bay.

old air photos, but they have been greatly modified by farming practices and embankment construction over the past century. At either end of the depression protective walls and tidal flood gates have been built. Salt marshes and mangrove swamps have been drained and reclaimed for both grazing and crop production (Fig. 4-3).

Vegetation communities of the depression are strongly disrupted by the man-induced drainage system. Prior to drainage, an interesting pattern reflecting salinity gradients probably existed. Remnants of a "swamp forest" containing Eucalyptus robusta, Melaleuca quinquenervia, Casuarina glauca and Livistonia. still exist. Two gradients would have been important in determining the floristic pattern: (i) parallel to the depression determined by tidal incursions from both ends; and (ii) normal to the axis of the depression as determined by ground-water seepage from the high dunes of the Outer Barrier, and perhaps also from the lower, more discontinuous dunes on the Inner Barrier.

The elevation of the depression, where it is composed of fine-grained sediments heavily enriched in organics, rarely rises more than 1 m above MHWS. Sandy shorelines, backbarrier "fans" and dune sand aprons from the Inner Barrier locally raise the elevation to more than +2 m MHWS. If sea-level had been well in excess of 2 m above its present level over the past 6000 years along this coast, there should be more decisive evidence in the form of shoreline deposits and mud-flat accumulation above present MHWS in this depression. However, it is possible that this area could provide some of the "fine detail" of sea-level oscillations over the last 6000 years, over which period relative sea-level along the east Australian coast may have oscillated $\pm$1 m (Thom and Chappell, 1975; Thom and Roy 1985).

One of the most exciting features of the interbarrier depression is the "winged spits" along the eastern or Outer Barrier shore. The distribution of these relict features is shown in Figure 4-1b. The form of a typical spit is shown in Figure 4-11, an aerial photograph of a lagoon shoreline accumulation near Williamtown. They resemble Azov-type spits described by Zenkovich (1967). A modern equivalent occurs in Big Swan Bay, Port Stephens. It appears that the spits are backbarrier sands which were reworked by west-wind waves along the shores of a shallow east-west oriented barrier lagoon. They rise no more than 2 m (mostly 1 m) above the elevation of the depression.

A date of 3120 $\pm$ 80 ^{14}C yrs BP (SUA-1023; see Appendix B for ^{14}C data) was obtained on shells (articulated Notospisula parva) recovered from estuarine muds at -0.5 MSL at Lavis Lane. These muds accumulated in the interbarrier depression, and can be interpreted as follows: the western part of the depression prior to the date of 3000 years was open water on which waves produced by west winds reworked backbarrier sands into shoreline features; by 3000 years ago mud flats had developed in the depression at a depth of 1 m below MSL; since that time muds have accumulated to MHWS completing the isolation of the spits from wave processes. The muds on-lap the spit sands. Colonization of the site first by mangroves and later by a Melaleuca and Casuarina community presumably post date the death of the Notospisula shells.

Fullerton Cove is the modern site of mud accumulation. Fines transported by the Hunter River are trapped in this basin (Roy, 1980). Shells such as Notospisula are common on the bed of Fullerton Cove. The

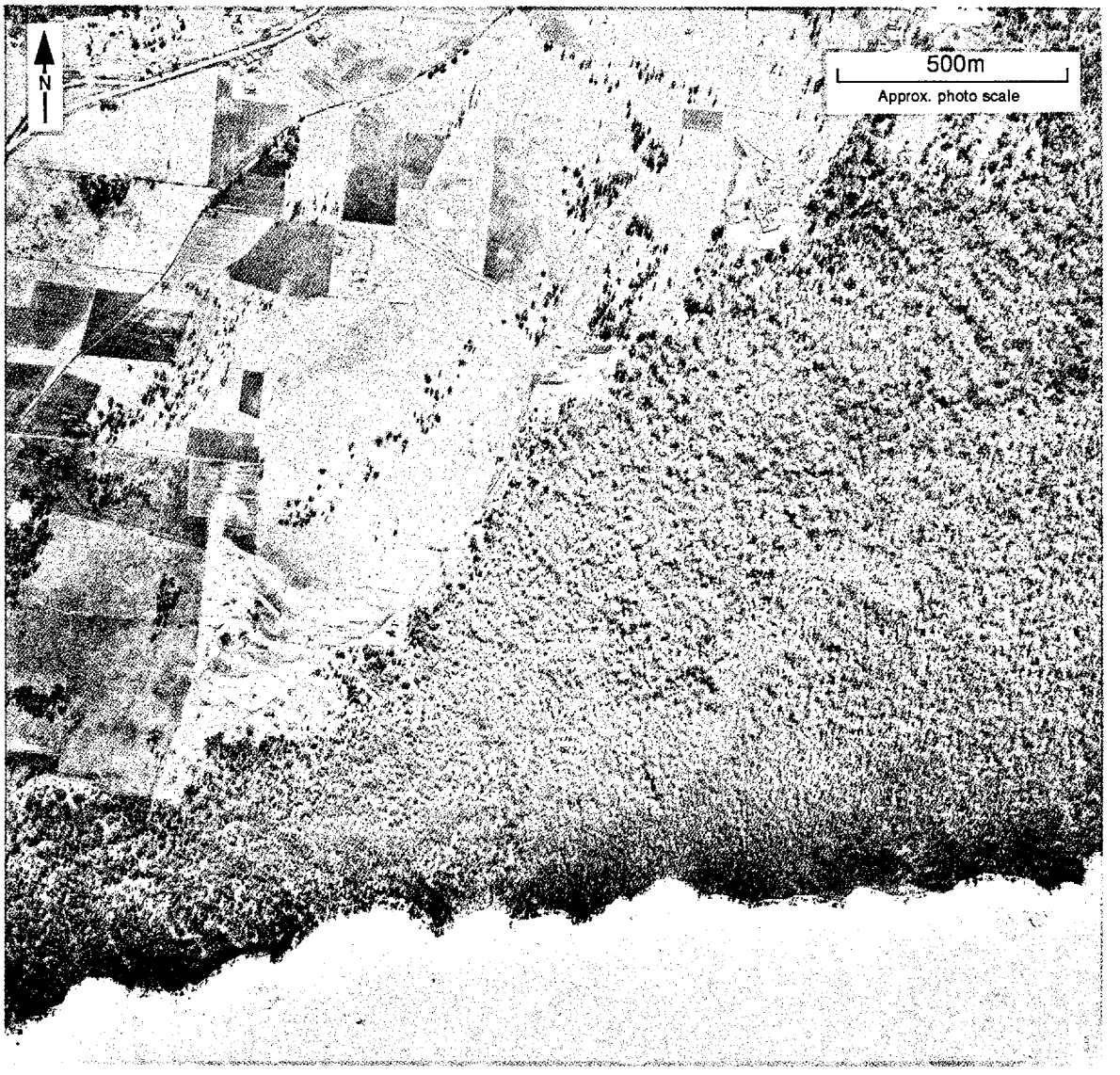


Figure 4-11: Portion of the Outer Barrier near Williamtown showing relict "winged spits" which have grown into the lagoon of the interbarrier depression prior to infilling by mud (NSW 1448, 5246, 17/4/66).

Hunter is forming levees across the mouth of this basin. The present-day shape of Fullerton Cove is largely the result of gradual encroachment by marginal tidal flats towards the centre of the estuary. Mangroves dominated by Avicennia marina occupy the upper intertidal zone forming a fringe up to 1 km in width. Recent rates of encroachment over the past 36 years vary from 4 to 8 m per year (Roy, 1980).

4.3 STRATIGRAPHICAL CHARACTERISTICS

4.3.1 Bedrock Configuration

The Hunter River has been confined to the southern half of the embayment prior to Inner Barrier formation, but not necessarily along the southern margin as today; this is shown by the location of a deeply entrenched bedrock channel (Galloway, 1965). The present mouth of the Hunter River lies approximately 10-15 km south of the main course followed during periods of low sea-level (Roy, 1980). Furthermore, Galloway's prediction of a depth greater than 300 feet east of Fullerton Cove is confirmed by Joint Coal Board Hole No. 10, which struck bedrock at -92.7 m (-304 feet). More recent seismic refraction investigations indicate that the main channel passed seawards beneath the contemporary shoreline midway along Newcastle Bight at a depth of about 120 m (Roy, 1980).

The present position of the Hunter was probably attained at the time of Inner Barrier development (see 4.3.4). Since the Inner Barrier has not been dissected by a major through-flowing stream, it is inferred that, during the Last Glacial low sea-level stage, the river entrenched itself to the south of the Hexham bedrock outcrop (Fig. 4-1b). There is little doubt that in the mid to late Holocene the Hunter has only occupied its present outlet position.

4.3.2 Stratigraphic Interpretation of Select Drill Holes

In Chapter 3 an attempt was made to classify deposits in the study area into facies types. Many of these types occur in the Newcastle Bight embayment.

Fine-grained sediments (with or without a high organic content) associated with estuarine and/or freshwater aquatic environments of Holocene or late Pleistocene age are recognized in three stratigraphic situations: (i) on the surface at or slightly above sea-level (to +6 m) behind sand barriers, where they form tidal flat veneers over bedrock or sandy sediments; (ii) as thick estuarine accumulations below sand deposits, or in basins beneath water-bodies; and (iii) in river valleys as fluvial-deltaic deposits. Fine-grained sediments may be quite thick (maximum known thickness is 70 m).

Coarser-grained sediments are observed at the surface in the form of sand barriers or as dunes mantling bedrock hills. Sand deposits extend from well above sea-level to -30 to -40 m. Sands of mixed mineralogy occur under fine-grained facies in the form of basal deposits, or over eroded portions of the Inner Barrier. These mixed sands and gravels cover the eroded surfaces; they appear to be of fluvial origin (Roy, 1980).

Just as a division can be made within the embayment between morphological features of presumed late Pleistocene age and those of presumed Holocene age, so can a distinction be made between facies units of the Inner Barrier and associated estuarine-fluvial environments, and the Outer Barrier with its associated lagoonal, estuarine, freshwater-aquatic and fluvial environments. There is a clear repetition of depositional environments during the two major phases of marine transgression and the following phases of sedimentary regression. Drilling in this embayment by a number of different agencies has made it possible to obtain a reasonable understanding of the stratigraphy. In order to build on already available knowledge, we established six sections normal to the coast across the Outer Barrier and interbarrier depression (for location see Fig. 4-12). These sections link A.N.U. drill holes with those drilled by Soil Mechanics Ltd. for the H.D.W.B. on the Inner Barrier. Using the A.N.U. power auger rig, 27 holes were drilled in the embayment (see Appendix 3 for grid reference of each A.N.U. drill hole). General stratigraphic patterns have been tested by using drill data from other sources including various heavy mineral mining companies (e.g. Mineral Deposits Ltd., Associated Minerals Ltd., Rutile and Zircon Mines), the Joint Coal Board, the Department of Main Roads, and earlier drilling by the H.D.W.B. (select hole location is shown in Fig. 4-12).

Before we discuss the distribution of stratigraphic units by means of cross-sections (4.3.3.1 to 4.3.3.4), it is necessary to outline in some detail the sedimentary properties of select drill holes. Down-the-hole variation in facies characteristics highlights the array of stratigraphic units found in this embayment.

4.3.2.1 A.N.U. drill holes 83 and 53

Drill holes 83 and 53 are located at the east end of the Outer Barrier on the beach-ridge plain (see Fig. 4-12 for location). Grain size and chemical analyses (total iron, carbon and $CaCO_3$) were undertaken on samples from hole 83 (Fig. 4-13), but only chemical analyses were conducted on select samples from drill hole 53 (Table 4-1). Coarse fractions of samples from each hole were described under binocular microscope.

In drill hole 83 six stratigraphic units were identified (Fig. 4-13). Each unit corresponds to a facies type which in this hole is linked to open ocean or marine environment (M); the remaining symbols are discussed in the context of each facies (see also Ch. 3). In Figure 4-13, the stages or periods are designated Q2 (Last Interglacial), Q4 (Early Holocene), Q5 (Mid Holocene); these symbols are used in the general correlation of depositional sequences undertaken in Chapter 10 for the whole region.

(i) Q5Mer: at the top of the sequence in drill hole 83 is a fine, yellow sand, mainly quartzose and very well sorted. Quartz grains are rounded to subrounded. The facies is free of shell carbonate. Samples 83-1 and 2 are positively skewed. The highest amount of free iron oxide in the drill hole was noted in 83-1 (0.65 percent); this was collected at 1 m depth in the B horizon of an Outer Barrier podzol (a type 5 soil, see Appendix A and Ch. 10). The facies clearly forms the upper part of the Outer Barrier. It

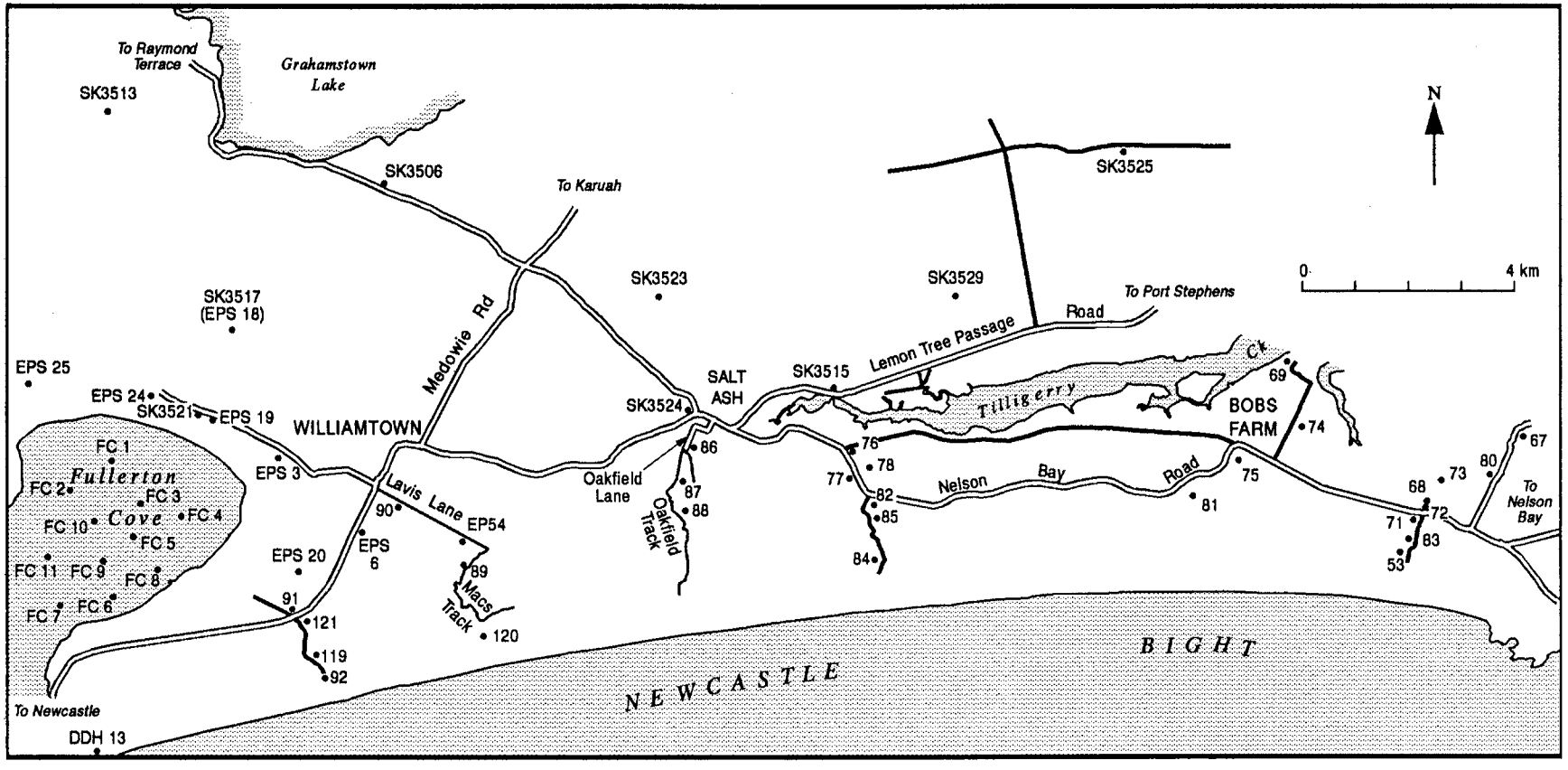


Figure 4-12: General location of drill holes and cross-sections discussed in Chapter 4.

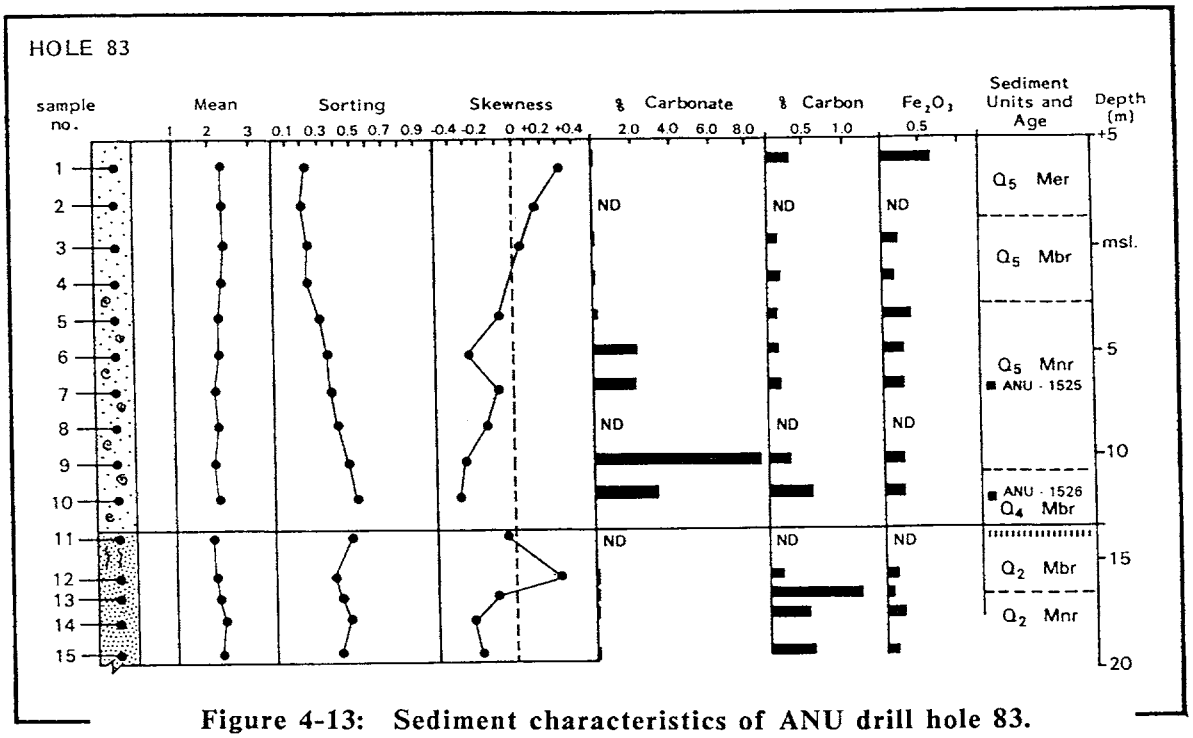


Figure 4-13: Sediment characteristics of ANU drill hole 83.

includes the upper 5-6 m of sediment of the beach-ridge plain, a regressive morphostratigraphic unit. Based on sorting and skewness a strong eolian contribution is suggested. Thus the facies is designated eolian regression associated with an open-ocean environment of deposition (Mer).

(ii) Q5Mbr: below 4 m is a thin (3 m thick), fine sand; it is yellow, quartz-rich and quite well sorted. The sands are less positively skewed. Only a trace of shell has been noted in the facies. No ^{14}C dates are available. It is interpreted as transitional between what is clearly foredune sand above and nearshore sand below, and thus is most likely to have been deposited in a lower beachface to upper nearshore environment of a prograding (regressive) shoreline. Unfortunately, at this end of Newcastle Bight, there is strong uniformity in mean grain size in all environments so this parameter is not useful in discriminating between facies types.

(iii) Q5Mnr: Figure 4-13 shows the thickest facies type in hole 83 to be a fine, moderately well sorted, yellow-grey sand. The sand is negatively skewed and tends to be less well sorted downwards. Although predominantly quartzose in composition, rock fragments and shell increase in amount downward (up to 8.6 percent carbonate in sample 83-9). Shells occur throughout the facies and clearly belong to the open-ocean nearshore environment (Bankivia assemblage). Most of the carbon found in this facies is in the form of finely disseminated particulate organics. A radiocarbon date was obtained on Bankivia fragments from sample 83-7 (6080 $\pm$ 125 ^{14}C yrs BP, (A.N.U.-1525). This date puts this facies in the mid Holocene time, i.e. period 5. Our interpretation is that the shelly sand was deposited in the nearshore zone during the sedimentary regression which formed the beach-ridge plain of the Outer Barrier.

(iv) Q4Mbt: The base of the Holocene section of drill hole 83 is characterized by a grey, fine sand which is more poorly sorted and negatively skewed than samples above. Sample 83-10 is relatively rich in shell carbonate, especially Bankivia fasciata; a ^{14}C assay on shell fragments yielded an age of 8260 ± 295 ^{14}C yrs BP, (A.N.U.-1526). This age is associated with period 4, i.e. the period of the Postglacial Marine Transgression. It is possible that this sand was initially deposited as a beach-shallow nearshore sand during the transgression and subjected to reworking as the sand body moved landward. The facies rests disconformably on a truncated soil surface of Late Pleistocene age.

(v) Q2Mbr and Q2Mnr: a sharp contact exists between the shelly sand of unit Q4Mbt and the underlying fine, well sorted, dark brown sand of unit Q2Mbr. This facies is devoid of shell and has been impregnated with humate (up to 1.0 percent in sample 83-13), except for a more leached sand at the contact (sample 83-11). It has the appearance of being a truncated soil. Samples from this facies are mostly negatively skewed suggesting a foredune-beach deposit which may grade down into a nearshore facies (Mnr). The facies Q2Mbr can be traced landwards into the Inner Barrier sand body of Last Interglacial age (period 2).

Drill hole 53 is also located on the Outer Barrier at the eastern end of the Newcastle Bight embayment (see Fig. 4-12). It is one of the deepest auger holes drilled during the A.N.U. stratigraphic programme on the N.S.W. coast. Table 4-1 summarizes the stratigraphy and chemistry of samples and interprets facies types and environments encountered in the 45 m hole. As in the case of hole 83, there are four facies of mid Holocene age above the Pleistocene soil discontinuity: Mer, Mbr, Mnr and Mbt. The transgressive facies, Mbt, is a lateral extension of unit Q4Mbt from hole 83. A radiocarbon date obtained from the nearshore shelly sand facies confirmed a middle Holocene age for this regressive sand body (Q5Mnr). A very sharp discontinuity exists at the contact between Holocene sands and the soil surface of presumed Pleistocene age (Table 4-1). Further details on the sedimentological and age characteristics of drill hole 53 are discussed below in 4.3.3.1 which describes the stratigraphy of the Anna Bay cross-section. This section includes drill holes 53 and 83 (see Fig. 4-19).

4.3.2.2 A.N.U. drill hole 120

Hole 120 is located in the centre of the Outer Barrier on the Lavis Lane transect (Fig. 4-12). The hole was drilled in the deflation plain seaward of Ridge II to a depth of 35 m.

It is possible to sub-divide hole 120 into eight facies units (Fig. 4-14):

(i) Q6Met: this facies is represented by a thin cover sand in the floor of the deflation plain. It is composed of a medium-grained, grey sand devoid of shell fragments. The sand is positively skewed and leached. We suggest that this facies is part of a shallow, eolian-reworked sand body forming the deflation plain of Ridge II of the Outer Barrier. As Ridge II is less than 3000 years old (see 4.3.3.2), then this cover sand is associated with a phase of Late Holocene eolian activity (period 6; see Ch. 10).

TABLE 4-1 Chemical Analyses Drill Hole A.N.U. 53 (Anna Bay)

Sample No.	Depth (m) Below G.S.	Strata Unit (see Fig. 4-19)	% Fe	% Fe_2O_3	% C	%CH_2O_2	%$CaCO_3$
1	1.1	U	.018	.025	.096	.24	.00
2	2.1	U	.063	.090	.18	.45	.00
3	3.2	U	.065	.093	.13	.32	.00
4	4.7	U	.053	.076	.032	.080	.00
5	-	-	-	-	-	-	-
6	8.4	U	.067	.067	.011	.027	.00
7	10.2	U	.15	.15	.017	.042	.00
8	12.0	U	.059	.059	.032	.080	4.5
9	11.7	U	.078	.078	.023	.058	4.6
10	-	-	-	-	-	-	-
11	13.9	U	.009	.009	.048	.12	.03
12	17.5	U	.080	.080	.029	.073	1.7
13	-	-	-	-	-	-	-
14	19.5	U	.078	.078	.45	1.1	1.0
15	19.8	U	.019	.019	.051	.13	.02
16	22.1	M	.076	.076	.85	2.1	.00
17	22.1	M	.12	.12	1.03	2.58	.00
18	23.9	M	.059	.059	.51	1.3	.00
19	24.7	M	.11	.11	.44	1.1	.00
20	-	-	-	-	-	-	-
21	30.2	M	.064	.064	.079	.20	.00
22	35.7	L	1.07	1.07	2.19	5.49	.00
23	-	-	-	-	-	-	-
24	34.2	M	.51	.51	.38	.95	5.2
25	33.5	M	.53	.53	.39	.98	7.5
26	32.8	M	.33	.33	.065	.16	10.2
27	32.0	M	.49	.49	.87	2.2	10.7
28	38.7	L	.14	.14	.11	.27	.00
29	36.9	L	.20	.20	.24	.60	.00
30	44.7	L	.008	.008	.019	.048	.00

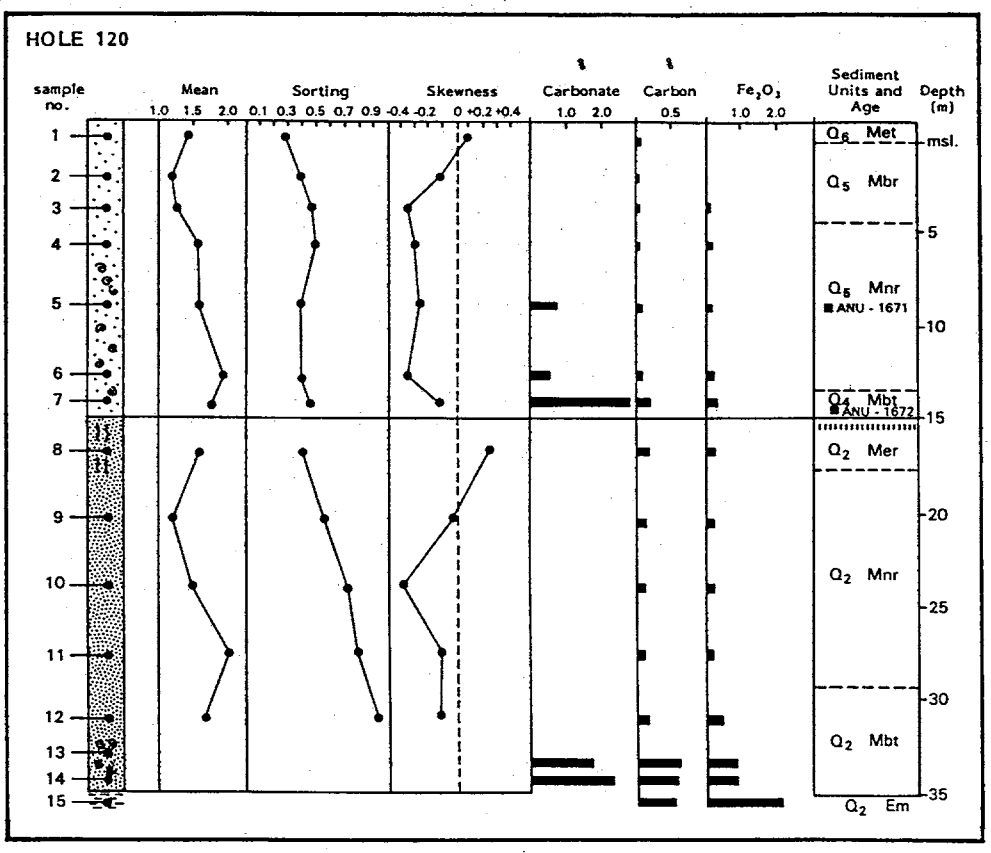


Figure 4-14: Sediment characteristics of ANU drill hole 120.

(ii) Q5Mbr: one metre below ground surface is a medium, yellow quartz (+90 percent) sand which is negatively skewed and somewhat less well sorted than the cover sand (sample 120-2 compared with 120-1 in Fig. 4-14). Grain size is slightly coarser in sample 120-2; the sand possesses a rolling population, two saltation populations and a suspension population (Ly, 1976, Fig. 4-1). This facies is interpreted as representing part of the regressive beach (or shallow nearshore) of period 5. The upper position may have been removed by deflation. The unit grades down into Q5Mnr.

(iii) Q5Mnr: at c. 5 m below ground surface, the apparent beach sand unit grades into a shelly, grey, medium to fine-grained sand. This sand has a more noticeable rock fragment and feldspar content (eg. 120-4 with 6.3 percent and 9.8 percent, respectively). The shells are mostly comminuted, but possess an assemblage dominated by Bankivia fragments. Whole specimens are observed. According to Ly (1976), samples from this facies, especially 120-5 and 6, are negatively skewed and are characterized by a rolling population, three saltation populations and a suspension population. The average slope of saltation populations is more gentle for samples from this facies than for those above. There is a tendency for grain size to fine downwards. This facies has many characteristics of sands in the nearshore zone seaward of the surfzone. A radiocarbon date was obtained on shell fragments from sample 120-5 (6440 $\pm$ 170 ^{14}C yrs BP, A.N.U.-1671). This date is

associated with the regressive build-up of the Outer Barrier in period 5.

(iv) Q4Mbt: at the base of the Holocene section is a thin, shelly, more quartz-rich (92 percent) grey sand. The sand in sample 120-7 is slightly coarser and more poorly sorted than from the facies above (Fig. 4-14). Shells are more abundant with a carbonate content up to three percent. Particulate carbon is also present in this facies. A radiocarbon date of 7110 $\pm$ 130 ^{14}C yrs BP (A.N.U.-1672) was obtained on shell fragments from sample 120-7. Grain size properties, the sharp change in carbonate content, and the age suggest deposition during the Postglacial Marine Transgression (i.e. period 4). It is proposed that this facies represents a sand sheet which was being reworked landwards by waves during the transgression. This interpretation must be regarded with caution, however, as the age is close to that from sample 120-5, and the degree of reworking associated with sedimentary regression is unknown.

(v) Q2Mer: a sharp contact exists between the base of the Holocene (Q4Mbt) and this facies. The sand of Q2Mer is medium-grained, light brown showing a trace of humate impregnation. It is quartz-rich and free of shell. This facies possesses quite distinctive grain size properties from the units above and below (Fig. 4-14). Sample 120-8 is a positively skewed sand which is finer than the sand from the facies below (120-9). We interpret this sand as a truncated soil profile of Pleistocene age. The sand was possibly deposited under eolian conditions as sea-level fell below 15 m following the formation of the Inner Barrier as shown in Figure 4-21 (Lavis Lane, 4.3.3.3). Presumably the soil was formed during low sea-level conditions of the Last Glacial (period 3, Ch. 10).

(vi) Q2Mnr: this facies is composed of medium to coarse sand which grades downwards from a pale brown colour to grey. Rock fragments and feldspar increase downward from 10 percent to 18 percent. Grain size decreases downward and sorting deteriorates towards the base. The sand tends to be negatively skewed (Fig. 4-14). It is possible that this unit represents the regressive accumulation of sand in the nearshore (and beachface?) zone during the period of formation of the Inner Barrier (period 2 or Last Interglacial).

(vii) Q2Mbt: the trend to fine downwards ceases at -29 m below ground surface. Sands at this depth become coarser, dark grey, rich in feldspar (18 percent) and rock fragments (11 percent) and quite shelly. A nearshore assemblage dominated by Bankivia characterizes this facies. No attempt was made to date shells from these samples, because experience elsewhere strongly indicated a "background" age in this stratigraphic position (see 4.3.2.3 and 4.3.3). This sand is quite poorly sorted and contains a few granule-sized grains near the base (sample 120-14). Sample 120-13 is rich in particulate organics. We infer a transgressive origin for this sand sheet deposited immediately prior to Inner Barrier formation. The abundance of rock fragments at the base of the hole suggests more reworking of sands derived directly from fluvial sources at this time.

(viii) Q2Em: at the base of the hole (-35 m below ground surface) is a very sharp discontinuity to a grey, slightly oxidized clay. This clay layer has a high free iron content (2.18 percent). This clay is interpreted as being deposited in an estuarine mud basin which accumulated behind a "proto Inner Barrier" as sea-level rose prior to the Last Interglacial (see 4.3.3 and 4.3.4). The clay sample 120-15 represents the upper part of a thick clay unit containing several discontinuities (see Chs. 5 and 10).

4.3.2.3 H.D.W.B. drill holes - Inner Barrier

A number of holes drilled for the H.D.W.B. by Soil Mechanics Ltd. on the Inner Barrier have been analyzed for chemical, grain size and age properties. Ly (1976) reports on the grain size and grain surface textures of samples from several Sk holes (e.g. 3515, 3521, 3517, 3513, 3506, 3525, 3529; for location see Fig. 4-12). Figure 4-15 summarizes the grain size properties of mean, sorting and skewness for all these holes.

Three or four facies units are generally present: (i) an upper unit which is positively skewed, well sorted, averages about 1.7 phi and typically has one saltation population and one suspension population; (ii) a middle unit which is negatively skewed, moderately sorted, has a mean about 1.50 phi and contains one rolling, one or two saltation and one suspension population; and (iii) a lower unit which is often negatively skewed, is moderately to poorly sorted, has a phi mean of about 2.00 phi or greater, and contains one or two rolling populations plus more than two saltation populations which are truncated at the finer end with or without a suspension population (see Ly, 1976, Table 4.1). In some holes a somewhat coarser sand occurs at the base of the sand body (e.g. Sk 3513, 3521, 3529).

Grain size distributions for sand with humate present (dashed line) and with humate removed are shown for hole Sk 3521 in Figure 4-16. Sorting improved without humate, but most noticeably skewness becomes more negative without humate. The three basic facies units are still recognizable. The upper sand is positively skewed. Toward the base (mostly grey sand) grain size is finer, sorting is even poorer, and skewness mostly negative. These units are interpreted as a deepening sequence representing subaerial eolian, beach - nearshore to nearshore environments of deposition (Q2Mer, Q2Mbr, Q2Mnr). As in the Pleistocene section of A.N.U. hole 120 (Fig. 4-14), a basal transgressive sand may be present (Q2Mbt).

Figure 4-17 shows various sediment and age characteristics of H.D.W.B. drill hole Sk 3523. This hole was drilled on the margin of the beach-ridge plain and involves minimal eolian reworking of the surface. The log of the hole indicates strong colour differenes between units. These colour differences reflect variations in the amount of humate enrichment. At the surface, grey sands, quite strongly leached of humic colloids and iron oxides, pass down into yellow and dark brown sand. The colour becomes lighter with depth until it is grey towards the base (see 3.3.1).

The chemical properties of Sk 3523 are listed in Table 4-2 (see Fig. 4-17 for graphic log). No carbonates occur in this hole, although some lower unit (grey) sands from the Inner Barrier contain a rich

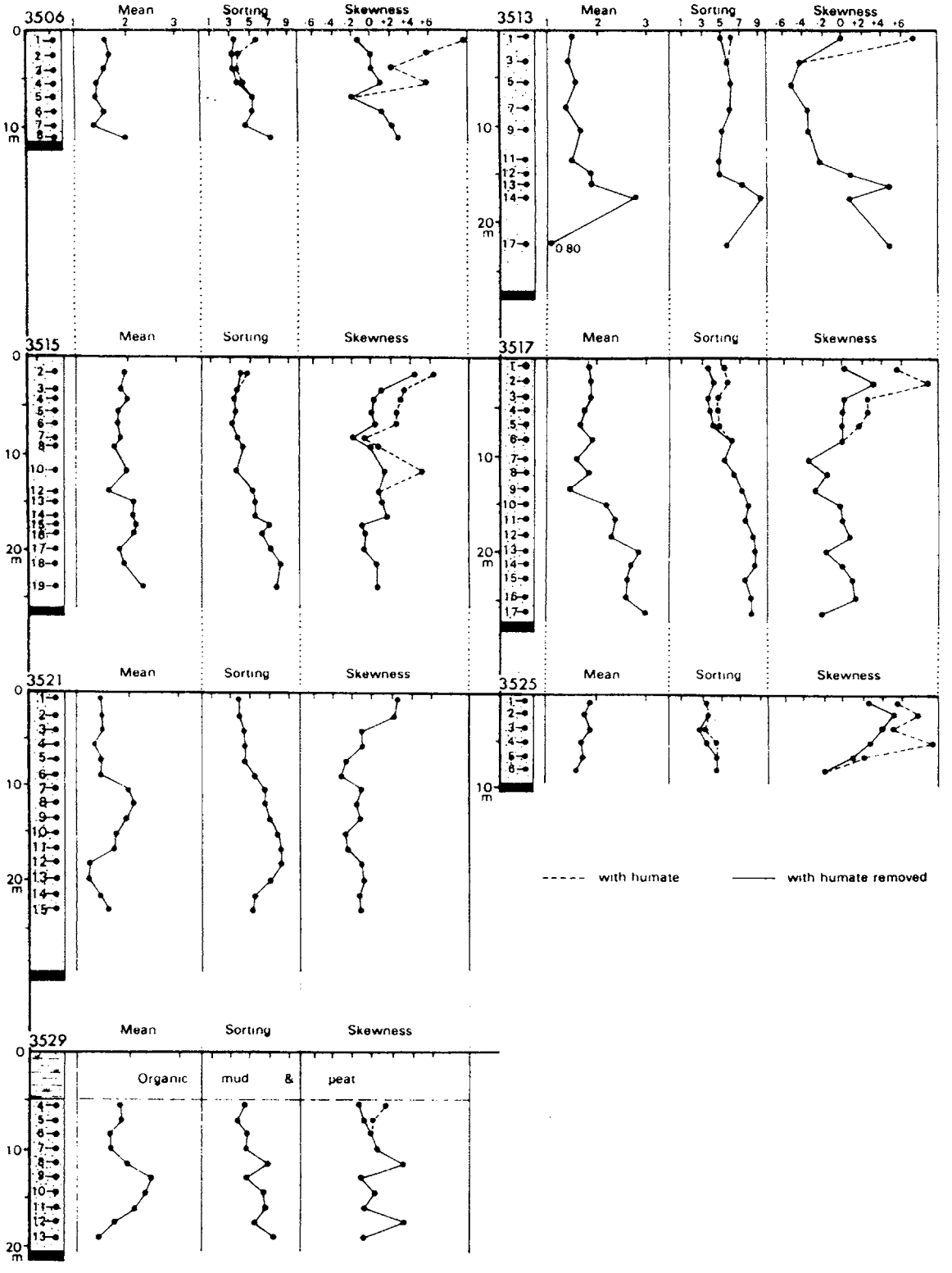


Figure 4-15: Grain size characteristics of selected drill holes on the Inner Barrier of Newcastle Bight (see Fig. 4-12 for location).

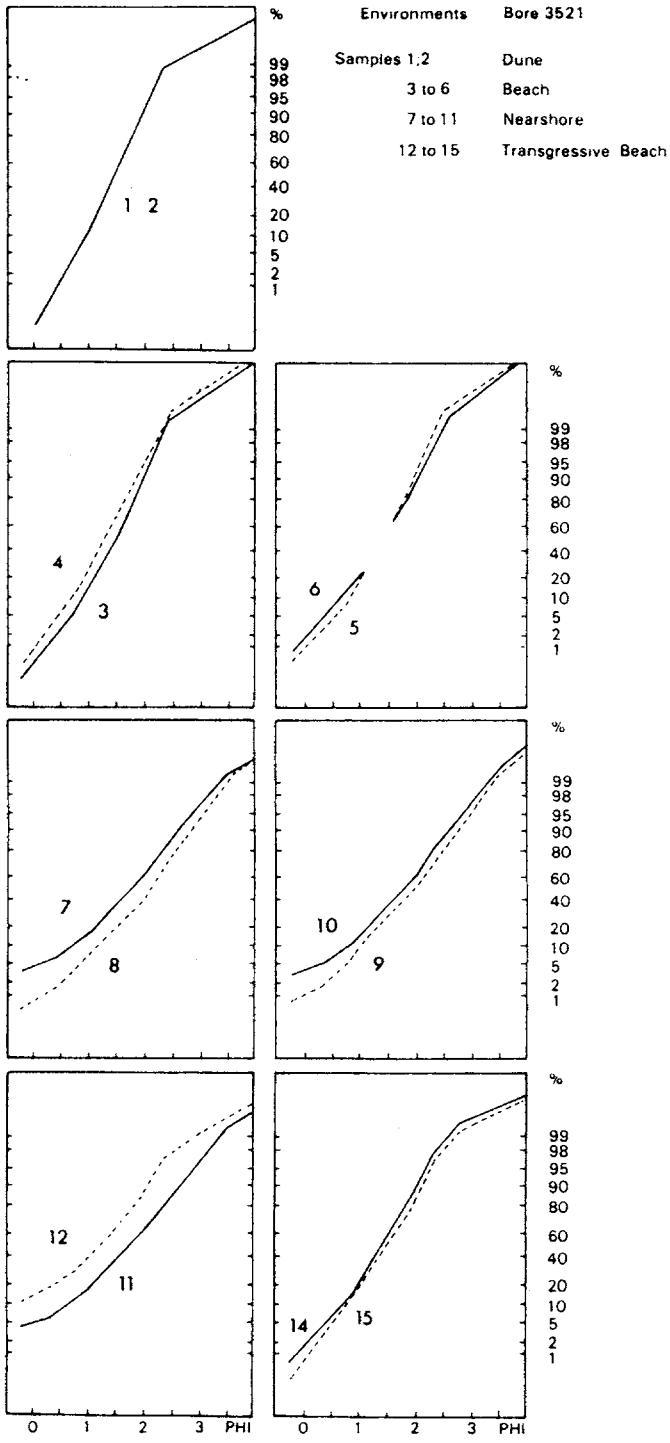


Figure 4-16: Grain size curves for H.D.W.B. drill hole Sk 3521.

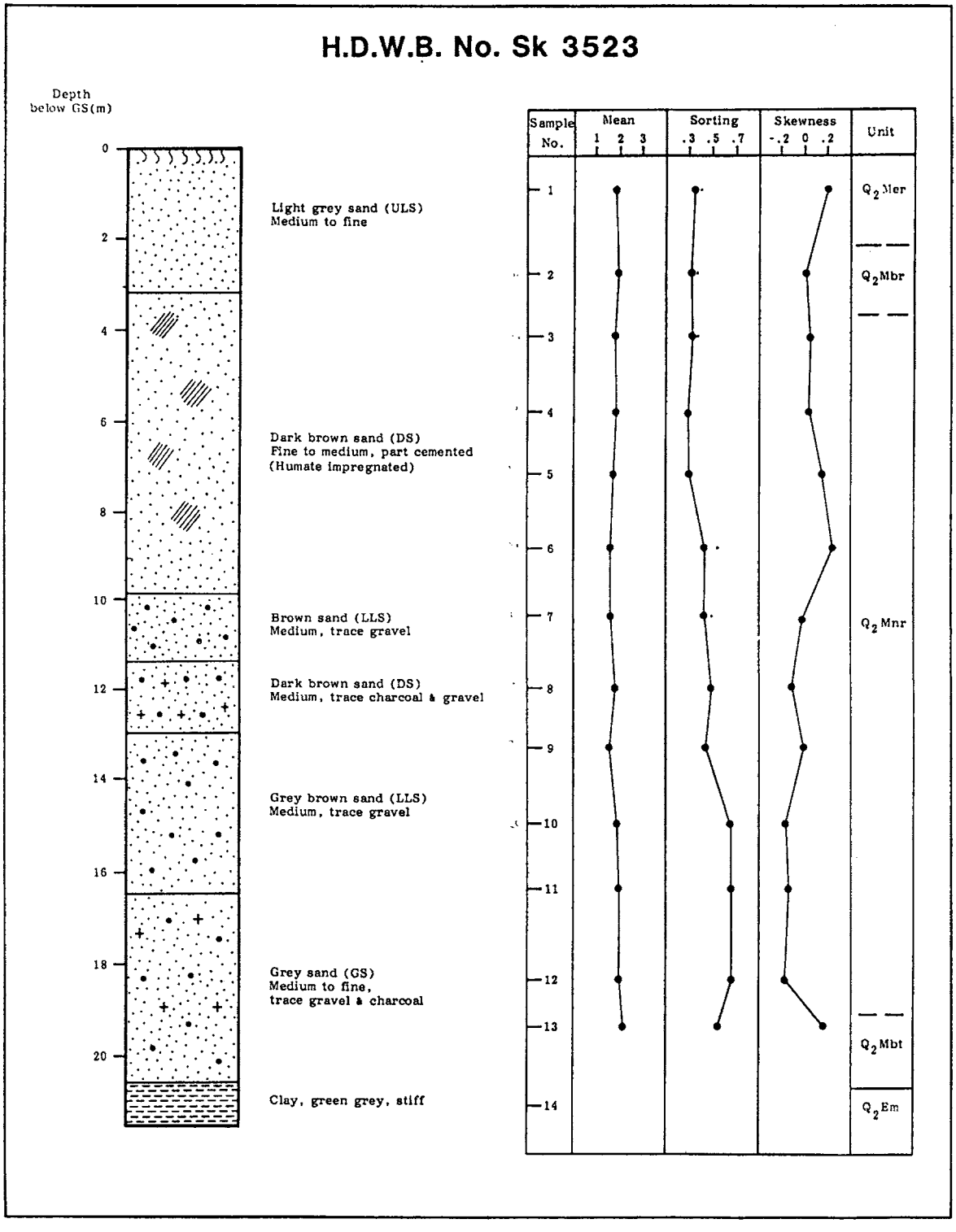


Figure 4-17: Log of H.D.W.B. drill hole Sk 3523. The elevation of the hole is +8m MSL. Symbols ULS, DS etc. denote units within the humate-impregnated zone of the Inner Barrier Sand (see 3.3.1).

TABLE 4-2 Chemical Analyses H.D.W.B. Drill Hole Sk 3523 (J. Caldwell Analyst)

Sample No.	Depth (m) Below G.S.	% Fe	% C (org)	Humic Fulvic Acid Ratio	^{14}C age HA	^{14}C age FA	ANU ^{14} Lab No.
1	0.76	.0039	.026				
2	2.6	.0036	.019				
3	4.0	.0021	.57	14.0	10450 ± 140		1492
4	5.6	.0030	.74	3.5	18900 ± 670	8980 ± 870	1535a,b
5	7.0	.0066	.88	3.4	24100 ± 600	15580 ± 270	1494, 1495
6	8.7	.011	.69	1.9			
7	10.2	.0066	.47	1.4	25350 ± 800	25350 ± 800	1496, 1497
8	11.7	.303	.40	1.0			
9	13.3	.021	.20	1.0	32360 ± 1040	21260 ± 1040	1575, 1576
10	14.8	.017	.13				
11	16.3	.020	.11				
12	18.3	.038	.10				
13	19.4	.048	.095				
14	20.9	.490	.15				

Bankivia assemblage (e.g. Sk 3524) typical of a nearshore environment of deposition (Mnr). The iron oxide content of the sands is very low, never exceeding 1 percent. Total organics show a more interesting picture. These organics are predominantly humic colloids and not particulate organic matter. A maximum content of 0.88 percent bulk organic carbon occurs in sample Sk 3523-5 at a depth of 7 m below ground surface. Below 13 m (sample 9) the amount is less than 0.20 percent.

The proportion of fulvic to humic acid increases with depth. Humines are absent. The radiocarbon age structures of humic and fulvic acid samples are shown in Table 4-2 for samples 3, 4, 5, 7 and 9 (A.N.U. Laboratory humate series). Consistently, humic acid samples date older than fulvic acids at a given depth. The radiocarbon ages range from 9,000 years to 25,000 years. They clearly demonstrate the Pleistocene age of these sediments, as well as support the hypothesis that humate is introduced from above by downward percolating soil water (see 3.3.1). There is a possibility that humic acids were not introduced into the sands during the period of eolian reworking at the western end of the Newcastle Bight Inner Barrier (Thom et al., 1981a). A four-stage model for humate impregnation is shown in Figure 4-18 (see also Ch. 10).

4.3.3 Stratigraphic Patterns

4.3.3.1 Anna Bay section (Fig. 4-19)

This stratigraphic section can be divided into two parts, a northern part which belongs to the Tomaree segment and will not be discussed here (see Ch. 5), and a southern part which crosses both interbarrier depression and Outer Barrier. The location of the section is shown in Figure 4-12.

The Anna Bay section contains five morphological units and associated sediment types:

(a) Modern beach and nearshore zone;
(b) Mobile dune sheet including the active transgressive dune (Ridge III), adjacent deflation depression and incipient foredune;
(c) Beach-ridge or strand plain which is being transgressed by the mobile dune sheet;
(d) Backbarrier sand flat behind the beach ridges;
(e) Interbarrier depression containing sediments associated with estuarine and freshwater aquatic environments.

Six A.N.U. holes have been drilled on this section, two on the interbarrier depression (Nos. 73 and 68), one on the backbarrier sand flat (No. 72), and three on the beach-ridge plain (Nos. 71, 83 and 53). Unfortunately, difficulties of access prevented deep drilling in the mobile dunes. Two shallow sludge-pump holes have been drilled in the deflation plain for purposes of collecting shell samples for radiocarbon dating.

Figure 4-19 shows three major stratigraphic units which are separated by disconformities. The upper and middle units are composed of sand. The lower unit is clay-rich mixed with sand in places. This unit is considered to be of estuarine origin. The disconformity between upper and middle units is abrupt and, as noted above in our discussion of

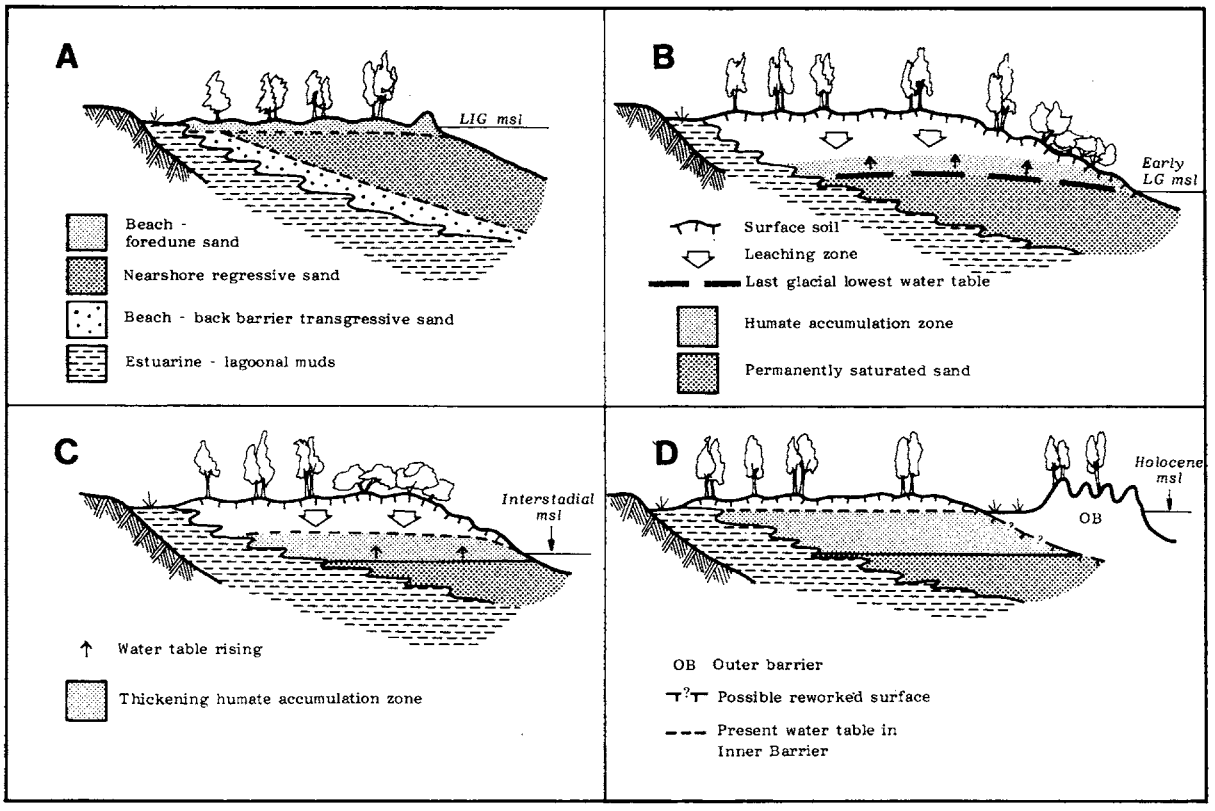


Figure 4-18: Model depicting possible mode of humate impregnation of Inner Barrier Sand during the Last Glacial period (Q3). Four stages are indicated: A - deposition of Inner Barrier during Last Interglacial (Q2); B - falling water table in free-draining sand to a level determined by modal sea level position on inner continental shelf during Last Glacial period (Q3) with initiation of humate accumulation at lowest level; C - progressive rise in water table associated either with humate impregnation of sand at the water table and/or rises during PMT in sea level on inner continental shelf (Q3,4); and D - rise of water table and sea level to present position in mid Holocene (Q5) with humate accumulating beneath a thin leached (A2) horizon of this giant groundwater podzol.

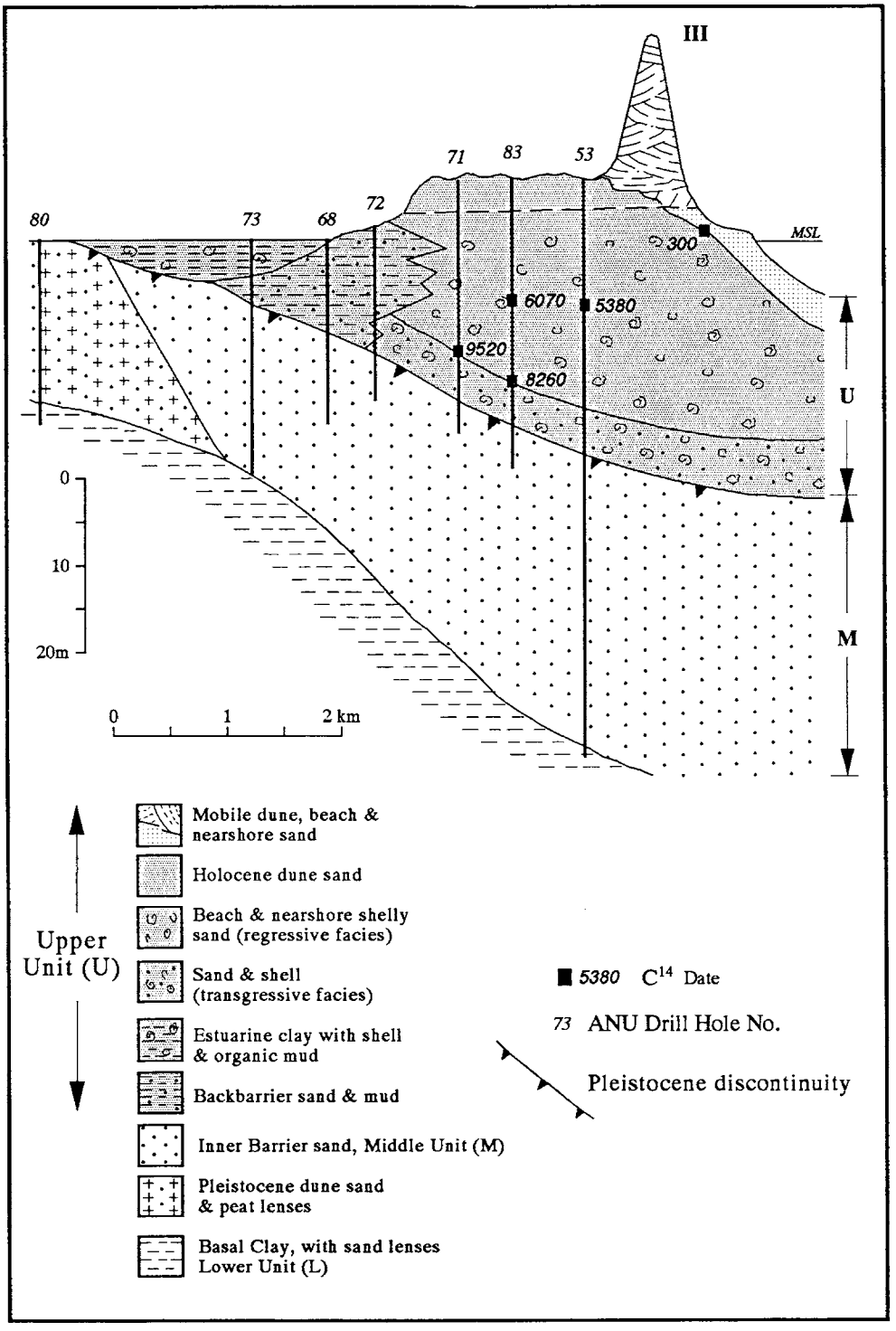


Figure 4-19: Stratigraphic section of Inner and Outer Barriers, Newcastle Bight, near the village of Anna Bay (see Fig. 4-12 for location). Topography is generalized.

A.N.U. drill hole 83 (4.3.2.1), is represented by a truncated soil profile containing humate-impregnated sand. At drill hole 53 there are thin peat lenses at the contact suggesting minimal reworking of the sand surface during the Postglacial Marine Transgression. The break between middle and lower units at drill hole 53 is gradual. More detailed characteristics of the section are as follows:

1. Upper unit. Drilling in the upper unit revealed the following sedimentary facies:

(a) Beach and nearshore shelly sand facies associated with modern beach and nearshore zones;
(b) Mobile dune sand facies;
(c) Beach-ridge sand facies;
(d) Nearshore shelly sand facies associated with beach-ridge progradation;
(e) Nearshore shelly sand facies associated with the Postglacial Marine Transgression;
(f) Backbarrier sand facies associated with the formation of the innermost beach-ridge;
(g) Backbarrier sand facies associated with the Postglacial Marine Transgression;
(h) Lagoonal organic mud facies;
(i) Estuarine shelly mud facies.

Specific characteristics of these facies are discussed in Ch. 3, and in 4.3.2.1 for A.N.U. drill holes 83 and 53. Chemical properties of samples from A.N.U. drill hole 53 are listed in Table 4-1.

Figure 4-19 depicts the generalized stratigraphic arrangement of facies in the upper unit. The figure also shows the radiocarbon ages of shell samples collected in A.N.U. drill holes 53, 83 and 71. Sediment properties and dates have been used in defining facies boundaries (see Ch. 3).

The upper unit is dominated by a seaward-thickening, nearshore shelly sand facies (Q5Mnr). This unit abruptly overlies a more poorly sorted shelly sand from which two radiocarbon dates have been obtained (A.N.U.-1330, A.N.U.-1526). These dates indicate deposition during the transgression. On the other hand, dates on shell hash (dominated by Bankivia fragments) from within the seaward-thickening unit suggest deposition following the termination of the transgression. Thus the thick unit could have formed during the sedimentary regression accompanying beach-ridge progradation. More than one phase of accretion is implied by the relatively young date of 3040 $\pm$ 90 ^{14}C yrs BP (SUA-1148) for shell fragments recovered below the modern deflation plain. However, the few dates obtained so far for the regressive facies in Newcastle Bight limits the extent to which positive conclusions can be drawn about the history of regressional deposition on this and other transects in Newcastle Bight.

Beach and dune sands of the beach-ridge plain are shown as one unit on Figure 4-19. Again, it must be stressed that distinguishing the lower and upper limits of the beach sand facies is not simple. The "error" here is probably $\pm$1 m. Thus beach ridges are formed of a sand which coarsens downwards and is shell-free (leached effect?). On the seaward

side unvegetated mobile dune sands are overriding the vegetated beach ridges, thereby reworking both eolian and beach facies of beach ridges into a transgressive dune ridge.

The relationship of transgressive and regressive nearshore shelly sand facies to backbarrier sand facies is uncertain. As shown in Figure 4-19, the lower transgressive sand laterally grades into backbarrier sediments. The latter are interpreted as washover deposits formed during the Postglacial Marine Transgression. Only a small portion of this facies, exhibited at the surface as a thin wedge-shaped sand extending into the interbarrier depression, was formed at present sea-level, possibly during or immediately prior to the formation of the innermost beach ridge. It appears that progradation of the beach ridges, involving deposition of the regressive nearshore shelly sand facies, led to reworking and truncation of the backbarrier sand facies formed during the marine transgression. This is shown in Figure 4-19 by a solid line at the contact between nearshore regressive and backbarrier transgressive facies. Heavy minerals were concentrated in this uppermost backbarrier facies.

Also illustrated in Figure 4-19 is the date of 300 $\pm$ 70 ^{14}C yrs BP (A.N.U.-1331) on wood from an *in situ* tree stump. This sample was collected from an exhumed soil surface on the deflated windward side of the mobile dune sheet. It provides a maximum age for the contemporary phase of dune mobility at this location. In common with a similar site near Broadwater Lake (Ch. 7), the soil lacks strong evidence of profile differentiation except for organic enrichment of the surface 20 cm or so.

2. *Middle unit*. The middle unit of pre-Holocene age (possibly Last Interglacial, see Thom *et al.*, 1981a) of the Anna Bay section shows the following two sedimentary facies:

(a) A beach sand facies (Q2Mbr) which is capped by a thin dune sand facies (Q2Mer). The dune sand is suggested by the positively skewed sand of samples 83-11 and 12 from hole 83. The contact at hole 53 is marked by a thin peat lens. Humate-impregnated sand characterizes the upper 3-5 m of all holes drilled into this facies on the Anna Bay transect.

(b) At about -20 m MSL, the beach/dune sand grades into a nearshore shelly sand facies rich in *Bankivia* (Q2Mnr). The rich fauna recovered in A.N.U. drill hole 53 has been dated as "background" (SUA-249). This fauna is not present in A.N.U. drill hole Nos. 73 and 68, the only other holes to reach the base of the middle unit. The lower 4 m of the middle unit in these holes is composed of coarse sand and granules, moderately poorly sorted and rich in "lithics". Clay lenses appear to be present. This sediment type is consistent with the model of a transgressive sand overlying a clayey "lagoonal" substrate.

3. *Lower unit*. The lower unit of the Anna Bay cross-section, seen in A.N.U. drill hole 73, is represented by a tight, plastic grey clay, which the drill penetrated only 30-70 cm (Q2Em). However, in hole 53, the clay is interbedded with fine sand, poorly sorted and rich in mud. A 1 m thick clay layer was intersected at -20 m MSL in drill hole 68 below which is sand for at least 5 m. The contact between lower and middle unit is sharp at this site, being delineated by the base of the coarse sand or shelly sand layer and the presence of clay. The disconformity

rises from -28 m MSL at hole 53 to -20 m MSL at hole 73.

4.3.3.2 Salt Ash section (Fig. 4-20)

The location of the Salt Ash section is shown in Figure 4-12. It contains six morphological units and associated sediment types (Fig. 4-20).

(a) Modern beach and nearshore zone;
(b) Mobile dune sheet including the active transgressive dune ridge III, adjacent deflation depression and incipient foredune;
(c) Vegetated long-walled transgressive dune ridges (I and II) and associated deflation depressions with small hummocky dunes;
(d) Backbarrier flat, discontinuous and partially overrun by Ridge I.
(e) Interbarrier depression flanking Tilligerry Creek;
(f) Beach-ridge plain with some "terrestrial" dunes of the Inner Barrier.

Seven A.N.U. drill holes have been drilled on this section, four in the interbarrier depression and backdune flat (Nos. 70, 76, 77, 78), two in the deflation plain of vegetated dunes (Nos. 82 and 84) and one near the crest of Ridge II (No. 85). As was the case with the Anna Bay section, lack of access prevented drilling on the mobile dunes and beach. Three main stratigraphic units were also recognized in the Salt Ash section: (i) somewhat complex upper unit associated with Outer Barrier formation and eolian reworking; (ii) a more uniform middle unit associated with Inner Barrier deposition; and (iii) a lower unit of predominantly compact clay. The disconformity between upper and middle units is marked by a sharp change from shelly grey sand or grey muddy sand to brown humate-impregnated sand often with different granulometric properties. The change from middle to lower unit is also sharp with the clay typically being blue-grey and quite difficult to auger drill. However, where the lower unit is in direct contact with the upper unit (see A.N.U. drill hole No. 84) the clay is quite oxidized.

1. Upper unit. The various facies comprising the upper unit are shown in Figure 4-20. They include:

(a) Beach and nearshore shelly sand facies associated with modern beach and nearshore zones;
(b) Mobile dune sand facies;
(c) Dune sand facies associated with long-walled transgressive dunes and deflation plains;
(d) Nearshore and beach shelly sand facies which were deposited during the progradation of the Outer Barrier (i.e. a regressional facies);
(e) Nearshore shelly sand facies associated with the Postglacial Marine Transgression;
(f) Backbarrier sand facies associated with the formation of the innermost shoreline deposit at the termination of the Postglacial Marine Transgression;
(g) Backbarrier sand facies deposited during the Postglacial Marine Transgression;
(h) Lagoonal organic mud, locally enriched in shell, forming the interbarrier depression;
(i) Muddy sand facies containing "estuarine" shells underlying (e);
(j) Nearshore-beach shelly sand and non-shelly sand which disconformably overlies the lower unit in hole 84.

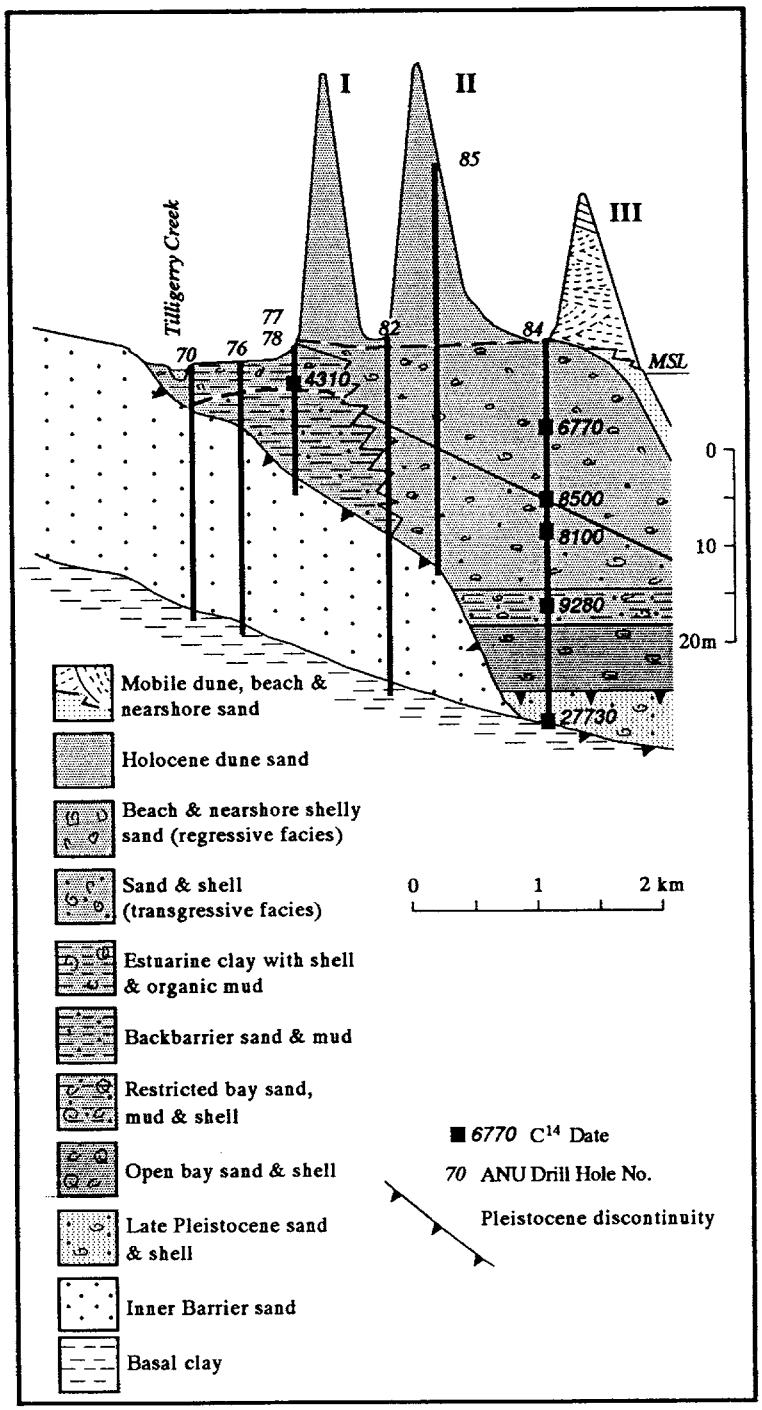


Figure 4-20: Stratigraphic section of Inner and Outer Barriers across the central region of Newcastle Bight near Salt Ash (see Fig. 4-12 for location). Topography is generalised.

Detailed properties of the more seaward facies are described in Table 4-3, which is a log of A.N.U. drill hole No. 84. This hole was located in the vegetated deflation plain between the mobile dune sheet and Ridge II. Down-the-hole variability in grain-size, shell composition, chemical properties and age is indicated in Table 4-3. This hole is remarkable for three reasons: (i) it contains a thick Holocene transgression and sedimentary regression sequence; (ii) it includes an "estuarine" sand of early Holocene age; and (iii) it passes through a "leached" sand into a dark grey shelly sand at c. -40 m MSL which is possibly Last Glacial in age (Thom et al., 1981a).

The sedimentary regression is well-documented in hole 84 by a fining-downwards sand section about 8 m thick. Shells are of the nearshore assemblage and become more abundant and better preserved with depth. A radiocarbon date of 6770 ± 220 ^{14}C yrs BP (A.N.U.-1675) has been obtained at a depth of -10 m. Although older than what is considered to be the main period of sedimentary regression (i.e. 6500 to 5000 ^{14}C years), the date is within the age range of reworked shelly material which has been interpreted elsewhere as having been laid down during this period (Thom et al., 1978; 1981b). Unfortunately, sampling of shelly material closer to the surface failed to realize sufficient shell for dating. The nearshore regressive sand is overlain by a medium-grained yellow to grey, moderately sorted and negatively skewed quartzose sand. This is presumably of open-ocean beach origin (i.e. Q5Mbr). The upper 1-2 m is interpreted as reworked dune sand material in the deflation plain, but this well sorted sand is much thicker where it forms transgressive ridges I and II (Fig. 4-20).

From -13 to -24 m below ground surface (c. -10 to -21 m MSL), hole 84 revealed medium to coarse negatively skewed sand, moderately well-sorted, and quite calcareous. Shells are mostly broken. The assemblage contained some species associated with nearshore environments. However, it also included Cacozeliana, suggesting that the rapidly receding barrier accompanying the Postglacial Marine Transgression was reworking shallow sand bodies colonized by sea grasses, which do not occur in very high energy, open ocean embayments. Two radiocarbon dates (A.N.U.-1676, 1677) show that this relatively thick sand body was deposited during the early Holocene (Fig. 4-20). The presence of sand and granules also indicates nearshore-beach reworking and accumulation during this marine transgression.

At -24 m in hole 84 there is a sharp contact between the nearshore transgressive facies and an underlying dark grey muddy sand, which contains few shells and is slightly calcareous. No diagnostic nearshore species were found amongst the shell assemblage. The fauna consists of sand snails (Conuber), Pecten, oyster fragments and Nassarius sp. This muddy sand may reflect a shallow estuarine environment of deposition. A radiocarbon date on these shells of 9280 ± 130 ^{14}C yrs BP (A.N.U.-1678) is interpreted as reflecting a sea-level of -20 m at c. 9300 environmentally corrected radiocarbon yrs ago. This date falls close to the lower estimate of sea-level during the P.M.T. recently determined by Thom and Roy (1985).

Below the estuarine shelly layer in hole 84 is a shell-free, fine to medium sand (Table 4-3). This sand commences at -36 m below ground surface. It is relatively rich in lithic fragments. At -40 m it grades into a shelly sand containing fragments of nearshore species. The sand

TABLE 4-3 Log of ANU Drill Hole 84

Location: In stabilized transgressive dune field of Outer Barrier in vicinity of Salt Ash (GR 015698 Williamtown 1:25,000)

Elevation: c. 3 m msl

Depths (in metres)	Description
0-1	Sand, yellow grey, medium, well sorted; grades to
1-3	Sand, light brown, medium-coarse, well sorted, slight to organic stain, becoming more grey with depth; sharp to
3-7.5	Sand, grey brown, medium, well sorted; grades to
7.5-13	Sand, grey, medium, moderately well sorted; slightly shelly becoming richer in shell fragments (eg Bankivia) with depth (ANU-1675); grades to
13-15	Sand, grey, medium-fine, moderately well sorted; abundant shells including Bankivia (ANU-1676); sharp to
15-24	Sand, light grey, medium-coarse with some rounded granules, moderately sorted; diverse shell types including Bankivia, Cacozeliana, Glycymeris, Nassarius, spp (ANU-1677); sharp to
24-25.6	Muddy sand, dark grey, slightly calcareous, some shells (Eg Nassarius sp.) becoming less calcareous (ANU-1678); grades to
25.6-33.5	Sand, grey, medium, abundant lithic grains, very sparse shell fragments
	DISCONTINUITY
33.5-36.5	Sand, dark grey, medium-fine, moderately well sorted, non-calcareous; grades to
36.5-39	Sand, dark grey, mediume-fine, moderately sorted, becoming calcareous with shell and well fragments (ANU-1679)
39-40	Clay, slightly sandy, oxidized with red mottles, very firm

is fine to medium, becoming coarser at the contact with the underlying clay. A radiocarbon date of 27,730 ± 2100 ^{14}C yrs BP (A.N.U.-1679) has been obtained on this shelly sand. The interpretation is based on our acceptance of this date as involving shell material which lived at the time of deposition (±2000 years), and there being no post-depositional contamination of the age. If these assumptions are correct, this date is extremely interesting because it pinpoints an interstadial high sea-level of c. -40 m close to 28,000 years ago. This is the time when Chappell and Veeh (1978) claim that a marine transgression formed the youngest Last Glacial coral terrace in New Guinea. From their estimates of uplift rates they have concluded that sea-level rose to about -40 m at this time. Our data support this conclusion providing a further assumption is made, viz. that the locality has undergone minimum post-depositional warping.

The landward half of the upper unit on the Salt Ash transect is clearly much thinner than the seaward portion. Figure 4-20 shows the surface of the Inner Barrier dipping beneath the upper unit. Three drill holes at the rear of the Outer Barrier and in the interbarrier depression encountered Holocene backbarrier sand lacking in diagnostic shell species. These holes are Nos. 70, 76 and 77. In holes 70 and 76 the sand is overlain by mud which grades downwards into a muddy sand and then into a medium to coarse, moderately well-sorted, grey sand. The interbarrier mud is lacking in A.N.U. drill hole No. 77, but the muddy sand layer still occurs. A.N.U. drill hole 78 is offset from the line of the section and was sited in a reentrant where dune transgressive sand (Ridge I) directly overlies interbarrier estuarine mud. Here Notospisula shells gave radiocarbon age of 4310 ± 100 ^{14}C yrs BP (A.N.U.-1332) at -2 m below MSL. This gives a maximum date on transgression by the dune sand which forms Ridge I.

Figure 4-20 shows the bulk of the shell-free sand under the landward side of the Outer Barrier as backbarrier facies. Most of this sand may have been deposited during the Postglacial Marine Transgression. Its negative skewness (except at the top) suggests overwash deposition by waves (Fig. 4-20). We suggest that the thin, upper muddy sand portion was deposited at the termination of the Postglacial Marine Transgression just before the barrier prograded. However, as will be discussed in the Lavis Lane section, there may have been some reworking of the upper sand by wind waves prior to estuarine mud infill.

2. Middle unit. Facies units discussed in the Anna Bay section also occur in the Salt Ash section. The main difference is that at Salt Ash the units can be traced from the subaerial surface of the Inner Barrier to beneath the Outer Barrier and interbarrier depression (Fig. 4-20). We have recognized dune, beach and nearshore facies within the Inner Barrier. Characteristics of these facies are described in 4.3.2.3 (H.D.W.B. drill hole Sk 3523). As shown in the figure (4-20), the nearshore unit is quite shelly at the base in the seawards portion (see A.N.U. drill holes 70, 76 and 82). A small piece of coral was recovered just above the clay contact in A.N.U. drill hole 82 at -32 m MSL.

3. Lower unit. This unit comprises the clay facies which underlies both Inner and Outer barriers. In A.N.U. drill hole 84 the clay is oxidized. Could this represent oxidization following removal of overlying Inner Barrier sands during an interstadial marine

transgression, or could this transgression have exposed an older weathered horizon in the clay? Bore Sk 3523 and A.N.U. drill holes 70 and 76 reveal a grey, stiff clay which is unoxidized.

4.3.3.3 Lavis Lane section (Fig. 4-21).

The location of this section is shown in Figure 4-12. It contains a similar suite of morphological features to those seen on the Salt Ash section (4.3.3.2). The main exception is that Inner Barrier beach-ridges are absent, the barrier surface at this section having been reworked into "longitudinal" dunes during the Last Glacial period (see 4.2.2.2). All other morphological units are present although at the line of the section transgressive dune Ridge I is apparently overlain by Ridge II.

There are three A.N.U. drill holes on this section (Nos. 90, 89 and 120) and they have been linked to two H.D.W.B. bores Sk 3513 and Sk 3517 (Fig. 4-21). Again three basic stratigraphic units are present corresponding to Outer Barrier and interbarrier depression (upper unit), Inner Barrier (middle unit), and the lower or clay unit. The contacts between units are similar to those noted above (4.3.3.1 and 4.3.3.2).

1. Upper unit. Facies characteristics here are more simple than was the case at Salt Ash. The unit extends no more than 16 m below MSL. A thin marine transgressive sand is overlain by beach and nearshore facies. The sequence for A.N.U. drill hole No. 120 is described in detail in 4.3.2.2 (see Fig. 4-14).

In Table 4-4 grainsize and chemical properties for the backbarrier facies are described. This is based on samples collected from A.N.U. drill hole 89 located on the backbarrier flat marginal to the interbarrier depression (see Fig. 4-12 for location). From the bottom up four facies units are recognized.

(i) Directly overlying the Pleistocene soil surface is an estuarine shelly sand and mud up to 2 m thick;
(ii) A slightly muddy sand, 7 m thick, grey in colour and free of shell overlies (i); the sand has strong negative skewness suggesting washover deposition.
(iii) A slightly shelly but muddy sand, dating 5410 + 190 ^{14}C yrs BP (A.N.U.-1669), occurs between -2 and -8 m MSL (shell material is highly fragmented but no open-ocean species were recognized).
(iv) A clean, moderately sorted, positively skewed sand up to 4 m thick, occurs beneath the ground surface.

The lower backbarrier sand and the estuarine muddy sand both appear to have been deposited during the Postglacial Marine Transgression. The dated sand with shell fragments is interpreted as washover sand deposited at the termination of the Postglacial Marine Transgression. This is overlain by backdune sand (backbarrier) forming low hillocks landward of transgressive dune ridges. The degree of reworking by wave-wind processes along the shores of the interbarrier depression lagoon is discussed in 4.2.4.

On the landward side, the backbarrier sandy facies grade laterally into a relatively deep mud basin. Notospisula is very abundant in this basin; shells from -0.5 m MSL were dated at 3120 + 80 ^{14}C yrs BP (SUA - 1023). The basin opens towards Fullerton Cove, an active sink for

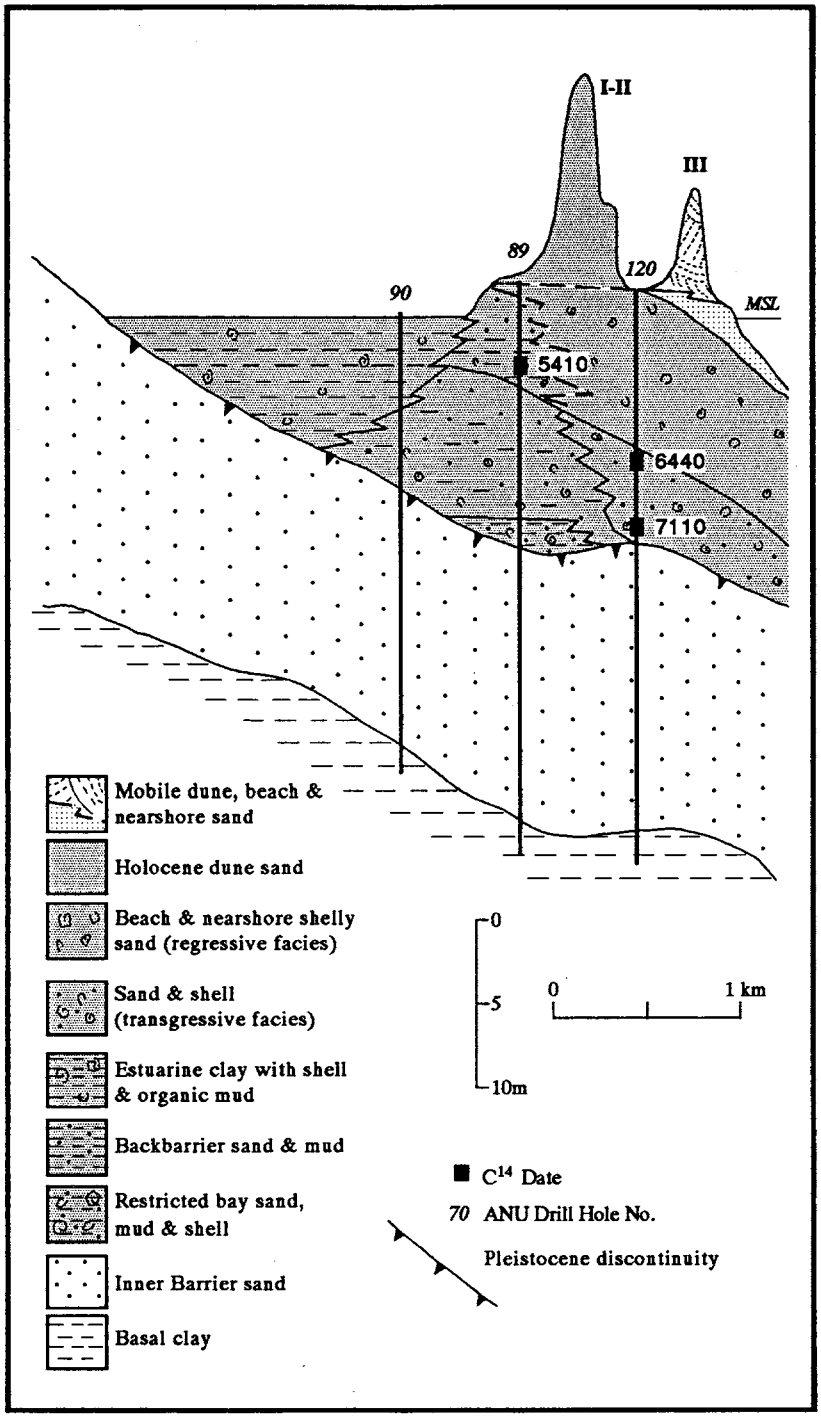


Figure 4-21: Stratigraphic section of Inner and Outer Barriers, Newcastle Bight, along the line of Lavis Lane (see Fig. 4-12 for location). Topography is generalised.

TABLE 4-4: Sedimentary Characteristics of A.N.U. Drill Hole 89

Location: Lavis Lane Transect GR 937672 Williamstown 1:25,000
Elevation: c. 2.5 msl in dune depression

SAMPLE NO.	DEPTH (IN M)	GRAIN SIZE (IN PHI UNITS)				SEDIMENT PROPERTIES						
		MEAN	STANDARD DEVIATION	SKEWNESS	KURTOSIS	QUARTZ %	ROCK FRAGMENT %	FELDSPAR %	AVERAGE ROUNDNESS QUARTZ	% ANGULAR QUARTZ	HEAVY MINERAL %	ENVIRONMENT
89-1	1	1.59	0.26	+0.19	+1.39	93.10	2.90	4.00	0.37	6	0.10	5 Me
89-2	3	1.58	0.31	+0.14	+1.68	90.80	5.10	4.10	0.37	10	0.46	5 Mer
89-3	4	1.55	0.30	+0.03	+0.57	92.40	5.00	2.50	0.38	10	0.10	5 Mer
89-4	7	1.52	0.58	+0.93	+7.18	92.90	3.60	3.50	0.37	15	0.30	5 Mbb
89-5	10	1.32	0.43	-0.33	+1.87	80.00	10.00	10.00	0.31	19	0.10	4 Mbb
89-6	12.5	1.36	0.45	-0.39	+1.84	86.30	7.50	6.20	0.32	18	0.11	4 Mbb
89-7	14	1.55	0.36	+0.08	+1.29	82.40	10.40	7.20	0.33	19	0.17	4 Mbb
89-8	17	1.51	0.47	+0.47	+5.27	-	-	-	-	-	-	4 Mbt
89-9	18	1.60	0.52	-0.93	+8.06	-	-	-	-	-	-	4 Mbt
89-10	20	1.38	0.46	-0.12	+0.50	-	-	-	-	-	-	2 Mbt
89-10a	21	1.15	0.55	-0.14	-0.20	-	-	-	-	-	-	2 Mbr
89-11	24	1.38	0.53	-0.21	+0.48	-	-	-	-	-	-	2 Mnr
89-12	27	1.79	0.77	-0.08	+0.44	79.90	17.30	2.80	0.26	54	0.65	2 Mnr
89-13	30	2.01	0.84	-0.27	+0.81	79.80	16.50	3.70	0.27	55	0.95	2 Mnr
89-14	35	1.97	0.65	-0.30	+1.33	82.90	11.80	5.30	0.27	50	0.53	2 Mnt
89-15	36	2.04	0.56	+0.12	+2.47	81.00	10.50	8.50	0.29	35	0.27	2 Mnt

fine sediments transported down the Hunter (Roy, 1977). On the seaward side, the lower backbarrier sands appear to be truncated by the regressive nearshore facies. However, Figure 4-21 shows that we interpret the upper washover (backbarrier) sandy sediments as contiguous with the regressive beach and nearshore sands.

2. Middle unit. The three facies previously described for the middle unit are well expressed in the Lavis Lane section. This is a typical case of a regressive sequence of dune over beach over nearshore sands (Ly, 1976). The nearshore facies may contain both transgressive and regressive material. Hole Sk 2579 drilled on the inner margin of the Inner Barrier near Grahamstown Swamp (Reservoir) intersects at -7 m MSL a coral and shell-rich sand which could be a transgressive unit. Table 4-5 presents the log of this hole. The corals were uncovered in great abundance during the excavation of a trench by the H.D.W.B. in 1973. Shell and coral species are listed in Table 4-5. The corals proved to be chemically unaltered and ideal for uranium-series dating. Dates reported by Marshall and Thom (1976) support the view that this facies, located about 7 m below MSL, is transgressive in origin. The dates are about 140,000 years before present (Table 4-5). They cover a period which represents a marine transgression terminating in the first "peak" of sea-level of the Last Interglacial (Chappell and Thom, 1978; Chappell and Veeh, 1978). Unfortunately, the relationship of these facies to what underlies the Grahamstown Swamp is unknown.

3. Lower unit. Undifferentiated clay deposits of presumed estuarine origin and pre-Last Interglacial age constitute the basal unit of the section. The clays thicken seaward and towards the centre of Newcastle Bight, approximately along the line of this section, reaching a maximum thickness of about 70 m (Joint Coal Board, drill hole No. 10). Deep drilling shows that these clay deposits disconformably overlie weathered bedrock or fluvial sands and gravels. The uppermost surface of the clay or lower unit dips seaward with slight undulations (Fig. 4-21).

4.3.3.4 Fullerton Cove section (Fig. 4-22)

At the southern end of Newcastle Bight, the Outer and Inner Barriers diverge enclosing a broad interbarrier depression. This depression opens into the delta of the Hunter River (Fig. 4-1b). Part of this delta is the marginal mud basin known as Fullerton Cove, which, as shown in Figure 4-1b, also forms part of the interbarrier depression. Roy has discussed a number of drill sections based on numerous drill holes (see Fig. 4-12 for location) which cross various parts of Fullerton Cove and the southern end of the Outer Barrier (Roy, 1980). Two of these sections are reproduced as Figure 4-22. Seven major lithofacies are recognized. Lithofacies 1 and 2 are part of the "lower" stratigraphic unit noted in the Lavis Lane, Salt and Anna Bay sections, lithofacies 3 is the "middle" unit, and lithofacies 6 and 7 are the barrier and interbarrier components of the "upper" unit. Near Fullerton Cove drilling has revealed the existence of two distinct lithofacies, 4 and 5, which are associated with the more riverine-estuarine character of the region adjacent to the Hunter River. The following discussion is based on Roy (1980).

1. Lower river gravel (QlTc). The lower river gravels were encountered on two drill holes in Fullerton Cove (F.C. 2 and 3), and were intersected in nearby coal drill holes (EPS 3,15,18,19,20,24 and 25). This unit

TABLE 4-5 Log Drill Hole H.D.W.B. Sk 2579

Location: Eastern end Grahamstown Embankment

Ground Surface Elevation: +14.4 m LWOST

Depth (in metres)	Description
0-12.2	Sand; brown to dark brown, medium (1-2% coarse); subangular
	(water table at -4.5 m G.S.)
12.2 - 15.8	Sand; brown; medium (5% fine, some rounded gravel); subangular
15.8 - 17.1	Sand; light brown; medium
17.1 - 19.5	Sand; grey to grey brown; medium to fine
19.5 - 20.7	Sand; grey; fine; broken and whole shells (*Cardita excavata*, *Chlamys lividus*, *Chama fibula*) and corals (*Goniopora* sp., *Blastomussa wellsi*)
20.7 - 22.2	Sand; clayey (grey); indurated
22.2 - 24.4	Clay; sandy (brown)
24.4 - 25.6	Clay; sand (grey) with pieces fresh fine grained sandstone

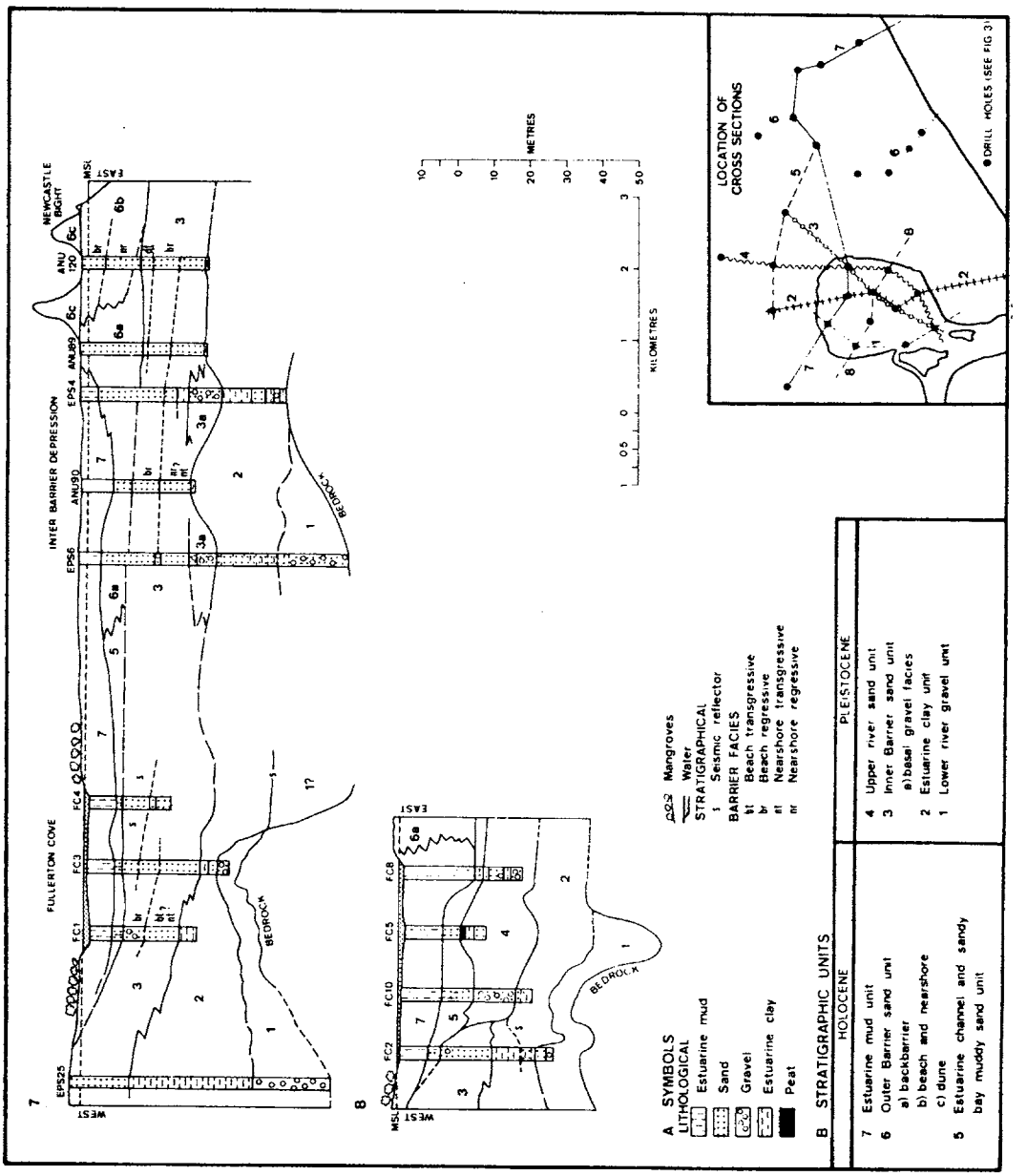


Figure 4-22: Stratigraphic sections in the Fullerton Cove area of Newcastle Bight based on Roy (1980).

overlies bedrock and reaches thicknesses of about 18 m along channel axes but thins about bedrock highs. In places the surface of the unit is eroded with a maximum relief of about 15 m. The gravels are brown, very poorly sorted and are composed of multi-coloured, sub-angular to rounded pebbles up to 10 cm in diameter of siliceous and igneous rock types. In its upper part the gravels fine upwards to grey quartz-lithic sands indicating a reduction in river flow prior to the initiation of the following phase of estuarine deposition. In F.C. 2 the gravel unit grades into the overlying estuarine clay indicating, in this case, a conformable relationship. Minor cementation by iron oxide has been reported in the lower layers, suggesting sub-aerial weathering.

2. Estuarine clay (Q1,2Em). Clay containing estuarine shells was encountered in drill holes F.C. 1, 2 and 10, beneath northern Fullerton Cove, and in all EPS drill holes to the north of the estuary. Clay extends beneath the Newcastle Bight embayment as a massive unit up to 55 m thick and underlies Port Stephens estuary (Ch. 5). Generally, the clay unit disconformably overlies the eroded surface of the lower river gravels in the study area, but, towards the inner margin of the embayment, it onlaps the rising bedrock substrate. The clay unit is less than 17 m thick beneath Fullerton Cove, but thickens to between 30 and 50 m immediately to the north and northeast of the estuary. This increase in thickness is partly due to its upper surface rising in a landward direction. In the southern part of the estuary, near the river, the clay unit has been removed by fluvial erosion. The lower part of the clay unit in F.C. 2 is quite sandy with a predominantly quartzose sand fraction, but in its upper part the sand content decreases to less than 5 percent.

The clay is compacted and partly weathered, and is interpreted as an estuarine mud that accumulated in a mud-basin environment formed by the drowning of the Newcastle Bight embayment during one or more marine incursions. Layers of sandy and gravelly clay indicate occasional episodes of river channel and deltaic deposition. Tidal flat deposits may occur, but have not been recognised on visual lithological criteria.

3. Inner Barrier sand. (Q2Mer, br, nr) The southernmost part of the Inner Barrier underlies Fullerton Cove and is exposed around its northern perimeter (Fig. 4-22). It was encountered in F.C. 1,2,3 and 4 and has been extensively drilled for ground water by the Hunter District Water Board in the area to the north and northeast of Fullerton Cove. The Inner Barrier sand unit ranges in thickness from 14 to 25 m. Its southern edge is thought to dip steeply southwards along an eastwest line passing through the middle of Fullerton Cove. This boundary is interpreted as an erosional feature produced by the Hunter River when it followed a course to the north of its present position.

Two main phases of Inner Barrier deposition are recognized: a basal transgressive phase and an overlying regressive phase. Transgressive deposits consist mainly of fine to medium, well sorted sands; these become slightly muddy in their lower sections where they interfinger with mud basin deposits (estuarine clay unit). To the northeast of Fullerton Cove, a localised sequence of gravel and sand was encountered near the base of the Inner Barrier in drill holes EPS 4,6 and 20. A more extensive, but thinner, gravelly sand layer occurs at the top of the transgressive unit. The transgressive deposit is interpreted as nearshore facies by Ly (1976); however, the presence of coarse sediments

within it suggests higher energy (and probably different source) conditions than those characterising the present-day nearshore environment in Newcastle Bight.

Regressive marine deposits comprise medium to coarse-grained, quartzose sands of beach origin that have prograded seawards over the lower transgressive unit. Seaward progradation is supported by the presence of southward dipping seismic reflecting horizons (beach bedding) in the uppermost part of the unit under Fullerton Cove. The beach deposits presumably formed a wide zone of beach-ridges capped by dune sand on the surface of the Inner Barrier; however, their original morphology has since been obliterated. The present-day surface of the Inner Barrier in the Fullerton Cove area is gently undulating with small east-west oriented terrestrial dunes. As noted above (4.3.2.3) Inner Barrier sands are often impregnated with humate, at least in the upper part.

4. Upper river sand (Q3Tc). Fluvial sediments deposited in a river channel were encountered in F.C. 5,6,7,8,9,10 and 11; their average thickness is about 20 m, but reaches a maximum in excess of 28 m beneath the southern part of the estuary. They occupy a position in the sequence topographically slightly lower than, but onlapping, the adjacent Inner Barrier sands. The main sediment types include terrestrial sands, gravelly-sands and occasional gravels. In F.C. 8 these sediment types tend to fine upwards into thin clay layers. Shell fragments in these finer beds indicate occasional estuarine incursions. In F.C. 5, which penetrated an erosional high on the surface of the upper river sand unit, a layer of estuarine clay at the top of the unit is overlain by a peat bed. Here conditions ranged from river channel, through estuarine mud basin, to swamp. However, minor sub-aerial exposure is indicated in F.C. 5 by rare occurrences of iron oxide aggregrates in some clay layers. Generally, evidence of extensive weathering is absent. Although many pebbles and sand grains are lightly stained by iron oxide, this is more likely due to erosion of weathered source rocks than to in situ weathering of the sediment. The surface of the upper river sand unit is eroded, probably by marine processes associated with subsequent marine incursion. The upper river sands reflect renewed fluvial activity resulting from the fall in sea-level that followed the emplacement of the Inner Barrier sand unit (Roy, 1980). Fluvial activity extended over the southern half of Fullerton Cove where it eroded the Inner Barrier and part of the underlying estuarine clay unit (Fig. 4-22). The base level of erosion possibly reached as much as -50 m MSL.

5. Estuarine muddy sand (Q4Ed, bb). Shelly quartzose sands, about 4 m thick, disconformably overlie the upper river sand unit and overlap the southern part of the Inner Barrier beneath Fullerton Cove (Fig. 4-22). In the northern part of Fullerton Cove the sands are quartzose, fawn to grey, slightly muddy, fine to coarse-grained, poorly sorted and contain only minor wood and shell fragments. In contrast, the sands in the southern part of the estuary are dark grey, very muddy, fine to medium-grained, well sorted and contain abundant shell. They are also slightly lithic in their basal section. These differences are attributed to variations in the underlying substrate from which the sand unit was derived through reworking of quartzose Inner Barrier sands in the north and lithic river sands in the south. The higher mud and shell content of the sands in the southern part of the estuary reflects deeper water conditions and lower depositional energy levels than farther north where

the sand unit appears to grade into marine backbarrier deposits. The rich mollusc assemblage has not been studied in detail. Dredging along the South Arm of the Hunter opposite the steel works revealed a similar unit. These sediments represent deposition in a broad, shallow estuarine channel or bay environment that formed in the early stages of the Postglacial Marine Transgression. Presumably tidal currents carried marine sand into an estuarine embayment - the proto-Hunter estuary - and deposited it as a tidal delta (see Roy and Crawford, 1980, Fig. 21). Existing deposits around the sides of the estuary were reworked by currents and waves. With continued rise in sea-level, water depth apparently increased, energy levels declined, and a period of estuarine mud basin sedimentation commenced involving periodic sand input and diverse mollusc assemblage.

6. Outer barrier sand (Q5,6Met,er,br,nr,bb). Quartzose marine sands of the Outer Barrier sand unit comprise the seaward-most deposits bordering the Newcastle Bight shoreline (Fig. 4-22). They flank the southeast side of Fullerton Cove and occupy the area between the estuary and the sea. The Outer Barrier includes nearshore, beach, transgressive dune and backbarrier deposits of which only backbarrier sediments underlie Fullerton Cove itself. The other units are found to the northeast and east of the estuary. The sediment characteristics of each facies type, as they occur in the southern Newcastle Bight area, are as follows:

(i) Backbarrier sands. Clean to very slightly muddy sands border the SE side of Fullerton Cove and extend along the landward side of the Outer Barrier. In Fullerton Cove they overlie the estuarine bay muddy sand unit and reach a maximum thickness of about 25 m. Farther to the north, beneath the interbarrier depression, the backbarrier unit thins to less than 15 m (average about 5 m) and forms a sheet-like deposit overlying the Inner Barrier.

(ii) Beach and nearshore sands. As along other sections of the barrier, beach and nearshore sands form a seaward thickening wedge and grade into the backbarrier deposits in a landward direction (Fig. 4-22). Transgressive and regressive phases of both beach and nearshore units are recognised in the sub-surface in A.N.U. drill holes 92 and 119. To the south and east of Fullerton Cove, Outer Barrier deposits extend to at least -35 m and, in Stockton DDH 13 and A.N.U. 92, overlie fluvial sediments and estuarine clays respectively. However, to the north they thin to about 15 m (A.N.U. drill hole 120) and onlap the Inner Barrier (see 4.3.3.3).

(iii) Transgressive dune sands. Transgressive dunes up to 20 m high form prominent ridges on the surface of the Outer Barrier near Fullerton Cove. At least three and perhaps four distinct dune masses are recognised and correspond to separate phases of dune instability (see 4.2.3.2).

7. Estuarine mud (Q5,6Em). At the southern end of the Newcastle Bight embayment the two barriers diverge with the result that the depression in which Fullerton Cove is located is wider and deeper than it is to the north. By about 6000 years ago, the lower Hunter valley, possibly as far inland as Maitland and including the interbarrier depression, was drowned to form an estuarine mud basin environment of deposition (see discussion in Thom et al., 1969, on significance of radiocarbon date on Notospisula

shells from Eskdale Swamp: 5900 ± 145 ^{14}C yrs BP, 0-1844).

Muds, derived from the Hunter River, accumulated to a maximum thickness of 22 m in Fullerton Cove (Roy, 1980). They interfinger with backbarrier sands along the inner edge of the Outer Barrier, and overlie estuarine channel sands. The mud unit widens and deepens westwards towards the Hunter River. Tidal flat deposits (low tide mud flats, mangroves and salt marshes) occupy the inter-tidal zone around all but the south side of the estuary; they also overlie estuarine muds in the infilled section of the interbarrier depression to the northeast. Drainage ditches on the north side of the cove reveal abundant estuarine molluscs including Anadara and Notospisula.

The supply of fine sediment in the Holocene has been sufficiently abundant to virtually fill the Hunter estuary, leaving Fullerton Cove as the surviving remnant of a former extensive estuary. The present-day interchange of mud between the Hunter River and Fullerton Cove has been investigated by P.W.D. (1969) in connection with port development. They suggest that during floods Fullerton Cove acts as a storage basin for mud which is released back into the Hunter River in the post-flood period and causes siltation in Newcastle Harbour. Bottom sampling and drilling in the port area show muds infilling parts of the channel that have been deepened by dredging (Roy, 1977).

4.3.4 Depositional History (Fig. 4-23)

The depositional history of the Newcastle Bight embayment is the best documented of all embayments discussed in this monograph. In this regard it provides the depositional "model" against which sequences in other embayments are compared (see Ch. 10). Salient points of the sequence are as follows:

(i) Very little is known about the age and stratigraphic extent of the basal fluvial sediments noted in the Fullerton Cove section (Q1Tc).

(ii) One of the most revealing stratigraphic properties of the Quaternary sequence in this embayment is the thickness, lateral extent and apparent lithologic homogeneity of the Pleistocene clay lithofacies. It will be shown that a similar unit occurs throughout the study area. However, it is only in Newcastle Bight and adjacent Port Stephens that we have enough drill data, supplemented by seismic studies, to be able to comment on the unit's geometry and stratigraphic significance. The thickness of "clay" is interpreted as a polycyclic accumulation of estuarine sediment with each cycle representing an interglacial/interstadial high sea-level (Roy and Thom, 1981). The "clays" accumulated in a large estuary behind a coastal sand barrier on the upper part of the inner continental shelf slope. This barrier has been designated the "proto-barrier" by Roy and Crawford (1980, Fig. 20). The buried upper surface of the clay unit possesses a relatively uniform seaward slope and is only eroded at the western end (Ly, 1976). The clay and underlying fluvial sand and gravel units (Fig. 4-22) form the Q1 or lower unit, and are associated with sea-levels lower than present (see Fig. 4-23 and Ch. 10).

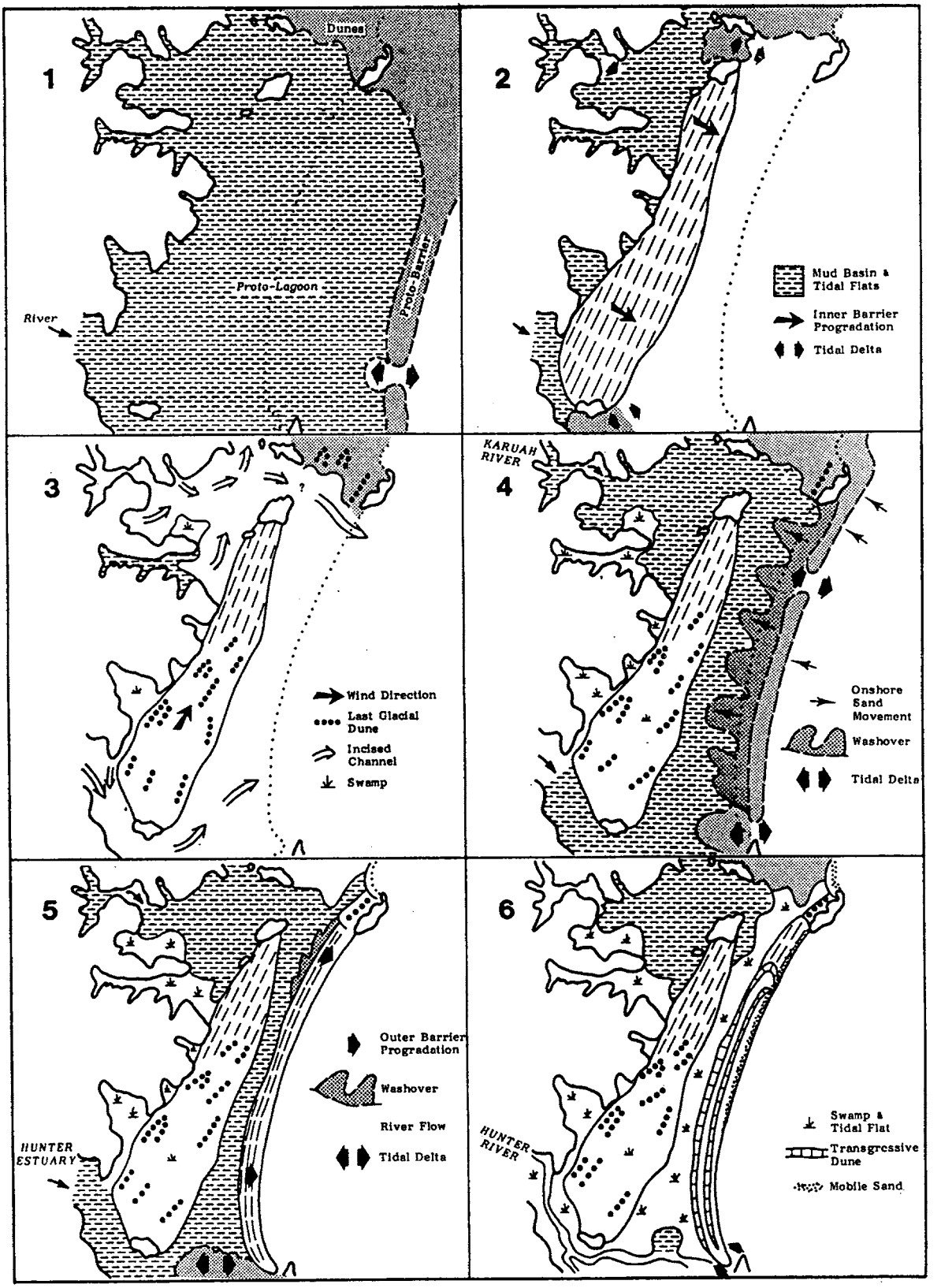


Figure 4-23: **Six stage model of the geomorphic history of the Newcastle Bight embayment (the stage numbers refer to time periods discussed in Chapter 10).**

(iii) The Last Interglacial (or Q2) is a better documented event in Newcastle Bight. Uranium-series dated corals at Grahamstown provide a reliable radiometric date by which the age of overlying deposits can be ascertained (Marshall and Thom, 1976). The age, stratigraphic position and environment of deposition of these corals support the idea that they lived during the transgressive sea just prior to the first high stand of the Last Interglacial (Chappell and Thom, 1978). What is uncertain is their relationship to backbarrier facies beneath the Grahamstown Swamp (now a reservoir). We are reasonably confident in correlating Last Interglacial beach-dune facies (= Inner Barrier) with (i) the clay-rich facies which rises to 5 m $\pm$ 2 m elevation in the vicinity of Pipeclay Creek at the western end of Port Stephens, and (ii) isolated shell-rich deposits in the Hunter Delta such as those at Largs (see David and Etheridge, 1890; Iredale, 1951; and Langford-Smith and Thom, 1969). The reduced nature of clays which occur immediately beneath Inner Barrier sands also suggests accumulation in a backbarrier-estuarine environment during the transgression. These clays form the uppermost deposit in the clay "pile" discussed above. Where they are not overlain by Inner Barrier sands they are oxidized (see A.N.U. drill hole 84). Figure 4-24 shows the buried surface of the Inner Barrier to slope gently seaward although it too is eroded in the west near the Hunter (see Roy, 1980, Fig. 8).

(iv) The impact of Last Glacial climatic change on sand deposits of the Inner Barrier appears to have been quite dramatic in this embayment. Channel incision by the Hunter River led to the deposition of fluvial sands (4.3.3.4, Q3Tc). A large part of this barrier has been reworked into longitudinal dunes (Q3Tc). However, only one period of reworking is implied by the absence of buried soils within dune deposits. The morphology and orientation of the dunes suggest sand transport from west to east. Strong westerly winds are said to be characteristic of periods of the Last Glacial (see Bowler, 1978). Our radiocarbon dates confirm this, indicating that sand movement was occurring as late as 11,000 years ago. That these dunes have been stabilized for a period longer than the age of vegetated Outer Barrier dunes and beach-ridges is clearly shown by differences in the degree of soil profile development (see Ch. 10).

(v) Another Last Glacial event recorded in the stratigraphy of this embayment is a marine deposit recovered in A.N.U. drill hole 84. This deposit occurs at c. 40 m below MSL and dates c. 28,000 ^{14}C yrs. Could this be the product of a marine transgression corresponding to an interstadial recognized elsewhere as occurring at this time (Chappell and Veeh, 1978)?

(vi) The period of the Postglacial Marine Transgression (Q4) is preserved in the stratigraphy with well-developed transgressive facies (open-ocean and backbarrier). In A.N.U. drill hole 84 (Table 4-3) there is evidence for an estuarine facies, which may also occur in the Hunter delta. There is also some evidence based on four drill holes near Bobs Farm (Fig. 4-12) that the transgressing proto-Outer Barrier was not as continuous between Stockton and Birubi Point as it is today. Dated samples recovered

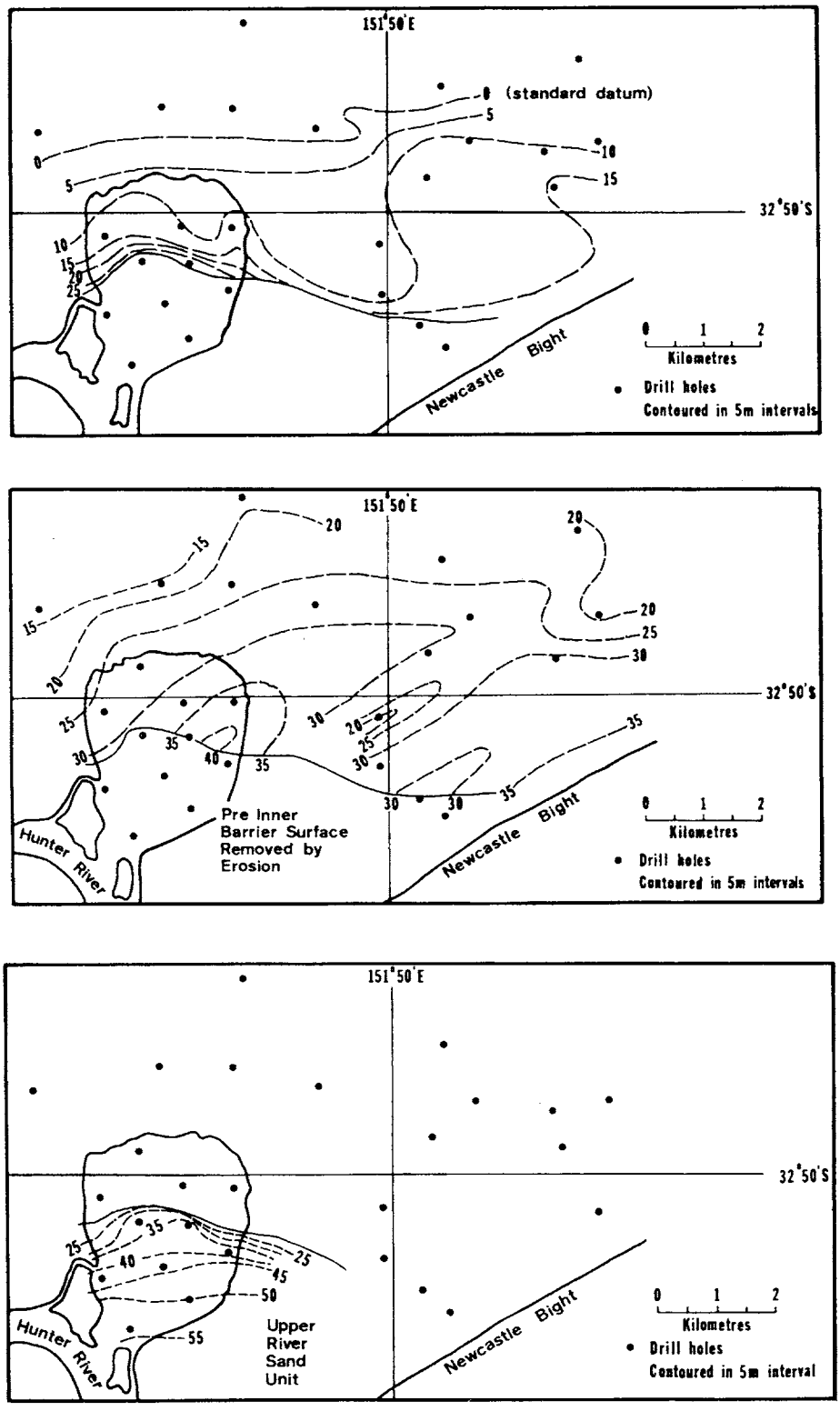


Figure 4-24: **Contours on the top of Inner Barrier sand surface (top), on the top of the estuarine clay/base of Inner Barrier sand (middle), and contours on the base of the fluvial sand (Q3Tc) in the vicinity of Fullerton Cove (from Roy, 1980, Fig. 7-9).**

from A.N.U. drill holes 74 and 81 show that at a depth of -10 to 15 m MSL a tidal inlet facies was formed 7800 to 8300 years ago (see Appendix B, ANU-1481,1334).

(vii) The period immediately following the stillstand of sea-level about 6000-6500 years ago was one of considerable geomorphic activity (Q5). The first major event was the establishment of the Outer Barrier enclosing an elongate "lagoon" (interbarrier depression). Along the shores of the progressively infilling interbarrier depression wind waves were reworking backbarrier sediments into projecting spits. The initial burst of progradation forming the beach ridges of the Outer Barrier was replaced about 4500 to 5200 ^{14}C years ago by the first "surge" of eolian activity (Ridge I).

(viii) The last 3000-4000 years of barrier history (Q6) have been dominated by the interplay of two sets of forces: one leading to the stabilization of mobile dunes initiated behind the open-ocean shore, the other leading to phases of dune remobilization. Dune transgression accompanying devegetation appears to have been initiated c. 2000 (Ridge II) and 300 to 500 (Ridge III) years ago. Eolian surges may simply involve the reworking of the initial input of sand from beach ridges and foredunes into transgressive dunes. However, the occurrence of younger shell fragments beneath the deflation plain of the Anna Bay transect (Fig. 4-19) strongly suggests deposition of some regressive barrier sand much later than that associated with the first major phase of progradation immediately following the commencement of the stillstand. Therefore, details of barrier accretion and eolian erosion in terms of precise timing and volumes of sediment added during barrier accretion compared to volumes lost by eolian transgression remain uncertain. As presented in this monograph, the chronologic sequence of deposition is only established in general terms, and much remains to be done before a more definitive history will be known.

5

Tomaree Hills – Port Stephens

5.1 REGIONAL SETTING

5.1.1 Bedrock Properties

The segment of the study area between Newcastle Bight and the entrance to Port Stephens is referred to as the Tomaree Hills. Unlike other segments described in this monograph, the Tomaree Hills is not differentiated on the basis of bay-barrier morphology or eolian features derived from it. The Tomaree segment obtains its character from the cluster of prominent bedrock hills at the southeast end of Port Stephens. These hills have been largely enveloped by several generations of eolian sand, but as will be shown below, these sand masses overlie the general clay unit which occurs throughout the study area.

This chapter will also discuss some of our findings on the Port Stephens estuary. The estuary was the subject of a detailed study by Roy. Aspects of estuarine morphology, sediment type and distribution, and stratigraphy are presented here because the evolution of Port Stephens is of major concern to those interested in the depositional history of this stretch of coast.

As indicated in Chapter 4, the eastern boundary of Newcastle Bight merges somewhat with the Tomaree Hills. Outer and Inner Barriers terminate against bedrock headlands, but the interbarrier depression

diverges with one part draining into Tilligerry Creek, the other becoming part of the sand and swamp complex behind Anna Bay (One Mile Beach). A line drawn between Soldiers Point and Birubi Point conveniently, if somewhat arbitrarily, divides the Tomaree segment from Newcastle Bight (Fig. 5-1).

Carboniferous rocks on south and north sides of Port Stephens have been included in the Nerong Volcanics Formation by Engel (1962) or the lower Kutting Series (Volcanic Stage) of Osborne (1950). The formation consists of volcanic lavas interbedded with minor amounts of conglomerate and arenite. It forms the western limb of the Girvan Anticline (Fig. 1-1); on the south side of Port Stephens the strata subscribe a broad arc suggesting probable closure of the fold (Engel, 1962, p. 209). Thus, the suite of volcanics and sedimentaries dips generally west and south in the Tomaree area (including Soldiers Point and Morna Point).

Volcanic outcrops, especially where they form sea cliffs, constitute an irregular rocky shore of reddish-grey quartz and feldspar porphyry. Toscanite, dacite and hornblende andesite are also common (see Sussmilch and Clarke, 1928). This sequence has been intruded by numerous basaltic dykes of presumed Tertiary age. Spectacular clefts occur along the ocean face of the high rock hills and offshore islands where these dykes have undergone differential erosion. Dykes vary in thickness from a few cm. to 5 m and in all cases seem to have been intruded along joints in the older lavas (Nashar and Catlin, 1959). They are olivine-free, feldspathic basalts and dolerites and occur as vertical swarms especially in the vicinity of Morna Point. Their distribution has been mapped by Nashar and Catlin (1959, pp. 100-101).

The distribution of bedrock outcrops in the Tomaree area is shown in Figure 5-2. This figure is partly based on the work of D. Nicholson, Geological Survey of N.S.W. It purports to show rock areas devoid of sand cover. Three types of outcrop can be distinguished: (1) coastal cliffs along both open ocean and estuary shores, where a dune sand mantle blankets the rock inland from the cliff margin; (ii) bedrock peaks such as Kurrara Hill, Stephens Peak, Glovers Hill, Gan Gan, etc. which protrude through the surrounding sand cover; and (iii) bedrock promontories or headlands such as Tomaree and Port Stephens standing isolated from the dune complex, but linked by narrow sand ridges to it.

The wave-washed surface of the bedrock has not been studied systematically. The development of pronounced platforms is inhibited by the apparent resistance of Carboniferous lavas to wave erosion and water-layer weathering. Close jointing within the lavas creates narrow, steep-sided bays containing boulder beaches. SCUBA diving has revealed continuation of the irregular rocky surface and boulder beaches to depths of 10-20 m below sea-level (e.g. near Boat Harbour). At greater depths a sand cover is more general.

Bedrock peaks, such as Gan Gan Hill and Glovers Hill, have a surface topography quite distinct from that of the surrounding dunes. The lower slopes are formed in sand and are smooth with inclinations being relatively gentle (less than 20 degrees in most cases). However, further up the slope where the surface is rocky, there is usually a sharp inflexion of slope, above which the slope steepens. The flora also changes with the Eucalyptus-Banksia woodland giving way to a more shrubby community on the rock surface in which Casuarina sp. is prominent.

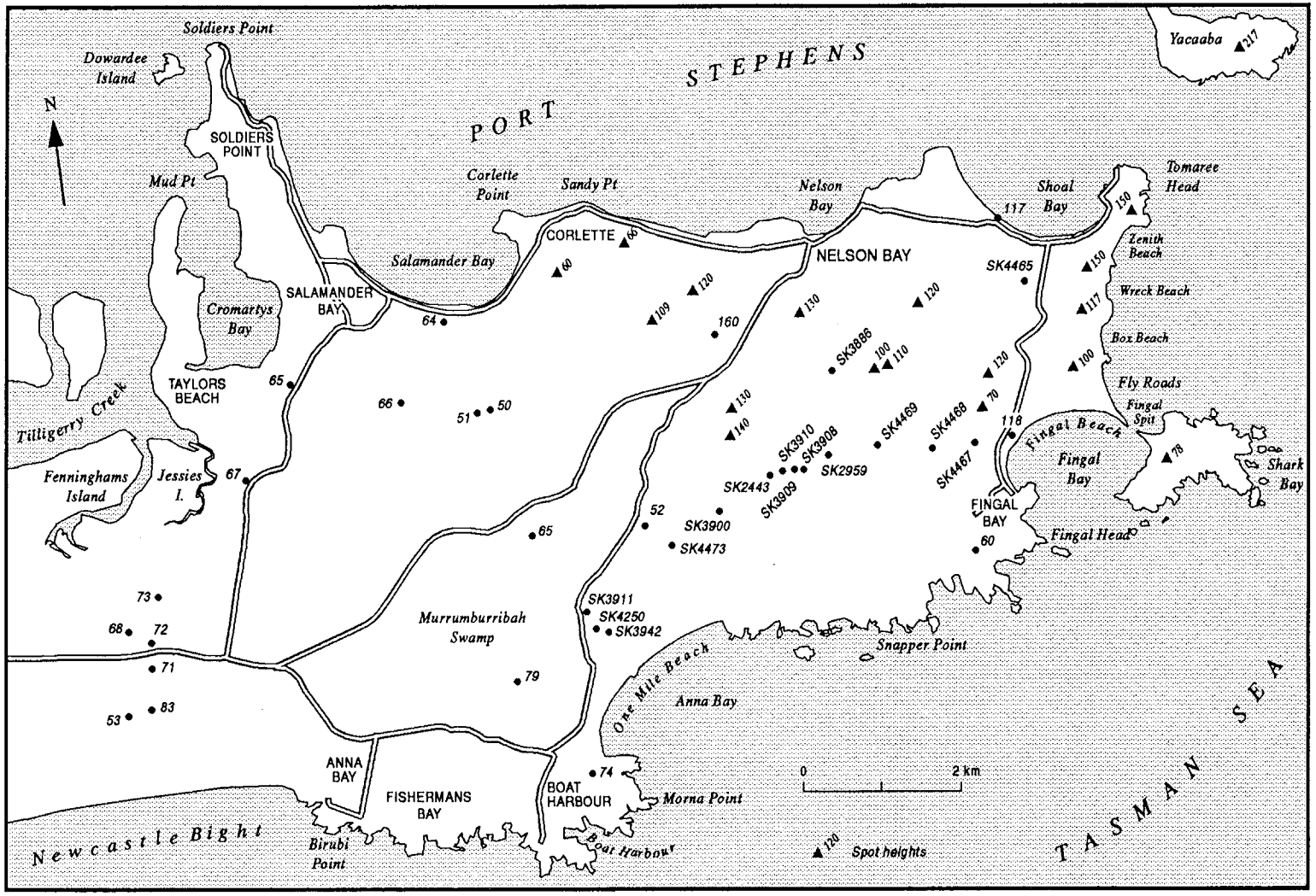


Figure 5-1: **Location map of Tomaree Hills segment showing elevation of major peaks and location of drill holes and stratigraphic sections. More details on topography are presented in Port Stephens (9332-IV-S) and Morna Point (9332-III-N) topographic maps (1:25,000).**

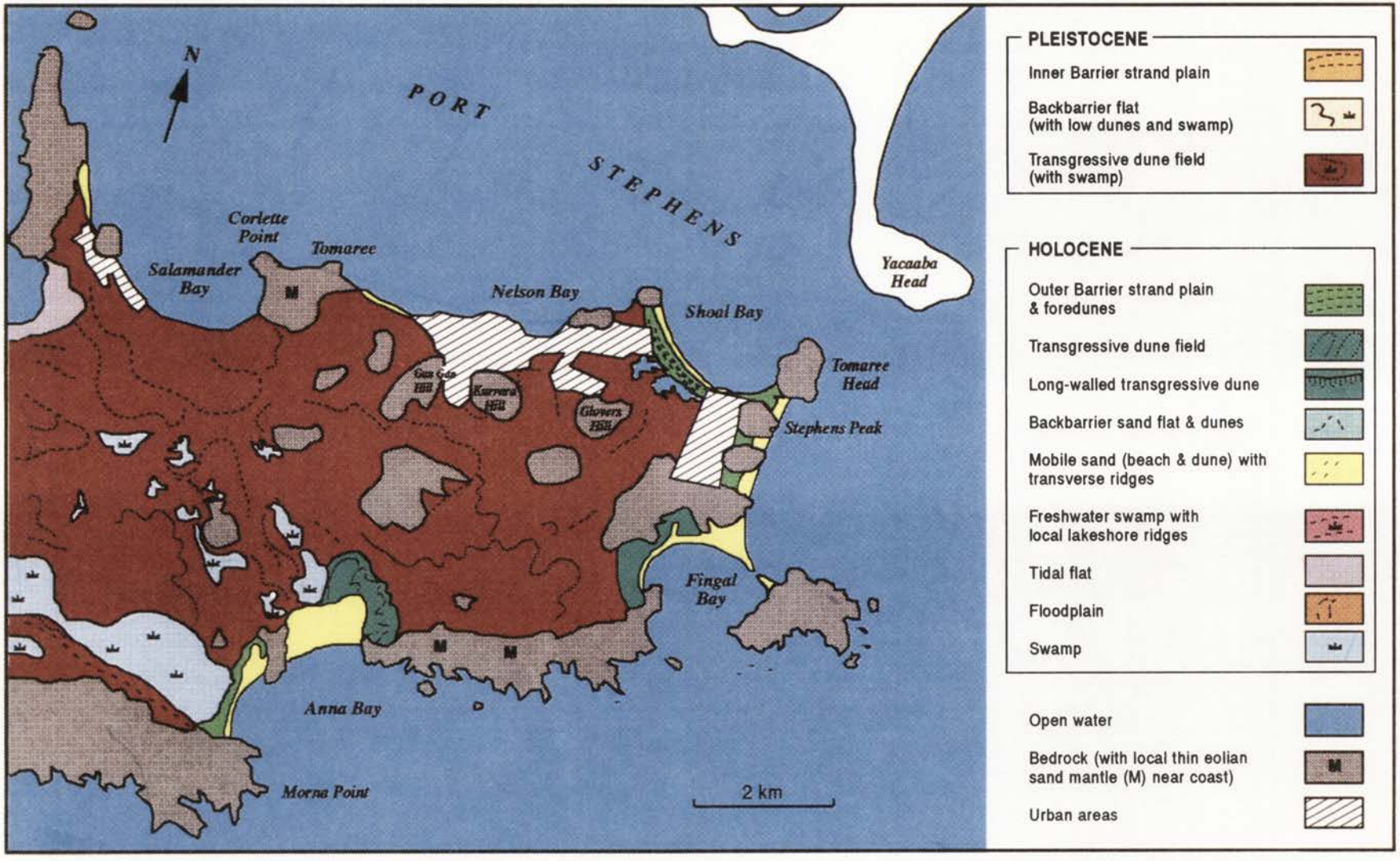


Figure 5-2: Generalized morphological map of Tomaree Hills segment highlighting distribution of bedrock outcrops enveloped by dune sand (based in part on mapping by D. Nicholson, Geological Survey of N.S.W.).

5.2 MORPHOLOGICAL CHARACTERISTICS

5.2.1 Major Morphological Features of Tomaree Hills and Port Stephens.

The Tomaree Hills is an area of considerable variability in relief ranging from lowland swamps and sand plains in the western part between Salamander Bay and Anna Bay, to the towering rocky peaks partially enveloped by sand in the east. A contour map highlights actual relief differences in the Tomaree segment (Fig. 5-1). In the western part of the segment the sand-swamp surface is generally below 10 m except where small bedrock knobs reach elevations of 50 m. However, to the east, commencing along a line between Corlette Point (east side of Salamander Bay) and the eastern headland of Anna Bay, the terrain mostly lies above 30 m (Fig. 5-1). Tomaree Headland, Stephens Peak, Gan Gan (South and North) and Kurrara Hill all exceed 150 m. There are a number of smaller bedrock hills which exceed 100 m (e.g. Glovers Hill).

Within the Tomaree Hills region two distinct depositional complexes can be recognized: (i) dune ridges and swamps; and (ii) beach and foredune deposits confined to small embayments exposed to ocean waves on the south and east flank of the Tomaree segment. The geomorphology of these depositional units will be discussed in 5.2.2.

Port Stephens is a large estuary open to the sea between Tomaree and Yacaaba headlands (Fig. 5-3). Early last century, Captain Stokes vividly described the outer part of the harbour.

> Here are a number of conical hills from 400 to 600 feet in height ... two of them, very remarkable headlands, and preserving the aboriginal names of Wacaba (Yacaaba) and Tomaree constitute the entrance points of Port Stephens. The sea face of Tomaree is a high line of cliffs from which projects a sand spit leaving only a narrow entrance ... Within the entrance are extensive sand banks, leaving between them and the south shore a narrow and some parts deep, channel subject to a rapid stream to tide.*

Bedrock topography dominates the northwestern side of Port Stephens. Here wooded steep-sided valleys have been drowned by the marine transgression (e.g. North Arm Cove). The southern side is composed of sand terrain linked to bedrock hills such as those at Tanilba, Lemon Tree Passage, Soldiers Point and Corlette Point. A major river, the Karuah, enters the estuary at the western end, whilst drainage of the Myall Lakes debouches into the eastern part of Port Stephens via an interbarrier depression (Lower Myall River). Figure 5-3 also shows another interbarrier depression, which is drained by Tilligerry Creek. This creek is connected to the estuary on the south side and discharges mainly tidal waters (see Ch. 4 for further discussion of this depression).

Port Stephens is hydrodynamically dominated by a semi-diurnal tidal regime (see Ch. 1). Along the N.S.W. coast there are many barrier

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* Captain Stokes in Discoveries in Australia, Vol. 1, Ch. 10, quoted by S. Sidney in Sidney's Emigrants Journal, London, 1850, Orr & Co., p. 79, and by A. Harris in Guide to Port Stephens in New South Wales, London, 1849, Orr & Co., pp. 213-214.

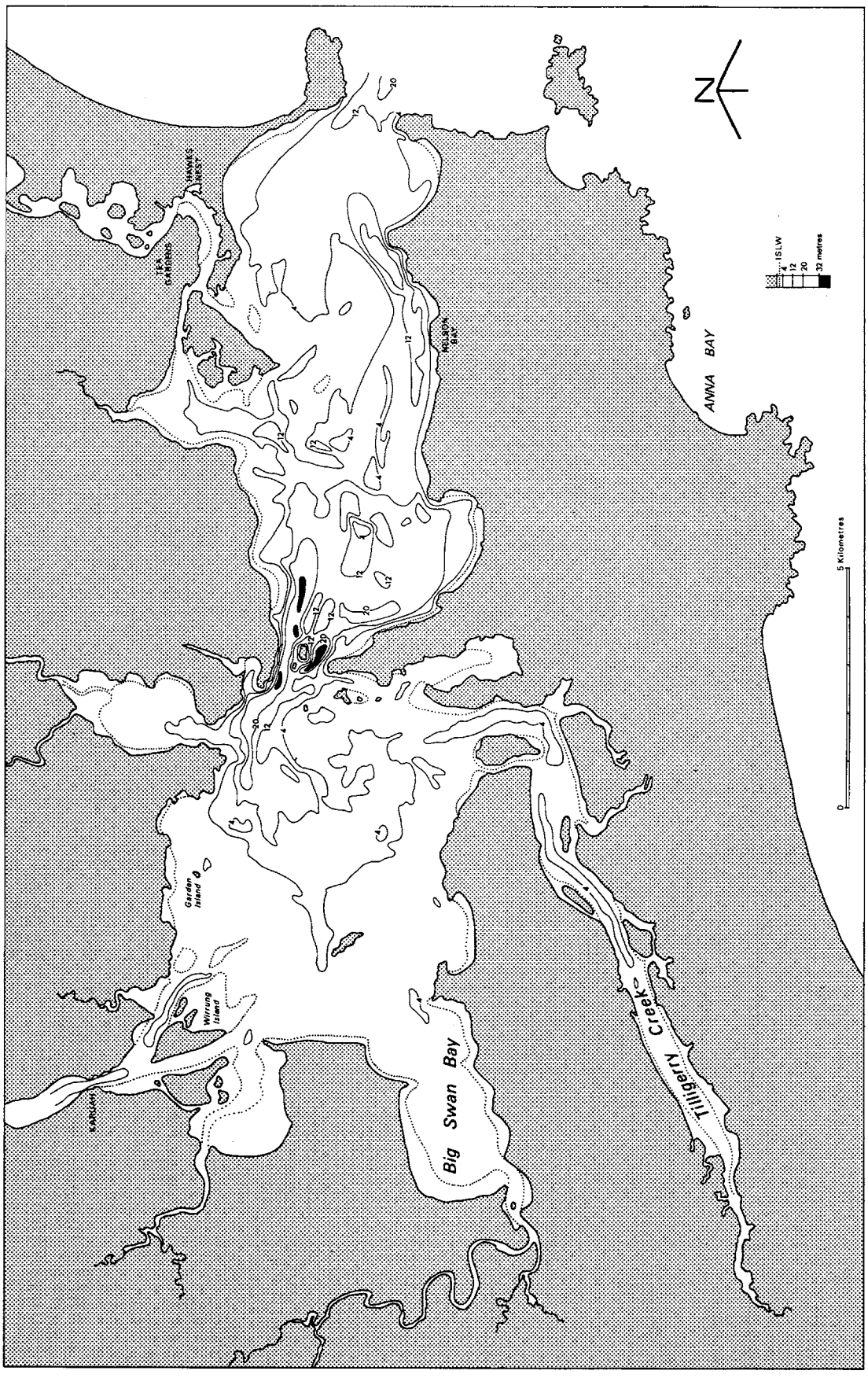

Figure 5-3: Bathymetry of Port Stephens.

lagoons which enter the sea through narrow tidal channels (e.g. Lake Macquarie). In these cases the tidal range rapidly diminishes away from the inlet (Roy, 1984). However, the wide entrance of Port Stephens permits much greater tidal exchange and maintains a more or less constant range throughout the estuary. Freshwater inflow only slightly modifies sea water salinities at times of high runoff at the mouths of the Karuah and Lower Myall rivers. The effect of high salinities is seen in the extensive mangrove-salt marsh flora, and in the molluscan fauna of estuarine sediments.

Topographically, Port Stephens can be divided into three parts: (i) shallow tidal delta sand-banks to the east; (ii) broad, locally deep mud basins in the centre; and (iii) to the west of Soldiers Point, an extensive shallow mud basin into which protrudes the fluvial delta of the Karuah River (Fig. 5-3). The morphological and sediment details of these areas will be discussed in 5.2.3.1 and 5.3.2.3, respectively.

5.2.2 Tomaree Hill Dunes

5.2.2.1 Stabilized Pleistocene dunes and swamps.

The bedrock framework within which Quaternary sediments were deposited in the Tomaree segment is the highly dissected southwest limb of the Girvan Anticline. Total bedrock relief (above and below present sea-level) exceeds 200 m with a cluster of closely spaced, conical-shaped peaks constituting the dissected remnants of the ancient lava sequence. This "tight" hilly terrain has been linked by unconsolidated sediments known to be over 70 m thick in places (see 5.3.1) much of which is sand (5.3.3.3).

Nowhere within the bedrock hill region or in the flatter western region between Anna Bay and Salamander Bay have sand beach ridges been observed. The morphology of surficial deposits is eolian in character. A detailed map of dune ridges (Fig. 5-2) clearly shows the arcuate form of sand deposits. These features are all well vegetated (Eucalyptus pilularis, Banksia serrata dominants) and often enclose swampy depressions. In the flatter, western portion of the Tomaree segment a distinctive west to east alignment of ridges is observed, but in the hilly eastern part of the dunes are confirmed to spaces between bedrock peaks (see Browne et al., 1986, for more details on Tomaree "land systems").

Western area. The lowland landscape of western Tomaree is a complicated maze of curved ridges enclosing swampy depressions. Dune morphology between Anna Bay and Salamander Bay is dominated by arcuate forms which have the appearance of a degraded parabolic dune complex (Fig. 5-2). The overall pattern is quite complex with individual ridges over-riding and merging with one another across a broad sand plain. Enclosed depressions are numerous at elevations of no more than 1 to 3 m above MSL. These depressions are swampy, many containing standing water even during very dry periods. A freshwater swamp flora dominated by Melaleuca and various reed species occurs in these wetlands. At the time of dune formation the depressions presumably were deflation surfaces. They became permanently water-logged as the water-table rose flooding the low-lying terrain. These depressions could be regarded as water-table window "lakes" (Fig. 5-4).

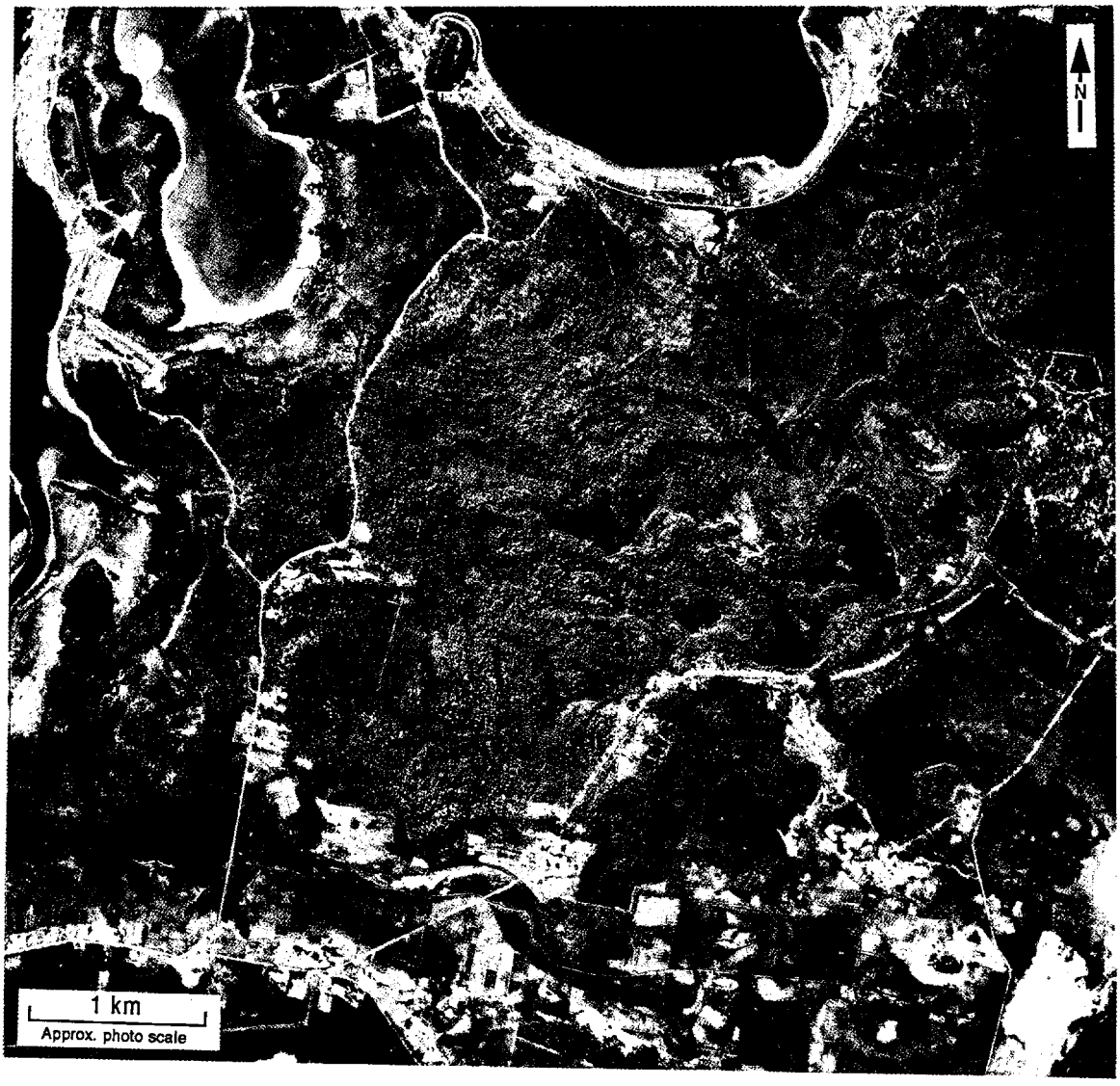

Figure 5-4: **Salamander Bay dune field and "watertable window" swamps and freshwater lakes which have formed in deflation basins of the Pleistocene dunes.**

Arcuate ridges within the western area mostly face the west or southwest. They may be several kilometres in length (Fig. 5-4). In section, the ridges are reasonably symmetrical. The dune sands are well-podzolized (see 5.3.2.2). An origin as nested parabolics involving the reworking of older Pleistocene sands is suggested for this dune field with effective winds being from the western quadrant (5.3.3). Time of formation must be when sea-level was lower than present because the flooded depressions, often at least 2 m deep, occur so close to present sea-level. It is suggested that the Postglacial Marine Transgression led to water-table "drowning" of dune deflation basins. Exact period of dune formation is unknown, but is most likely to be within the Last Glacial on the basis of comparative soil morphology (see Ch. 10).

A linear dune ridge possessing similar soil properties to those just described occurs north of Morna Point (Fig. 5-2). This ridge is sheltered from the south by the extensive Morna Point bedrock ridge. In common with other dunes in the area, it is well vegetated by a Eucalyptus woodland except where cleared for housing or farming. The Morna Point sand ridge is nearly 4 km in length and trends east to west. At the western end it is forked with both arms forming low hummocks above the surrounding swampy surface. To the east, where it is single crested, the ridge is slightly sinuous. It cuts across an extension of the bedrock surface east of the Anna Bay Public School. The ridge has a tapered terminal end near the intersection of the Anna Bay road and the road to Boat Harbour. In profile the ridge is quite symmetrical with the general beaded form of rounded hillocks and broad cols noted from similar features in the Tomago area (see Ch. 4). The ridge stands c. 10-13 m above the surrounding sand and swamp surface. Again, it appears that westerly winds at times of lower sea-level were responsible for dune development (see 5.3.3). Soil profiles on the Morna Point sand ridge are similar to those of Tomago "longitudinal" ridges and the dunes near Salamander Bay (Appendix A; see also Ch. 10).

Eastern area. The Tomaree bedrock hills are flanked by prominent sand ridges some of which rise to +50 m MSL, but mostly are less than 30 m high. Dune ridges occur between Gan Gan South and the coastal bedrock outcrop between Anna Bay and Fingal Bay (Fig. 5-2). A prominent ridge extends northwards towards Nelson Bay wrapping itself around the eastern and southern sides of Gan Gan South and Kurrara Hill. These ridges enclose depressions against the bedrock hills. Elsewhere the bedrock is mantled by a veneer of dune sand except along the rocky shorelines and summits of peaks (Fig. 5-2).

In the eastern area where the bedrock is veneered with a sand cover, details of eolian morphology are difficult to observe. Mention has been made of the sharp break-of-slope between rocky summits and the "apron" of mid to lower slope dune sand mantle. On many of the peaks, such as Gan Gan and Kurrara Hill, the mantle reaches elevations of 70-80 m above MSL. It is observed in exposures on the road up to the lookout (Telecom Station) on the east side of Gan Gan North. Clearly the sand mantle thickens downslope. Peaks nearer Shoal Bay and Fingal Bay are covered by sand to heights rarely exceeding 50 to 60 m.

Finally, there are the broader low-level sand depressions which occupy the valleys between the dune ridges and bedrock peaks (Fig. 5-2). Mostly these surfaces are relatively smooth and occur at elevations of 15 to 30 m. Melaleuca is a dominant tree. Locally, the sand surface is

swampy. An interdune surface slopes to the west where it merges with the dune-swamp complex less than 10 m in elevation behind Anna Bay (Fig. 5-1). This terrain can be observed along the road between Anna Bay and Nelson Bay, to the southeast of the Gan Gan military camp.

5.2.2.2 Holocene beaches and dunes.

The rocky shoreline margin of the Tomaree Hills is strongly indented. Here embayments appear to follow joint patterns within the Carboniferous volcanics. They are often quite rectangular in shape, facing in various directions to the east and west of Anna Bay (Fig. 5-2). Many of the narrow, relatively steep-sided bedrock bays contain a concentration of well-rounded boulders at the head. The boulders are composed of quartz-porphyry. Above high water these boulder beaches are covered by shrubby trees including Banksia integrifolia and Leptospermum laevigatum. In this study, no systematic effort has been made to survey the levels of boulder beaches in relation to exposure or any other factor. However, elevations of +5 m above HWST are not uncommon. Sussmilch and Clarke (1928) have described the most extensive feature, the so-called "raised beach" of Morna Point. The locality is strictly the southern side of Boat Harbour (Fig. 5-1). SCUBA investigations have shown the continuation of the boulders to 15 m below sea-level along this side of the bay. An extraordinarily deep "hole", 30-40 m below sea-level, occurs at the mouth of this bay. These boulder beaches are similar to those studied by Oak (1981, 1984) at Yacaaba (Ch. 6).

Several sandy beaches occur along the rocky, open-ocean shores of Tomaree. They are often of mixed mineral composition indicating sand derivation in part from the local bedrock. Shell fragments composed of rock littoral species are also abundant in the sands. Many of these pocket beaches occur between Point Stephens and Tomaree Headland. They are typically steep beaches (reflective type) backed by low dunes. At Zenith Beach, on the south side of Tomaree Headland, a blowout oriented to the SSE has cut the foredune and enabled sand transport to occur almost into Shoal Bay. Again neither beach morphology nor beach composition has been systematically studied.

The Tomaree Hills segment also includes six larger beach-dune systems within relatively broad bays between rocky headlands. Two of the bays are exposed to open-ocean waves (Anna Bay and Fingal Bay), one bay is exposed to highly diffracted waves inside the entrance of Port Stephens (Shoal Bay), and the other three bays are influenced by predominantly wind waves within Port Stephens (Nelson Bay, Dutchmans Beach and Salamander Bay) (Fig. 5-1).

Anna Bay. This is clearly the most exposed embayment of the six (Fig. 5-1). The bay is divided into two parts by a low rock ridge (Middle Rock); the southern part is known as One Mile Beach and lies in a relatively protected position behind Morna Point. Here the foredune is low and undissected. To the north, pronounced blowouts cut through the wooded foredune, the flora of which has been described in detail by McDonald (1971, 1973, Fig. 2). Anna Bay reproduces on a smaller scale what is seen in the Fens Embayment (Ch. 6), namely the progressive destruction of the established foredune from south to north. A mobile dune sheet widens to a maximum width of 0.8 km to the north of Middle Rock behind Samurai Beach (Figs. 5-1, 5-5). This sheet in 1960 possessed



Figure 5-5: Mobile dune development at the northern end of Anna Bay (behind Samurai Beach). In 1960 there were four active transverse dunes on this dune sheet. Over the last two decades the dune sheet has continued to spread northwards but in places has been encroached upon by sand-binding vegetation (see Cockburn, 1986). (Airphoto N.S.W. 1417-5097, 14/11/65).

at least four free-moving asymmetrical dunes of the reversing type. In Figure 5-5 the encroachment of sand-binding plants over these dunes is illustrated. Vegetation on the incipient foredune has become more extensive during the last two decades at Anna Bay. The smaller dune sheet south of Middle Rock is dotted with "remanie" knobs containing a buried soil surface. Here the deflation surface is covered with a coarse sand and volcanic gravel lag deposit. Some of the boulders may have been transported from local headlands by the aboriginal people. Large rounded stones of similar composition also occur within shell middens at Birubi Point (Hall, 1928).

The foredune complex at Anna Bay is interpreted as part of a stationary barrier which formed during Holocene "stillstand" period. The complex foredune ridge has been periodically reworked by eolian activity. The ridge merges at the northern end of the bay with two parabolic dunes which are vegetated by a Eucalyptus-Banksia woodland. Preliminary soil investigations confirm the morphologic impression created by sharp topographic relief, that these dunes are mid to late Holocene in age. Apparently, an episode of eolian instability, which occurred at the north end during an early phase of barrier development, was terminated by vegetative stabilization processes. The current phase of instability as manifested by mobile dunes to the north of Middle Rock destroyed much of the established foredune, but in recent decades plant colonization appears to be very active. However, Cockburn (1986) has shown that the dunefield behind Samurai Beach is still migrating to the north and the northwest. Sediment for the migration appears to have been provided by reworking of the dunes themselves resulting in an overall decrease in the elevation of the dunefield. The shoreline of the beach is relatively stable. Stability of the beach and decrease in dune height are in contrast to observations from Newcastle Bight (P.W.D., 1977; Robson et al., 1986).

The Anna Bay barrier blocks off a low depression behind One Mile Beach. This depression is the northern extension of the long interbarrier depression behind the Newcastle Bight Outer Barrier. From Fullerton Cove to One Mile Beach, the surface rises no more than 1 m above HWM; local farmers have been forced to drain the depression and install tidal flood gates. A local resident (the late Mr Joe Robinson) informed one of us in 1960 (BGT) that the original drain from the Anna Bay "Flats" was dug through the foredune at the south end of One Mile Beach. However, dune and beach sand movements made this drain impractical and they were forced to connect their drains to Tilligerry Creek. In fact, blowout instability behind One Mile Beach in 1927 resulted in the relocation of the Anna Bay-Nelson Bay road to the west (J. Robinson, pers. comm.).

Fingal Bay. This bay differs from Anna Bay in two respects: first, it possesses a relatively narrow mouth confined by bedrock headlands; and second, one of the headlands is really a bedrock island tied to the mainland by a sandy tombolo (Fig. 5-6). In plan the bay is almost circular, and this is related to the tight opening facing south which causes strong refraction of long period waves from east to south directions. The south end of the bay is backed by a complex layered dune sequence exposed by wave erosion. This sequence will be described below (5.3.3.3). It extends northwards into a prominent foredune ridge well vegetated by Banksia and Eucalyptus sp.

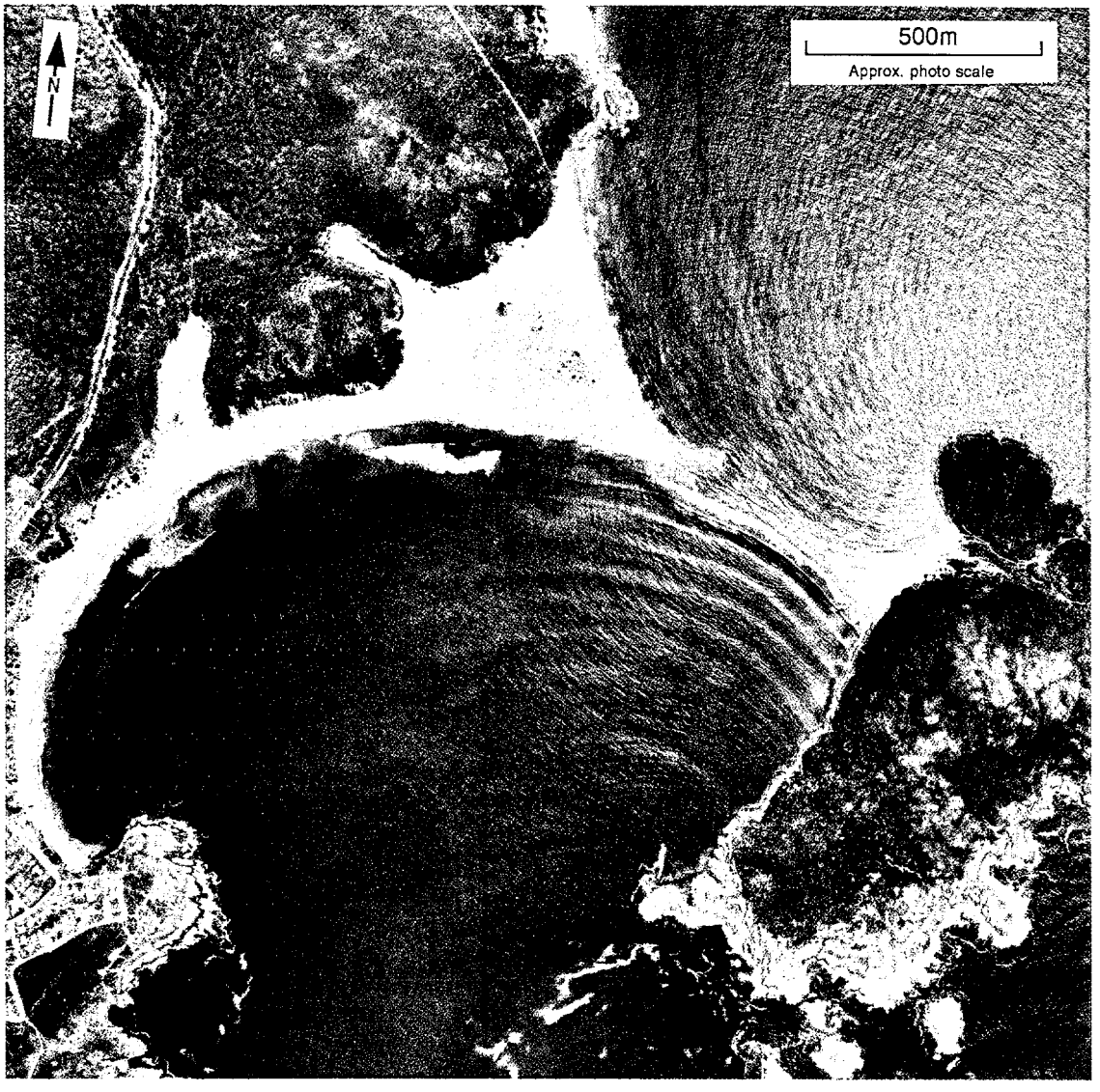

Figure 5-6: **Fingal Bay and Port Stephens tombolo. The blowout dune at the northern end of the beach faces due south. (Airphoto N.S.W. 1417-5051, 14/11/65).**

Towards the north, the beach at Fingal Bay steepens and coarsens. The inshore zone often contains crescentic bars. A well-developed berm backed by an ephemeral incipient foredune has been noted. A prominent blowout facing southeast cuts the foredune ridge. This blowout is long, with a width to length ratio of 1:3. The mouth of the blowout is well vegetated by Spinifex and the deflation hollow is frequently wet and partially vegetated.

Immediately north of the blowout the vegetated foredune abuts bedrock, but as the bay begins to curve to the east, the bedrock terminates and the sand mass forms a tombolo connected to Point Stephens (Fig. 5-6). This sand surface is poorly vegetated and large sections of it are awash at high tide. The tombolo is subjected to strong wave action from both north and south sides. Southerly waves are mostly responsible for its erosion. Crescentic inshore topographies are smaller in size on the northern side compared to the southern side. The landward part of the tombolo is reworked by winds into low hummocky dunes.

Shoal Bay. Shoal Bay is located on the south side of the entrance to Port Stephens just inside the entrance. One headland is Tomaree whilst the other is Halifax Point (Fig. 5-1). The embayment is oriented east-west and curves gently to the northwest in the manner of a half-heart or zeta-shaped bay. The beach is remarkable in a number of ways. There is a gradual but marked increase in beach width from the sheltered east end in the lee of Tomaree towards the west. The subaerial beach coarsens and steepens in this direction (see Magazinovic, 1985, for details). The west end of the beach is steep and is characterized by a hierarchy of well-developed cusps rising to 3 m above HWM. These cusps are always present at the western end of Shoal Bay. As many as three sets have been observed with the upper set possessing the maximum spacing. Waves responsible for cusp development are highly diffracted swell waves which pass through the narrow opening at the entrance of Port Stephens. These waves perfectly mimic the plan form of the beach at the west end of Shoal Bay. Here the beach is a classic reflective type with waves approaching over a relatively deep inshore zone to plunge on a prominent step at low water. Sand grain size is coarsest near the step and fines offshore across a rippled but non-barred inshore zone.

The foredune complex at Shoal Bay has been disturbed by building construction. However, it locally blocks off swampy depressions. In common with Fingal Bay, the ridge is vegetated by tall Eucalyptus pilularis as well as Banksia integrifolia and B. serrata. The "maturity" of the flora suggests erosional retreat of the frontal dune complex (see 5.3.3.4).

Other Bays. Other beaches of the Tomaree area, occurring within the Port Stephens estuary are quite narrow. Typically, they are composed of medium to fine quartz sand (for instance, Nelson Bay, Dutchmans Beach and Salamander Bay, Fig. 5-1). They are not subjected to open-ocean waves except perhaps to some highly diffracted swell during major easterly storms. Visual observations indicate the absence of periodic berm development. However, in recent years westerly wind-waves have caused local erosion of the backshore and property damage. At Corlette Point residents have constructed rock walls in order to mitigate erosion. The degree to which building construction has accentuated erosion processes is unknown. In Salamander Bay, the beach is quite narrow (less 20 m), except at the west end, and the sediments in the shallow nearshore zone

are muddy sand. Aspects of beach erosion in the Nelson Bay area have been studied by Nielsen (1979).

5.2.3 Port Stephens

Port Stephens can be regarded as a complex barrier lagoon permanently open to the sea at its western end (Figs. 2-1, 5-3). It is comparable with many estuaries along the N.S.W. coast where fluvial processes have relatively less impact today on morphology and hydrology than during periods of low sea-level (e.g. Port Hacking, Port Jackson, Broken Bay; see Roy et al., 1980). Port Stephens has been described as a drowned-river valley, or "ria valley" (Sussmilch and Clarke, 1928). However, this is true only to the extent that river channels flowed around or through ancient Pleistocene sand barriers which linked bedrock hills during the Last Glacial low sea-level period, and that these valleys have been "drowned" by the Postglacial Marine Transgression.

5.2.3.1 Subaqueous morphology.

In Figure 5-7 the major modern depositional units are shown for those parts of Port Stephens below LWM. The basic division is into those depositional features dominated by fluvial processes and those dominated by tidal processes. In the former, tidal forces tend to modify the landform and sediment complexes which are primarily dependent on fluvial action, and in the latter, waves entering Port Stephens through the mouth have a local effect on deposits where the form and composition of those deposits is predominantly of tidal origin.

Port Stephens can be conveniently divided into two sections, east and west of Soldiers Point (Fig. 5-3). To the west of this bedrock ridge, the estuary consists of a shallow (less than 10 m) basin blocked by the Inner and Outer Barriers of Newcastle Bight. Into this portion of Port Stephens flows the Karuah River, the only river of any significance which brings sediment into this estuary. There are clear subaerial and subaqueous levees extending about 4 km into Port Stephens from the bedrock confines of the river channel near the township of Karuah. Levee configuration indicates splitting of channel flow into two main distributaries. The deltaic form shows no sign of wave reworking. Sediments consist of muddy lithic sands. Except for a narrow band of sand around the shores, the remaining part of western Port Stephens is a mud basin. This basin serves as a pro-delta environment of deposition of the Karuah River. Tidal currents are believed to be mainly responsible for the dispersion of the fines throughout the estuary including into the more remote bays and tidal creeks. Shell bioherms occur within the mud basin of western Port Stephens (Fig. 5-7; see Peat and Roy, 1975).

The eastern section of Port Stephens contains no recognizable landforms associated with fluvial deposition. Although the Lower Myall River debouches into this part of the estuary, it is morphologically a tidal channel in its lower reaches and mainly serves as a conduit for removing excess water from the Myall Lakes (see Ch. 6). Tidal and, to a lesser extent, wave processes rework sands and muds in eastern Port Stephens into two major landform units: tidal delta and mud basin. Prominent shell bioherms (e.g. West Bank; see Peat and Roy, 1975) project through mud basin and tidal delta sediments (Fig. 5-7). The mud basin is deeper (to 20 m) in eastern Port Stephens, although in the narrow channel east of Middle Island the estuary achieves its maximum

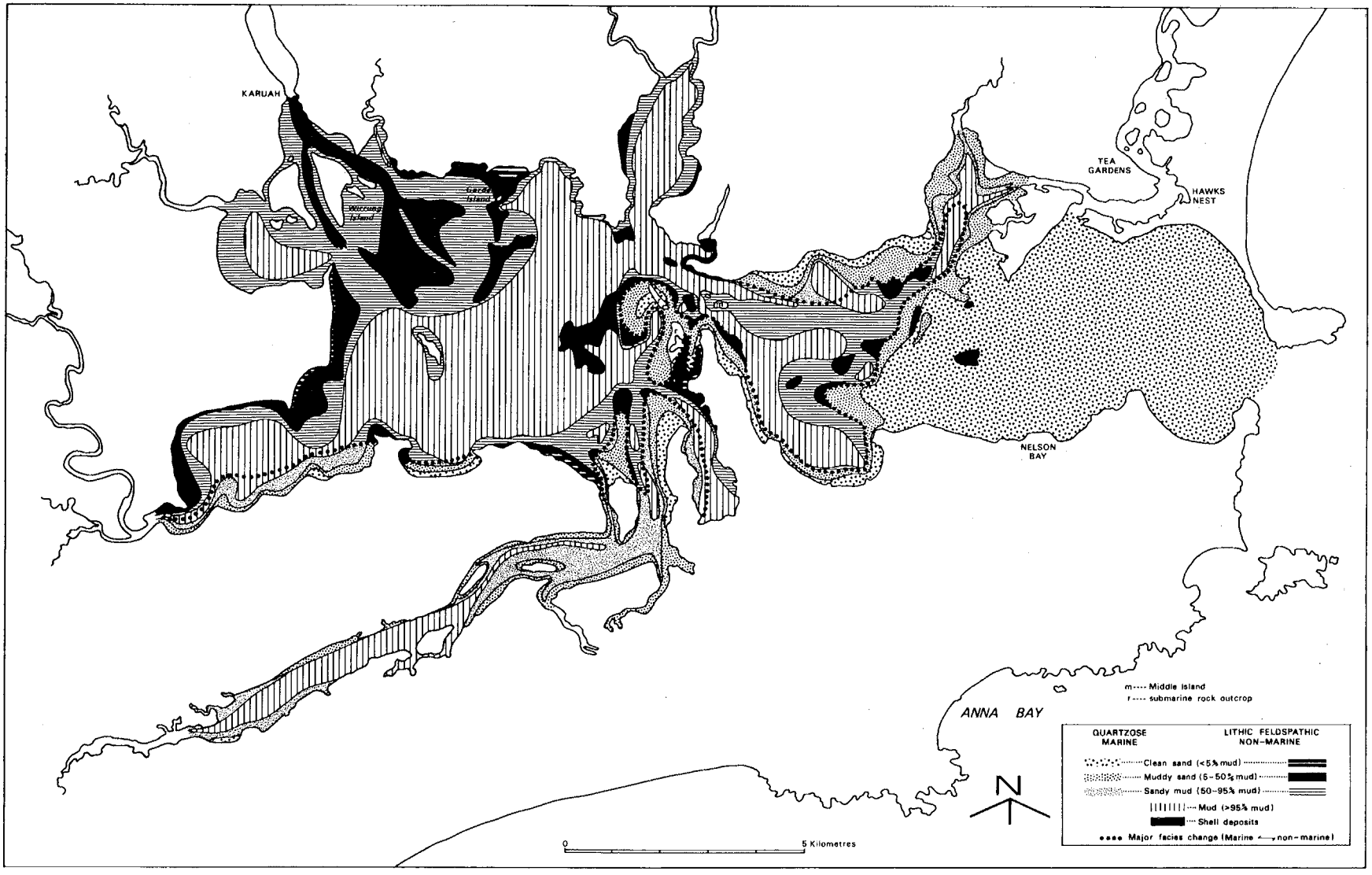

Figure 5-7: Depositional environments of Port Stephens.

depth of 33 m. Except for a deep tidal channel between Corlette Point and Nelson Head, the flood tidal delta in the eastern section is very shallow (mostly less than 4-8 m; Fig. 5-3). A complex sand wave pattern of this flood tidal delta is illustrated in Figure 5-8. At low tide waves may break on these sand shoals which extend across the mouth of the estuary. Surface sampling, drilling and diving have shown the local occurrence of bioherms within the tidal delta sand body. Sea grasses, especially Zostera, grow in patches on tidal delta sand. Details on the configuration and tidal dynamics of this sand body are the subject of a report by P.W.D. (1973; see also Nielsen, 1979).

5.2.3.2 Subaerial morphology: Myall Point.

Myall Point or Winda Woppa spit is one of the few areas in eastern Australia where map coverage extends back into the 18th century. Table 5-1 lists maps and charts known to the authors on eastern Port Stephens, including the Winda Woppa spit. The table lists map or chart title, the surveyor or institution responsible for the survey, the scale, location of the original plan and reference number (where applicable). Of all the maps listed in Table 5-1 at least 7 are quite useful in defining changes in location and morphology of the spit.

Particularly exciting was the discovery amongst the so-called "Watling Drawings" of an "eye map" drawn by an unknown artist in November, 1791 (see D-Ombrain, Newcastle Morning Herald, October 11, 1958). This map is reproduced here as Figure 5-9. Although crude in outline, the basic shape of eastern Port Stephens is recognizable. A channel hugs the south shore and exceeds 6 fathoms (c. 12 m) in depth, to the north of which is a "sandy bottom" area with two prominent shoals, "Pelican Shoals" and "Stingrea Shoals". The map is marked "Here I suppose no passage for a Vessel" to the north of these shoals.

By itself the "Watling Drawing" chart would be of little help in deciphering the history of eastern Port Stephens, but in 1795 W.R. Broughton surveyed the eastern part of Port Stephens. His chart more accurately depicted the shoreline. On the north side it shows the entrance to the Lower Myall River, a prominent point on the south side of the river and an "island" to the southwest (Fig. 5-10a). A "Chart of part of the coast of New South Wales from Ram Head to Northumberland Isles" by Matthew Flinders in 1800, although on a very small scale, shows the estuary shoreline in fine detail including an "island" in a position similar to that indicated by Broughton.

The island is not present on the Australian Agricultural Company map of 1826. This map indicates a broad shoal area on the north side of the port cut by a channel. An east-west trending "sandy Waynderrebah Beach" is marked, and for the first time the bedrock outcrop, now known as Barnes Rocks (referred to as Murrogee Rocks) is located. The spit extends at least 1 mile west of this outcrop. Charts by Bingle and Johns are of little help, but those by Johnson in 1838 and P.P. King in 1845 clearly show a continuous spit of sand projecting southwest of the rocks (Fig. 5-10b). Myall Point is the name given to this spit on King's chart. This spit clearly is separated from a scrub-covered island [mangrove?] to the northwest.

The chart by Sidney in 1866 (Fig. 5-10c) and the Lands Department



Figure 5-8: **Active flood tidal delta of eastern Port Stephens showing complex pattern of channels and megaripples on the sand surface. The destroyed sand spit (Myall Point) has been reworked into sand shoals in front of the mangrove-covered Corrie Island (Paddy Marrs Bar). Date of photo is 18 August 1963 (N.S.W. 1188-5108).**

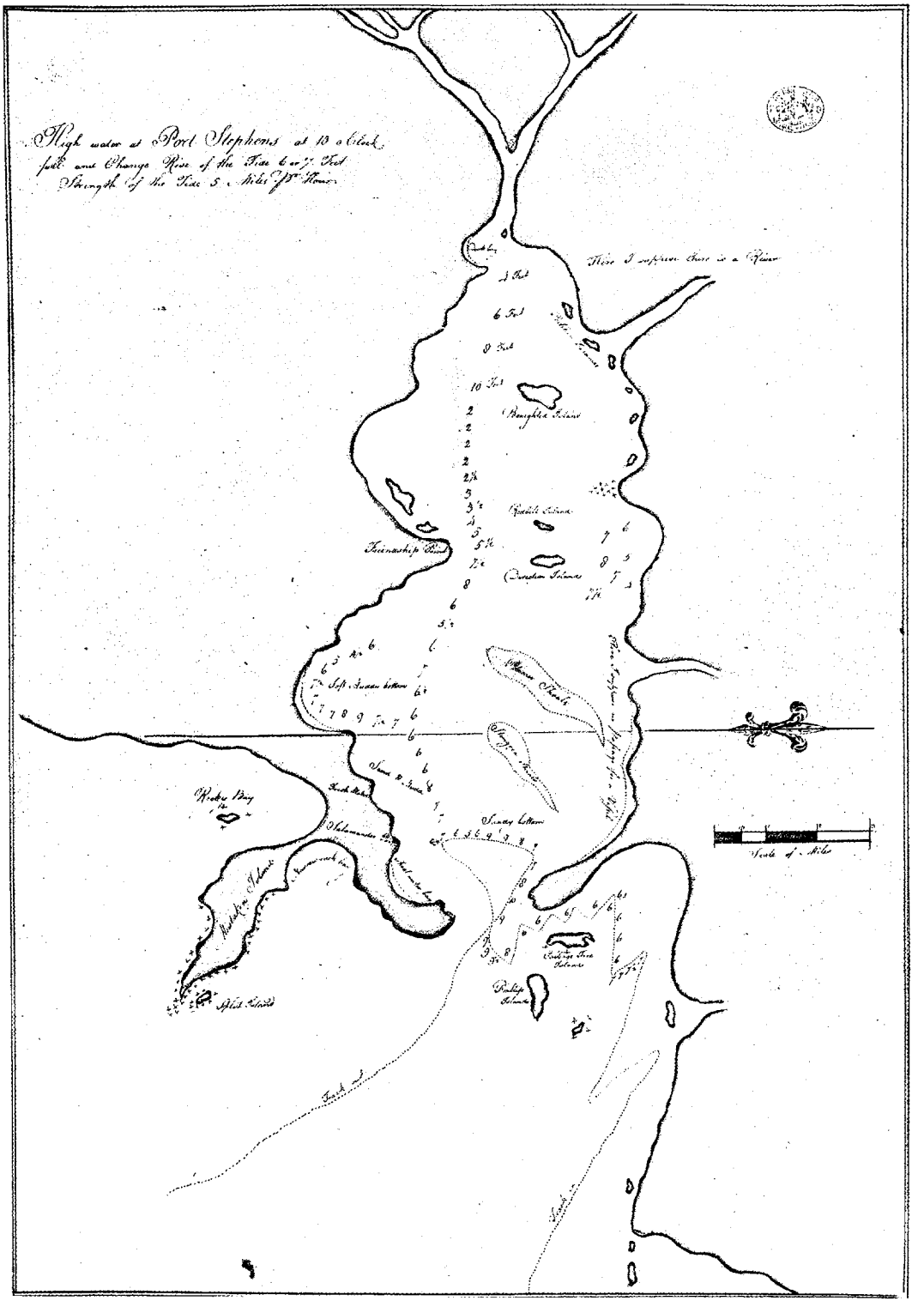

Figure 5-9: "Watling Drawing" of Port Stephens. This sketch map was produced by an unknown artist in November 1791, and is the first known map of the area.

TABLE 5-1 Charts of eastern Port Stephens 1791-1920

DATE	SURVEYOR/CARTO.	SCALE	LOCATION	REF. NO.
1791	Unknown; in vessel 'Salamander'	-	Brit. Museum (Nat. Hist.)	T. Watling Drawings fol. 5 (ms.)
1795	Charles Grimes (Dept. Surv. Genl.)	1:63 360	Hist. Records	N.S.W. Vol. 2
1795	W.R. Broughton in HMS Providence	1:63 360	(MODUK) Hyd. Dept	c642/2 Aus. fol 1 (ms.)
1822	J. Bingle in HM Cutter 'Sally'	1:126 720	Various	Published in J. Cross N.S.W. map. 1827
1826	J. Armstrong Aus. Agr. Co.	1:33 500	(MODUK) Hyd. Dept. and ANU Archives	Engraved
1828	W. Johns in HMS Rainbow	1:36 400	(MODUK) Hyd. Dept.	Published chart 1070
1838	G. Johnson in HMS Conway	1:21 000	(MODUK) Hyd. Dept.	L 1667 Xd (ms.)
1839	J. Lort Stokes in HMS Beagle	1:72 000	(MODUK) Hyd. Dept.	L 3831 Xd (ms.)
1845	P.P. King as Aus. Agr. Co Commissioner	-	Various	Published chart 1070
		1:42 000	(MODUK) Hyd. Dept.	L 4680 Xd (ms.)
1851	J. Lort Stokes in HMS Acheron	1:72 000	(MODUK) Hyd. Dept.	L 9297 49c (ms.)
1866	F.W. Sidney in Schooner 'Edith'	1:24 000	(MODUK) Hyd. Dept.	D 9558 XI (ms.)
1889	Parish map (Fens)	1:320	NSW Lands Dept.	Published map
1909	G.H. Halligan Harbours & Water Supply	1:720	NSW Public Works Dept.	27716
1920	C. Scott in HMS Fantome	1:25 000	Various	Published B.A. chart 1070

(MODUK) Hyd. Dept. = Ministry of Defence, United Kingdom, Hydrographic Department

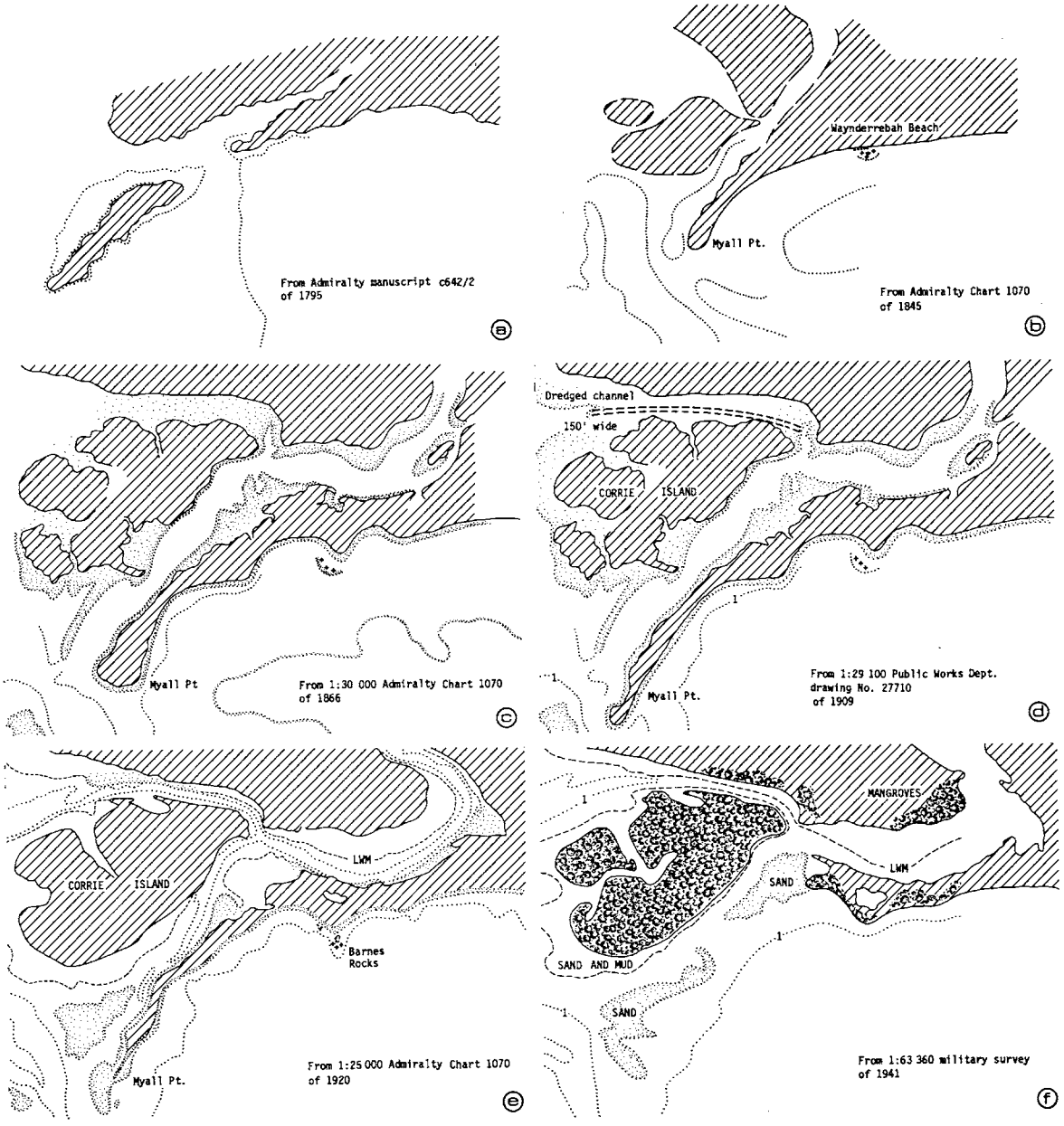

Figure 5-10: **Six maps-charts of Winda Woppa - Corrie Island area of eastern Port Stephens covering the period 1795 to 1941. Bathymetric contours are in fathoms. The maps are approximately the same scale and highlight the growth and destruction of Myall Point.**

parish map of 1889 both noted vegetation on Myall Point. Sidney's chart noted a "low sand point with small scrub", whilst on the parish plan "Sandy Soil, Tea Tree Scrub, Honey Suckle" was inscribed. By 1909 (Halligan's chart) and 1911 (P.W.D. Survey), the spit appears to have achieved its maximum length (Fig. 5-10d). However, the detailed survey of the estuary conducted by Scott in H.M.S. "Fantome" in 1920 reveals a more tapered point, and the spit is approximately 200 m shorter than it was 10 years before (Fig. 5-10e).

Dramatic changes took place in 1927. The late Mr Harry Legge of Bombah Point attributed the sudden removal of about 1300 m of the spit to a storm event in 1927 (see Thom, 1974). This storm was accompanied by heavy rainfall and flooding in the Upper Myall River and Myall Lakes. Lake levels rose 3 m above normal (= MSL) levels. Mr Legge also described very rough seas at the time. Unfortunately no chart, plan or map has been found close to the time of the destruction of Myall Point. However, a 1938 P.W.D. survey indicates that an intertidal sand flat may be present at the site. The 1941 topographic survey by the Australian Army clearly shows the position of Winda Woppa, and the smoothed SE-facing shore of Corrie Island. Tidal-delta shoals occur seaward of Corrie Island (Fig. 5-10f). On the 1976 topographic map at 1:25000 scale (Port Stephens 9332-IV-5), a bar feature is shown and named Paddy Marrs Bar southeast of Corrie Island.

Field observations since 1961 confirm that the seaward face of Corrie Island is eroding back into the mangroves (Figs. 5-8) and that sand is littoral drifting to the southwest to form a recurved spit. Winda Woppa beach is being extended to the west (Fig. 5-8, 5-10f). Figure 5-11 dramatically illustrates the degree of foredune erosion on Winda Woppa. A vegetated sand ridge extended from eroded foredune hillocks at the west end of the Yacaaba tombolo to Barnes Rocks (see Ch. 6). Since 1960 the foredune has clearly undergone landward retreat. Tall Melaleucas, a species which probably propagated in a swale depression behind the foredune, are being enveloped by sand up to 4 m thick. We estimate a retreat rate of 1-2 m per year since 1941. Recent housing construction on Winda Woppa has been accompanied by local foredune conservation measures. However, low points on the foredune crest were overwashed during the 1974 storms, and hence indicate the fragile nature of this spit (see Gordon, 1982).

The old charts and maps (Fig. 5-10) can be interpreted as follows: a spit was initiated from a sand shoal about 170 years ago, conforming in plan with the diffracted swell wave pattern which enters Port Stephens and crosses the shallow sand surface of the flood tide delta. The spit (Myall Point) reached its maximum length about 1910. It was "trimmed" by erosion until 1927 when it was catastrophically removed in a storm. Since then, there has been considerable reworking of sand landwards to form a beach across a formerly sheltered mangrove island (itself initiated in the early 19th century.*). Lateral extension of both Corrie Island to the southwest and Winda Woppa to the west has occurred in recent years.

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* Corrie Island first appears as a recognizable island in 1826 in the A.A.Co. map. This map refers to "Low Mangrove Land". Three wells had been dug on the SE shore. Another small island named Yawayabih (?) occurred in the channel between Corrie Island and the west-oriented (at that time) Waynderrebah Beach.

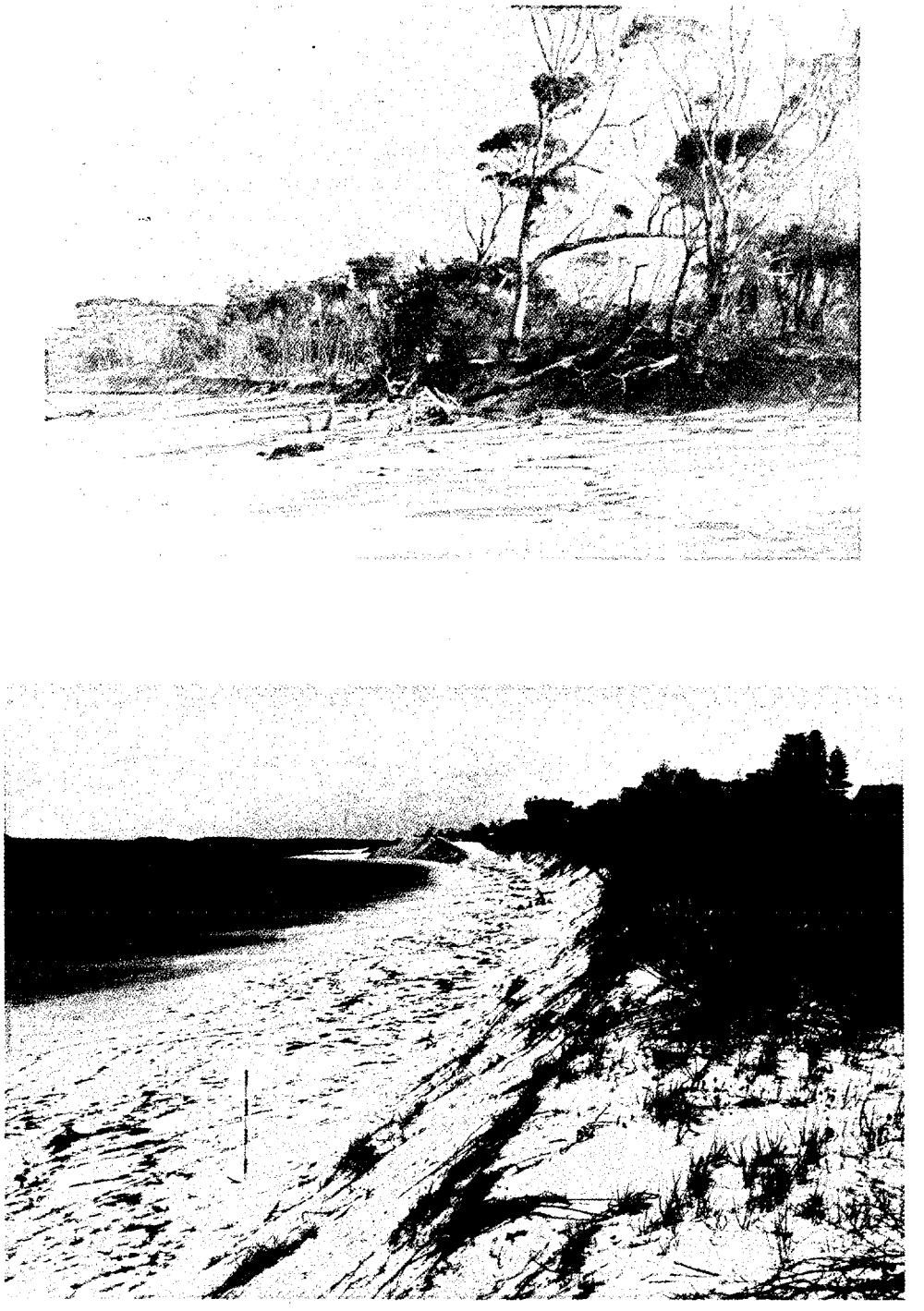

Figure 5-11: **Views along eroding beach at Winda Woppa. Upper photo was taken in July 1960. The lower photo taken in February 1988, shows attempts at localized beach nourishment in background.**

What do these changes mean? It is possible to correlate changes in subaerial morphology on the north side of eastern Port Stephens with the various configurations of the submerged tidal delta. If anything, there has been a net loss of sand from the tidal delta since accurate charts became available (i.e. since 1851). It is not known if the accumulation and growth of Myall Point was in response to a net gain in tidal delta sand during late 18th and early 19th centuries. We may speculate but certainly cannot prove that the dramatic erosion in 1927 was the culmination of progressive deepening of water over the tidal delta sand mass. Alternatively, the 1927 event could have been a "freak" storm and consequently the combined flood and wave erosion would have destroyed the feature no matter what long-term tendency was operating on the sand shoals to seaward. Nevertheless, the unique series of maps over nearly 200 years provides an excellent record of coastal change, the significance of which may not yet be fully appreciated.

In this monograph little attempt has been made to document the wide variety of other shoreline features which occurs within Port Stephens. Some of these are discussed by Nielsen (1979). Of some interest would be a study of the low relief sand spits near Tanilba, which suggest active segmentation of Big Swan Bay. Mangrove and salt marsh tidal flats in both western and eastern portions of Port Stephens also deserve further geomorphologic study.

5.3 STRATIGRAPHICAL CHARACTERISTICS

5.3.1 Bedrock Configuration

The Tomaree Hills section of the study area with its prominent bedrock hills and ridges enveloped by sand possesses an extremely complex bedrock configuration. Most other embayments are characterized by gently inclined bedrock valleys facing seaward. In the Tomaree area the strike ridges have been eroded into a series of hills or peaks presumably by fluvial processes during periods of lower sea level. It is most unlikely that marine erosion has carved the valleys that separate the peaks. A river drainage system operating at a base level well below present sea-level over a long time period (see Ch. 10), was responsible for the dissection of the Carboniferous volcanoes. This drainage system may have been part of a tributary network of the proto-Karuah Valley.

Bedrock configuration beneath Port Stephens is also complex. The eastern part of the estuary is underlain by bedrock ridges and peaks. These features are now buried by Quaternary sediments except at prominent points such as Middle Island, Soldiers Point and Barnes Rocks. The proto-Karuah channel appears to have been located west of Soldiers Point, and to have drained to the south beneath Inner and Outer barriers. It is thus responsible for the excavation of bedrock at the eastern end of Newcastle Bight (see 4.3.1). Two other channels are recognized: a proto-Kore Kore Creek and a channel draining east through the present "heads". Figure 5-12 depicts the buried bedrock topography beneath Port Stephens. Maximum depths are -49 m beneath western Port Stephens and -72 m beneath Salamander Bay (Fig. 5-12). This drainage configuration is based on seismic reflection studies and drilling conducted by the N.S.W. Geological Survey.

In this chapter we are more concerned with the relationship between bedrock morphology and Quaternary sediments especially in the Tomaree

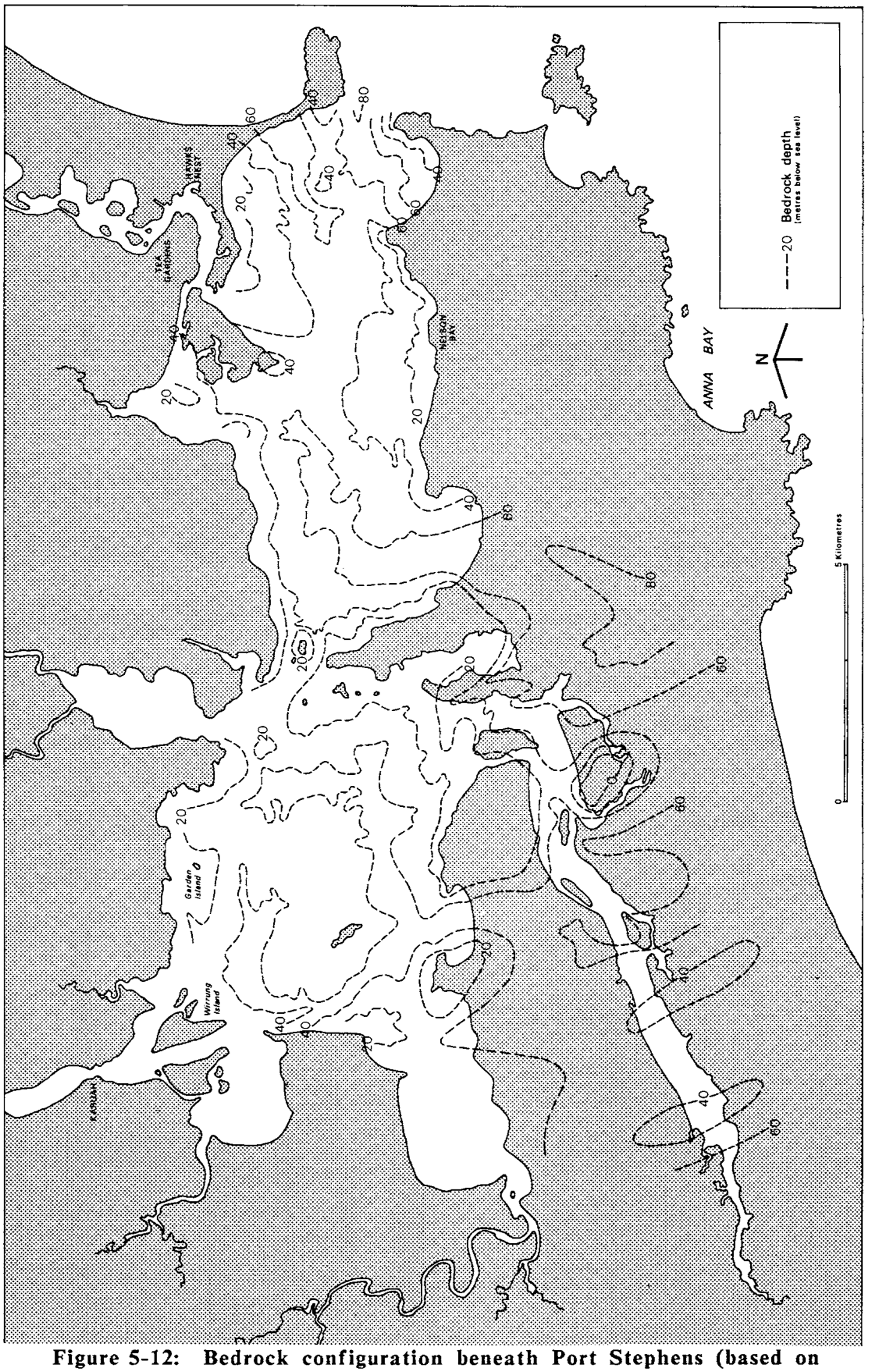

Figure 5-12: Bedrock configuration beneath Port Stephens (based on drilling and seismic surveys of Geological Survey of N.S.W.).

Hills. Drilling by the H.D.W.B. since 1941 and the A.N.U., plus geophysical studies by the N.S.W. Geological Survey, have led to the construction of a generalized map of the bedrock surface in the eastern Tomaree region (Fig. 5-13). Using a combination of resistivity, gravity and seismic refraction methods, the geophysists had two objectives; (i) to determine the bedrock topography in the area of the "Anna Bay Sandbeds" (i.e. the sand fill between Anna Bay and Shoal Bay); and (ii) to determine the extent and depth of a clay layer which was intersected in a few drill holes. Figure 5-13 summarizes the results for the buried bedrock surface, and sections shown in Figure 5-14 indicate the generalized profiles of overlying sand and clay units as well as depth to bedrock. Bedrock channels appear to radiate from a central "core" occupied by three hills: Kurrara Hill, Glovers Hill and an unnamed peak south of Kurrara Hill. However, they may have been connected to the proto-Karuah channel system through Anna Bay. In the sections shown in Figure 5-14 the impression is that bedrock channels lying at depths of 50 m or more below MSL possess relatively even thalwegs, perhaps broken by "steps". Although information on the northern part of the area is sparse, there is some suggestion that a continuous bedrock trough extends

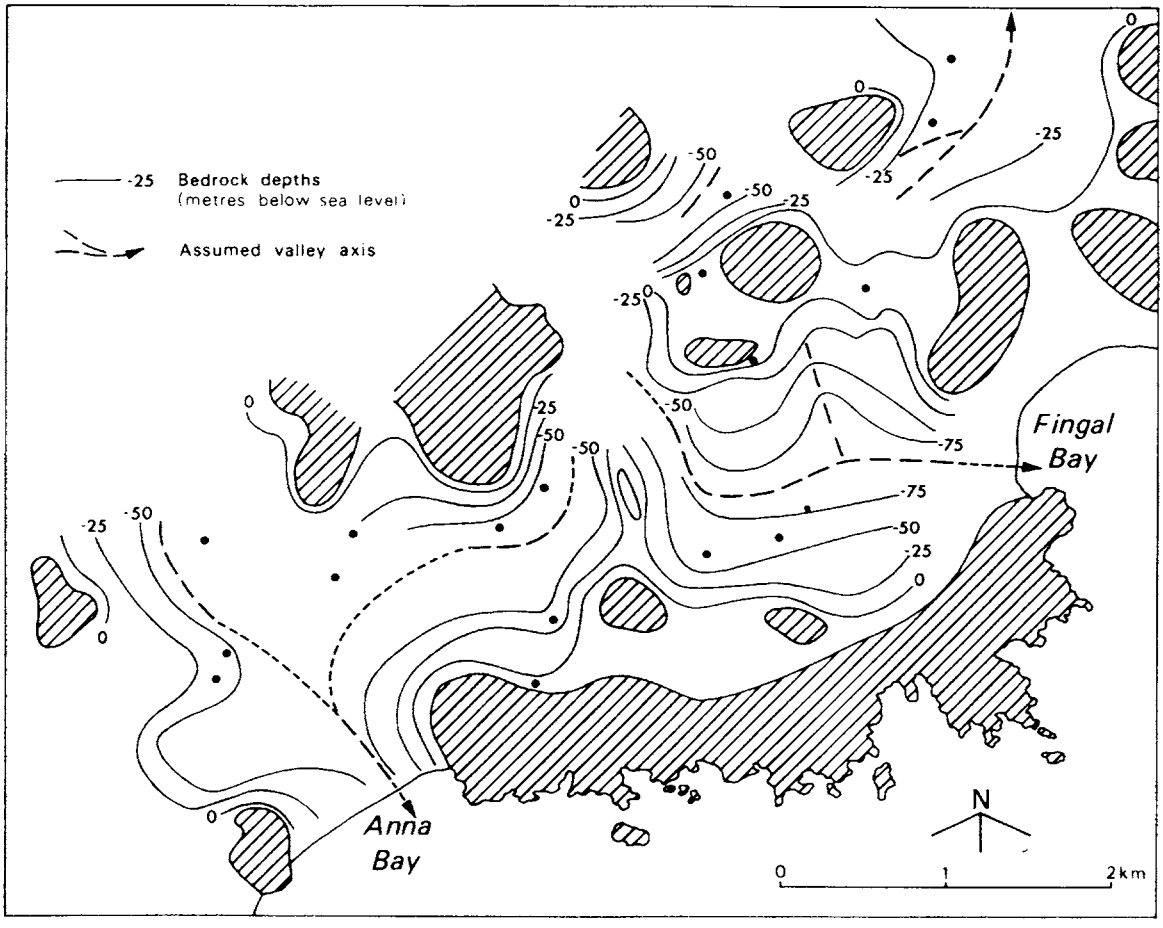

Figure 5-13: Bedrock configuration beneath sand dunes of Tomaree Hills showing possible drainage patterns of early Pleistocene-Tertiary age (based on drilling of H.D.W.B. and seismic surveys of Geological Survey of N.S.W.).

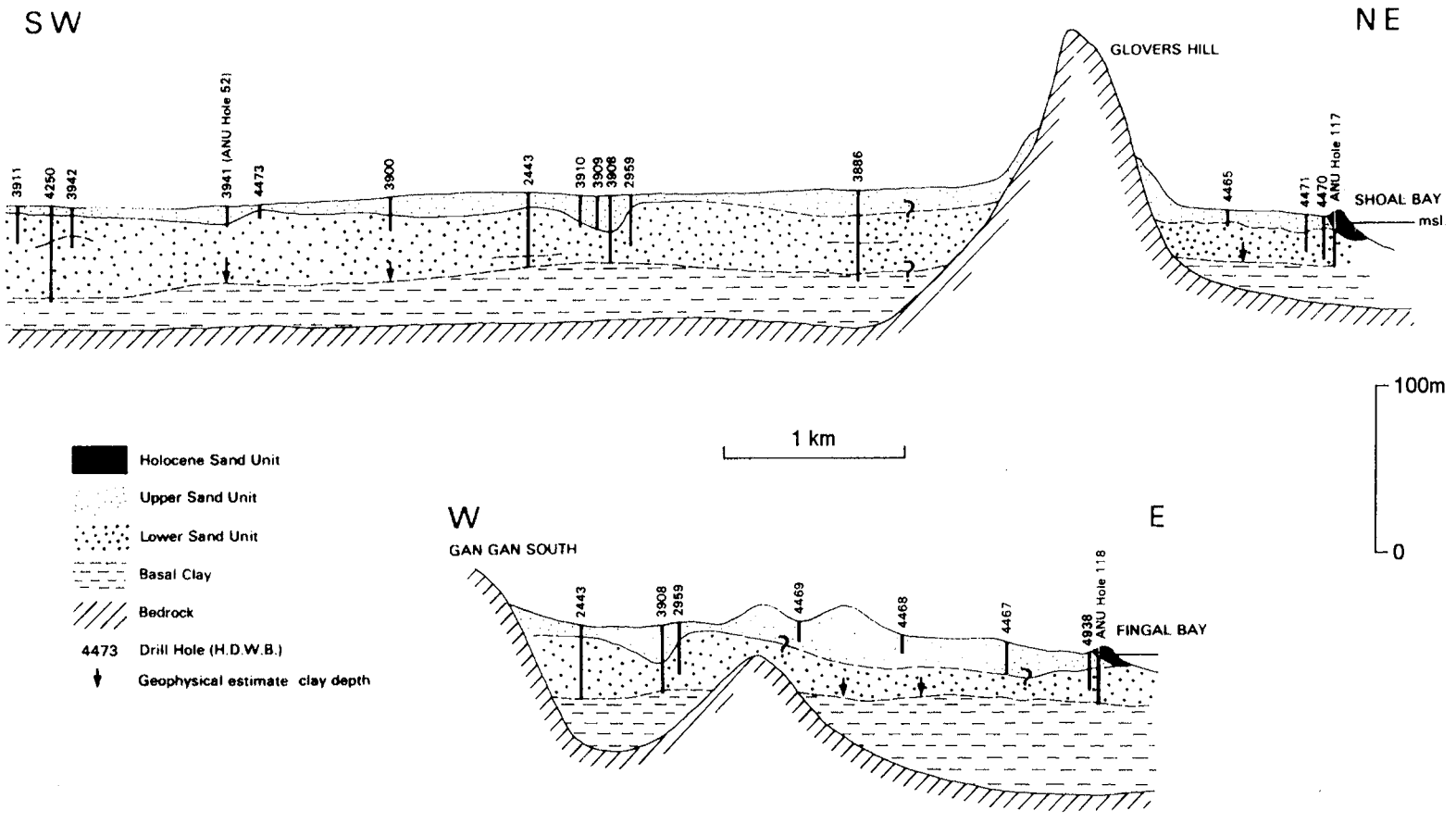

Figure 5-14: **Two generalized stratigraphic sections across Tomaree Hill dunes. Three sources of data used: H.D.W.B. and A.N.U. drilling, and Geological Survey of N.S.W. seismic survey. Dashed line within Lower Sand Unit represents possible soil discontinuity (see Fig. 5-1 for location).**

north to south on the western side of Kurrara Hill. This may have been the main drainage channel from the Duck Hole area on the north side of Port Stephens, although it is possible that most of this drainage flowed between the present "heads" of Port Stephens. The present mouth of the estuary may have been the opening of major Port Stephens drainage only in late Quaternary times, perhaps only in the Holocene, because prior to clay infill the main outlet was the bedrock channel west of Kurrara Hill. For the moment, further discussion of this point is speculative and must await deeper drilling in the Tomaree Hills and in Port Stephens.

5.3.2 Stratigraphic Units

5.3.2.1 Holocene sand deposits

The Tomaree Hills contain limited areas of Holocene deposits compared to Newcastle Bight and other segments of the study area. The distribution of Holocene sand deposits is shown in Figure 5-2. Mostly these are foredune-beach complexes in the larger bays (e.g. Anna Bay, Fingal Bay and Shoal Bay). Except for limited work on a section in Fingal Bay (see 5.2.2.2), and at Shoal Bay (Magazinovic, 1985), no further studies have been undertaken on Holocene sands in this region. The only study of Holocene swamp deposits is on exposed peats on the beach at Fingal Bay (see Macphail, 1974).

5.3.2.2 Pleistocene eolian deposits

Most of the Tomaree area is covered by Pleistocene dune sands (Fig. 5-2). Again only limited work has been undertaken on the sediment properties of these sands. They are interpreted as eolian in origin on the basis of geomorphology rather than granulometry. However, size analyses by H.D.W.B. and ourselves consistently show the occurrence of medium to fine, well sorted sands throughout the area mapped as Pleistocene sands on Figure 5-2.

These sands are invariably dominated by quartz with minor amounts of heavy minerals and lithic grains. In the western portion of the Tomaree area near Salamander Bay, the heavy mineral content has been sufficient to warrant mining. Rutile and Zircon Mines Ltd. has drilled and mined this area extensively in the period 1970 to 1976. Nowhere were heavy minerals concentrated in lenses which would have implied beach sand deposition.

The conclusion that the dune sands are Pleistocene in age is based on two observations. Firstly, no radiocarbon dates from the Tomaree Hills on organic materials which have been buried by dune sand, have dated less than "background". In other words, the surface transgressed by the most recent dune sand sheet is consistently beyond the range of radiocarbon dating. Secondly, soil profile morphology in the dune sands compares favourably with those from the Tomago dune ridges (Type 3 soil, Appendix A). If we accept a pre-Holocene age for the reworking of the Tomago Inner Barrier, then it is appropriate to consider the Tomaree sands as being emplaced and vegetated during the Last Glacial (Q3Te in Ch. 10). The problem is exactly when in the Last Glacial and whether we are dealing with one or more episodes of dune migration.

Until organic deposits older than about 40,000 years can be dated,

it is not possible to determine a chronological sequence for dune sand deposition except on a relative basis. However, most drilling is very shallow (5 to 10 m) and drill logs of many holes are confusing. On more than one occasion we have redrilled a mining company or H.D.W.B. hole looking for what was termed "peat" only to find a slightly more enriched humate-impregnated sand.

The dune sand cover of the Salamander Bay-Anna Bay area in the west to Fingal Bay-Shoal Bay in the east, as well as in Kurrara Hill-Nelson Bay area to the north, is apparently quite uniform in its degree of morphological preservation and soil profile morphology. It forms what is termed the upper sand unit. Soil profiles are described in Appendix A. Much more detailed soils-geomorphic mapping is needed to separate discrete phases within the dune sheet, if they exist. At this stage we conclude that a major eolian episode involving west to east sand transport took place during the Last Glacial in the Tomaree Hills, and that, during this episode, most of the area was at some stage subjected to eolian activity.

In Figure 5-14 an attempt is made to show the thickness of the upper sand unit. Its base is defined by either (i) a peat/organic clay layer; or (ii) the occurrence of sand with charcoal; or (iii) the presence of clay in the sand; or (iv) as noted in drillers logs, the transition downwards from brown to grey and back to brown sand implying a buried soil containing humate-impregnated sand. The unit varies considerably in thickness from less than 2 metres to over 20 m. Thicker deposits occur where the dune sheet forms a ridge or where it fills "depressions" within an older surface.

The sand body which occurs beneath the upper sand unit is referred to as the lower sand unit. However, it is clear from the few drill holes which penetrate to the clay layer, that the lower sand unit contains numerous horizons. It is therefore a composite unit. The sand is locally "clayey", or there may be "wood" or "peat" in layers within the sand body. The continuity of these layers is unknown. The lower sand unit is often quite thick (+40 m is common), and appears to be the main component of valley fill in the Tomaree Hills (Fig. 5-14). Nowhere has shell been recovered from this unit. A.N.U. drill holes 50, 64, 66 encountered the lower unit.

We are not sure whether an extremely well podzolized sand which occurs on the north side of Kurrara Hill is the surface expression of part of the lower sand unit. An excellent exposure exists behind the Nelson Bay Bowling Club (see profile description Appendix A). Similar profiles have been observed at the east end of Shoal Bay (Type 1 in Ch. 10). The highly leached, slightly clayey sand at the east end of Fingal Bay (see 5.3.3.3) may also be part of the lower sand unit. A recent thermoluminescence age of 168±37 Ka was obtained from the Nelson Bay site. Iron enrichment and degree of induration and thickness of the B horizon are much more pronounced in the Nelson Bay profile than in the soils of the upper sand sheet (see Appendix A). However, a complete soil profile developed within the lower sand unit has not been observed beneath podzolized sands of the upper sand unit.

Below the dune sands is a clay layer. Several drill holes bottom in this layer. In Figure 5-14 it is suggested that the clay layer is fairly

uniform in thickness (20 to 30 m); this estimate of thickness, based on geophysical surveys, may be in error by as much as ±25 percent. Furthermore, the layer appears to be draped across the bedrock surface. It does not appear to rise above -20 m MSL. Thus its surface is substantially lower here than is the clay that underlies the innermost parts of Inner Barriers (see Chs. 4,6,7). Where drilled, the clay is quite plastic, dark grey to black in colour, and organic rich. No oxidized samples were recovered. A "background" ^{14}C date was obtained on one sample recovered from 29 m below ground surface (A.N.U. drill hole 50-13).

In one drill hole (A.N.U. drill hole No. 66), located in the Salamander Bay-Anna Bay lowland, a very distinctive angular lithic sand was recovered at -37 m below MSL. The lithic sand may be a relic of an ancient fluvial deposit that predates clay deposition.

In summary, three main Pleistocene sediment units have been recognized in the Tomaree Hills: upper sand, lower sand and basal clay. The upper sand is apparently uniform in age, composition and soil profile morphology, but variable in thickness. In contrast, the lower sand is probably composite in age, variable in texture and lithology with very limited surface expression. The clay unit is entirely subsurface, may contain sand layers, and is usually organic rich. It may represent an early phase of the thick, composite clay unit found in other embayments of the study area (Q2Em, see Ch. 10). A fourth unit composed of lithic sand may locally underlie the clay. No Pleistocene marine sand facies have been recognized.

5.3.2.3 Estuarine facies.

The basic sediment properties of estuarine facies have already been described (Ch. 3). Stratigraphical units are shown on a generalized cross section of Port Stephens in Figure 5-15. More detailed stratigraphic information based on drill logs of the N.S.W. Geological Survey is illustrated in Figure 5-16.

There are eight lithofacies units in Figure 5-15. Four units of Pleistocene age are: (i) basal sand and sandy gravels, quite lithic in character and containing seismic discontinuities; it is presumably fluvial in origin (Q1Tc); (ii) a compact plastic clay, quite variable in thickness, containing seismic discontinuities as shown in Figure 5-17, iron oxide bands, and an eroded upper surface; this is presumably an estuarine prodelta mud facies (Q1,2Em); (iii) an upper lithic sand body deposited in fluvial channels cut in the lower two units; it is particularly well-developed in eastern Port Stephens (Q3Tc); and (iv) a quartzose sand confined to the eastern end of the estuary, locally impregnated with humate, and which is of possible marine origin (i.e. deposited as a tidal delta or sand barrier). Clearly the clay unit is polycyclic and only the upper part may be associated with the Last Interglacial marine transgression. The marine sand of the eastern estuary could be Inner Barrier equivalent as it overlies the clay facies, and is indurated and leached in part.

Holocene lithofacies include: (i) a tidal delta shelly sand in eastern Port Stephens (Q5,6Ed); (ii) shell bioherms which rise from topographic highs on the Pleistocene surface (Q4,5Es) (Peat and Roy, 1975); (iii) a prodelta unit of mud which is rich in shell especially

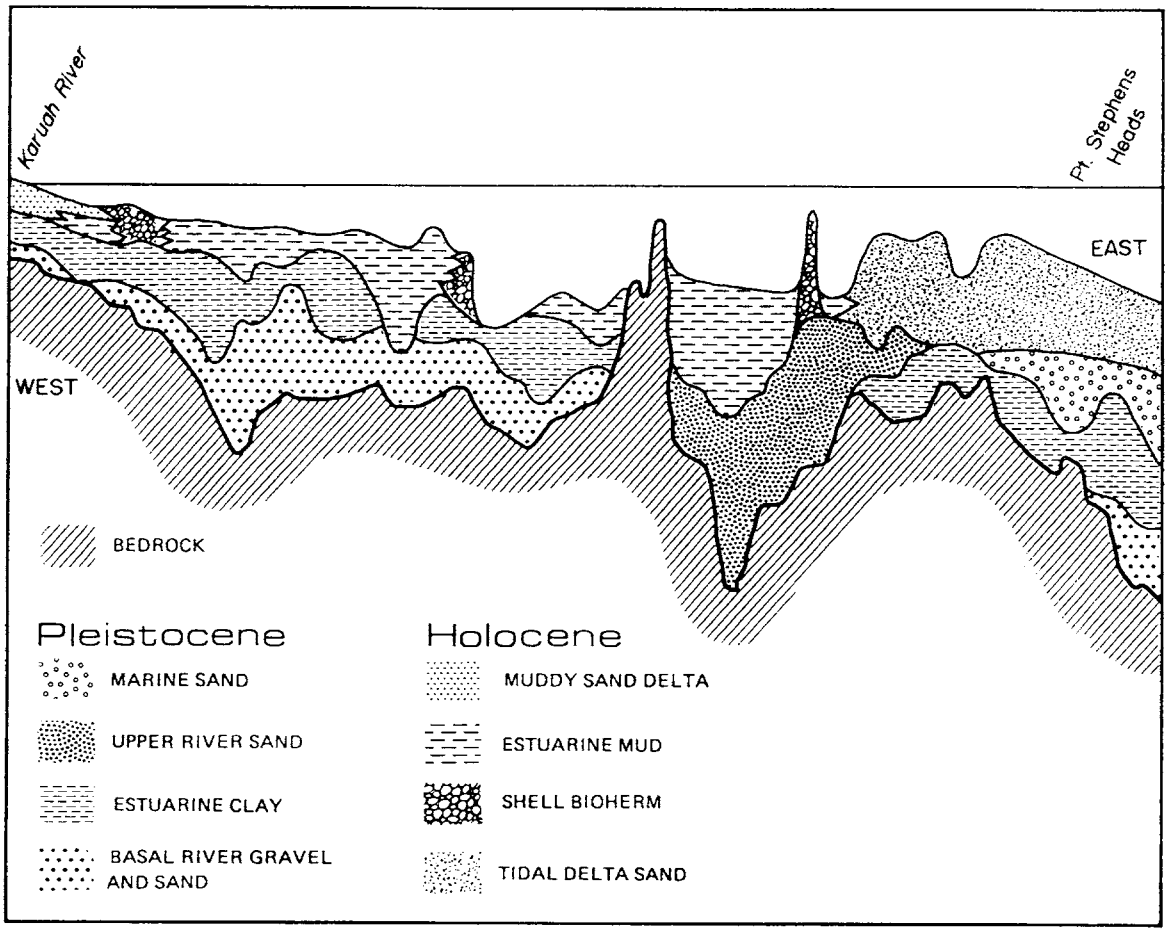

Figure 5-15: Generalized stratigraphic section of Port Stephens from Karuah River delta in the west to the eastern entrance of the port (for further details on the stratigraphy of Port Stephens see Peat and Roy, 1975).

Notospisula (Q5,6Em); and (iv) muddy sand forming the Karuah deltaic deposits in western Port Stephens (Q5,6Tdsm). Other lithofacies including tidal flat muds and beach-nearshore sands are also found in Port Stephens, but are not considered significant components of the overall estuarine sequence.

5.3.3 Stratigraphic Patterns and Depositional Sequence

Four generalized sections are used to show stratigraphic relationships between facies in the Tomaree Hills-Port Stephens area (Figs. 5-14, 15, 16, 18, 19; for location see Fig. 5-1). These relationships when coupled with our knowledge and assumptions regarding the age of these deposits make it possible to draw some conclusions as to the depositional sequence in this area.

5.3.3.1 Port Stephens section (Fig. 5-15 and 16).

In western Port Stephens, the channelized bedrock surface is filled with 10 to 20 m of fluvial silts, sands and gravels. These "lithic" sediments are overlain by Pleistocene estuarine clays which reach within 5 m of present sea-level. Soft estuarine muds of Holocene age not only

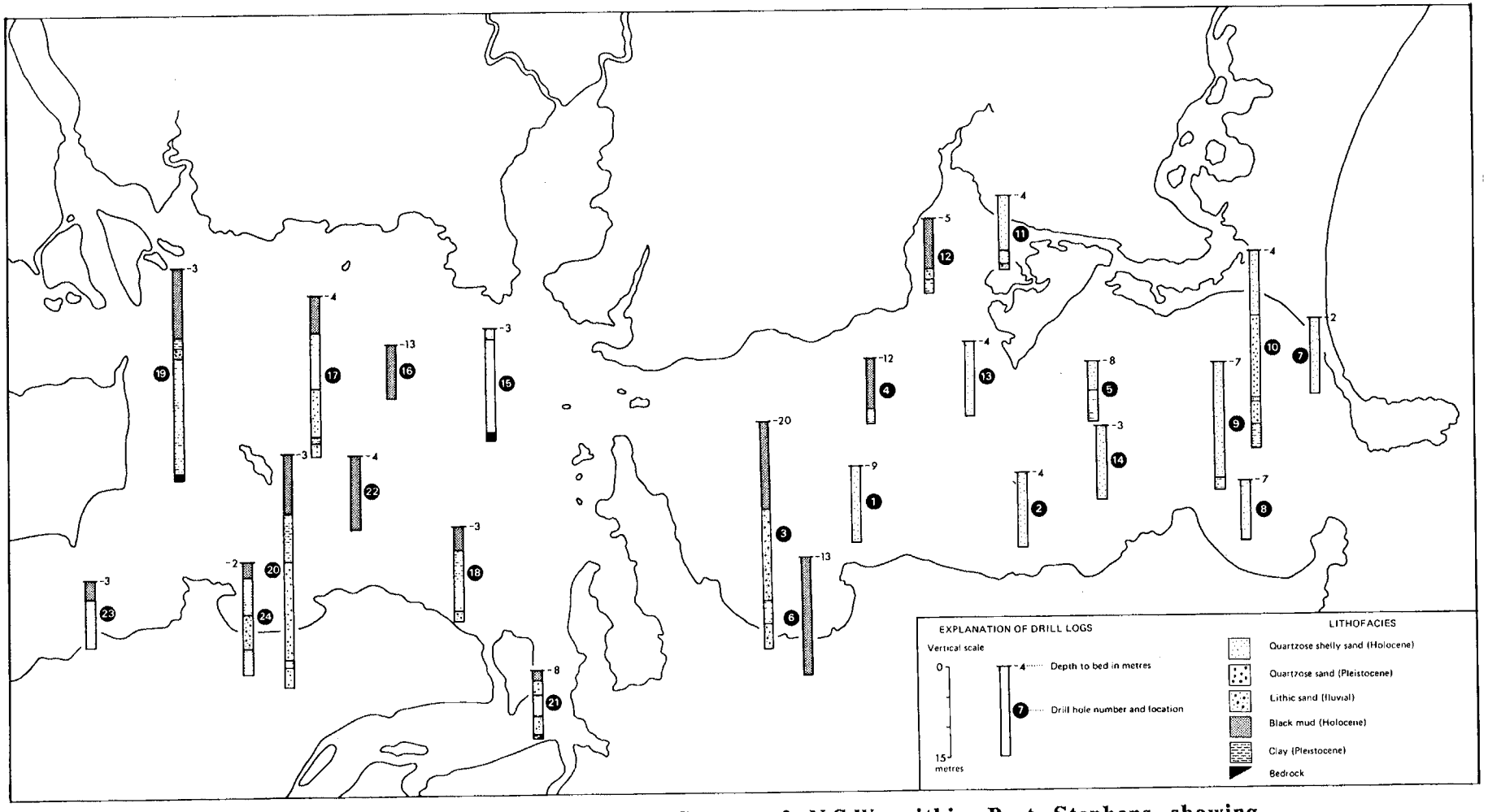

Figure 5-16: Drill logs of Geological Survey of N.S.W. within Port Stephens showing lithofacies.

fill channels cut into the clays in western Port Stephens, but also form a thin blanket across the clay surface (Fig. 5-15). The muds onlap the base of the shell bioherms.

In central Port Stephens the Holocene muds lie directly on fluvial sands. The section indicates that the sands in central Port Stephens post-date Pleistocene clay deposition, i.e. they represent channel fill during the Last Glacial (Q3Tc). If they do, then the Karuah River flowed east past Soldiers Point after being diverted by the Inner Barrier in Newcastle Bight during the Last Interglacial. The assumed pre Last Interglacial age of deposits in the Salamander Bay-Anna Bay lowland makes it likely that this channel entered the sea via the present estuary mouth during the Last Glacial. A bedrock sill may inhibit this direction of flow for channel depths in excess of 25-30 m. The sill may have perched river drainage above this level during lower sea-level periods. However, the maximum known depth of Last Glacial incision occurs in Salamander Bay and is overlain by a thick mud sequence (Fig. 5-15).

Eastern Port Stephens is dominated by a wedge of quartzose sand. This is interpreted as a Holocene tidal delta sand deposit which entered the estuary during and subsequent to the Postglacial Marine Transgression (Q4Md). These sands overlie the eroded surface of compact estuarine clays, sandy clays and humate-stained sands of possible Last Interglacial age, or older. A basal fluvial sand-gravel occurs beneath the clays (Q1Tc).

5.3.3.2 Salamander Bay section (Fig. 5-18).

This section is a continuation of the Anna Bay section described in 4.3 (see Fig. 4-19). On the north side of the inter-barrier depression shown on this section are Pleistocene dune deposits forming part of the Salamander Bay-Anna Bay dune-swamp complex, the low topographic relief of which has already been discussed.

The upper sand unit in this area rarely exceeds c. 5 m to 8 m in depth below MSL. Underlying peat deposits such as that recovered in A.N.U. drill hole 80 (ANU-1327) dated "background". We consider the upper sand body to be derived both from the Inner Barrier and the older dune sands of the lower sand unit during the Last Glacial (Q3Te), and are thus "terrestrial" not "marine" dunes. Sand transport was from west to east as indicated by the morphology (Fig. 5-4).

The lower sand unit appears to fill a broad channel cut in the Pleistocene clay (Fig. 5-17). As mentioned in 5.3.2.2, the lower sand unit is a quite complex facies interbedded with peat and muddy sand layers. The relationship between these sands and those of the Inner Barrier is not clear. It is suggested that they pre-date the Inner Barrier which, as shown in Figure 5-17, underlies the Outer Barrier to the south. Under Salamander Bay, the so-called fluvial sand unit may be related in time with the lower sand unit of the dune-swamp complex. If this is so, then the emplacement of the extensive sand body probably took place under combined fluvial-eolian conditions prior to the deposition of the Inner Barrier (Q1Me,Te,Tf).

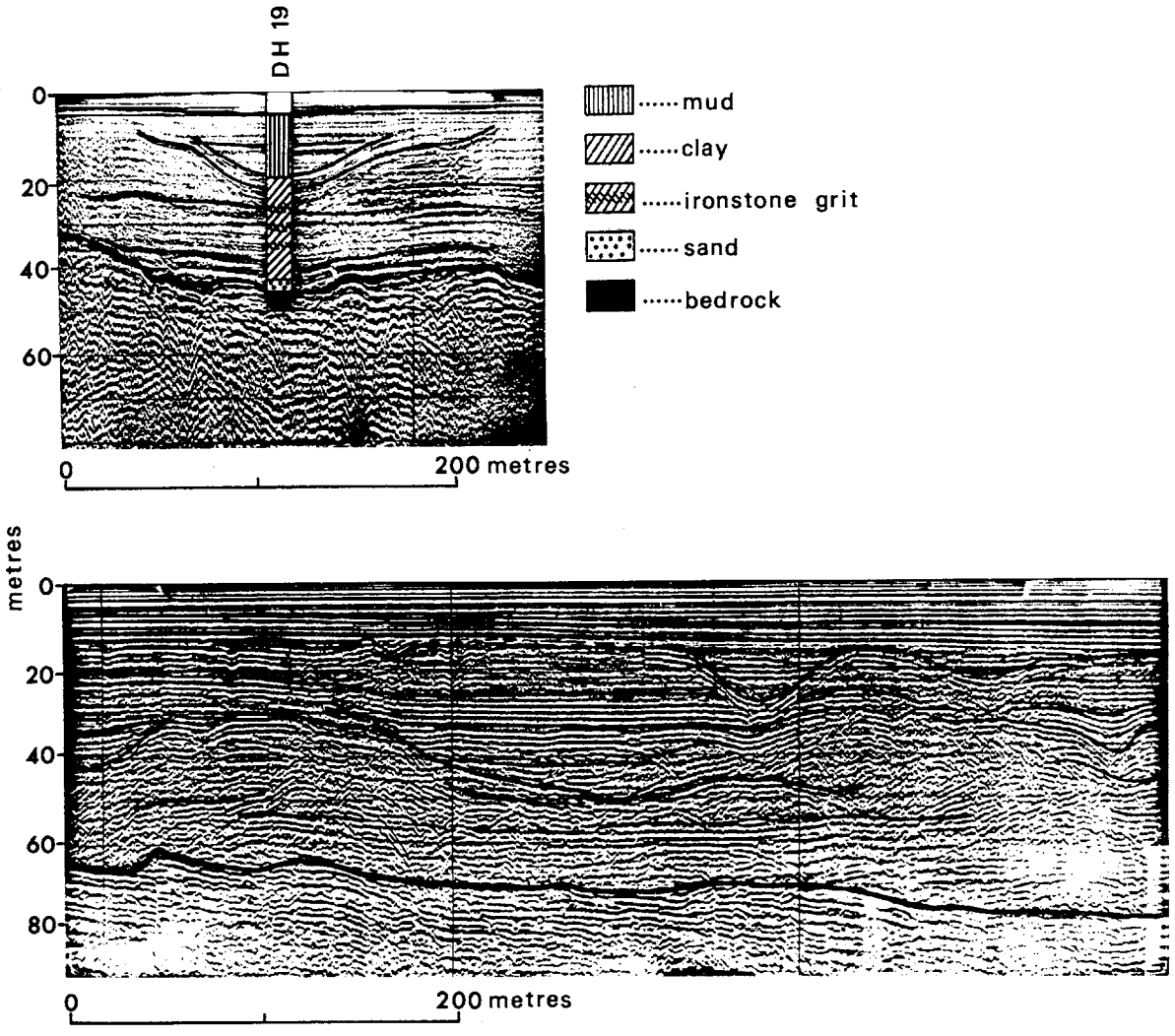

Figure 5-17: Seismic reflection profile in western Port Stephens in conjunction with the log of DH 19. Discontinuities within the clay unit (Q1,2Em) are apparent in both the seismic record and the drill log (based on estuarine survey of Port Stephens by Geological Survey of N.S.W.).

5.3.3.3 Anna Bay to Shoal Bay and Gan Gan South to Fingal Bay sections (Fig. 5-14).

Many aspects of these sections have already been discussed (see 5.3.3.2). Certain points require emphasis and elaboration.

(i) Bedrock peaks rise from channels cut to depths of 50 to 70 m below MSL.

(ii) The compact clay unit appears to be draped across the bedrock but is not itself cut by distinct channels; this point requires verification by detailed drilling as the upper surface is defined by somewhat inadequate geophysical methods (±25 percent error). Furthermore, the contact used in selected drill logs only refers

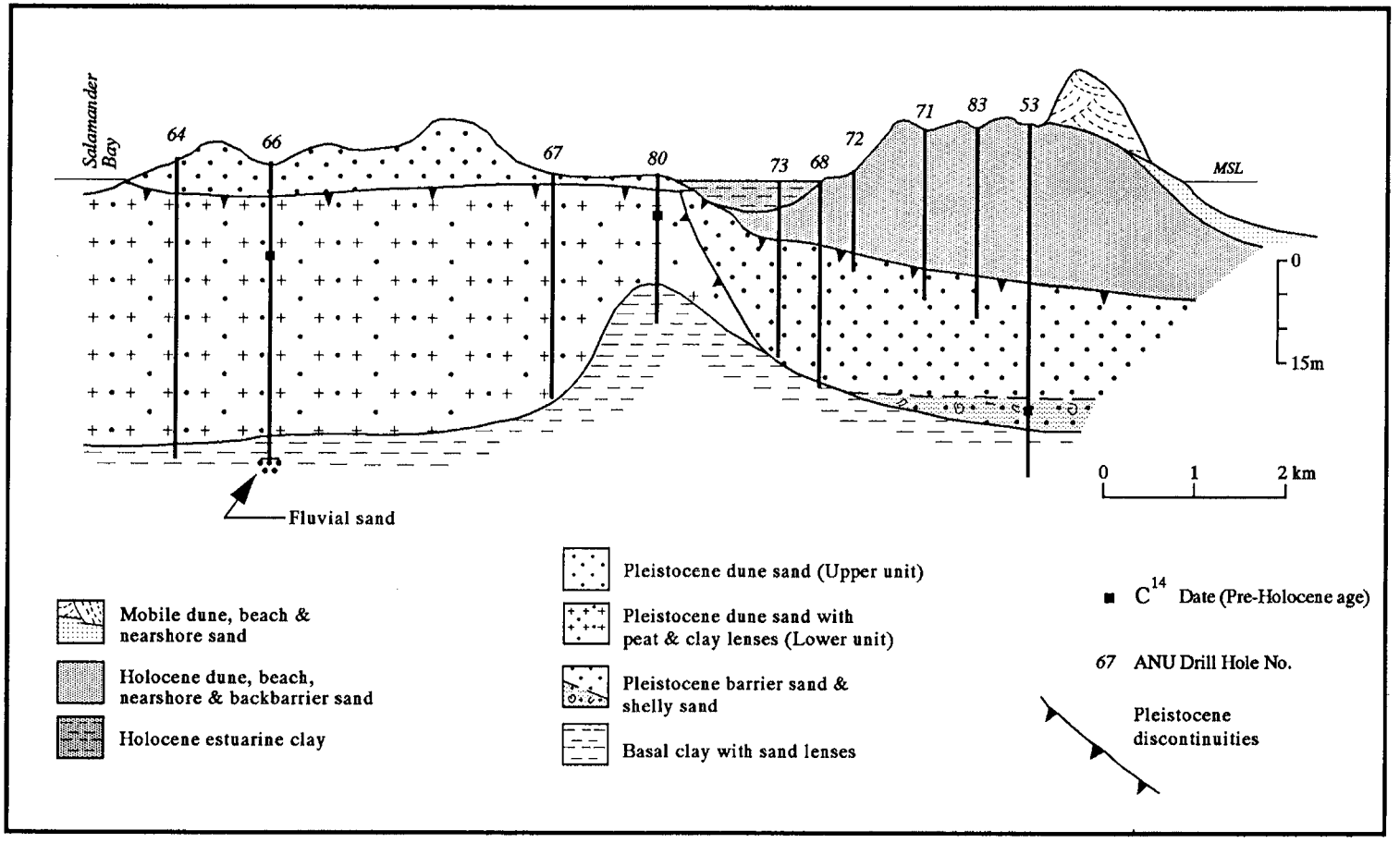

Figure 5-18: Stratigraphic section from Anna Bay village to Salamander Bay. This represents a continuation of Fig. 4-19 (see Fig. 5-1 for location).

to compact clay not to clayey sand horizons within the lower sand unit. However, if it is assumed that the clay unit as shown in Figure 5-14 is undissected then drainage from Karuah, Kore Kore, and other rivers has not passed through the eastern Tomaree Hills since the clay was deposited.

(iii) As indicated in Figure 5-14, the clay layer does not exceed -20 m below MSL in elevation. Its upper surface is mostly between -20 and -35 m below MSL. This is lower than the upper surface of the clay beneath the Inner Barrier. Certainly there is no evidence in the Tomaree area of the clay attaining elevations in excess of present sea-level as it does behind the Newcastle Bight, Fens and Upper Myall Pleistocene barriers. We consider that the clay in the Tomaree is equivalent in age to lower parts of the thick clay wedge of Newcastle Bight (i.e. Q1Em), and that the upper clay section of Last Interglacial age is missing in Tomaree because of prior burial beneath the lower sand unit.

(iv) The lower sand unit is clearly a composite deposit containing quartz sand, clayey sand and clay layers plus organic horizons (peat, organic clay and wood, especially charcoal). Drill data suggest soil disconformities within the unit, but it is not possible to sub-divide the unit at this stage. No marine fossils have been recovered at least in the sands, but clay layers need further study especially for micro fossils. It is suggested that the lower sand unit is pre-Last Interglacial, and most likely involves several episodes of eolian activity, swamp accumulation and perhaps tidal-flat deposition (Q1Me,Te,To).

(v) The surface equivalent of the lower sand unit may be the exposed highly podzolized soils found in Nelson, Shoal and Fingal bays. The partly indurated, milky quartz sand located at the east end of Fingal Bay has its equivalent facies below sea-level (see Fig. 5-19).

(vi) The upper sand facies is a more uniform unit lithologically and is characterized by a typical late Pleistocene podzol (soil type 3 in Ch. 10; Q3Te). As shown in Figure 5-14 only a small part extends below present sea-level. Eolian activity involving west to southwest winds was probably responsible for this sand being thrust between bedrock hills partly smothering exposed rocky surfaces (Fig. 5-2).

5.3.3.4 Fingal Bay section (Fig. 5-19).

One of the more interesting exposures in the whole study area exists at the east end of Fingal Bay (Fig. 5-19). Unfortunately, this exposure is well developed only after a period of storm wave erosion of the foredune. Drilling at the west end of the section has provided further data, albeit somewhat confusing, on the character of the section below sea-level.

Parts of the section were observed by David and Guthrie (1904). They noticed peat and in situ tree trunks beneath the foredune and on the beach at Fingal Bay, and correlated these organic deposits with a peat recorded in a drill hole at -80 feet below sea-level near Anna Bay. From this correlation they deduced subsidence towards Newcastle (ibid,

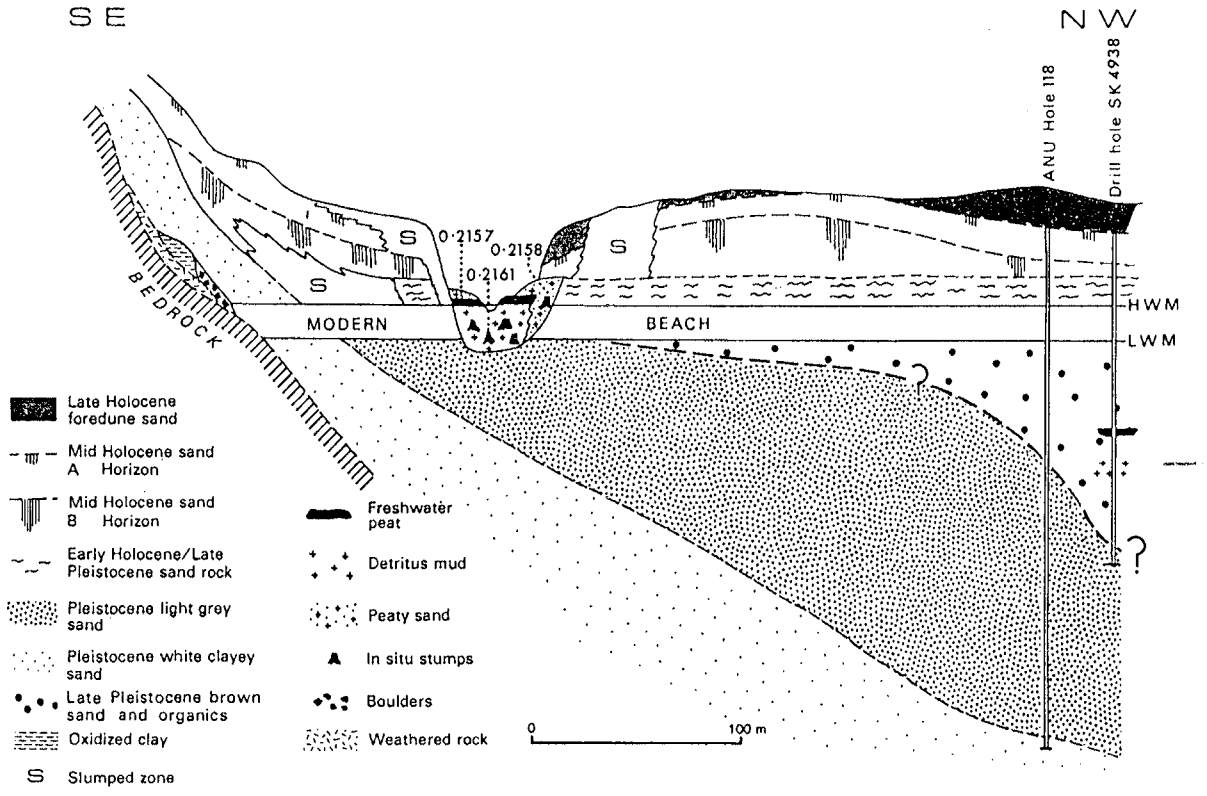

Figure 5-19: Generalized section parallel to beach and foredune at the southern end of Fingal Bay.

p. 104). Thom (1960) disagreed with this interpretation, pointing out that the Fingal Bay peat was quite localised and could be explained by exposure of a "lagoonal bog" on the beach due to wave erosion of the foredune. Subsequent study of the flora by Martin confirmed the local origin of the peat (Thom et al., 1969). In this paper the authors used the site as one of a number on the N.S.W. coast to support their view that sea-level had not risen above present HWM since the time of peat accumulation. Macphail (1974) undertook a detailed pollen analytical study of the peat above and below present high tide level and concluded:

> The vegetational changes recorded appear to show the effect of a rising post-glacial sea-level on plant communities occupying coastal Pleistocene sand dunes through rising watertable levels and alterations in dune topography. Pollen curves reflect the destruction of local and seaward dune Eucalyptus-Angophora forest and establishment of the ti-tree/paperbark swamp more characteristic of the present-day beach hinterland (ibid, p. 222).

His detailed section is reproduced here as Figure 5-20.

Emphasis in these studies has been on the peat and stumps. However, the entire east end of the bay is of interest from the vicinity of the surf club to the rocky headland, a distance of about 500 m (Fig. 5-19). However, much of the original topography of the foredune and hinterland has been disturbed by sewerage, parking and road construction.

The section at Fingal Bay runs parallel with the beach. The weathered bedrock surface, truncated by wave erosion at HWM, dips sharply to the west to form the deep bedrock channel at -75 m (Fig. 5-13). Where exposed beneath overlying dune sands, the bedrock contains about one metre of clay which is quite gritty and rich in weathered feldspar phenocrysts of the coarse-grained volcanics.

The clay-bedrock surface is overlain by hard wavy iron oxide bands cementing the quartz sand. These bands form a layer up to 40 cm thick, and are the basal part of a white, clayey, partly indurated sand. The sand forms a low cliff 4 m high at the east end of the bay. It possesses a creamy to white clayey matrix. There are slight iron oxide stains within the sand which is eroded by surface water into steep-sided pinnacles ("badland" erosion). A similar but non-indurated whitish grey sand was encountered at the base of A.N.U. drill hole 118 at the west end of the Fingal Bay section (Fig. 5-19). In this hole the creamy grey, medium fine sand with a fine milky matrix extended to a depth of -22 m below LWM where the clayey sand layer, quite cohesive, was encountered. As suggested above, we are correlating both the creamy grey sand and the clayey sand with the lower sand unit of the Tomaree Hills section.

A H.D.W.B. hole (SK4938) drilled 80 m west of A.N.U. hole 118 at the site of the waste water pumping station did not recover any of the creamy grey sand. At a depth of 15 m below MSL "medium sand with c. 15 percent cemented sand pieces" was sampled. This sand is grey brown to grey. We are tentatively correlating it with the creamy grey sand of A.N.U. hole 118 (Fig. 5-19). In SK 4938 the sand above this layer is a brown, medium, moderately well sorted unit containing layers of peat and "decomposed timber pieces". These organics have not been dated. As

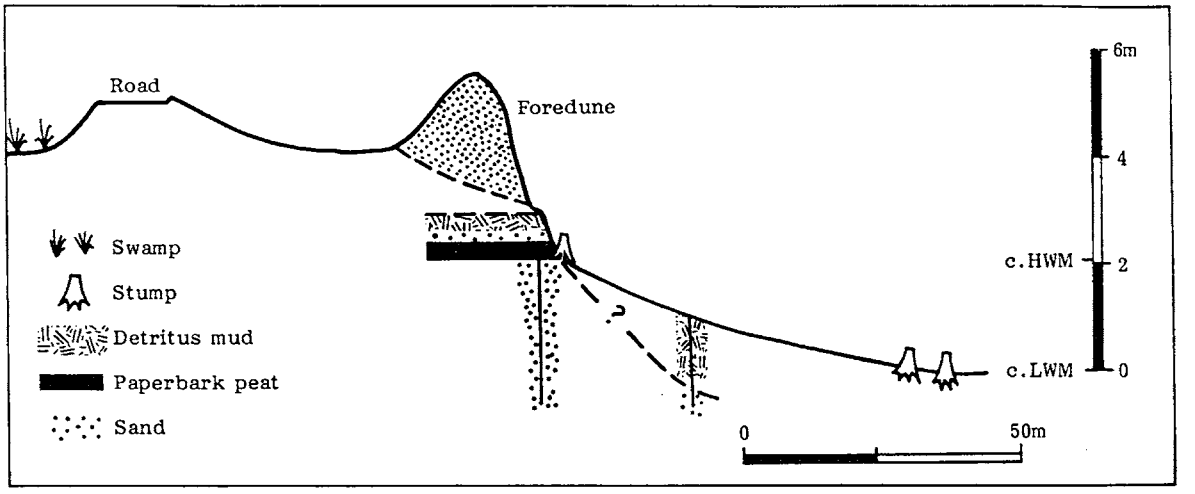

Figure 5-20: Details of organic exposure at creek outcrop at southern end of Fingal Bay (from Macphail, 1974)

shown in Figure 5-19 a sharp discontinuity, perhaps representing a channel margin, separates the older creamy, coloured sands from the brown sands containing organics. The brown sands are correlated with the upper sand unit of the Tomaree Hills section (Q3Te).

The surface unit at Fingal Bay consists of a well podzolized sand which is medium to fine and moderately well sorted. This quartzose sand continues with only one interruption along the line of the section. The interruption is the creek in which the peat deposits are contained (Fig. 5-19). To the east the sand directly covers the bedrock at heights of +15 m. To the west the sand takes the form of a "foredune" ridge noticeably vegetated in the few undisturbed sites by a Eucalyptus-Banksia serrata community. Where the sand thickness above sea-level exceeds 4 m the general profile morphology is as follows:

A1: dark grey, medium sand, abundant roots, 20 to 30 cm thick;

A2: leached light grey, medium sand, loose, fewer roots, 80 to 100 cm thick;

Bh: brown to dark brown with black humate-impregnated sand nodules, friable, weak semi-cohesive humate columns (no bleached sand pipes).

This profile sits abruptly on the clayey sand at the east end of the section. At the contact there is local enrichment of organic colloids. However, beneath the foredune, soil profile morphology is still quite marked. Humate enrichment and depth of the B horizon are not as advanced, particularly in the degree of piping, as the "typical" soil of the upper sand unit (or soil type 3 of Appendix 1).

At the west end of the section the free-draining podzolized sand overlies a humate-impregnated layer 2 to 3 m thick. After the storms in 1974 this layer was exposed on the beach beneath the "foredune" sand from

just to the west of the creek with peat to the creek east of the Surf Club, a distance of over 300 m. Transverse to the beach the humate-impregnated sand extends beneath the foredune and appears to form a ground-water podzol in the swampy area now partly reclaimed. The humate-rich sand was sampled in a pit behind the foredune. Organic analyses and ^{14}C dates are shown in Table 5-2. Humate enrichment extends to at least HWM. The Holocene dates confirm organic colloid emplacement presumably in a low-lying swampy environment landward of the foredune. That these indurated sands now outcrop on the beach as well as extending beneath the foredune, is further evidence of the retrogradation of the shoreline in Fingal Bay. There is no clear evidence at this site for humate extending below present MSL and thus indicating a lower Holocene sea-level as reported by Ward and Grimes (1987, p. 332) for southern Queensland, where shells occur in soft-humate cemented sand below MSL.

The problem is whether the sands containing the humate (the sand rock unit of Fig. 5-19) were deposited prior to the Holocene. If this is so, the sands may correlate with the upper sand unit of the Tomaree area. As noted above, soil profile morphology on the "foredune" is not quite as marked compared to where the sand overlies bedrock at the east end of the section or with "typical" soils of the upper sand unit of Tomaree. One possibility is that at Fingal Bay there has been eolian reworking of the dune sands into mid Holocene times. These sands may have been emplaced prior to the Postglacial Marine Transgression, and eroded back to form the present ridge in the Holocene. This interpretation involves: (i) eolian deposition of the brown sand unit throughout the bay by sand transport from the west at times of low sea-level in the Last Glacial; (ii) reworking of the upper sand unit within the bay during the later part of the P.M.T. into a ridge parallel to the present shore as a blanket cover over the bedrock to the east; (iii) formation of humate and freshwater peat in depressions or beneath a swampy surface since sea-level reached its present position and (iv) further foredune reconstruction since about 4000 years ago initiated by beach face erosion in Fingal Bay. This interpretation is consistent with the arguments of Macphail (1974) related to changing flora in the east part of the bay over the last 6000 years. Further 14C dates are required on the peat and wood from the brown sand in order to test this interpretation. Unfortunately, the H.D.W.B. did not retain samples collected at hole SK4938.

The organic deposits clearly lie within a channel in the podzolized sand unit (Fig. 5-19). Macphail (1974) has described in detail the lithology and pollen composition of the organic layers (Fig. 5-20). The stumps are Melaleuca and in one case provide a maximum limit on when sea-level was at its present position. In free-draining sands it is unlikely that this tree, which dated 6550 $\pm$ 150 ^{14}C yrs BP (0-2161), could have grown at a level now at LWM (1.8 m below estimated HWM) if sea-level had been at its present position. From modern analogs sea-level was probably 1 to 2 m below its present position. Furthermore, the stumps are up to 50 m seaward of present-day growth positions suggesting considerable retreat of the shoreline since peat formation and tree growth 3600 to 6500 years ago.

The final sediment unit on Figure 5-19 is designated "late Holocene foredune sand". This unit thickens to the west and overlies the podzolized sand on the flanks and crest of the "foredune". It is related

TABLE 5-2: Humate Profile at Fingal Bay

Location:
Humate-impregnated sand exposure at base of cliffed foredune in April 1975 and in trench 60 m to south in lee of foreduen (GR 222766 Port Stephens 1:25,000).

Elevation:
Between HWM and +4.8 m msl (= elevation of ANU Drill Hole 118).

Profile Description (depth below ground surface in cm):

0-33	Sand, medium, dark grey; abundant roots, grades to
33-115	Sand; medium; light grey; loose; fewer roots; sharp to
115-185	Sand; medium; very dark brown to black; forms semi-indurated organic hardpan; grades to
185-245	Sand; medium; dark brown becoming lighter and less indurated with depth, some vertical organic stained "streaks", scattered charcoal fragments at 220-230 cm (base of trench at 245 cm)

Sample FB-Z from near base of trench at c. 2.4 m msl

ANU 1580	humic acid fraction	2170 ± 70 ^{14}C years
ANU 1581	fulvic acid fraction	3140 ± 120 ^{14}C years

Sample FB-Y from outcrop humate-impregnated cliff at HWM (c. +0.8 m msl)

ANU 1577	humin fraction	5890 ± 160 ^{14}C years
ANU 1578	humic acid fraction	3950 ± 60 ^{14}C years
ANU 1579	fulvic acid fraction	4270 ± 90 ^{14}C years

to contemporary shoreline erosion and localized dune sand transport.

5.3.3.5 Depositional history

The depositional history of the Tomaree Hills-Port Stephens area can be summarized as follows:

(i) Pre-Last Interglacial deposition (Q1) consists of both extensive clay and sand lithofacies. For the most part these deposits occur below present sea-level (e.g. the clay unit under both Port Stephens and Tomaree, and the lower sand unit in the Tomaree Hills). However, exposures of highly podzolized sands in the Tomaree area support the model of extensive eolian deposition within this area over an extended period of Quaternary time. From the meagre drill data, supplemented by seismic reflection studies in the estuary, we feel reasonably confident in arguing that the pre-Last Interglacial deposits represent a number of events, but it is impossible at present to chronicle these events.

(ii) Unlike other embayments in the study area, it is not clear what deposits in the Tomaree Hills are Last Interglacial in age (Q2). The Inner Barrier as such is not represented here, although beneath Port Stephens the upper unoxidized part of the compact clay may be of this age. That some sand was deposited in the Tomaree region, especially in the lowland between Anna Bay and Salamander Bay, at this time is most likely.

(iii) A major period of eolian reworking is envisaged throughout the Tomaree area in the Last Glacial (Q3Te). Inner Barrier landforms, if present, may have been substantially modified at this time. Winds from the western quadrant were plainly responsible for sand movement; in other words, these "terrestrial" dunes (or upper sand unit) were active when the shoreline was further east and at a much lower level than it is today.

(iv) The Quaternary history of fluvial drainage in Port Stephens and through the Tomaree Hills at times of lower sea-levels is most unclear. Four outlets are possible at different times, or perhaps together at some stage. A major bedrock channel exists to the west of Soldiers Point which may have received Hunter River as well as Karuah River discharge at some stage. This channel has been infilled with fluvial sand and pre-Last Interglacial clay. East of Soldiers Point there is evidence for three bedrock channels: one is through Salamander Bay to Anna Bay, another is from Nelson Bay to Anna Bay, and the third is out through the present "heads" (i.e. between Yacaaba and Tomaree headlands). Pleistocene sediment of varying ages infills all these old channels. The presence of a bedrock sill in eastern Port Stephens may have restricted seaward drainage through the present "heads"; however, it is possible that a narrow channel, as yet undiscovered, was maintained through the heads at lower sea-levels during the Last Glacial.

(v) Mid-Holocene sedimentation (Q5) is restricted in the Tomaree area to fringing dunes and swamp deposits. Port Stephens has received a fresh blanket of mud plus sandy deposits of the tidal delta, fluvial delta and shoreline environments. Shell accumulations such as bioherms are spectacular Holocene sediment bodies within the estuary.

(vi) There is evidence for shoreline erosion in Tomaree and Port Stephens in the late Holocene (Q6). This is documented at Fingal Bay. A spit inside the estuary, Winda Woppa-Myall Point, has undergone growth and decay over the last 200 years. Shorelines within the estuary have experienced erosion as at Shoal Bay and Corlette Point.

6

Fens

6.1 REGIONAL SETTING

6.1.1 Bedrock Properties

The Fens embayment extends from Port Stephens northeast to Sandy Point. The northern shore of Port Stephens forms the southern boundary of the embayment. The Outer Barrier of this embayment is connected to Yacaaba, a Carboniferous outcrop 218 m in height. This hill is also the northern headland of Port Stephens (Fig. 6-1a,b).

The landward margin of the Fens embayment is composed of Carboniferous Wootton Beds, and is quite irregular in plan. It does not show obvious evidence of marine cliffing, except on the points of projecting strike ridges. The low dip of the Girvan Anticline (Engel, 1962) possibly explains the flat to gently undulating summit surface of the bedrock margin around the Fens bay. A rock ridge extends seawards to the Lower Myall River at Monkey jacket, separating the extensive main Fens Inner Barrier to the north from a smaller Inner Barrier segment near Tea Gardens (Fig. 6-1a). The main section extends for a distance of 10 km to the north towards a small lagoon called The Grasswater (shown on Bombah Point 1:25,000 map as Brasswater). At the rear of the embayment, 8 km from the present shoreline, the margin consists of gently sloping valley fill and swamp deposits which merge with the sand terrain of the Inner Barrier. The northeastern margin of the embayment is formed by

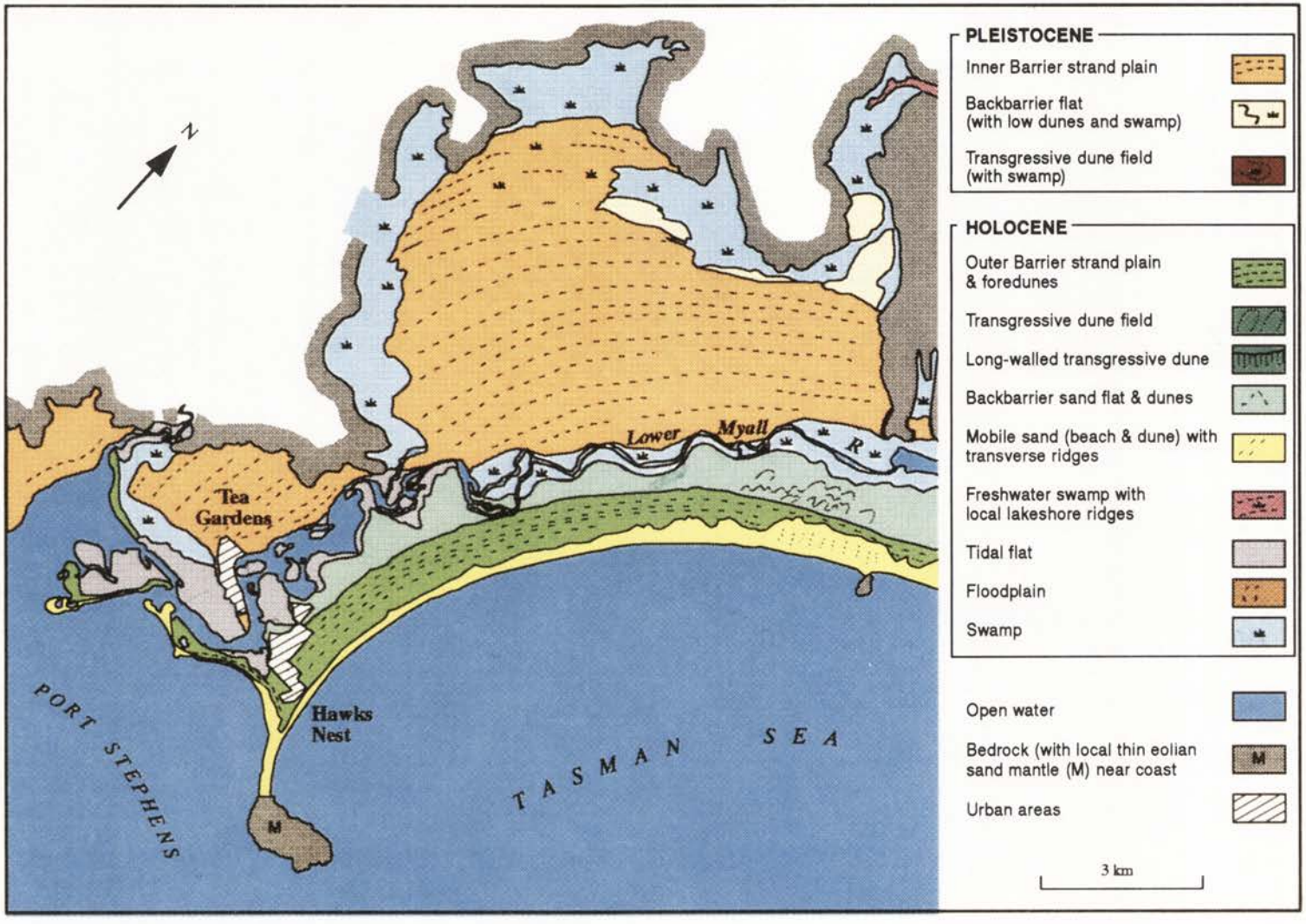

Figure 6-1a: Generalized morphological map of the Fens embayment.

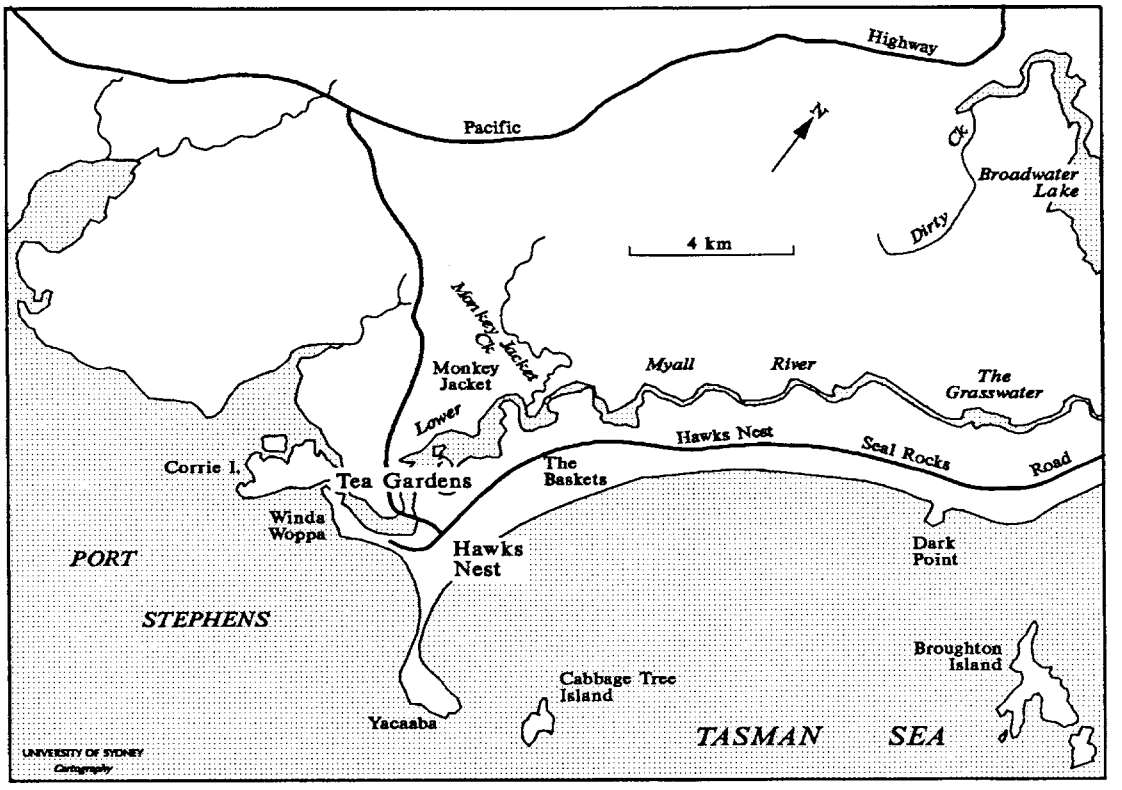

Figure 6-1b: Location map of Fens embayment showing position of general embayment section (see Fig. 6-21).

strike ridges which extend almost to The Grasswater.

There is no bedrock boundary at the northeastern end of the Outer Barrier, but an abrupt change in coastal orientation at Sandy Point marks the transition from the Fens to the Eurunderee Outer Barrier which extends across the mouth of Broadwater Lake. Dark Point, near the northeastern end of Fens Outer Barrier, is an isolated outcrop of Carboniferous rock, aligned with the strike ridges.

Figure 6-1a shows the occurrence of a number of bedrock islands at both ends of the embayment. These are composed of Carboniferous volcanics and are drowned extensions of the strike ridges. Broughton Island is the largest island and has a markedly irregular outline resembling the classic "skeleton" island configuration described by Cotton (1969). Eolian sands and aboriginal middens occur on this island. Other offshore outcrops are much smaller and are frequently steep-sided. They are significant to the depositional environments of the Fens embayment in that they modify the approach of incident waves by refraction.

6.1.2 Dynamic Environment

Wave energy enters the broad Fens embayment from northeast to south directions. The sweeping Fens beach curves sharply in the southern section in the lee of the three southern offshore islands and Yacaaba Head (Fig. 6-1a). The northern two-thirds of the beach curves much more gently to face the SSE and SE. The shoreline has a zeta-curve configuration, which has apparently been adjusted in its plan shape to the predominantly southeasterly swell.

Shepherd (1970, Figs. 2-16 to 2-22) has prepared refraction diagrams for the stretch of coast between Yacaaba Headland and Seal Rocks. He used the method of Wiegel (1964), constructing the diagrams graphically on the Sugarloaf Point and Morna Point-Broughton Island R.A.N. Survey sheets. A variety of wave lengths and directions was employed. Selected refraction diagrams for the Fens embayment are illustrated in Figure 1-7. The Wiegel type diagrams show that refracted long period (10-12 sec) SE and SSE waves best "fit" the beaches. Short period waves (<8 sec) and waves from northeast, east and south directions do not conform to the plan of the beach. Their incidence probably results in local erosion or deposition which in the long-term is insignificant to the evolution of the plan form. Refraction of southeasterly waves around Broughton Island helps explain the cuspate foreland of Sandy Point. Refraction coefficients are quite low in the lee of the island on both sides of the Point. They are low for southeast waves, as well as for east and south waves, at Hawks Nest and along the Yacaaba tombolo. The refraction diagrams show that Fens Beach is protected by headlands and islands from the full effects of southerly waves which according to Shepherd's (1970) analysis of wind records, should account for 60 percent of wave energy in this area.

Silvester (1962) has argued that the zeta-curved beach is the equilibrium plan form for shores experiencing an oblique swell wave approach. A relative sediment deficiency exists at the south end of the bay ever since the barrier was initiated. Inshore wave energy is distributed so as to maintain the zeta form by minimizing long-term effects of littoral drift in any direction. Wind energy is also

predominantly from the south although coastal sands are also freely moved by winds from other directions. The effect of south to southeast winds is most felt towards the northern half of the bay, as manifested by the northerly increase in beach-ridge height and the development of mobile dunes. Winter westerlies and summer easterlies are capable of reversing mobile transverse dunes (see 6.2.4.2).

6.2 MORPHOLOGICAL CHARACTERISTICS

6.2.1 Major Morphological Features

The approximate area of the Fens Embayment is 100 km^2. This area includes the Inner and Outer barriers and the interbarrier depression, but not the extensive alluvial-colluvial valley fill landward of the Inner Barrier. The maximum length of the embayment is 14.5 km measured along the long axis of the Outer Barrier and the maximum width, near the centre of the embayment is 8 km.

There are three major depositional units: the Inner Barrier, the interbarrier depression and the Outer Barrier. Our studies have concentrated on these features; we have not investigated the extensive valley fill deposits at the rear of the embayment.

6.2.2 Inner Barrier

The Fens Inner Barrier with an area of 50 km^2 infills a broad embayment to the northeast of Port Stephens. The rear and lateral boundaries of the barrier consist of low bedrock hills and clay flats. A lagoon behind the Inner Barrier is restricted to a small blocked valley shown in Fig. 6-1a at the northern corner of the bay. This swamp is contiguous with the lake waters of Nerong or Dirty Creek-Broadwater Lake. Its organic fill has not been drilled.

Major drainage routes are confined to the margins of the Inner Barrier. At the rear of the barrier drainage is diverted first east and then north through a gap in the hills to join Dirty Creek. Along the southwestern margin drainage is south through swamps before entering the Lower Myall River via Monkey Jacket Creek (Fig. 6-1b).

The general orientation of the barrier is NE-SW which is parallel to the present shoreline. Although the altitude of the major part of the Inner Barrier varies between +7 and +10 m MSL, the outermost kilometre dips seawards to reach an altitude of only +1.3 to +2 MSL at the interbarrier depression (see Drury, 1981, Fig.2). The northeastern section of the barrier is slightly lower than the remainder of the barrier. The fact that Inner Barrier ridges remain preserved at heights as low as approximately 1 m above high tide mark along the river indicates that it is unlikely that Holocene sea-levels have exceeded present sea-level by more than 1 m.

The main Fens Inner Barrier is composed entirely of beach ridges or relict foredunes forming a distinctive strand plain. The ridges are not as pronounced, regular or parallel as those of Eurunderee Inner Barrier to the north (see Ch. 8). The general trend of the ridges is approximately parallel to that of the Outer Barrier and the present coastline (Fig. 6-1a). The longitudinal curve of the ridges is more

irregular towards the rear of the barrier. This suggests that bedrock projections from the sea bed influenced wave refraction when the inner part of the barrier was prograding. However, the beach ridges become more regular and parallel to seaward, probably reflecting a smoother sea floor over which the regressive sands were deposited.

Beach ridges vary in width from less than 30 m at locations where preservation of the original ridge/swale spacing has been favoured, to over 100 m where considerable degradation has occurred. Examination of aerial photos indicates that a close spacing of ridge traces, comparable with that of Fens Outer Barrier, is found at the northeastern extremity of the Inner Barrier. Here the watertable lies very close to the surface. Similarly, in the innermost or western section of the barrier, where valley fill clay has buried low-relief ridges and swales, evidence of the original spacing of beach ridges is preserved. Ridges cannot be discerned in the field in this area, but the former spacing is indicated by linear trends in ground cover, as shown on air photos (the location of the clay-veneered ridge plain is shown in Fig. 6-1a). The ridge/swale pattern is also very poorly defined in the higher central part of the barrier where the watertable is relatively high and where swales have not been utilised as channels for surface runoff.

Beach-ridge amplitude rarely exceeds one metre. The only major exception is at the northeastern end of the barrier where the innermost ridge has an amplitude far greater than average. This ridge, which is 300 m in width, rises from +6 m MSL at the swamp level, to +9.4 m MSL at the crest, and then falls to +7.9 m MSL where it merges with the level barrier surface to the south.

Small areas of Inner Barrier sand occur west of Tea Gardens and adjacent to Port Stephens at Pindimar. They are lower than Fens Inner Barrier and vary between +3 m MSL, near the bedrock margin, to +1 m MSL adjacent to the tidal flats of Port Stephens and the Lower Myall River. The ridges decline in altitude longitudinally away from the bedrock margin by about 1.5 m over a distance of less than 2 km.

Beach-ridge orientation in Fens Embayment indicates that during the period of Inner Barrier deposition the dominant ocean waves arrived from essentially the same direction as at present. The beach ridges of the Inner Barrier near Tea Gardens are oriented towards the east, indicating that the dominant waves were refracted around the northern side of Yacaaba, and that access to the ocean from the southeast and south was relatively restricted.

6.2.3 Interbarrier Depression

The depression extends between the Inner and Outer Barriers of Fens Embayment for a distance of 15 km from Port Stephens in the southwest to The Grasswater in the northeast. It varies in width from 1.6 km near Tea Gardens to 0.8 km near The Grasswater and occupies an area of approximately 16 km^2.

The Fens interbarrier depression is interpreted as an extensive estuarine/lagoonal complex linking Port Stephens with the Myall Lakes in the mid-Holocene. In the subsurface, backbarrier sand deposits and the oldest ridges of Fens Outer Barrier overlie estuarine deposits (see 6.3).

This indicates that the interbarrier zone has been protected from high-energy open ocean conditions since towards the end of the Holocene transgression. This is confirmed by the stratigraphy (6.3) and by the fact that Fens Inner Barrier ridges at the margin of the interbarrier zone have not been modified by the action of ocean waves during Holocene time.

The depression is now occupied by tidal flats and freshwater swamps associated with the Lower Myall River (Weate, 1975; Atkinson et al., 1981). Weate (1975) has described the flora and fauna of the extensive wetlands of the southern section of the Lower Myall River.

Encroachment vegetation successions are playing a major role in the continued infilling of the depression. The height of the interbarrier surface is closely related to sea-level. A number of levelled profiles indicate that the surface lies at elevations of less than one metre above spring high tide mark in the Lower Myall River. The microtopography of the depression has not been studied. However, vegetation patterns outline what appear to be the arcuate landward edges of low-relief washover fans on the now relict backbarrier flat surface (see Fig. 6-2 and N.S.W. coastal wetland air photographs at 1:25,000 scale). At the northern end of the embayment there is a zone of hummocky dunes on the backbarrier flat (Fig. 6-1a).

The Lower Myall River is 25 km in river length. The spring tidal range declines from 1.2 m at Tea Gardens to a few centimetres at the entrance to Broadwater Lake. No systematic study of tidal currents has been undertaken, but it appears that the river is dominated by ebb currents when the Myall Lakes are in flood and by flood tide currents during periods of drought. During a 12 hour period in November 1967, when the Myall Lakes were at their average summer level (approx. MSL), maximum discharges of 54.2 m per sec. for the flood current and 50.5 m per sec. for the ebb current were recorded at Tamboy near Broadwater Lake. In 1976 during a winter rainy period, brackish waters were limited to the lower 4 km of river. Atkinson et al. (1981) describe salinity variations in the Lower Myall River as part of a general study of the ecology of the Myall Lakes.

6.2.4 Outer Barrier

Fens Outer Barrier extends for a distance of 14.5 km between Yacaaba Head and Sandy Point. Its average width is 1.5 km and it covers an area of about 30 km^2. It consists of a beach-ridge or relict foredune plain, foredune-mobile dune complex and a beach-nearshore zone.

6.2.4.1 Beach ridges

The destruction and burial by mobile dunes of many of the seaward ridges of Fens Outer Barrier, especially towards the northern end, limits any study of longitudinal variation in beach-ridge characteristics to the innermost 100 to 300 m of the barrier. Only the four innermost ridges are present along the entire length of the barrier. However, these ridges have now been almost entirely mined for heavy minerals. Fens Outer Barrier ridges are generally parallel to the present beach and to each other, but occasionally merge or diverge. However, the inner ridges at the southern end of the barrier in the vicinity of Hawks Nest face due



Figure 6-2: **Vertical air photograph of a portion of the Fens embayment (NSW 1188-5130, 18/8/1963). Both Inner and Outer Barrier topographic patterns are depicted on this photo. The subdued partly deflated and dissected relief of the Inner Barrier is highlighted by organic swamp infill of many swales. The terrain is further enhanced by clearance for pine tree cultivation. An interbarrier depression occurs seawards of the Inner Barrier and contains the sinuous channel of the Lower Myall River. The depression is heavily timbered by Casuarinas and Melaleucas. Arcuate patterns on the flat surface of the depression may represent landward edges of relict washover fans. The parallel beach ridges or relict foredunes of the Outer Barrier are being consumed by an active transgressive sand sheet.**

east, a direction offset from the present beach by about 10 degrees. Ridge curvature becomes more pronounced seawards, until the most easterly ridges parallel the present coastline. This change in ridge alignment during progradation was a localized phenomenon and may be explained in terms of ridge accretion into a deepening offshore zone.

Fens Outer Barrier is bisected by a Carboniferous inlier at Dark Point (Fig. 6-1a and b). Drilling by Mineral Deposits Ltd. has shown that the ridges and underlying heavy mineral seams curve northwards parallel to the present coastline beneath the dune sheet at Sandy Point.*

Surveyed cross-sections (Fig. 6-3) show the innermost ridges to increase steadily in altitude in a northerly direction. If the ridges were formed by accretion as successive foredunes, then a positive correlation between onshore wind energy and ridge height would be expected, assuming rates of cut and fill to have been uniform along the beach over time (see Fig. 6-4 and Shepherd, 1970). It is not possible to compare present foredune height and wind energy as the former has been destroyed along the greater length of Fens Beach. Where the present foredune is preserved in the southern and central section of Fens Beach, and along parts of Eurunderee Beach, there is a marked tendency for it to increase in height with increased exposure to southerly winds. However, Hesp (1982, p. 307) has shown that onshore eolian sand transport increases with increasing beach width and decreasing gradient and beach mobility (i.e. with increasing dissipativeness). He considers that exposure to winds is of less importance than subaerial beach morphology in determining the rate of eolian sand transport (see also Short and Hesp, 1982).

Table 6-1 summarizes morphometric properties of the beach-ridge plain at Fens. Ridge-swale amplitude shows no overall trend, but is greatest near Sandy Point. Ridge amplitudes over the major part of Fens Outer Barrier for the most part range between 0.9-1.5 m. Ridge widths, width/height ratios and width/amplitude ratios show no substantial correlation with any other variables. Beach ridges are noticeably wider in spacing near Hawks Nest (section 1, Fig. 6-4, Table 6-1). There are two possible explanations:

(i) Owing to relatively lower onshore wind energy at the southern end of Fens Beach, less eolian sand was incorporated into the ridges within a given period, resulting in lower ridge heights (Hesp, 1982).
(ii) Wave energy values are relatively low at the southern end of Fens Beach. Less frequent and less effective beach cut would have enabled relatively wide, low ridges to form.

Only four sections (1, 2, 3 and 4) are considered to be of sufficient length (over 600 m) to enable the application of statistical methods to examine possible tilt across the system (Fig. 6-5). When either ridge heights or swale heights are correlated with distance seawards from the crest of the innermost ridge, no statistically significant trends are found at the 95 percent confidence level. Ridge heights of section 1 were similar, but less pronounced. In sections 2, 3 and 4, ridge and swale regression lines were almost horizontal, apart from the swales of section 3, which showed a slight, though not

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* D. Staupe, Mineral Deposits Ltd., pers comm. 1973.

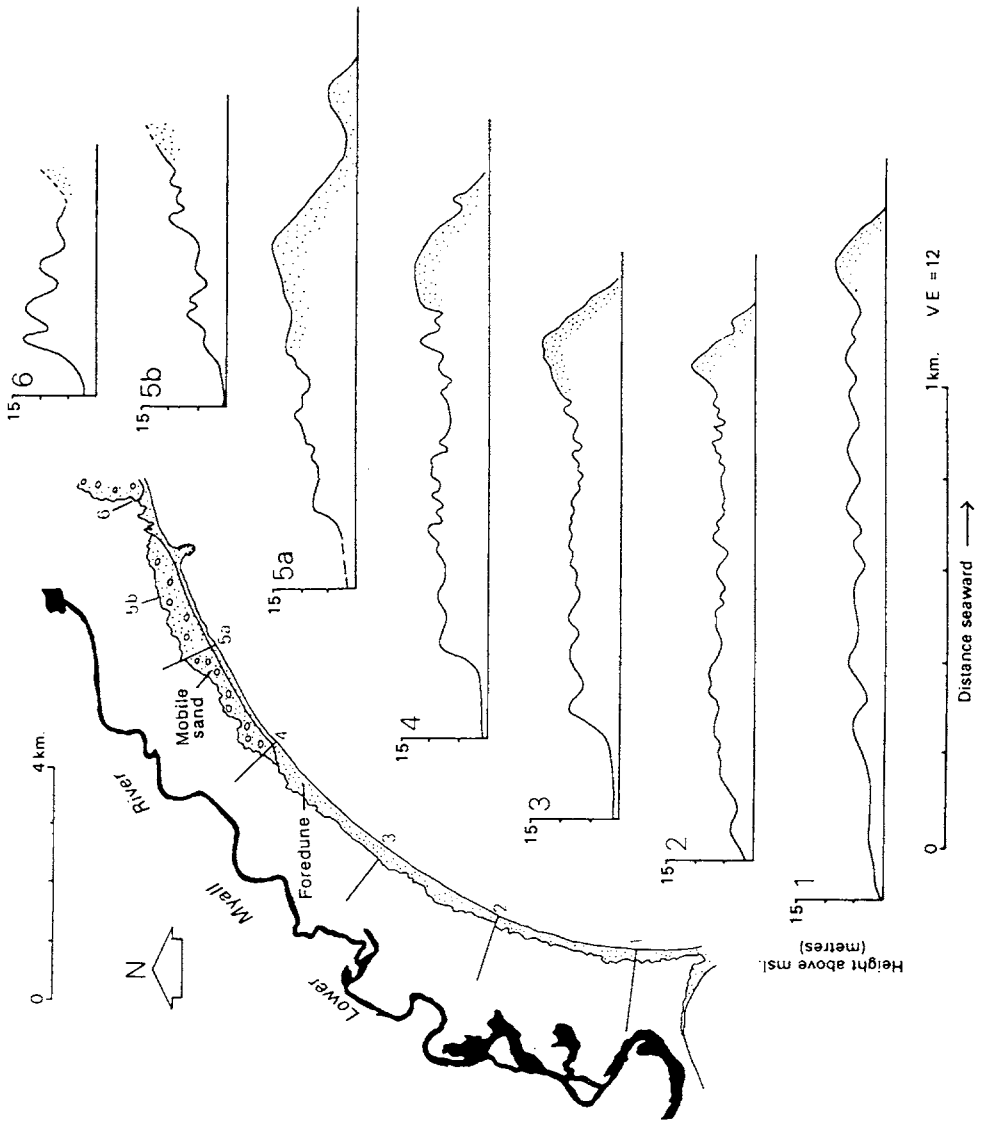


Figure 6-3: Topography sections across the Fens Outer Barrier.

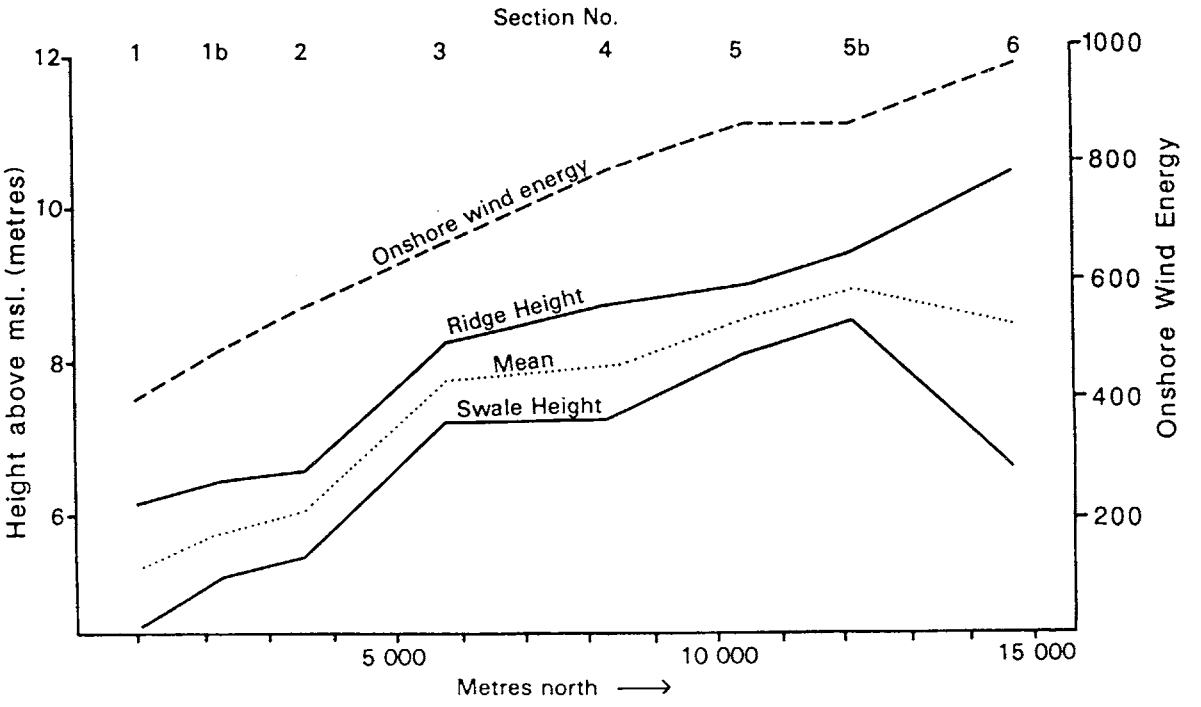


Figure 6-4: Elevation of average beach ridge and swale heights (above MSL) along the Outer Barrier of the Fens Embayment north from Hawks Nest. Also shown is Shepherd's (1970) calculation of onshore wind energy (expressed in dimensionless units) following Landsberg (1956).

statistically significant, seaward tilt. Modification of ridge heights by the compaction of underlying sediment is considered unlikely, as the Outer Barrier overlies thick sandy Inner Barrier sediment (see 6.3). The latter would have suffered negligible compaction itself and any argillaceous sediment underlying the Inner Barrier would probably have undergone compaction prior to Outer Barrier progradation.

It is doubtful whether regression lines are of much value in determining tilt or minor sea-level change in a system as narrow as Fens Outer Barrier (see review by Bowden and Kirkpatrick, 1974). On exposed sandy coasts ridge and swale heights are also related to factors other than the sea-level height which prevailed during their formation, as is amply illustrated by the northerly height increase of Fens Outer Barrier (Fig. 6-4). Transverse differences in ridge height can be caused by medium to long-term variation in onshore wind energy, the supply of sand to the littoral zone, the frequency and intensity of beach cut and vegetation density variations (Thom, 1964; Hesp, 1984b). The morphology of the ridges and swales of Fens Outer Barrier provides no evidence of sea-level change during barrier progradation, or of subsequent tilting. The youngest ridges, which are preserved only in the south, are higher than the landward ridges.

The oldest ridge of the Outer Barrier at Fens tends to be broad compared with the other ridges and there is a marked topographic break between this ridge and the backbarrier flat to landward. The flat is covered with swamp trees including Casuarina, Melaleuca, Livistonia and Eucalyptus robusta. It is about 4 m lower in elevation than the innermost ridge which is covered by the typical dune woodland or forest community.

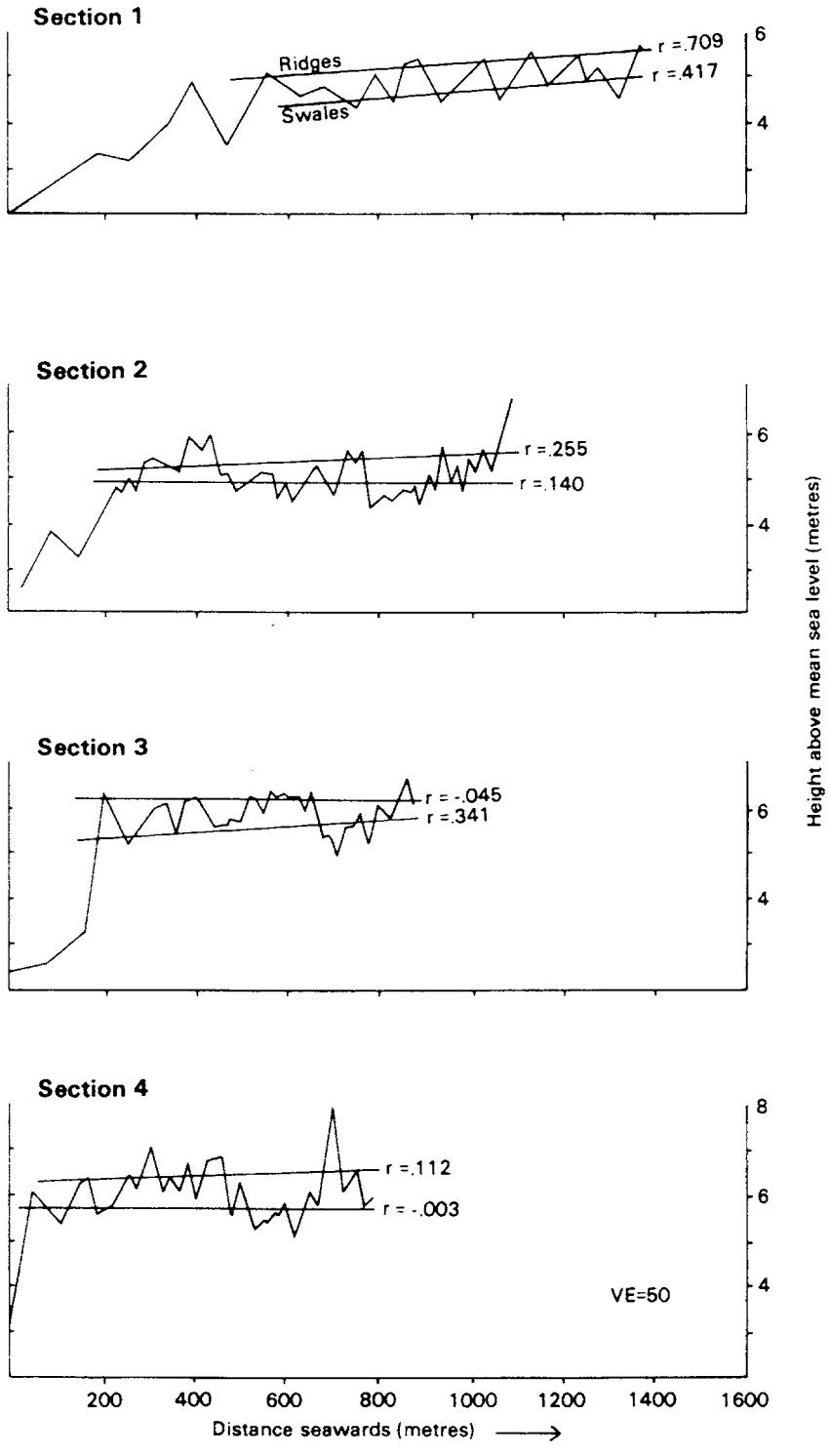


Figure 6-5: **Trends and correlation coefficients for ridge crest and swale elevations on four sections on the Outer Barrier of the Fens embayment (see Fig. 6-3 for location of sections).**

TABLE 6-1 Morphometric Properties of Outer Barrier Strand Plain, Fens Embayment (dimensions are mean values in metres)

Section Number	Ridge Height	Swale Height	Elevation	Amplitude Ridge/ Swale	Distance Between Ridges
1	6.25	4.64	5.44	1.50	117
2	6.66	5.54	6.16	0.98	47
3	8.32	7.29	7.80	1.03	52
4	8.81	7.32	8.04	1.38	46
5a	9.07	8.23	8.65	1.09	62
5b	9.52	8.59	9.04	2.27	57
6	10.54	6.74	8.64	3.37	68

The beach ridges are quite regular in plan and possess a low rounded crestline. This could indicate that a vegetation cover was quickly established and maintained. The successional development of plant communities on the beach-ridge plain has long been disturbed by other ecological factors such as sea salt flux, which declines landwards, and periodic fires (see Myerscough and Carolin, 1986). Figure 6-6 clearly shows discontinuities between Eucalyptus and Banksia scrub communities on the Outer Barrier. These discontinuities cross beach ridges of different age.

One of us (Bowman, 1979) has investigated the development of podzol soils in the Fens Outer Barrier and has found that the degree of soil development is not strongly related to the present vegetation pattern on the beach-ridge plain. Age of a soil profile and depth to the watertable are more influential factors. Figure 6-7 illustrates the range of morphological characteristics of the Outer Barrier podzol soils. Soil Profiles 1, 2 and 3 represent a sequence of soils of differing age, all developed in swales with uniform quartzose parent material and Banksia scrub vegetation. The ages of the profiles are 3800, 4500 and 5000 radiocarbon years respectively, which encompass the full age range of these beach-ridge soils (see below for a discussion of age structure of this Outer Barrier). As these profiles show, the degree of soil development varies from moderate in Profile 1, to strong in Profile 3. Profiles 4 and 5 on Figure 6-7 were also located in swales, had quartzose parent material and are both 5000 years old. They differ from the other profiles in having Eucalyptus woodland and Angophora woodland vegetation, respectively. The close similarity of these profiles to Profile 3 of the same age, topography and parent material is evident. Profile 6 (on

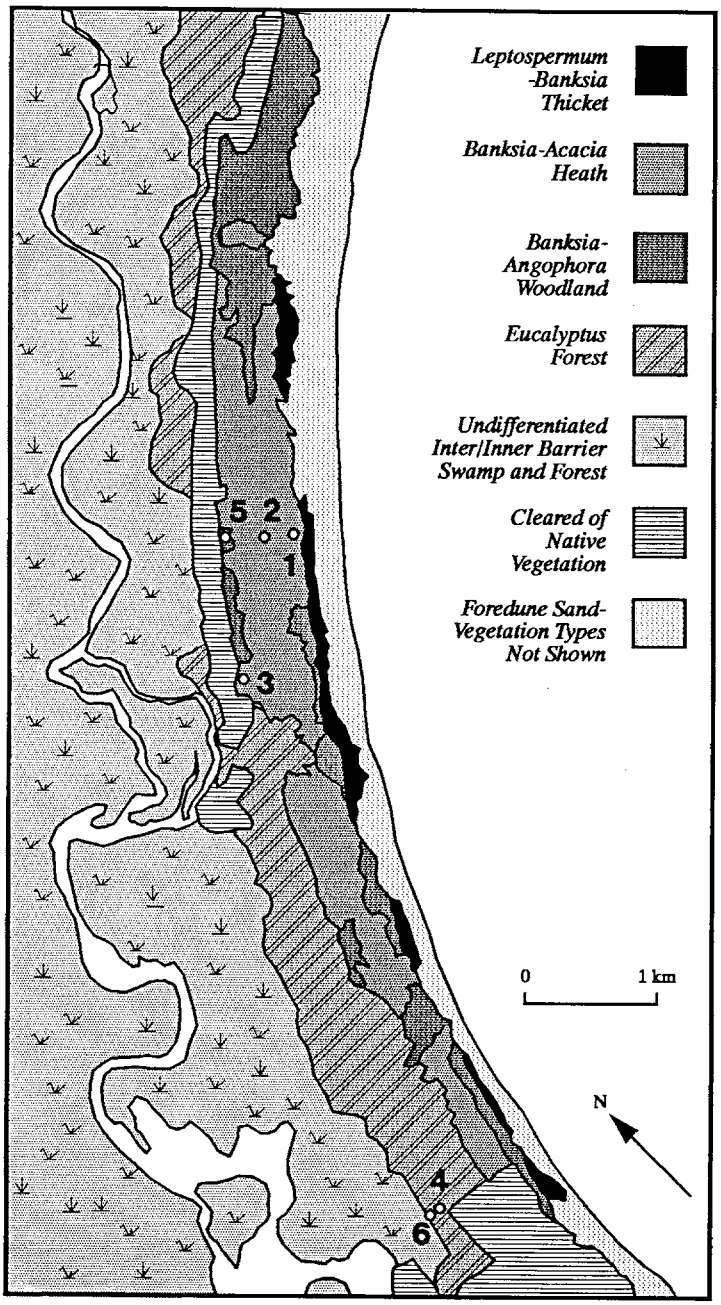


Figure 6-6: Vegetation of the Outer Barrier for a portion of the Fens embayment and location of soil sites (after Bowman (1979). Descriptions of the soil sites are provided in Figure 6-7.

Figure 6-7) is from the landward side of the beach-ridge plain, from an area with Eucalyptus woodland vegetation. It is also 5000 years old but differs from all the other profiles in having a permanent watertable only 2 m below the ground surface. As is evident from the figure, the morphology of Profile 6 is substantially different from the morphologies of the other profiles. This is attributed to the effect of the high watertable (Bowman, 1979).

To further illustrate the characteristics of the podzols, Figure 6-8 presents a barrier cross-section on which the soil sampling points in Profiles 1, 2 and 3 have been located, and on which isopleth lines, indicating the distribution of selected cations, have been superimposed. Cation analytical techniques are described in Bowman (1979). Figure 6-8a shows the distribution of iron across the three profiles of different age. Increased development and differentiation of the A^1, A^2 and B horizons is evident across the section from right to left (seawards to landwards). Figure 6-8b shows the distribution of aluminium, and again the development of the A^1, A^2 and B horizons increases across the section, although not as markedly as for iron. Figure 6-8c shows calcium distribution which is much less regular than iron or aluminium. Calcium concentrations are very low throughout the profiles, indicating complete leaching of shell carbonate from these soils.

6.2.4.2 Foredune and mobile sand sheets

The dune region separating the beach ridges from the unvegetated backshore of the Fens beach consists of two gradational dune types: the vegetated frontal dune complex, and areas of mobile sand. As the shoreline curves north there is a progressive change in the extent to which the frontal ridge is preserved. The trend reflects an increase in exposure to southerly winds towards the north of the embayment. The exception is the area of eroded dunes on the Yacaaba "tombolo", at the extreme southern end of the embayment.

Yacaaba Tombolo. The partially stabilized surface of the Yacaaba tombolo shows the impact of both wave and wind processes. The tombolo is subjected to wave attack from two directions. Ocean waves refracted around Yacaaba Head cut into sandy beaches on both the Port Stephens and Fens open ocean sides. Wave bores have been known to wash across low points on the tombolo in historic times (e.g. in late 1950s and observed by Hesp in 1978). Large waves from the south are probably responsible for the mobilization and concentration of boulders on the south flank of Yacaaba. A boulder beach, developed on the north side of Yacaaba, has been studied by Oak (1981, 1984). Wind waves generated by northeast and east winds periodically cut back the beach on the Fens side, and waves generated within Port Stephens under the influence of westerly winds erode the western shore of the tombolo (see Gordon, 1982). It is these east and west winds which modify the surface of the tombolo. The wind

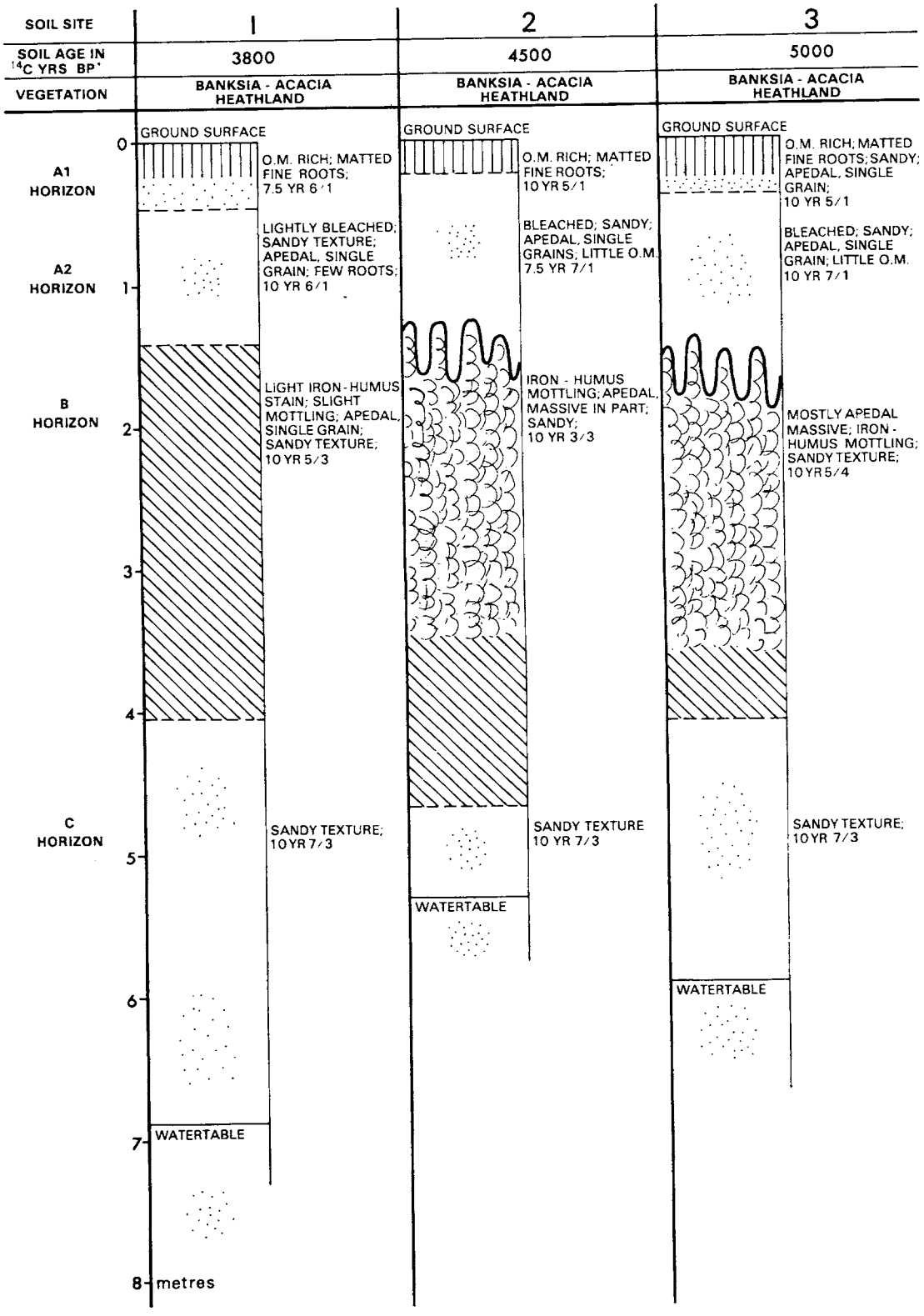
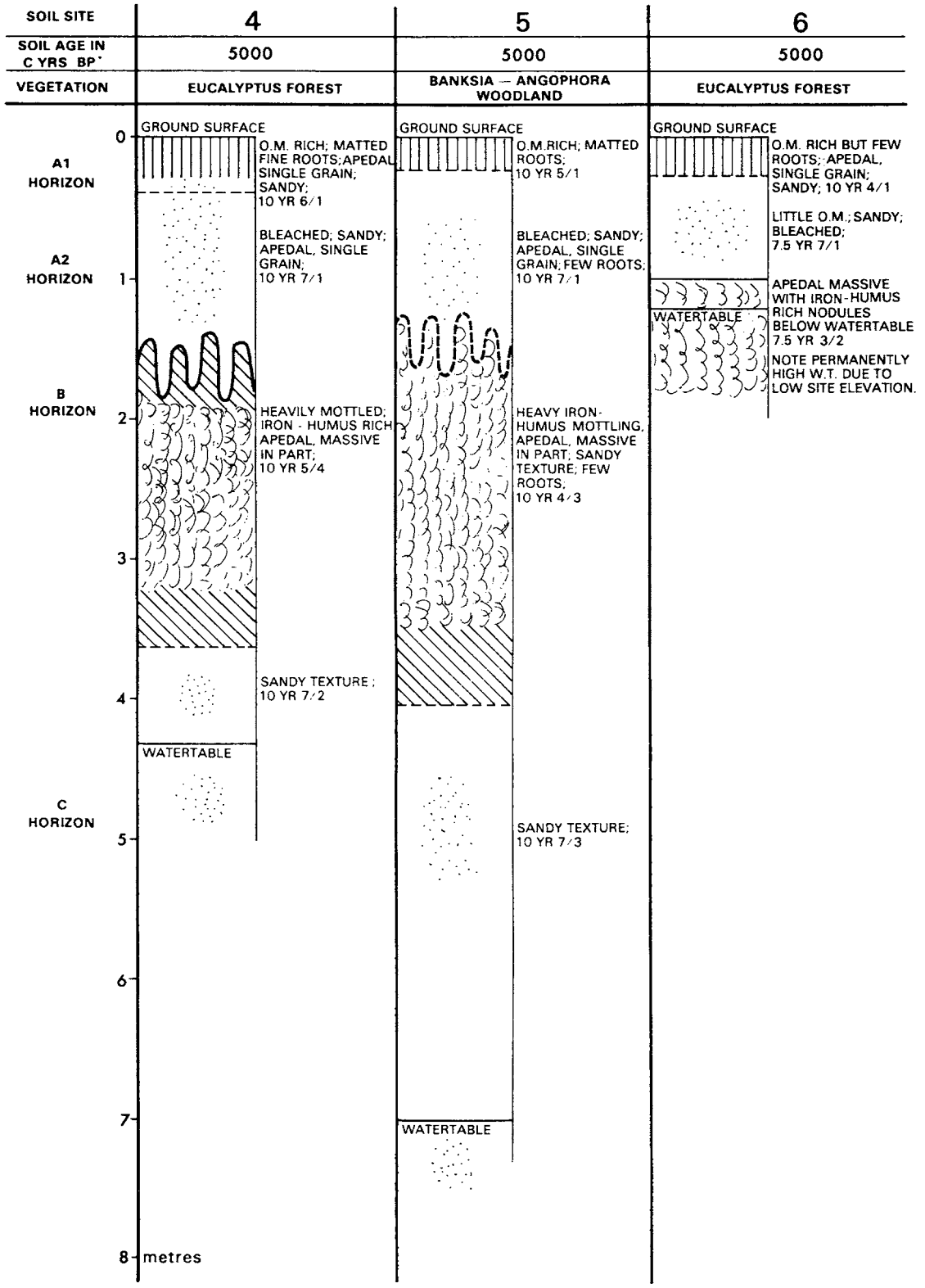


Figure 6-7: Soil profile characteristics for surfaces of different age and vegetation located on the beach-ridge plain of the Fens Outer Barrier (see Bowman, 1979, for more details on profile properties). Ages are based on radiocarbon dates on shell in beach facies.


SOIL SITE
4
5
6
SOIL AGE IN C YRS BP*
5000
5000
5000
VEGETATION
EUCALYPTUS FOREST
BANKSIA — ANGOPHORA WOODLAND
EUCALYPTUS FOREST
A1 HORIZON
A2 HORIZON
B HORIZON
C HORIZON
0
1
2
3
4
5
6
7
8
metres
GROUND SURFACE
O.M. RICH; MATTED FINE ROOTS; APEDAL SINGLE GRAIN; SANDY; 10 YR 6/1
BLEACHED; SANDY; APEDAL, SINGLE GRAIN; 10 YR 7/1
HEAVILY MOTTLED; IRON - HUMUS RICH APEDAL, MASSIVE IN PART; 10 YR 5/4
SANDY TEXTURE; 10 YR 7/2
WATERTABLE
GROUND SURFACE
O.M.RICH; MATTED ROOTS; 10 YR 5/1
BLEACHED; SANDY; APEDAL, SINGLE GRAIN; FEW ROOTS; 10 YR 7/1
HEAVY IRON-HUMUS MOTTLING, APEDAL, MASSIVE IN PART; SANDY TEXTURE; FEW ROOTS; 10 YR 4/3
SANDY TEXTURE; 10 YR 7/3
WATERTABLE
GROUND SURFACE
O.M. RICH BUT FEW ROOTS; APEDAL, SINGLE GRAIN; SANDY; 10 YR 4/1
LITTLE O.M.; SANDY; BLEACHED; 7.5 YR 7/1
APEDAL MASSIVE WITH IRON-HUMUS RICH NODULES BELOW WATERTABLE 7.5 YR 3/2
WATERTABLE
NOTE PERMANENTLY HIGH W.T. DUE TO LOW SITE ELEVATION.

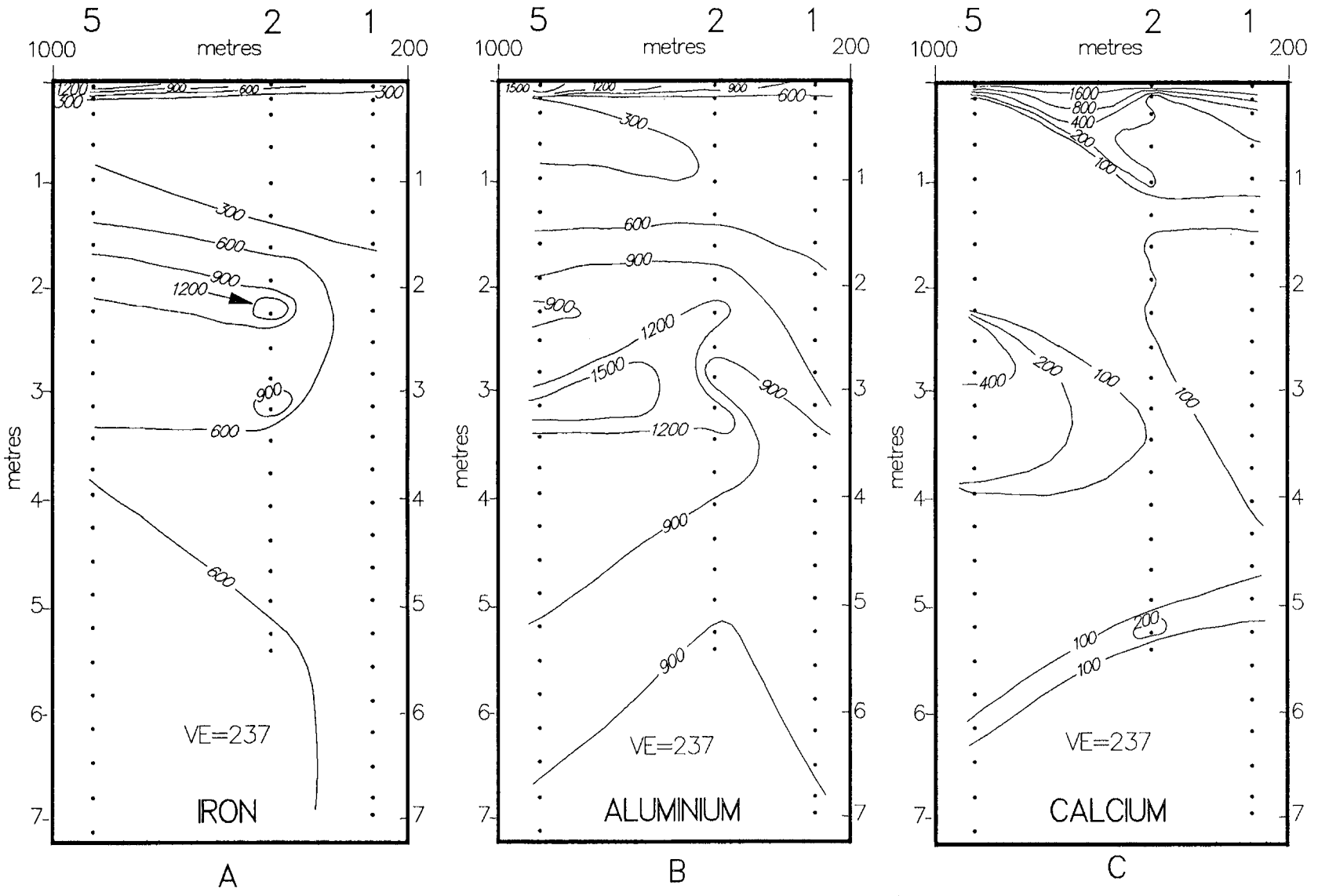


Figure 6-8: Distribution of iron, aluminium and calcium in the soil profiles along the dated Fens transect located in Figure 6-6.

deflated surface of the tombolo is disrupted by a hummocky established foredune with wind-scoured flanks. There is also localised development of an incipient foredune (Hesp, 1984a) and a high, free-moving reversing dune on the tombolo.

Easterly to northeasterly winds sweep sand off the beach on the Fens open ocean side of the tombolo. This sand accumulates in the vegetated dune hummocks or in the reversing dune. The latter forms a barchanoid shape. The slipface is rarely more than 5 m in height in summer although the sand hill of which it is part rises to plus 20 m above HWM. In winter, the dune reverses and the slipface exceeds 10 m in height. Sand is transported seawards by westerly winds across the deflated surface between vegetated hummocks, and from the free-moving reversing dune.

Gordon (1982, Fig.8)has estimated how much sand is transported by westerly waves and winds along the relatively steep reflective beach on the Port Stephens side of the tombolo. Erosion of Winda Woppa in historic times (see Ch. 5) may contribute sediment to the tombolo by littoral drift, from where a portion is quickly incorporated into the dune complex by westerly winds. The episodic nature of wind-wave erosion on the tombolo is indicated by a buried podzol profile and Banksia stumps in remnant knobs of the old established foredune complex. As shown in Figure 6-1a, the Outer Barrier zone of beach ridges merges at the southern end of the Fens bay into a single broad established foredune.

The origin of the connecting sand ridge called tombolo in this study, between Yacaaba and the beach ridges of the Outer Barrier, has not been established. It could have grown either by foreland extension from either side or by upward in situ growth involving vertical beach and dune sedimentation.

Fens Embayment foredune. An established foredune extends from Yacaaba tombolo to Dark Point. In the southern end of the embayment, the foredune is low (8-9 m high) asymmetric and well vegetated (Fig. 6-3). This ridge was locally highly unstable in the vicinity of the Hawks Nest Surf Life Saving Club in the 1940-1960s period until it was stabilised by the N.S.W. Soil Conservation Service. The instability appears to have been caused by pedestrian and equestrian usage. Hand augering indicates the leeward portion of the foredune here overlies an older beachridge.

The established foredune ridge becomes increasingly more erosional, asymmetric and less vegetated towards Dark Point. From Hawks Nest to around 5 km north, the ridge is relatively well vegetated (60- 70 percent cover) with woody shrubs on the stoss (seaward) slopes. Further to the north the stoss face of the foredune is increasingly steeper, less vegetated and small saucer blowouts are common. As the stoss faces have been eroded by wind, and the sand blown landwards, deflation swales and eventually basins have developed on the seaward edge. The basin becomes wider towards the north and is pronounced in the most northern 4 km of the embayment, where it fronts a transgressive dune sheet (discussed below).

When first studied by one of us (B.G.T.) in 1960, the established foredune between 7 and 10 km north of Hawks Nest was broken by blowouts. These have gradually increased in size to the present day. North of 10 km only remnant knobs were preserved (Fig. 6-9). Few of these now remain, the more seaward ones being partially covered by "fresh sand" and



Figure 6-9: **Contrasting degrees of development of established and incipient foredunes in central Fens (near location b on Fig. 6-10). The upper and central photos were taken in 1960 and show remnant knobs and a Spinifex covered "terrace". The lower photo (Dec. 1979) is a view to the north.**

pioneer plants, and the more landward ones being removed by wind erosion.

The age of the established foredune at Fens is not clearly understood at this stage. Soil development on the surface of the ridge is poor to non-existent, as accretion continues. A soil developed on beach-ridges is buried beneath the foredune. There is also a report from a local resident at Hawks Nest that two vegetated ridges upon which horse stables were located, occurred seaward of the present surf club. The club is now sited on the crest of the "established" foredune. This report has not yet been confirmed by historic maps, and these dunes may have been two well developed incipient foredunes formed during a relatively long period of shoreline stability prior to major storm events commencing in 1950 (Thom, 1974).

Whether these combined factors are indicative of net shoreline erosion or "cyclic-type" phenomena associated with occasional foredune formation, erosion, landward migration and then rebuilding on a relatively stable shoreline, cannot be ascertained at present. The current phase of beach progradation and dune rebuilding which has occurred since the 1974 and 1978 storms along this embayment (Hesp, 1984a and Fig. 6-10), supports the latter view. However, radiocarbon dates (detailed later), and the scarped, buried beach-ridge soils lying beneath the foredune tend to favour the occurrence of some shoreline recession.

An incipient foredune ridge or terrace flanks the established foredune along the length of the embayment. Spinifex hirsutus is the dominant colonising plant. The foredune has been fully or partially removed several times in the last 20 years by wave erosion (e.g. 1950, 1958, 1967, 1974, 1978). Figure 6-10 illustrates incipient foredunes formed following the 1974 and 1978 storms along Fens. Figure 6-10a portrays dune development near Dark Point at the northern end of the bay. Successive spring growth of swash-deposited Spinifex seedlings and shoots, on a slowly prograding beach has allowed the development of two dune ridges. Of particular interest is the fact that these ridges are beginning to approximate the shape and volume of some of the smaller beach ridges (i.e. relict foredunes) of the Fens Outer Barrier (see Hesp, 1984a). Figure 6-10b illustrates the formation of an incipient foredune in central Fens. Here, the low, sparsely vegetated terrace formed in 1976, following the 1974 storms, was destroyed in the 1978 storm. Subsequently, an incipient terrace was gradually reformed and since 1983 this terrace has developed into a pronounced ridge.

A study of the sedimentary structures of established and incipient foredunes by one of us (P.H.) has revealed the existence of both swash and eolian cross-beds within the ridge (Figs. 11, 12). Figure 11a is a view of a section of an established foredune in central Fens excavated for placer minerals. Patterns of internal stratification are shown in Figure 11b. The lowest cross-beds (below 1-1.5 m) are swash sediments. These underlie low-angle (<15°) eolian cross-beds (A) formed during initial foredune formation. These are truncated by a high-angle curved erosional bounding surface (B) interpreted as a blowout. This was later filled and the surface stabilized (cross-hatched buried soil). The dune was then scarped (C). Subsequent scarp eolian filling and crestal accretion (D) took place probably within an increasing vegetation cover. Prevailing wind blows left to right. Figure 12 shows another section in central Fens; swash deposits characterise the lower part of the section.

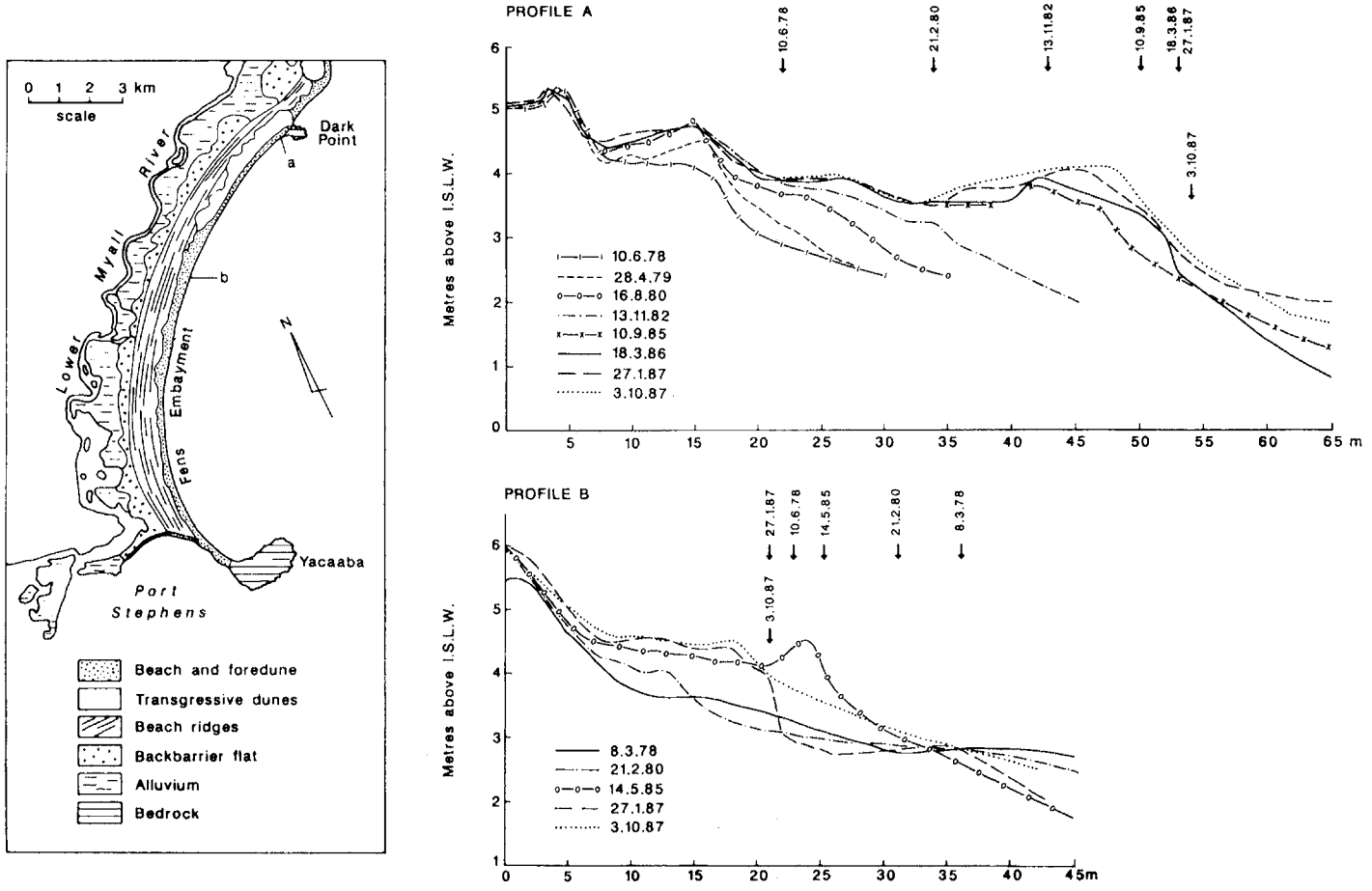


Figure 6-10: Incipient foredune development at two locations: (a) near Dark Point and (b) in central Fens embayment. Surveys have been conducted between 1978 and 1987. The upper arrows indicate the seaward limit of vegetation growth at various dates.

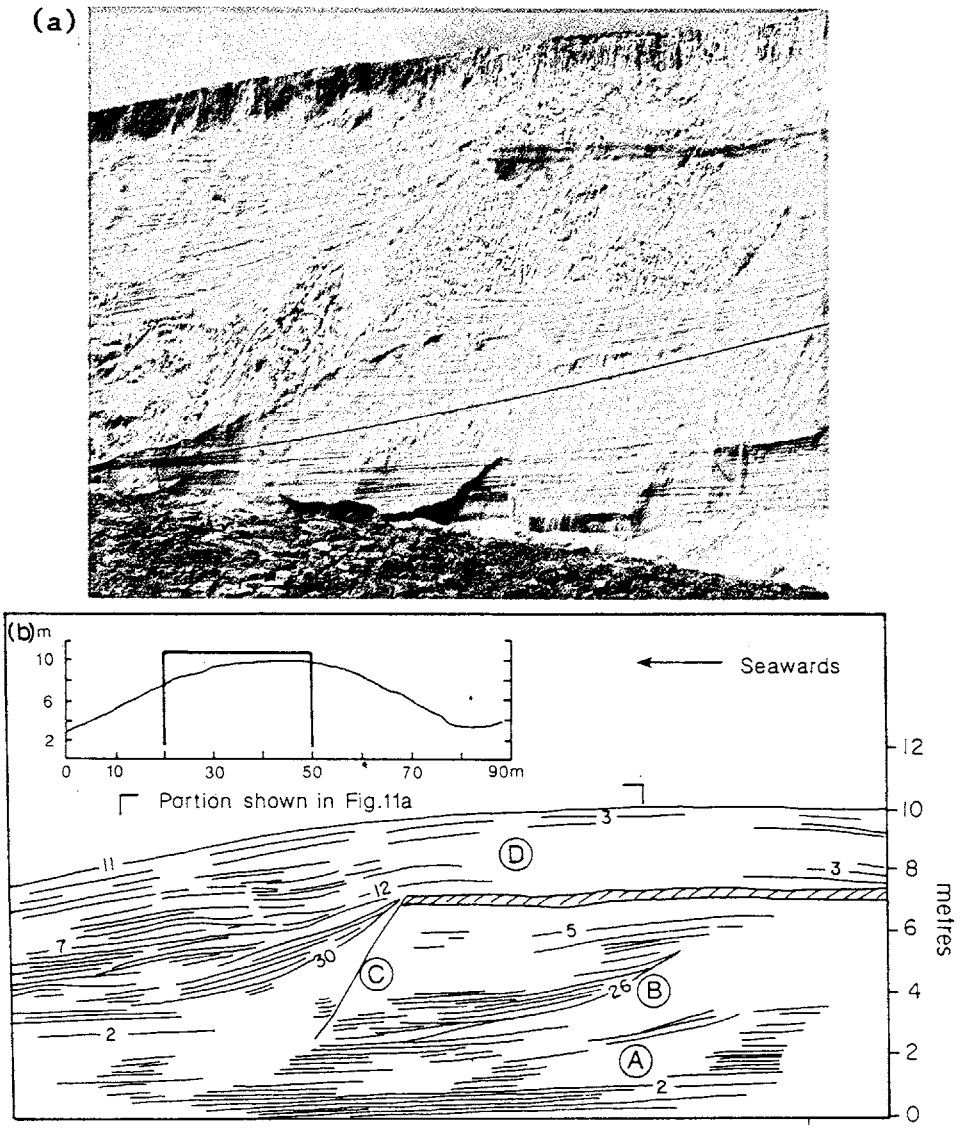


Figure 6-11: Section in the established foredune at central Fens.

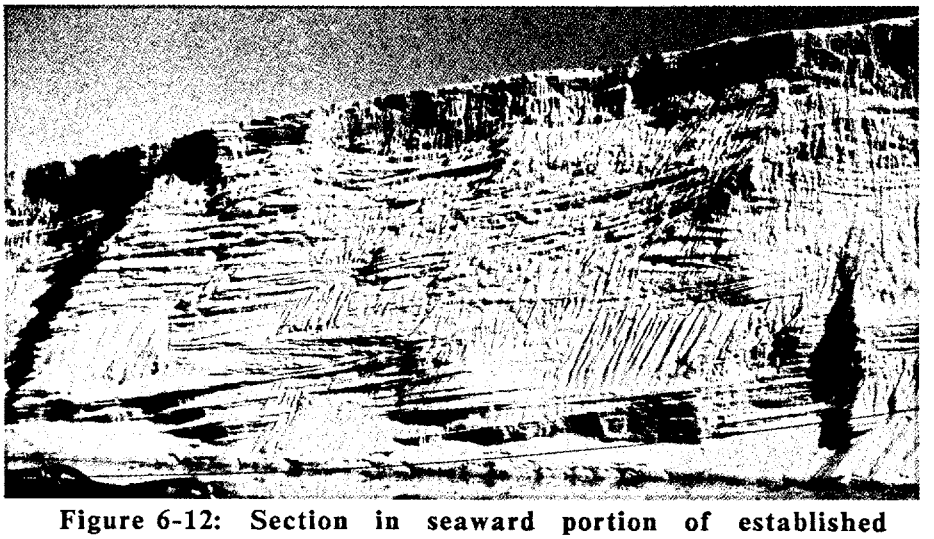


Figure 6-12: Section in seaward portion of established foredune near Hawks Nest.

Fens Embayment mobile dune sheet. The transgressive, mobile dune sheet in the northern section of Fens is 5 km long and up to 0.5 km in width Fig. 6-13). Sand is advancing inland as a high transgressive ridge, and the vegetated Outer Barrier at the north end of the Fens embayment is being buried by the low tongues of sand. Estimated rates of inland penetration are between 0.5 and 1m/yr based on air photo coverage over a 30 year period. This dune sheet was noted by Commander Sidney on his survey in 1856 (Sheet 5, South Coast of Australia, Port Stephens to Tacking Point). Up to 18 reversing dune ridges have been observed on the Fens dune sheet. There is some evidence that vegetation is today expanding on the deflation plain on the eastern side of the dune sheet. Consolidation of the incipient foredune over the last decade is causing a restriction of the supply of sand from the backshore to the dune sheet. Even within the mobile sand area, plants such as Spinifex are colonizing the surface and creating lobes between vegetated hummocks and "shadow" dunes. A buried soil can be observed on the windward flanks of the mobile dune sheet. Rounded and broken boulders occur within the remnants of an eroded foredune (especially near Dark Point headland). Aboriginal shell middens associated with the boulders and artifacts have been recovered at the site.

Sandy Point. North of Dark Point to Sandy Point, and along the cuspate foreland in the lee of Broughton Island (Fig. 6-1b), the foredune ridge remains discontinuous. Blowouts cut the foredune on the south flank of the cuspate foreland. A mobile dune sheet occurs on Sandy Point. It is subjected to wind and wave erosion from both sides of the foreland. Although not as large as the Fens sheet, it has penetrated farther inland. Part of the dune sheet was mined by Mineral Deposits Ltd. in the late 1960s and "rehabilitated" with Spinifex. Heavy minerals of economic value were found in buried beach-ridge deposits beneath the mobile sand sheet.

Upwind of the mobile dune sheet is an irregularly-shaped deflation plain. This plain is periodically inundated by freshwater. In 1978 the area contained a diverse flora of plants tolerant of wet sandy conditions (e.g. Acidanthera brevicollis, Scirpus nodosus, Juncus maritima, and Hydrocotyle). Interestingly, Commander Sidney did not record this dune sheet on his 1856 chart, only the sheet near Dark Point. North of Sandy Point the foredune ridge is more continuous. Here it forms the high "stationary" barrier of the Upper Myall-Broadwater embayment (Ch. 7).

6.3 STRATIGRAPHICAL CHARACTERISTICS

6.3.1 Bedrock Configuration A limited number of bore holes and a resistivity study shows that Quaternary sediments overlie a seaward sloping basement of rock or weathered material.

In the centre of the embayment beneath the Inner Barrier, Quaternary sediments extend to -25 m MSL (Dury, 1981, Fig.2). At the Yacaaba bore site near the coast (David, 1907) bedrock occurs at about -50 m MSL, and at the Hawks Nest bridge site bedrock was encountered at c.-40 m MSL (Fig.6-20). In places the rock basement appears to be overlain by a zone of residual weathered material of mainly clay size. Four size analyses by the Public Works Department (N.S.W.) of this material from the Tea Gardens-Hawks Nest bridge site showed clay (30-70 percent), silt (18-34 percent) and sand (4-36 percent). The sand-sized fraction consists primarily of subrounded to angular quartz and feldspar grains. The only



Figure 6-13: Mobile dune sheet at northern end of Fens embayment near Dark Point showing reversing transverse dunes in 1960.

organic remains present were pollen grains of probably Carboniferous or Permian age (identified by A.R.H. Martin).

The lack of drill holes which penetrate the sands and clays inhibits reconstruction of buried bedrock topography. However, it is unlikely that a deep buried channel exists within this bay because of the limited size of the subaerial catchment.

6.3.2 Stratigraphic Units and Sediment Properties

6.3.2.1 Holocene deposits

Extensive studies have been undertaken by one of us on the sediment properties of Outer Barrier sands (Shepherd, 1970). These studies concentrate on the grain size and mineralogic characteristics of beach-ridge, modern foredune and beach zones. Work on modern environments is summarized in Chapter 3. Drilling by A.N.U. in 1974 along a transect in the centre of the bay (Fig. 6-14) enabled the collection of samples from the various stratigraphic units. Hand augering/sludge pumping by Bowman and Shepherd has yielded additional samples from the Holocene regressive sands (see Fig. 6-14 for location). These have been supplemented by material collected from the Lower Myall River and offshore using dredging and SCUBA methods of sampling. More recently, Oak (1981, 1984) has completed a study of boulder beach characteristics on Yacaaba headland, and Hesp (1982) has analyzed many samples from the foredune complex.

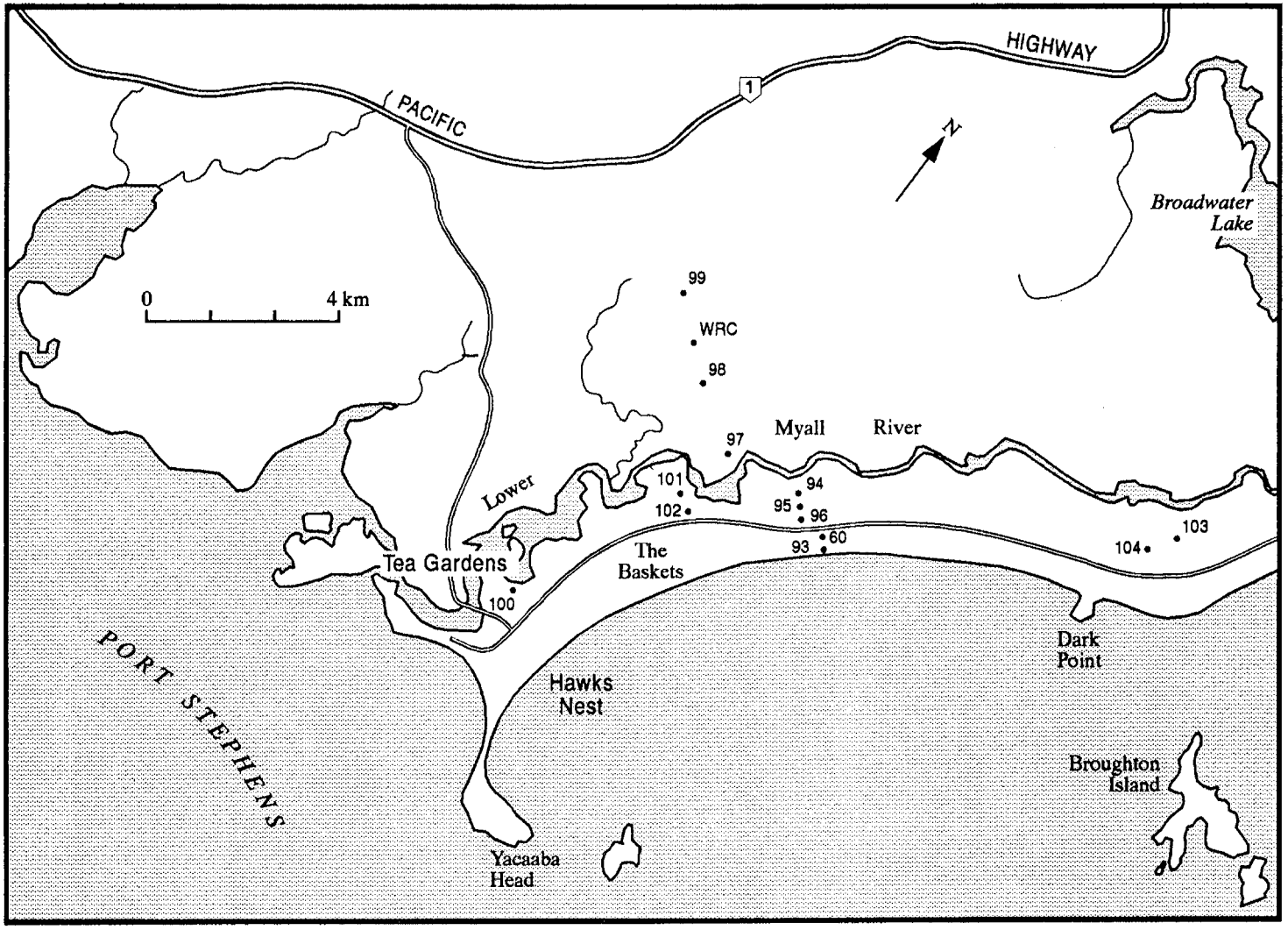


Figure 6-14: Location of drill holes on Fens Outer Barrier used to date nearshore regressive sand facies which underlies the beach-ridge (or strand) plain.

Surface samples were collected from six profiles across the Fens beach-ridge plain (Shepherd, 1970, p. 110ff; Fig. 6-3 shows location of profiles). The method of sampling was shallow augering to the water table and in some places sludge pumping to 10 m below ground surface. The samples were sieved at 1/2 phi intervals and the Inman parametres calculated graphically.* In addition, the percentage weight of each sample coarser than 0.7 mm (0.5 phi) was calculated.

Mean size and size deviation tended to increase as the percentage weight of the fraction +0.7 mm became greater. Coarser sands were mostly negatively skewed. As height above MSL increased mean grain size decreased, and as distance from the sea decreased the percentage weight +0.7 mm became greater. The hypothesis that beach ridges possess a relatively finer, better sorted sand cap over a coarser, more poorly sorted sand is supported by this study.

The coarse layer occurs up to a maximum elevation of 2 to 3 m above MSL at the southern end of Fens and at 3 to 4 m at the northern end. The course sand to gravel layer extends from Hawks Nest to Dark Point in the Outer Barrier, with a very well marked layer of pebbly material occurring at +2.5 m MSL behind the Dark Point headland. At other Outer Barrier localities in N.S.W. granules are much more locally concentrated (e.g. Shoalhaven Bight). On the more exposed part of Fens beach at present the concentration of coarse sediment during storm periods reaches heights of c. 3 m above MSL.

The transition between fine and coarse sand facies, which possibly reflects a change in depositional environment from eolian foredune to beach swash, is not always easy to detect. Variations from the conditions described above were observed. On some occasions the beach sand may become coarser, more poorly sorted and more negatively skewed than usual. On the other occasions it may be indistinguishable from some other incipient foredune or foredune sand, irrespective of what method of obtaining size parametres is used. Within certain boreholes there would be no radical change in the nature of the sediment; indeed, in some rare instances the eolian sand may even be slightly coarser than the underlying marine sand (see further discussion in Shepherd, 1970).

Figure 6-15 depicts the variation in grain size parametres along a section which crosses the innermost 300 m of the beach-ridge plain near Dark Point (Fig. 6-3). Some of the finer sand may have been lost by washing from the sludge samples collected below the water table. Figure 6-15 indicates a marked change in some boreholes from what is interpreted as "marine" or beach sand to eolian or indeterminate sand at a height of +2 to +4 m MSL. Sand deposited in an apparent eolian environment lies above a boundary at +3 m to +6 m MSL. In between is an intermediate zone which is probably composed of former incipient foredune sand. This is negatively skewed in places and may locally be relatively coarse and poorly sorted. Where this is the case it is underlain by, or is just landward of, a much coarser layer. It is likely that some of this coarse sand would have been incorporated into an incipient foredune by wind transport.

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* Shepherd used this procedure in contrast to that adopted by Ly (1976, 1978b), Bowman (1979) and Thom who have used moment measure statistics on the basis of 1/4 phi sieving (see Ch. 3).

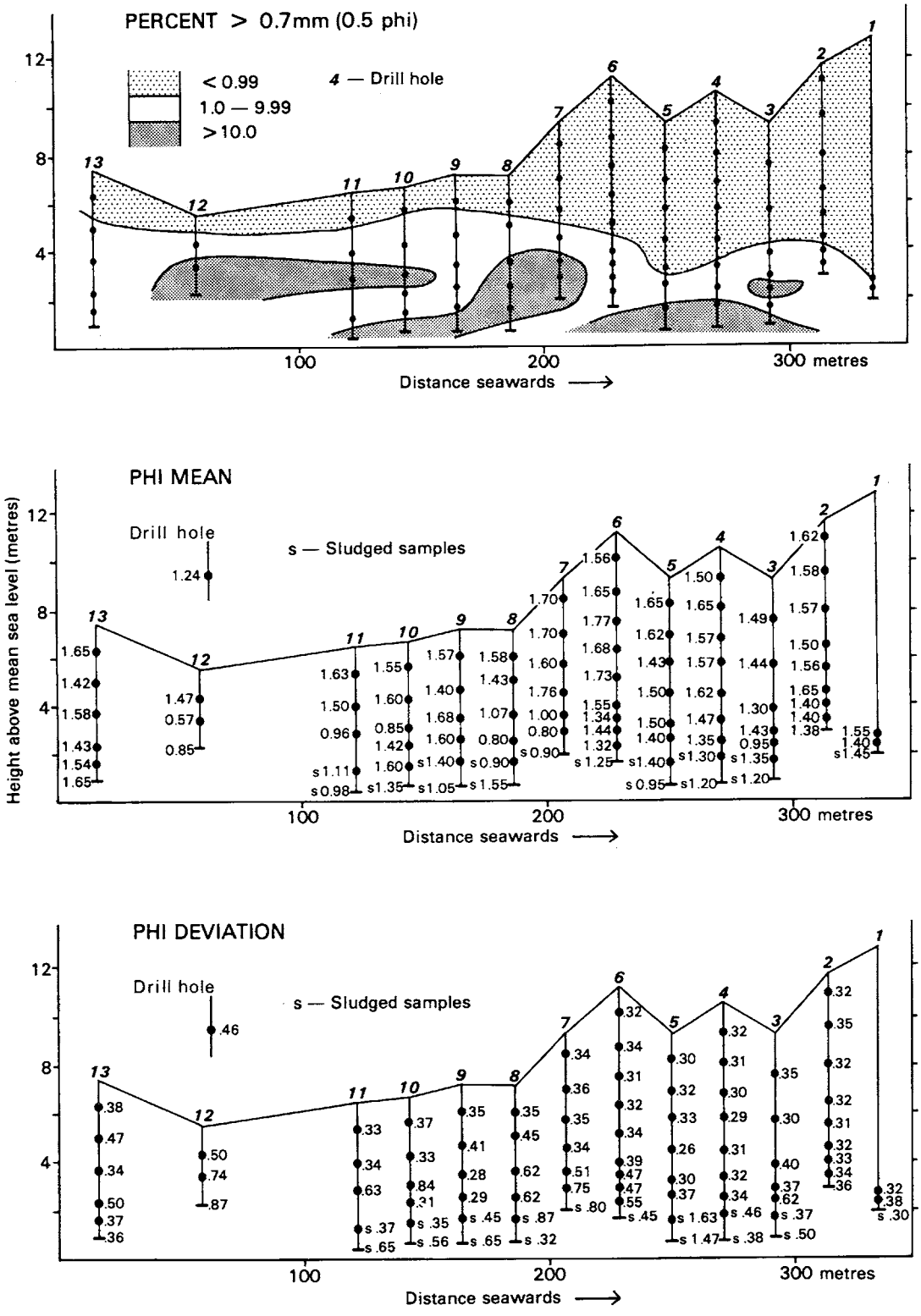

Figure 6-15: Variation in grain size properties (Inman size statistics) with depth and distance along a transect across the beach ridges (relict foredunes) in central Fens. Samples were collected by hand augering and sludge pumping methods.

Grain size variability with depth below sea-level is also well marked. The power auger holes penetrate deeper water facies and unconformities, supplying information on the total spectrum of grain size variability with different depositional environments and the ages of barrier sediments. Figures 6-16 documents size parametres for three A.N.U. drill holes on the Outer Barrier (93 and 94) and one hole on the Inner Barrier (97). Three parametres are shown, based on moment measure statistics of samples sieved at 1/4 phi intervals. Figure 6-17 shows four other parametres (organic carbon, total iron, $CaCO_3$ and heavy mineral) for these few holes along a section c. 7 km north of Hawks Nest.

Above the Pleistocene unconformity mean grain size for the Outer Barrier regressive facies (i.e. those sediment units associated with beach-ridge progradation) displays characteristics very similar to those observed in Newcastle Bight (Ch. 3 and 4). This is illustrated by drill hole 93 (Fig. 6-16). The mean size increases downwards to a maximum of 1.25 phi at 7 m below ground surface (2 m below MSL) then progressively fines to 2.00 phi at the unconformity (21 m below ground surface). Sorting progressively deteriorates with depth. Most samples in this drill hole are weakly skewed. Three facies are identified: an eolian upper unit, a coarse beach-inshore middle unit, and a shelly nearshore unit, which becomes finer with depth. Carbonate values shown in Figure 6-17 do not exceed 2 percent in the nearshore unit although it is likely that there are layers of higher shell concentration. Faunal characteristics of the nearshore unit support the inference that the sands accumulated under open ocean conditions. Bankivia fasciata dominates the assemblage (see Ch. 3). Heavy minerals are locally concentrated on the beach facies (see below).

A.N.U. drill hole 94 is located on the backbarrier flat (see Fig. 6-14 for location). Grain size parametres do not show systematic trends such as those in hole 93. Sharper breaks are indicated (Fig. 6-16), but this point is not well documented by these analyses because samples were collected at 2 m intervals. Organic carbon values are generally higher in this hole (Fig. 6-17). Three facies are identified, the interpretation being supported by faunal characteristics. These facies will be described below (see 6.3.3 and Fig. 6-21).

The distribution of heavy minerals in the Fens Outer Barrier is of interest because this is an area which has been intensively mined by two companies (Mineral Deposits Ltd. and Rutile & Zircon Mines). Economic deposits occur mainly in the beach and incipient foredune environments of deposition and to some extent in backbarrier sands. Mining paths mostly parallel the shore and indicate how such concentrations are predominantly swash-aligned.

Information was supplied by Mineral Deposits Ltd. to one of us (M.S.) for drill hole samples collected at 1 foot (30 cm) depth intervals across the innermost 400 m of the Fens Outer Barrier over a distance of 8 km. Heights of the tops of the drill holes have been accurately surveyed. Figure 6-18 shows the height distribution of samples containing >3 percent and >10 percent heavy minerals. There is a marked concentration of heavy minerals within the interval +1 to 4 m MSL. If the highest concentrations only occur on the upper foreshore into the backshore (see Ch. 3), which upon the present beach at Fens is in the height range +2 to 3 m MSL, it is apparent that during the period of Outer Barrier progradation heavy minerals were deposited at sea-levels

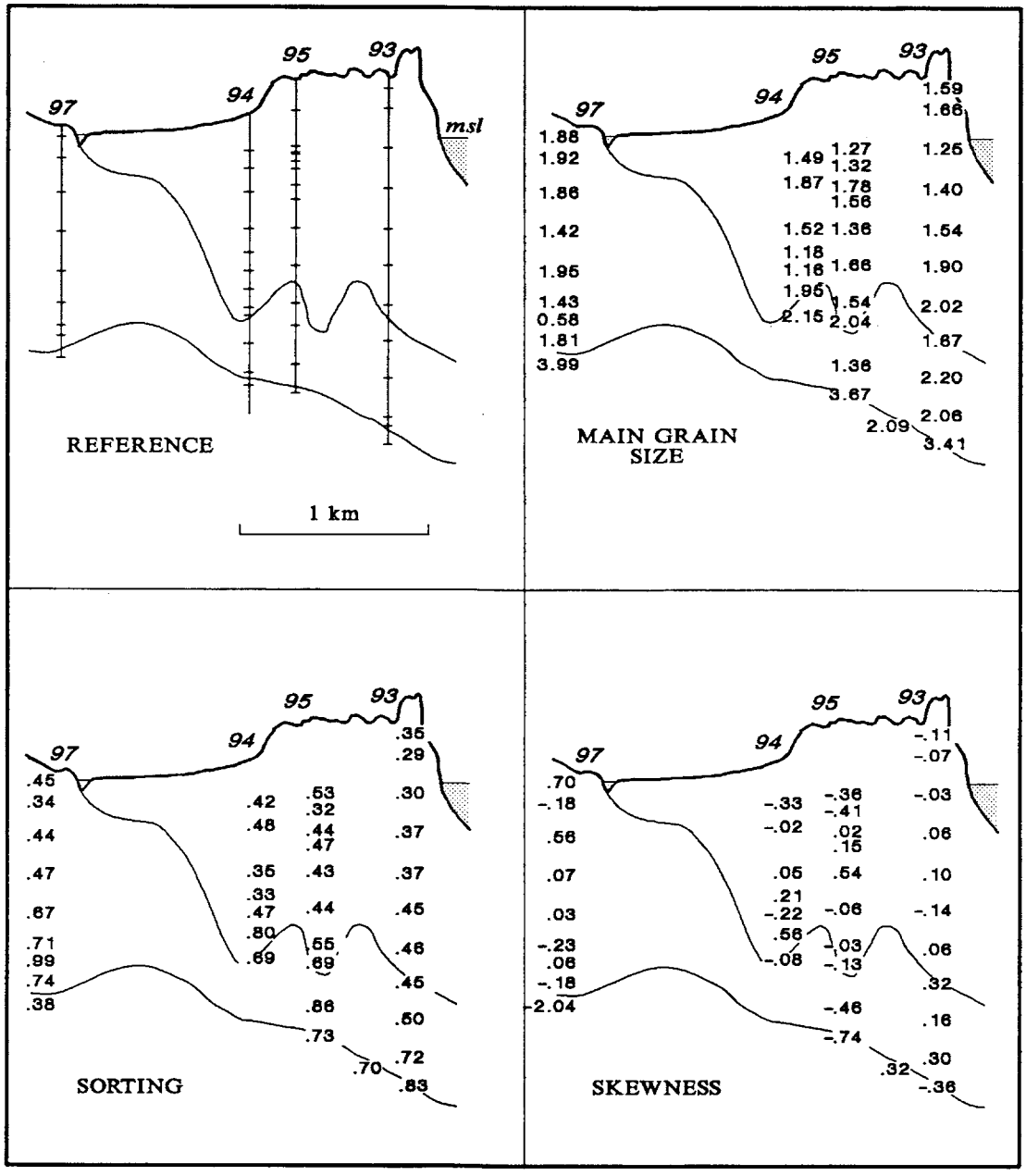

Figure 6-16: **Mean grain size, standard deviation and skewness values (moment measure statistics) for ANU drill holes 93, 94, 95 and 97 (see Fig. 6-14 for location).**

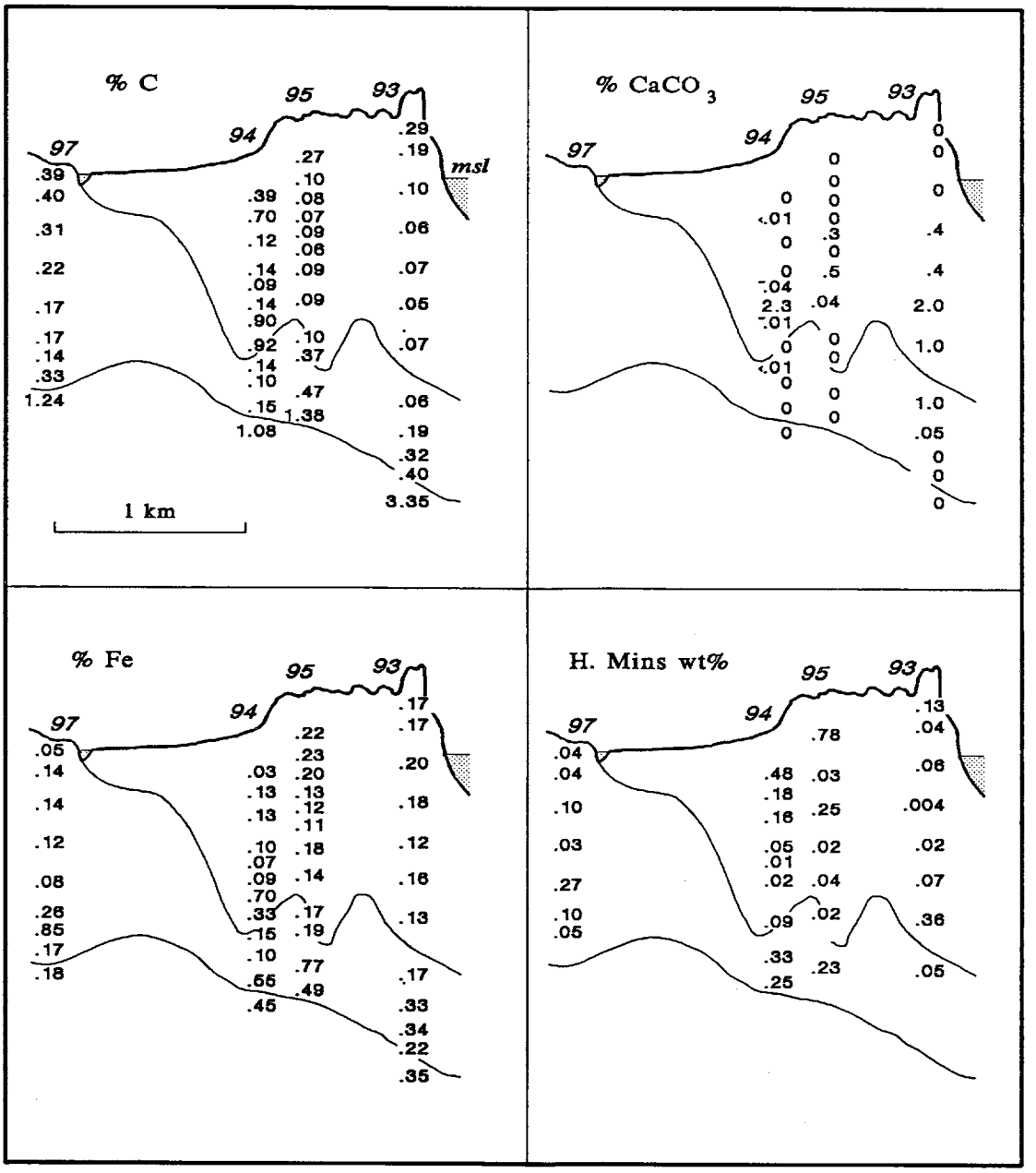

Figure 6-17: Iron, carbon, carbonate and heavy mineral distribution in drill holes 93, 94, 95 and 97 in the Fens embayment.

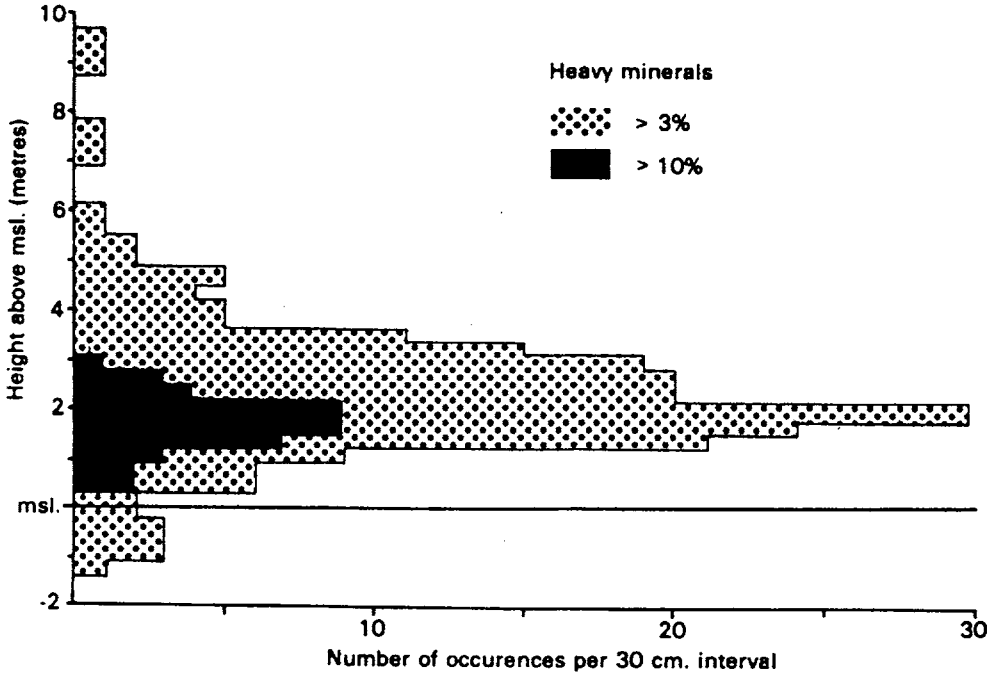

Figure 6-18: Heavy mineral concentration in relation to elevation (data supplied by Mineral Deposits Ltd).

close to the present. Cross-section data on the elevation of heavy minerals, as drawn from exploratory drill holes, indicate that such heavy mineral seams are consistently +0.3 to 1 m MSL at the inner margin of the Outer Barrier. Perhaps this suggests that sea-level was not quite at its present level when the initial barrier ridge was deposited. However, other factors could explain the lower elevation; for instance, more pronounced wave height attenuation across shallower nearshore profiles. Data from the backbarrier flat show heavy mineral concentrations of 1 percent or less at elevations not exceeding 1 m above MSL.

Mineral Deposits Ltd. has kept detailed records of heavy mineral size and composition along the innermost ridges of Fens Outer Barrier (see Shepherd, 1970). Whereas grain size, rutile, zircon and ilmenite percentages were fairly uniform within each ridge, a marked difference was seen when the two innermost ridges were compared. The oldest ridge contains more zircon that rutile, and both minerals are coarser in average size (by 0.1 - 0.2 phi) than in the second ridge which contains more rutile than zircon. Samples analysed by Rutile & Zircon Mines indicate the rutile/zircon percentages to be approximately equal throughout the barrier, except for the innermost ridge and the present foredune, where zircon predominates. It seems likely that zircon, which is the denser of the two minerals, has been especially concentrated within reworked sediment. Gardner (1955) has described a similar relationship from the Outer Barrier at Cudgen, northern N.S.W. Here highest zircon values, relative to rutile, occur in the innermost parallel ridge, and in the present foredune. He considers high zircon values and relatively large heavy mineral grain sizes to result from stable coastlines and high energy conditions.

Variation in heavy mineral content with depth is shown in Figure 6-17. For Outer Barrier drill holes (93, 94, 95) the highest concentrations are in the upper 3 m in the Holocene part of the hole, except for sample 93-7 which could be part of the transgressive facies of the Outer Barrier (see 6.3.3). In common with modern shallow nearshore environments, relict facies associated with this environment are characterized by low heavy mineral content. Estuarine sediment units in hole 94 are also low in heavy minerals. Where the heavy mineral content is high the proportion of non-magnetics increases. The rutile-zircon and ilmenite-magnetite ratios remain relatively constant with depth.

6.3.2.2 Pleistocene deposits.

In the Fens embayment, Inner Barrier sediments have been sampled in three ways: Shepherd has concentrated on surficial sands, whilst Thom has analyzed variations in one drill hole (A.N.U. hole 97). Drury (1981) has extended Thom's survey with drilling on the Inner Barrier for the Water Resources Commission.

Samples collected across the Inner Barrier at Fens were sampled from beneath beach-ridge crests at depths of 0.6 to 1 m (i.e. above the water table in the leached horizon). As discussed in more detail in Chapters 3 and 8, these sands possess characteristics common to all beach-ridge sands of Pleistocene age. These characteristics may be summarized as follows:

(i) Sand size distribution is markedly bimodal;

(ii) Major mode is medium sand (phi mean 1.5 to 2.1), but a lesser mode commonly forming 1 to 2 percent is composed almost entirely of silt.

(iii) The highest percentage of silt-clay material occurs at depths of about 1 m (based on drilling and close sampling to depths of 2 m at 5 locations);

(iv) Excluding the fine mode, the surface sands are very well sorted and comparable in character with the eolian facies of Outer Barrier beach ridges;

(v) Figure 6-19 clearly shows the mean diameter to become finer across Inner Barrier beach-ridge set in a seaward direction (observed in 4 of 5 sampled lines at Fens).

(vi) Sand comprising the high innermost ridge of the northeast end of the Fens Inner Barrier contrasts with the basic trend in being particularly fine. This ridge is also relatively rich in heavy minerals at a depth of 5 m below ground surface where the ground surface is c. +10 m MSL (see Shepherd 1970, p. 183, Fig. 4-23).

The Inner Barrier sand body is no greater than 25 m thick. A.N.U. drill holes (97, 98, 99) and several holes drilled by the H.D.W.B., and the Water Resources Commission (Drury, 1981), bottomed in a heavy clay (see Fig. 6-21). The clay surface appears to dip smoothly to the east, but there are insufficient holes to construct an isopach map. In general, the sand can be divided into two units: a

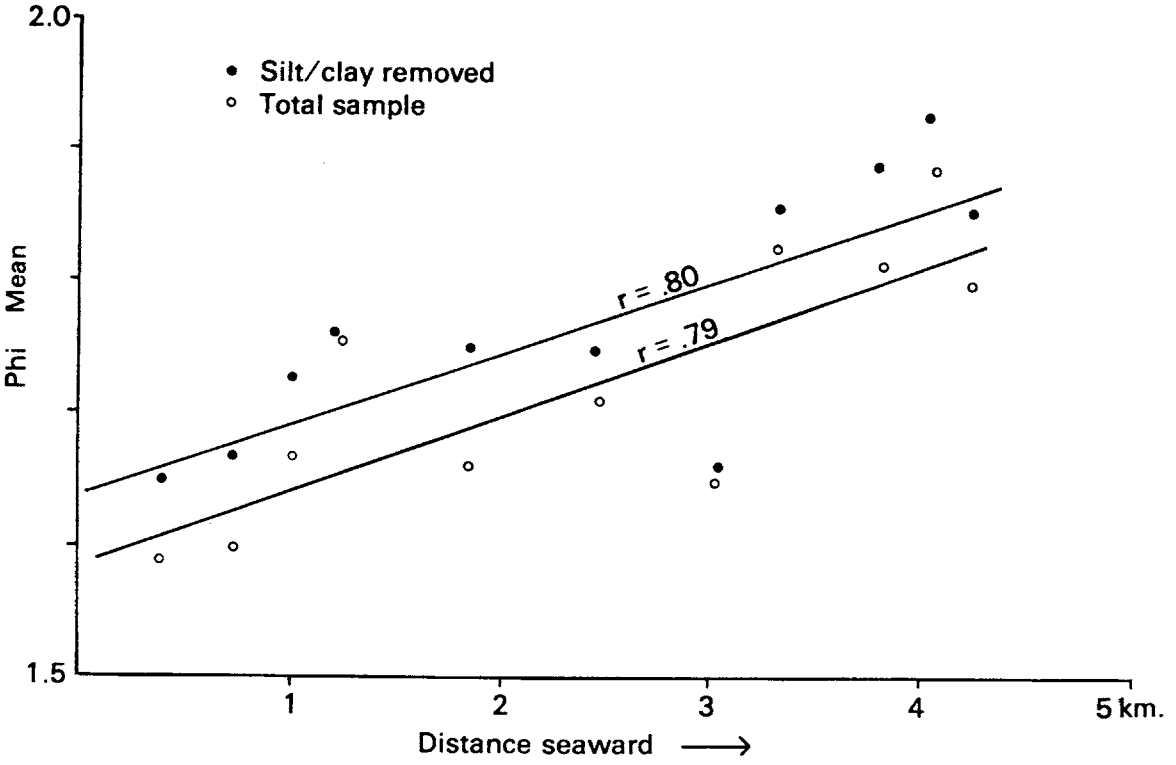

Figure 6-19: Mean grain size for 11 samples collected across the central portion of the Fens Inner Barrier. Grain size becomes finer in a seaward direction with and without the silt/clay fraction.

humate-impregnated sand which has an even thickness of close to 10 m, overlying a grey sand quite coarse in places and rich in lithics. Figures 6-16 and 17 depict down-the-hole variation in grain size and other parametres at drill hole 97. The markedly coarse and poorly sorted nature of the basal sand is clearly shown. The uppermost sand is not only medium size (c. 1.90 phi) and well sorted, but also positively skewed. This is consistent with Shepherd's data suggesting a thin eolian cap over a beach facies. Nearshore facies is probably indicated by the finer sand at 15 m below ground surface. The coarse and lithic nature of the lower 15 to 20 m of sand is interpreted as a transgressive facies. The source of the jasper, quartz and lithic granules in this unit is not known. They are quite angular and may be locally derived. No shells were recovered in this facies (see also Drury, 1981, for description of bore holes).

The clay unit in the Fens embayment conformably underlies the Inner Barrier sand, but has been truncated by Holocene deposits (see 6.3.3). Few holes penetrate the clay. In Figure 6-20 the depth to bedrock and thickness of the clay at the Tea Gardens-Hawks Nest Bridge site is shown. At 25 m below MSL the clay unit commences and extends to at least 40 m. It is unoxidized and blue grey in appearance under the barrier sands, but internally it contains "laterite" horizons indicative of weathered surfaces and stratigraphic discontinuities. The Yacaaba bore reported by David (1907) has the clay at 27 to 50 m below MSL beneath the Outer Barrier.

6.3.3 Stratigraphic Pattern and Depositional Sequence (Fig.6-21)

The stratigraphy of the Outer Barrier in the Fens embayment is presented in Figure 6-21. Location of drill holes from which data for these figures were obtained, is shown in Figure 6-14. Select holes off the line of the section have been used in the general stratigraphic reconstruction. Further work involving more closely spaced drilling to greater depths along more sections will be needed to test the configurations proposed in Figure 6-21.

Morphostratigraphically, the Fens embayment represents the simplest case of dual barriers where both exhibit dominance of the prograded type of bay barrier. As such it was used by Thom (1965) and Langford-Smith and Thom (1969) as a model or type locality. Thom (1965, Fig. 3), working with limited drill hole data obtained from various sources (e.g. H.D.W.B.), attempted to reconstruct the stratigraphy. The section was reproduced by Bird (1973, Fig. 5). In the published section Thom was particularly interested in defining the thickness of the humate-impregnated sand (or "sandrock"); he speculated on its extension beneath the Outer Barrier. As shown in Figure 6-21 the general characteristics predicted in 1965 have been confirmed: however, there are many details which were lacking in the earlier section.

Pleistocene. A basal clay unit extends throughout the entire embayment. As mentioned in the previous section, its thickness is poorly known, except at two localities near the south end of the bay. Stratigraphic discontinuities within the clay are likely (Fig. 6-20), but cannot be defined on any generalized section at this time (Drury, 1981).

The unoxidized upper surface of the clay unit beneath the Inner Barrier constitutes an even slope extending from the present ground surface (c. +6-8 m MSL) at the rear of the barrier to -20 m at the Lower Myall River (Fig. 6-21). It appears to increase in slope towards the rear of the bay. Water wells drilled for the A.M.P. Society on their property "Durness" show the clay rising close to the surface (Mr B. Osmond, Manager, pers. comm, 1978). Towards the western part of the embayment the basal fine-grained unit is more silty.

Beneath the Outer Barrier the surface of the clay unit is somewhat more variable in character. In one A.N.U. hole (94) the clay is oxidized, but elsewhere it is quite reduced in appearance. The surface slope shown in Figure 6-21 is more uneven than beneath the Inner Barrier.

Characteristically, the clay unit grades up into Inner Barrier sand (Q2Mnt). An intermediate unit is no more than 2-3 m thick and is a muddy sand, quite poorly sorted and containing a few granules. This facies transition is more marked in the western or landward part of the embayment. It is interpreted as the product of trangressive processes during a Pleistocene (Last Interglacial?) marine transgression. The clay unit, as noted elsewhere, is believed to represent an esturine lagoonal environment. The upper unoxidized surface of the clay formed during the transgression which preceded Inner Barrier formation.

At Fens the inner third of the southern part of the Pleistocene beach-ridge plain is covered by a veneer of clay up to 2 m thick (see Fig. 6-1a for location). As mentioned previously, this clay cover

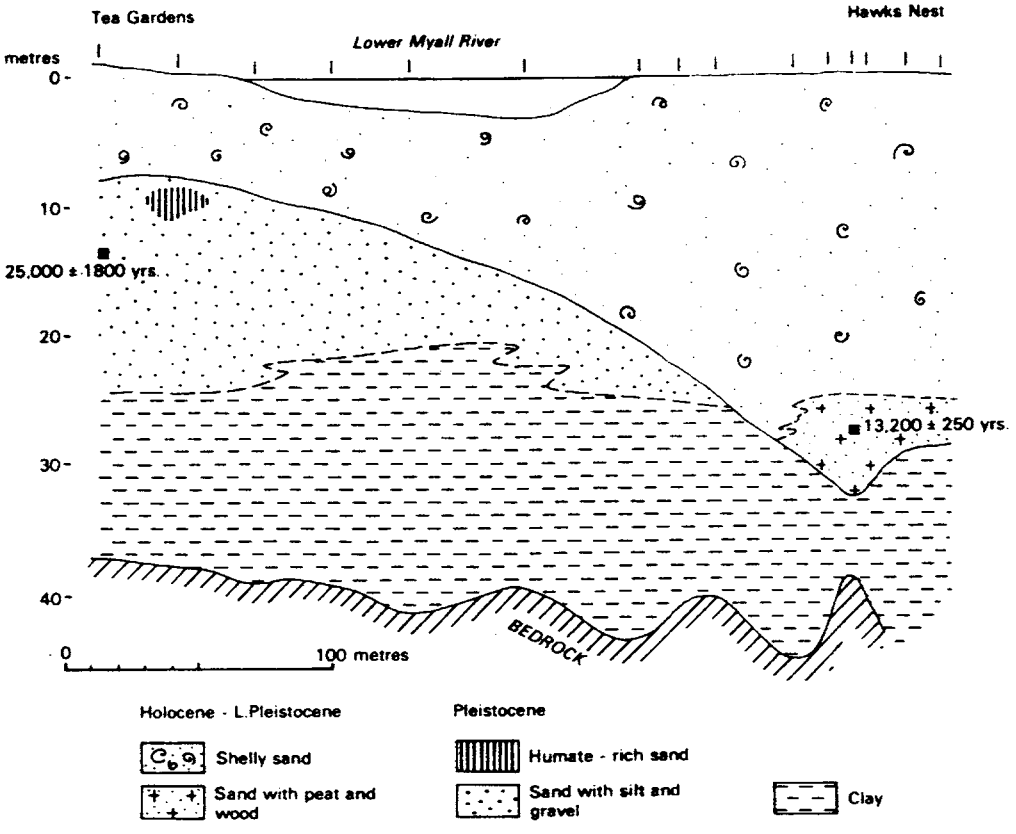

Figure 6-20: Stratigraphic section at site of the bridge between Hawks Nest and Tea Gardens (data supplied by P.W.D.).

partially obscures, but does not obliterate, the pattern of the underlying ridge and swale topography. As suggested in Figure 6-21 lagoonal sediments merge with the silty clay alluvial-colluvial materials which form the valley fill and lower slope deposits on weathered bedrock at the rear of the embayment. These valley-fill sediments may also interfinger with fine-grained sediments which underly the barrier sands. Further drilling is required to test these suggestions.

What is important is that the streams which drain the catchments behind the Fens Inner Barrier are relatively restricted in size, compared to the Upper Myall River, or Boolambayte Creek. They have not maintained a prominent channel through the beach-ridge plain. The cover of clay over much of the inner third of this plain appears to be related to three factors: (i) the limited size of these catchments; (ii) their ability to yield fine-grained sediments which have accumulated in a very shallow depositional basin; and (iii) the presence of a relatively high beach ridge within the plain which effectively served as a dam to waters draining from these catchments

In summary, the Inner Barrier sand sheet has developed in a manner similar to that discussed for the Inner Barrier in Newcastle Bight. A typical offlap regressive sediment sequence is apparent associated with the progradation of beach ridges following termination of a marine

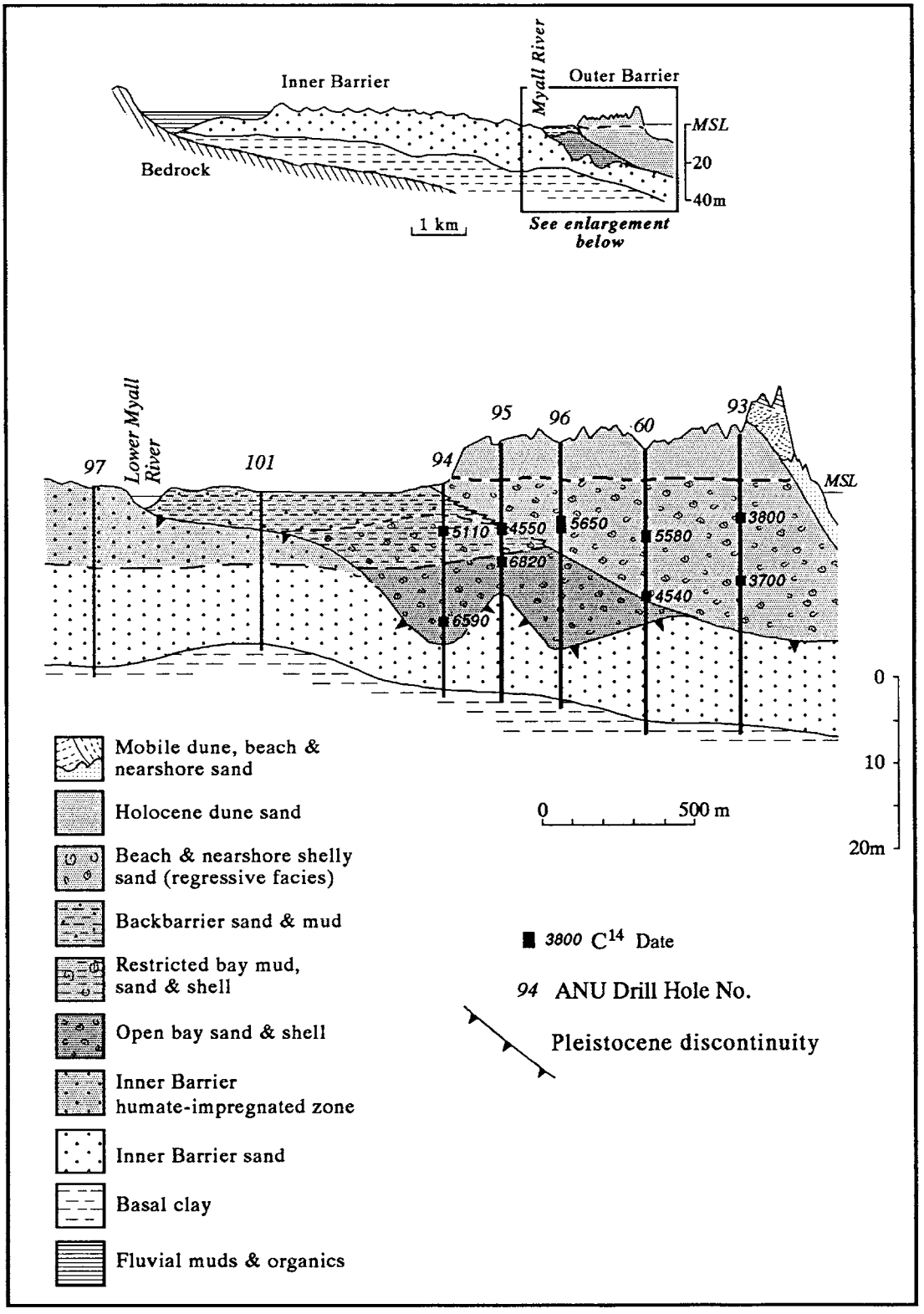

Figure 6-21: Generalised stratigraphic sections for the Fens embayment (see Fig. 6-1b for location).

transgression. The inner clay-covered ridges are best explained by the damming of small catchments by a high sand ridge. Fine grained sediments were trapped over the flooded inner portion of the beach-ridge set. Whether the relatively high ridge which serves as a dam was formed following a minor transgression during the Last Interglacial (Chappell and Thom, 1978) is unknown.

Holocene. Beneath the Outer Barrier the surface of the Inner Barrier is uneven. Only in one hole (A.N.U. 101) has humate-impregnated sand been observed. Elsewhere there is an abrupt transition from shelly Holocene sands to non-calcareous, leached sands with different sediment size properties (Figs. 6-16 and 17). The section shown in Figure 6-21 suggests channel dissection of the Inner Barrier surface beneath the present Outer Barrier prior to c. 7500 years ago. Channel formation is also seen at the Hawks Nest bridge site (Fig. 6-20). We do not know when and how this dissection took place.

The detailed stratigraphy of the Fens Outer Barrier based on six drill holes shows facies relations on a section 7 km north of Hawks Nest (Fig. 6-21). A transgressive nearshore sandy facies was not recognized in these drill holes. For purposes of interpretation the section can be divided into two parts: an outer part reflecting high-energy depositional environments; an inner part representing comparatively quiet-water deposition.

The outer part of the Holocene barrier can be divided into four sediment units. These are:

(i) A wedge-shaped, nearshore shelly sand facies (Q5Mn) from which 8 radiocarbon dates have been obtained (further dates have been obtained from elsewhere in this unit Thom et al, 1981b);

(ii) a tabular, coarse, beach sand facies (Q5Mb) containing highly fragmented shells in the lower part and abundant granular materials;

(iii) a dune sand (Q5Mer) of medium grain size with low angle cross-bedding and with a beach-ridge surface morphology; this unit is well podzolized (Bowman 1979);

(iv) a narrow ridge of cross-bedded sand forming a foredune complex (Q6Mef) which is partially covered by sand-binding plants, lacking clear signs of soil development on the surface, but containing buried soil remnants within it; this unit grades into a mobile dune sheet at the north end of the bay (Hesp, 1982; Short and Hesp, 1982).

Minimum radiocarbon dates from the Outer Barrier nearshore shelly facies indicate that most beach-ridge formation occurred during the period 5000 to 3300 ^{14}C yrs BP. This conclusion revises the Fens Holocene progradational sequences proposed by Shepherd (1970, 1974) and Thom et al. (1978) which were based on fewer radiocarbon analyses. The barrier appears to have ceased growing seaward by about 3300 ^{14}C yrs BP, or alternatively, the barrier has been eroded back to its present position removing later phases of progradation. Although the latter did happen to a minor degree, the height and mass of the established

foredune, its complex structure involving locally buried soils, and the position of such rocky headlands as Dark Point and Yacaaba, limit the likelihood of extensive barrier growth in the past seawards of the present shoreline.

The inner part of the Outer Barrier depositional sequence contains four "backbarrier facies". The sectional arrangement of these facies is shown in Figure 6-21. They are shown as a layered sequence with the deeper water environments occurring lower in the section.

(i) At the base is a very shelly sand containing a diverse "open bay" fauna (Q4Esbb). The diversity of the fauna increases southward towards Port Stephens; the upper contact of the unit rises closer to the surface in this direction. This is shown in the analysis of molluscs collected from a Rutile and Zircon Mines dredge pit 4 km to the south of the section depicted in Figure 6-21, and from A.N.U. drill hole 100 at Hawks Nest (Table 6-2). The shelly sand appears to infill the channels carved into the Inner Barrier surface. The presence of Protholatia and Cacozeliana in vast numbers implies a sand surface well vegetated by macrophytes such as Zostera and Posedonia. Sea-level was nearing its present position when this assemblage was deposited (6590 ± 220 ^{14}C yrs BP, A.N.U.-1527).

(ii) Overlying the shelly sand is a muddy sand characterized by an environmentally more restricted fauna. This is a tabular unit which contains non-shelly mud and sand layers. The fauna indicates a shallow water estuary (Q5Esbb). Anadara trapezia is the dominant species. The degree of bed cover by macrophytes is unknown. However, the movement of sediment by tidal currents was less effective at the time this unit was accumulating, as suggested by the muddy matrix of the sand. The input of sand to this environment was probably by periodic overwash across a low barrier to seaward. A radiocarbon age of Anadara at 5110 ± 110 ^{14}C yrs BP was obtained from A.N.U. drill hole 94 (A.N.U.-1666).

(iii) Washover processes also explain the elongate sand body which overlies the shelly sands along the length of the barrier(Q5Ebb) and forms the surface of the interbarrier depression. Although only 2 to 4 m thick at the section and to the south, this third depositional unit thickens to 6-7 m at the north end of the bay (A.N.U. drill hole 103, Table 6-3). It is a medium to coarse sand, locally rich in heavy minerals, non-calcareous and impregnated with humic colloids above MSL. A mining pit near Hawks Nest revealed parallel bedding, dipping sightly landward.

(iv) The surface sand unit is covered by a thin layer (<1m) rich in organic plant detritus derived from the dense swamp vegetation (Q6To). It rises to no more than 2 m above MSL.

Details of the age structure of the Fens Outer Barrier have been discussed elsewhere (Thom et al., 1978, 1981b; Bowman, 1979). Radiocarbon dates are listed in Appendix B. Backbarrier dates on "open bay" estuarine molluses, which show minimum signs of post-death reworking, indicate sand accumulation behind a relatively unstable barrier plus 6500 ^{14}C yrs ago (A.N.U.-1527, 1529). A similar fauna may

TABLE 6-2 Log of ANU Drill Holes 100 and 103

Drill Hole No. 100

Location: Backbarrier flat at Hawks Nest in Swan Bay Estate (GR 224857 Port Stephens 1:25,000)

Elevation: c.1.5 m msl

Depths (in metres)	Description
0 - 1	Sand, black becoming dary grey; organic rich topsoil, becoming slightly muddy and moderately sorted, grades to
1 - 5	Sand, grey, wet, medium, moderately sorted slightly muddy towards base with few coarse grains and less well sorted; sharp to
5 - 7	Sand with shell and some mud, poorly sorted, quite calcareous; abundant species characteristic of sandy bay flat
	Discontinuity
7 - 8.5	Sand, grey, medium, moderately sorted, non-calcareous, abundant white quartz grains; single "nodule" brown semi-indurated sand; sharp to
8.5 - 11.5	Sand, brown, medium to coarse; organic stained grains of quartz; some lithic grains, dark brown organic nodules semi-indurated; grades to
11.5 - 20.5	Sand, light brown grey to grey, medium to fine, moderately well sorted; abundant white quartz grains many quite angular; sharp to
20.5 - 27	Sand, yellow, medium to fine, moderately well sorted becoming more greyer with depth; some heavy minerals noted; grades to
27 - 29.5	Sand, darker grey, slightly muddy with some grey firm clay lenses; sharp to
29.5 - 30	Clay, dark grey, compact and dewatered

Drill Hole No. 103

Location: Backbarrier flat near Dark Point (GR 317943 Bombah Point 1:25,000)

Elevation: c.1.5 m msl

Depths (in metres)	Description
0 - 4.5	Sand, dark grey to grey becoming browner with depth; medium to coarse; organic stain quite marked at -1 to 1.5 m where slightly indurated; grades to
4.5 - 7.3	Sand, brown grey; medium to coarse, slightly muddy, moderately sorted
	Discontinuity
7.3 - 9	Sand, grey; fine, well sorted, some charcoal fragments; sharp to
9 - 14	Sand, brown; medium with odd coarse granules of quartz and rock fragment, organic stained becoming greyer below 12 m and coarser, grades
14 - 20	Sand, grey; coarse, moderately sorted, abdundant rounded fine gravel of varying roundness; grades to
20 - 23.5	Sand, brown grey; medium to coarse, moderately well sorted becoming coarser with depth containing rounded granules; sharp to
23.5 - 25	Sand, dark grey; fine to medium slightly muddy, poorly sorted; grades to
25 - 27.5	Sand, grey to light grey; moderately sorted, some coarse quartz grains; sharp to
27.5 - 28	Gravel layer, coarse sand possibly clay ball
28 - 29	Clay, grey to dark grey; some sand layers in upper part becoming very compact and dewatered

have been accumulating 4 km to the south 5100 years ago (4980 ± 110 ^{14}C yrs BP, A.N.U.-1665). This suggests that the "open bay" was contracting southwards towards Port Stephens during the early stillstand period. The more restricted Anadara - rich shell bed dates this age in the central part of the bay (see Fig. 6-21, 5110 ± 110 ^{14}C yrs BP, A.N.U.-1666).

Summary The Late Quaternary depositional sequence at Fens can be summarized as follows (Fig. 6-22):

(i) Deposition of clay within an estuarine basin during several interglacial (?) high or rising sea-level periods (Q1). During these periods sea-level was lower than present along this coast (see Ch. 10). Exposure of the clay surface at times of low sea-level led to weathering:

(ii) During the Last Interglacial marine transgression (Q2) clays and clayey sands accumulated behind a rising barrier, the transgressive facies of which penetrated the embayment burying the clay unit.

(iii) The Last Interglacial high sea-level (Q2) is represented in Fens by two parts to the beach-ridge plain: one, an inner low-lying swampy surface containing undissected close-spaced beach ridges buried in part by a surficial clay cover; and two, an outer sand surface of well-defined beach ridge and swale topography. It is conjectural at present to relate the first part to a sea-level close to present c. 135,000 yrs ago and the second part to a slightly higher sea-level c. 120,000 yrs ago.

(iv) During the oscillating low sea-level period of the Last Glacial (Q3) there was no eolian reworking of the Fens Inner Barrier. The higher part of this barrier blocked drainage from small inland catchments, and clays accumulated over much of the inner part of the plain as a thin (2 m) blanket. Humate was precipitated (and shells were leached) within the Inner Barrier sands during this period (see Fig. 4-18).

(v) A low-relief barrier which only partially enclosed a faunal-rich sandy bay was initiated within the Fens embayment about 7000 ^{14}C yrs ago (Q4), when sea-level was approximately 10 m below its present position.

(vi) After sea-level reached its present position c. 6000 to 6500 ^{14}C yrs ago, a narrow, low sand barrier probably formed a highly mobile open-ocean shoreline (Q5). It is inferred that this shoreline was subjected to extensive washover and eolian instability. Relevant dates are SUA-881 (5800 ± 80 ^{14}C yrs BP) and A.N.U.-1530 (5650 ± 100 ^{14}C yrs BP). Shelly material from this feature has been reworked and incorporated into the regressive nearshore sands which form the first phase of barrier progradation at Fens.

(vii) The Outer Barrier commenced progradation shortly after 5000 yr and proceeded rapidly (Q5). Critical dates for this event are GaK -1469 (4930 ± 80 ^{14}C yrs BP) and GaK-1470 (4950 ± 80 ^{14}C yrs BP) both from within the nearshore shelly facies. A.N.U.-1528 (4550 ± 110 ^{14}C yrs BP) on estuarine shells from near the

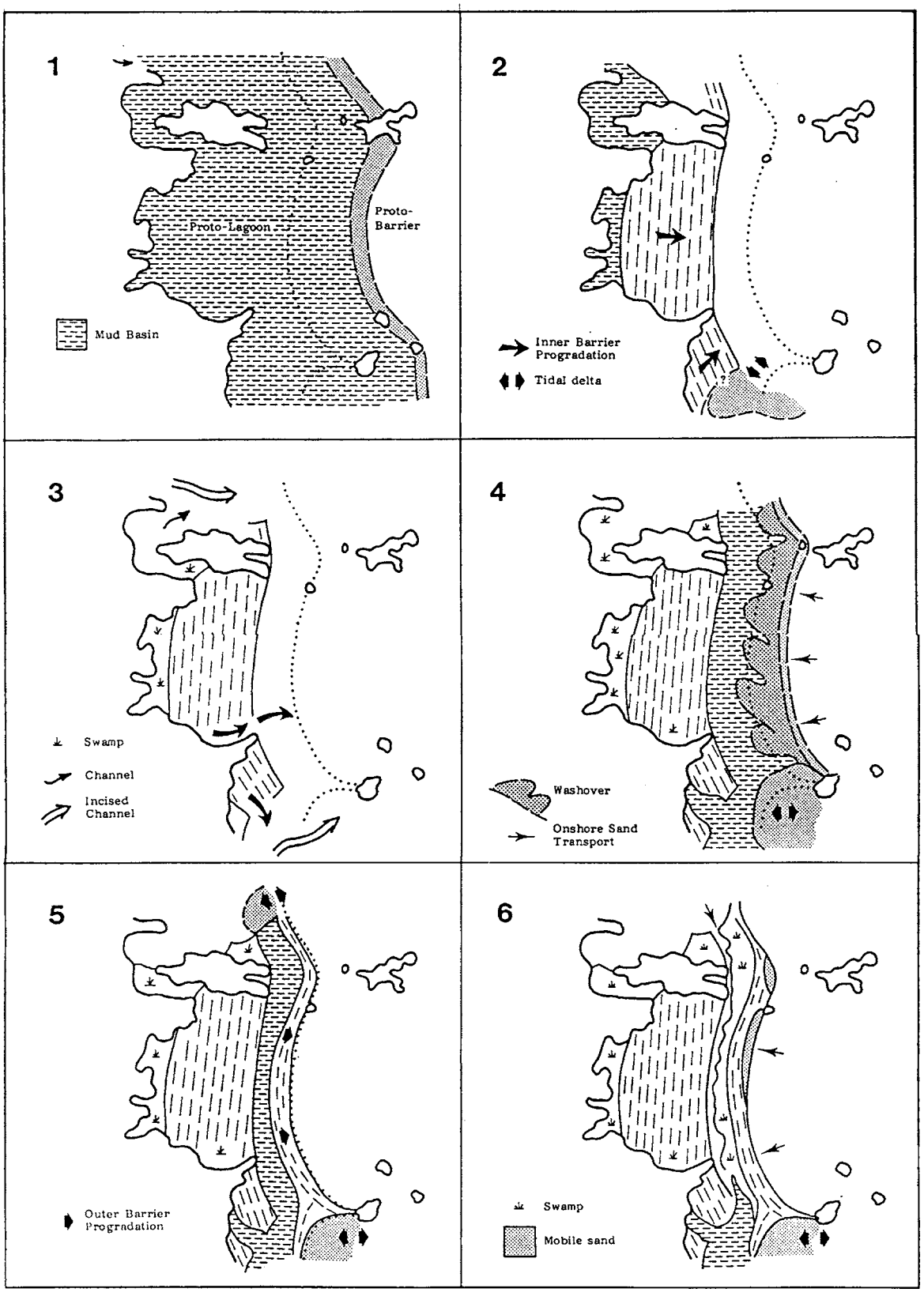

Figure 6-22: **Six stage model of the geomorphic history of the Fens embayment (the stage numbers refer to time periods discussed in Chapter 10).**

contact with coarse beach sands of the initial washover barrier, and A.N.U.-1336 (4540 ± 330 ^{14}C yrs BP) were both deposited soon after progradation had commenced. This event probably coincided with the closure of Broadwater Lake and the diversion of the Myall River along the interbarrier depression (see Ch. 7). Progradation continued (probably intermittently) until at least 3300 yr. Dates SUA-882 (4090 ± 90 ^{14}C yrs BP), A.N.U.-1531 (3800 ± 180 ^{14}C yrs BP), A.N.U.-1532 (3700 ± 80 ^{14}C yrs BP) and SUA-804 (3590 ± 70 ^{14}C yrs BP) are all from this progradational sequence. Two samples are considered to have been reworked from an earlier barrier deposit, and are thus anomalously old (A.N.U.-1335, 5580 ± 530 ^{14}C yrs BP; A.N.U.-1530, 5650 ± 100 ^{14}C yrs BP). A discussion of the significance of anomalously old shell hash dates in barrier age reconstruction is included in Thom et al. (1978, 1981b).

(viii) Over the last 3300 to 3000 years, a complex foredune has developed involving burial of an organic-rich soil along the seaward margin of the Outer Barrier at the northern end (Q6). This foredune is now undergoing extensive eolian erosion. At the southern end, there is some evidence for historic shoreline recession involving foredune "roll back". The rate and extent of recession cannot be precisely determined, nor is it known for sure whether it was purely an historic event (i.e. last 100 years or so). Estuarine conditions confined to the southern end of the interbarrier depression near Port Stephens (Weate, 1975). Elsewhere the depression and backbarrier sand flat have been covered by a fresh to brackish water swamp.

7

Upper Myall – Broadwater

7.1 REGIONAL SETTING

The Upper Myall embayment can be divided into two parts: a narrow ria-like landward portion and a more open seaward part. It extends farther inland than any other embayment in the region. Open-ocean sand deposits occur 15 to 16 km from the modern beach (Fig. 7-1a).

The Upper Myall valley occupies the trough of the Myall Syncline, and accordingly follows the general NE-SE strike of the region (see Engel, 1962). Permian sandstones and shales are exposed along the axis of the syncline and underlie the floor of the embayment. The margins are steep strike ridges composed primarily of Alum Mountain Volcanics which are of Carboniferous age and reach heights of 50 to 200 metres. The bedrock valley is quite narrow averaging 4 km in width. A major part of the valley floor to the north of the Inner Barrier is underlain by gently inclined slope deposits of predominantly clay grade; a narrower zone adjacent to the river is composed of floodplain and terrace alluvium. Bore records indicate that similar deposits extend beneath the Upper Myall Inner Barrier (see 7.3.1).

The boundaries of the seaward portion of Upper Myall Embayment are less distinct (Fig. 7-1a,b). Bedrock ridges which form the Upper Myall River valley become discontinuous to the southeast and occur only as isolated outcrops. Consequently the embayment is not bounded at the

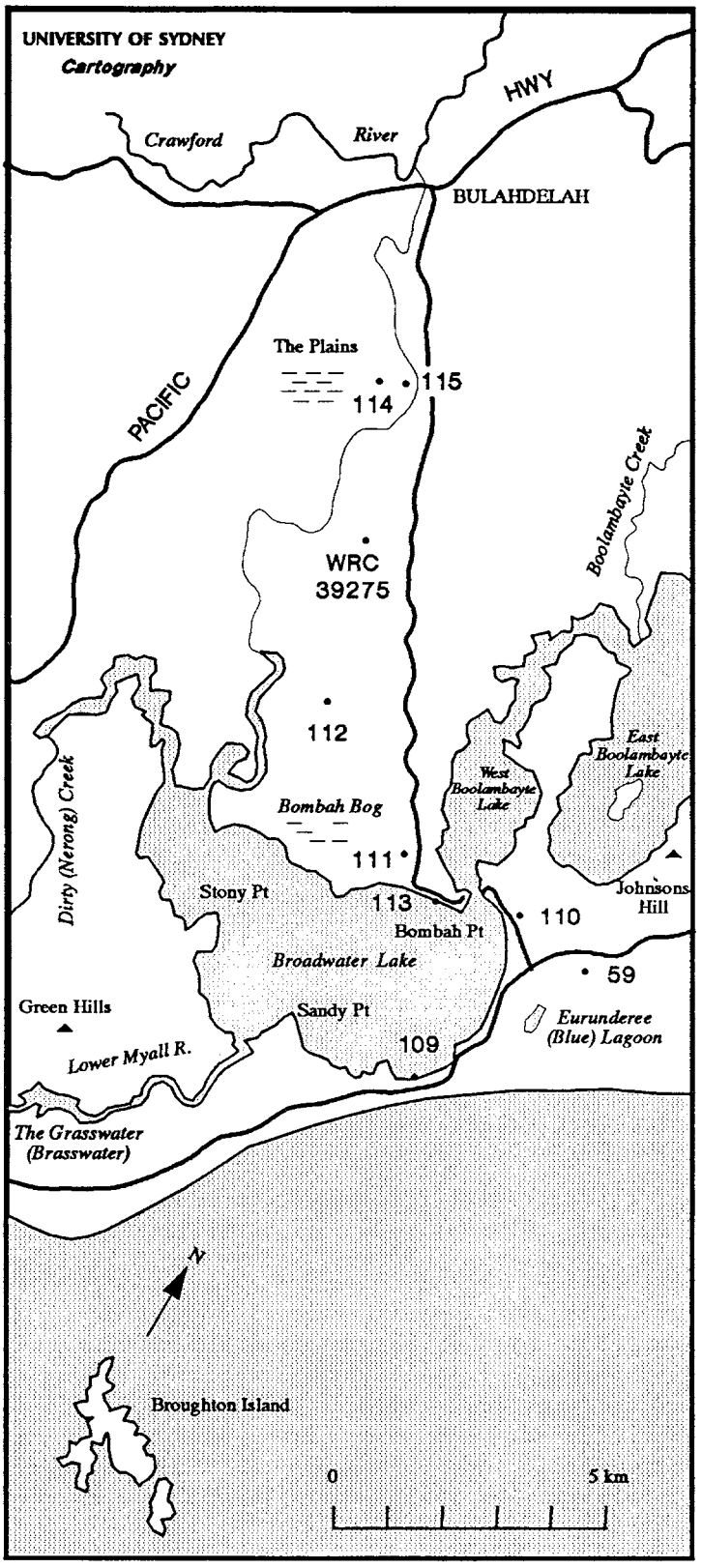

Figure 7-1a: Location map of the Upper Myall-Broadwater embayment including location of drill holes.

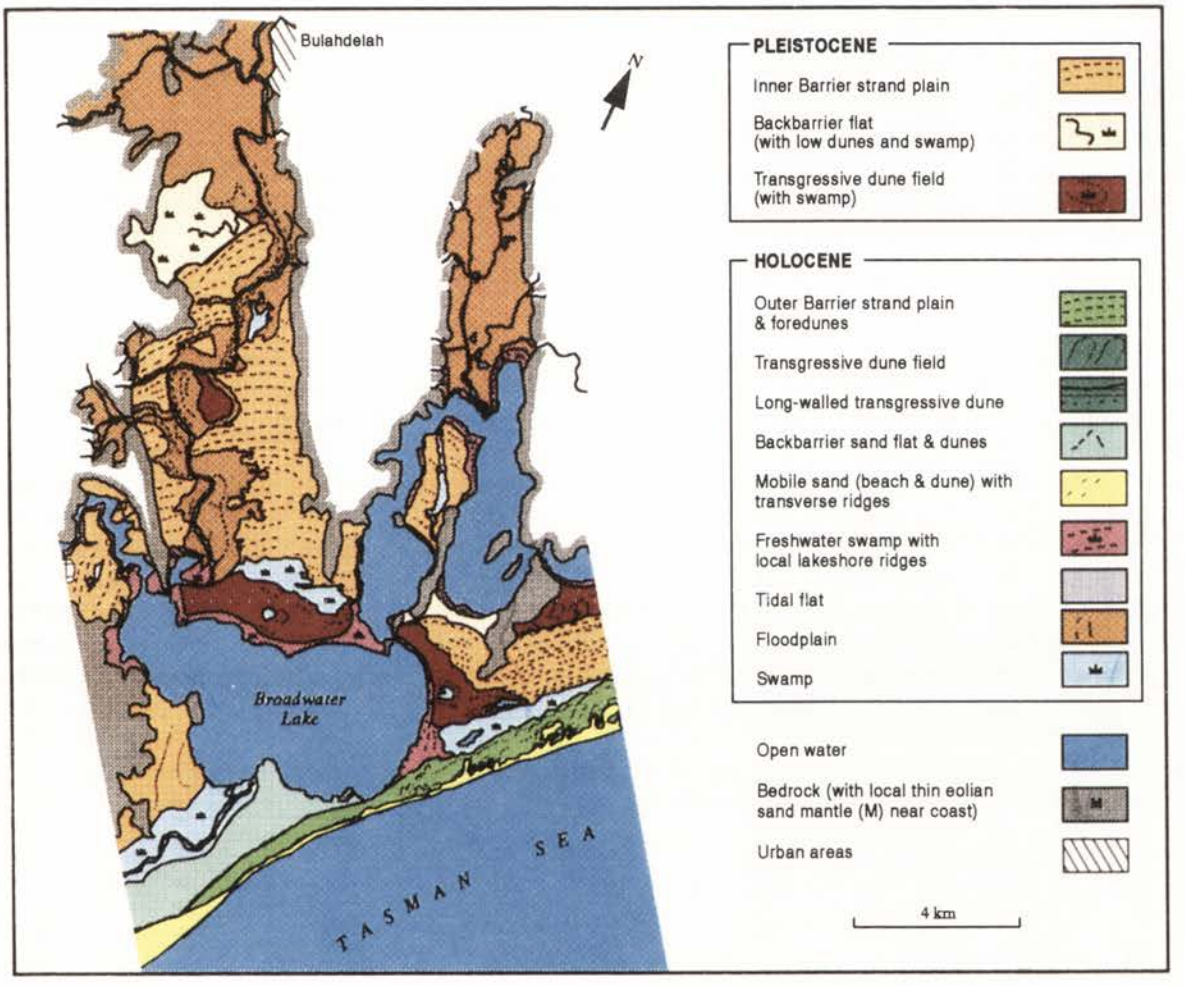

Figure 7-1b: **Generalized morphological map of the Upper Myall-Broadwater embayment.**

coastline by bedrock promontories. The western part of Broadwater Lake is separated from the Fens Inner Barrier by a broad inlier of the Crawford Formation. This forms a ridge up to 80 metres in height (Green Hills, Fig. 7-1b). Sandy Point, a cuspate foreland developed by the accumulation of sand in the lee of Broughton Island, forms the boundary between Fens and Upper Myall Embayments. The marked change in coastal orientation at Sandy Point is governed by wave refraction around Broughton Island (Fig. 1-7). However, Broughton Island continues the trend of the strike ridge of Nerong Volcanics. This ridge dips beneath the Quaternary cover near Dirty Creek, so that this boundary is indirectly controlled by geological structure.

The Upper Myall Embayment is separated from the inner part of Eurunderee Embayment by a strike ridge of the Crawford Formation which extends from Toms Hill to Violet Hill and continues as an inlier at Johnsons Hill (Fig. 7-1a,b). We are also including in the Upper Myall Embayment the lower section of Boolambayte Valley which is occupied in part by Boolambayte Lake and by Inner Barrier deposits forming Boolambayte Peninsula between East and West Boolambayte Lake (Fig. 7-1a,b). The rear of this portion of the embayment is occupied by floodplain and slope deposits of the Boolambayte Valley.

In the absence of detailed knowledge of the subsurface bedrock topography, it is assumed that the Carboniferous ridge which terminates 1.5 km south of Johnsons Hill extends further seaward as a subsurface feature to intersect the coastline approximately 2 km northeast from Mungo Brush. If this arbitrary boundary is adopted, the shore deposits of Broadwater Lake fall within Upper Myall Embayment, but the Outer Barrier sand complex extends across the boundary as a continuous feature into the Eurunderee segment (Figs. 2-1, 7-1a).

7.2 MORPHOLOGICAL CHARACTERISTICS

7.2.1 Major Morphological Features

Upper Myall Embayment is a two-part embayment open to the southeast. The embayment is only 3-4 km in width in the Upper Myall Valley but widens to 9 km at the coastline.

Figure 7-1a shows the following major morphological features of the embayment:

(a) Upper Myall Inner Barrier and enclosed swamps and flood plain
(b) Miscellaneous Inner Barrier deposits
(c) A parabolic dune complex bordering Broadwater Lake
(d) Broadwater and Boolambayte Lakes
(e) Lakeshore beach ridges
(f) Interbarrier deposits
(g) Outer Barrier

7.2.2 Upper Myall Inner Barrier Complex

The major area of sand deposition within the embayment is the Upper Myall Inner Barrier which occupies the lowermost 9.5 km of the Upper Myall Valley from 3 km southeast of Bulahdelah Bridge to the northern shore of Broadwater Lake. The barrier varies between 3 and 4 km in

width. Inner Barrier and associated deposits cover a total area of 32 km^2, of which sandy ridges cover 25 km^2. The barrier is bisected by the Upper Myall River whose flood plain covers an area within the barrier of 7 km^2. The thickness of the Quaternary infill is less than that of other embayments in the region, varying from 10 m near the northern margin to over 20 m near Broadwater Lake. Three depositional units have been recognized within the Inner Barrier complex: beach ridges, floodplain, and two types of swamps (swale and backbarrier).

7.2.2.1 Inner Barrier beach ridges

The Upper Myall Inner Barrier consists almost entirely of beach ridges. In plan the ridges are more strongly curved than those of other barriers in the region, reflecting the narrow width of the embayment and the effect of wave refraction at the margins of the embayment (Fig. 7-2). The ridges are markedly curved towards the rear of the embayment where they trend northeast-southwest. Our interpretation is that this pattern has been determined by former wave refraction patterns: wave crests would have travelled faster in the deeper eastern part of the embayment with the result that the first prograding beaches would have been asymmetrical with the strongest curvature towards the east. The alignment of the outermost ridges of the barrier complex indicates wave approach from the southeast.

The elevation of the Inner Barrier surface is remarkably constant throughout its length and breadth, normally lying within the range +5.5 to 6.5 m MSL. This contrasts with the elevation of the inner portions of other Inner Barriers in the region which are generally 3-5 m higher. However, other Inner Barriers were apparently exposed to greater wave and wind energy and the difference in altitude can be explained by these factors rather than any difference in sea-level during progradation.

The major part of Upper Myall Inner Barrier consists of flat-topped ridges spaced 100 to 200 m apart. However, the southernmost "ridge", which lies between Bombah Bog and Broadwater Lake, is a wide composite feature, more complex in morphology than other ridges of the barrier. Near its southern margin its surface has been modified by eolian action. Isolated dune mounds occur on this ridge attaining heights of 5-10 m above the sand plain. The "ridge" averages 1 km in width and its flatter parts, where a very subdued ridge/swale topography is discernible, average +6 to +7 m MSL. The presence of slightly higher beach ridges and formerly mobile dunes on this outermost section of the barrier can be attributed to its greater exposure to wind energy than is the case for the landward, more protected section of the barrier. There is no direct evidence, other than a broader swale, for this outer "ridge" being significantly younger in age than the rest of the Inner Barrier sand ridge complex.

The Inner Barrier surface where undissected exhibits very little variation in relief. Ridge-swale amplitudes rarely exceed one metre. One dune mound has been observed landward of Bombah Bog and is oriented west-east (GR 307054, Myall Lake 9333-II-5, 1:25000). This dune is c. 100 m in length and 7-9 m high. The beach ridges appear to be composite features, each ridge consisting of a number of ancient degraded "foredunes". The original swales appear to have survived complete degradation only where they acted as drainage channels for surface runoff. In places dissection of the ridges into "blocks" has taken place



Figure 7-2: **Vertical air photograph of the Upper Myall Valley showing dissected pattern of prograded beach ridges (Inner Barrier). Holocene flood plain and swamp deposits infill areas between the sand ridges (see Fig. 7-1a).**

(Fig. 7-2). Adjacent to the flood plain of the Myall River a number of swales has been deeply incised. Inspite of considerable postglacial infilling with both marine and freshwater deposits, the channels remain as major topographic depressions on the barrier surface (Fig. 7-2).

The landward margin of the barrier is bordered by a low terrace which extends for 1.5 km, and varies between 100 and 300 m in width. The terrace is composed of muddy sand and has a lobate form. It is interpreted as a backbarrier surface formed by washover processes. It slopes from approximately +3 m MSL to +2 m MSL where it borders "The Plains" swamp (Fig. 7-1a,b).

7.2.2.2 Flood plain of the Upper Myall River

Below Bulahdelah the valley of the Upper Myall River has been incised into the Inner Barrier, causing many beach ridges to become truncated. Subsequent infilling has resulted in the formation of a sinuous flood plain between 0.5 and 1.0 km in width which bisects the Inner Barrier (Fig. 7-1a). Floodplain alluvium of mixed silt and sand overlies estuarine deposits (see 7.3). The flood plain normally varies between +0.3 and +1.0 m MSL but locally reaches +1.5 m MSL. Levee and point bar topographies are best developed toward Bulahdelah. No fluvial terraces are present where the river flows through the barrier. However, the river does cut through the sand barrier at two localities (see Fig. 7-1a), and it is possible that here the sand deposits between the abandoned channel and the present river have been fluvially reworked.

7.2.2.3 Swamps

Deposits of peat or peaty sand are commonly found within Inner Barrier swales but are superficial (less than one metre thick). However, a number of swales has been entrenched to form re-entrants which join the margin of the flood plain. These have since been infilled with clay and peat to form swampy depressions up to 800 m in length; they usually slope towards the river.

A large example of a swamp in the Upper Myall Valley is Bombah Bog. This bog has been the subject of a detailed ecological and palynological study by Dr. A.R.H. Martin and his students and will be discussed in more detail in Section 7.3.

"The Plains" swamp occupies a depression which is bordered on the south by the innermost sand ridges of the Inner Barrier. It covers an area of 2.5 km^2. Its dense tree and shrub cover restricts access; it appears to be a former barrier lagoon (Fig. 7-1a).

7.2.3 Miscellaneous Pleistocene Sand Deposits

Although the Inner Barrier in the Upper Myall Valley is the major Pleistocene deposit within this embayment, there are a number of smaller sand areas which cover a combined area of 8.5 km^2. These sand areas have been mapped as Pleistocene in age because of their subdued relief, location, deep podzolization and thick horizons of humate impregnation. They have not been studied in detail, but are considered to be equivalent in age to the Inner Barrier (7.3.3). The largest of these areas comprises the Boolambayte Peninsula, but others occur to the west of the

Johnsons Hill outcrop, and along the western margins of Broadwater and West Boolambayte Lakes (Fig. 7-1a,b).

7.2.3.1 Boolambayte Peninsula

The area of sandy deposition lying between the western and eastern arms of Boolambayte Lake is termed Boolambayte Peninsula (see Fig. 7-3). The peninsula has little surface relief and is not characterised by the clear beach ridge and dune topography of other Inner Barriers. However, a faint east-west lineation may be distinguished on some vertical aerial photographs indicating that this area may originally have been formed by beach-ridge progradation. The barrier surface varies between +3 and +10 m MSL. Outcrops of Carboniferous bedrock occur on the peninsula. The course of Boolambayte Creek during barrier formation and during the Last Glacial is not certain. However, during Inner Barrier formation it probably followed the line of a swamp which trends NNW-SSE to bisect the barrier remnants (Fig. 7-3). Mineral company bore logs (R-Z Mines) indicate that the swamp is not underlain by channel-fill deposits which would almost certainly be present if Boolambayte Creek had continued to follow such a course during the Last Glacial (see 7.3). During this period it seems more likely that Boolambayte Creek incised a valley or valleys adjacent to the bedrock margins of the barrier, a site where fluvial erosion is often concentrated elsewhere (e.g. the southern margin of Fens Inner Barrier). Postglacial drowning would have resulted in the formation of Boolambayte Lake which nearly encircled these sand deposits to create a peninsula. This also explains the isolated deposits of Inner Barrier sand along the western shore of West Boolambayte Lake.

7.2.3.2 Pleistocene deposits adjacent to Boolambayte Lake

A number of small sand deposits of pre-Holocene age fringe the Carboniferous hills at the western margin of West Boolambayte Lake. These do not show a ridge-swale sequence, but reach altitudes of about +4.5 m MSL. A lower deposit (maximum +2 m MSL) is bisected by Boolambayte Creek immediately to the northwest of its delta. The total area of these deposits is about 0.6 km^2.

7.2.3.3 Inner Barrier deposits adjacent to Broadwater Lake

Subdued Inner Barrier beach ridges extend along the northeastern shore of Broadwater Lake towards the bedrock ridge of Johnsons Hill. They cover an area of 2.6 km^2 and have been mapped as part of the Eurunderee area (Fig. 8-1b). With a height of +6 to +9 m MSL, they are similar in altitude to Eurunderee Inner Barrier ridges which lie on the eastern side of the same outcrop. However, ridge and swale topography of the Eurunderee Inner Barrier is far more pronounced. The ridges west of Johnsons Hill are aligned to face a south-southeasterly direction of wave approach. In plan their curvature decreases away from Johnsons Hill, to which they are tied, until they are truncated by the lakeshore. Mining company bore logs indicate that the sands extend to at least 15 m below sea-level.

A further series of Inner Barrier deposits occurs on the southwestern shore of Broadwater Lake (Fig. 7-1a). To the south of Stony Point no clear ridge-swale topography is evident, but these deposits form a surface at about +6 m MSL. South of Dirty Creek, a larger area of



Figure 7-3: **Boolambayte Peninsula located between east and west portions of Boolambayte Lake. The bulk of the peninsular is composed of humate-impregnated sand bisected by a relict channel, now a freshwater swamp (Bulahdelah F, Run 6 (6-7-80), Scale 1:2,200)**

Pleistocene sand contains traces of ridges and swales aligned to an easterly refracted wave direction. Associated with these Inner Barrier deposits are swamps which probably represent channels incised in response to lower base-levels during the Last Glacial and have been subsequently infilled. Little drilling has been conducted in this area. Inner Barrier sand, with an altitude of +2 to +4 m MSL, also occurs adjacent to the northern shore of Dirty Creek (Fig. 7-1a,b).

7.2.4 Broadwater Parabolic Dune Complex

The Inner Barrier which extends towards the Johnsons Hill outcrop from the northeast shore of Broadwater Lake is interrupted at its southern end by a parabolic dune complex. This complex extends into Eurunderee embayment (Fig. 8-1a,b). The dunes are nearly 2 km in length and are aligned west-east. They consist of two narrow ridges up to 10 m in height, forming a nested set, one inside the other. Both enclose water-filled depressions. These have formed on the deflation surface of an ancient parabolic dune as water-table window lakes. Sedges and Melaleuca trees occur within these depressions. That this dune complex is younger than the Inner Barrier but older than Holocene will be demonstrated below (section 7.3.2.2).

Myerscough and Carolin (1986) recognize a distinctive plant community on this parabolic dune complex. They refer to the community as Intermediate Dry Forest, intermediate in structure and composition between Dry Sclerophyll Forest, which typically occurs on areas of Holocene sand, and Dry Heath Forest, a community which is found on the Inner Barrier. Within the Intermediate Dry Forest, Banksia aemula and B. serrata occur together (Myerscough and Carolin, 1986, p.424, Fig.9).

7.2.5 Broadwater and Boolambayte Lakes

Broadwater Lake is enclosed by an Outer Barrier and can be regarded as an interbarrier lagoon. Boolambayte Lake is enclosed only by Inner Barrier deposits and bedrock hills. The geomorphological history of these lakes is far from simple; the shores of both lakes truncate Inner Barrier deposits in a manner which suggests that more than lakeshore processes have been involved. It is probable that both the Upper Myall River and Boolambayte Creek incised valleys into Inner Barrier deposits during the Last Glacial, and that postglacial drowning of the valleys created the initial outline of the lakes. This outline has subsequently been modified by erosional and depositional lakeshore processes operating at present sea-level.

7.2.5.1 Lakebed morphology and sediments

Broadwater Lake is a relatively shallow, flat-bottomed lagoon (see Fig. 7-4 for bathymetry). Bed morphology and sediment type are related to aquatic communities, exposure to wave energy, wind-generated as well as fluvial currents, and relict processes. Where the bed is composed of sandy sediment, elongate sand bars occur in water depths which rarely exceed 1.5 m. These bars are normally found adjacent to the barriers and consist of well-sorted medium sand which is often slightly negatively skewed (Shepherd, 1970).

A striking transverse bar pattern is apparent on one air photo (NSW

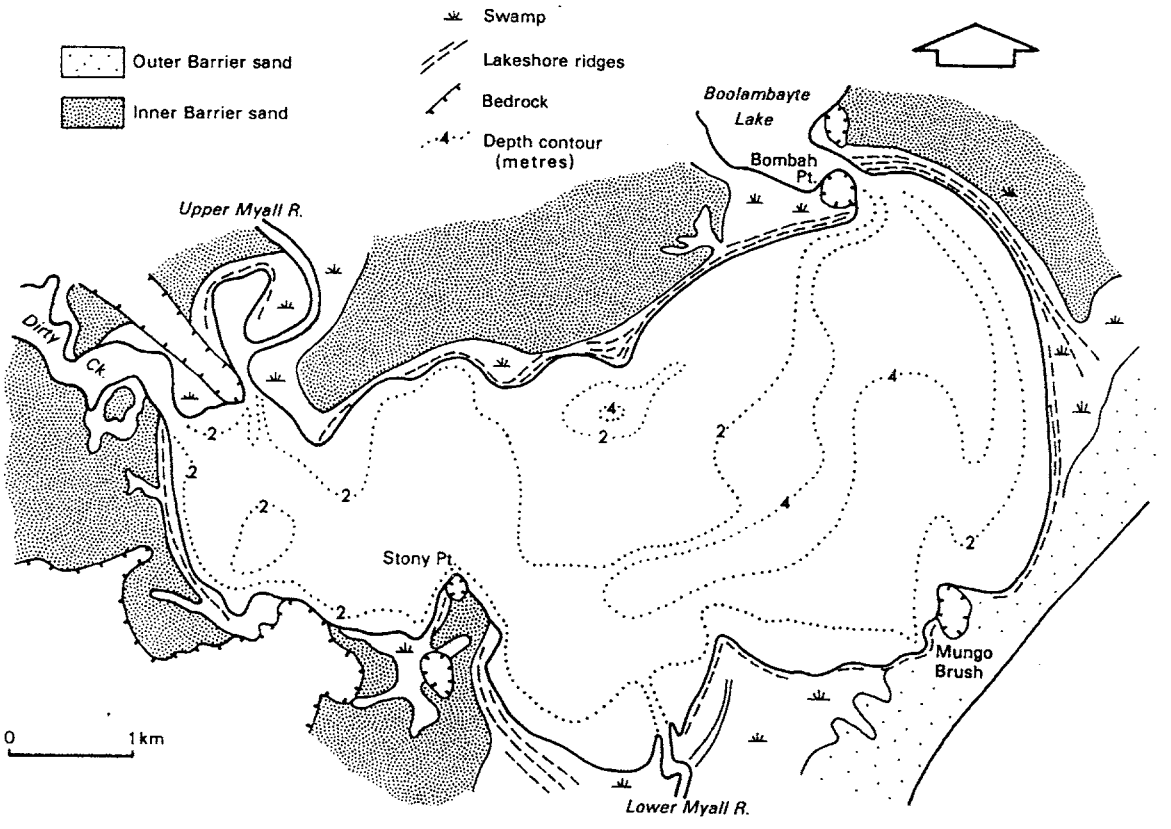

Figure 7-4: Bathymetry of Broadwater Lake.

Coastline 2035-5022, 9.9.72) of the eastern Broadwater shoreline (see Fig. 7-4). Towards the north, the bars are oriented at an angle to the shore and point west, but to the south the transverse bars are larger and point southwest. Farther south where the fetch is due west across the Broadwater, the transverse bars cease and are replaced by a shore-parallel sand shoal. Clearly defined, narrow channels separate each of the transverse bars. Morphodynamic processes responsible for such a pattern have not been studied in this area. However, restricted fetch of westerly wind waves from the northern portion of the shore probably explains the switch in orientation (Fig. 7-4).

Muddy sediments dominate where water depths range between 3 to 4.5 m. Locations sheltered from dominant south and west winds and waves, such as in Dirty Creek, contain mud at depths of less than 2 m. The mud consists primarily of clay, silt and organic material, but the sand fraction increases near river mouths and at locations where there is current scouring. This process occurs in the narrow strait near Bombah Point, near the mouth of the Upper Myall River, and adjacent to rocky headlands. Maximum lake depths are recorded in such locations (Fig. 7-4).

Active sedimentation of sand and mud is occurring near the mouth of the Upper Myall River and in the flood-tide delta where the Lower Myall River enters Broadwater Lake. The deepest portion of western Broadwater Lake has the form of a meandering channel, approximately 1 km in width and 6 km in length (Fig. 7-4). This may be a remnant of the Last Glacial course of the Upper Myall Valley, with or without modification by mid-Holocene tidal currents. Until subsurface sediment sampling is carried out in the Myall Lakes it will not be possible to confirm hypotheses such as these.

7.2.5.2 Lakeshore morphology

Sand deposits on the eastern side of Broadwater Lake are presumably inherited from processes which occurred during and at the termination of the Postglacial Marine Transgression. Drilling adjacent to the lake north of Mungo Brush produces some information about these sediments (7.3.2.1). More drilling is required within the lake to define the extent of these sands.

Relict shore platforms with cliff-foot elevation up to 2-3 m above MSL fringe the bedrock hills along the eastern shore of West Boolambayte Lake. A well developed degraded cliff platform occurs on the south side of Broadwater at Stony Point. Similar platforms are well developed around Myall Lake and will be discussed in more detail in Chapter 8.

Holocene lakeshore morphology varies with degree of exposure to wave energy and the composition and slope of the shore. Mudflat accretion has taken place along the shores of sheltered bays and where westerly and southerly fetches are restricted. In such localities clay and silt in suspension are derived from either floodwaters of the Myall River and Boolambayte Creek, or the lake bed by wave action. These sediments are trapped by the fringing reed vegetation. As sedimentation is more active at the outer edge of the reed fringe it is possible to observe this edge as an emerged feature enclosing a narrow body of water parallel to the shore. Along shores which have prograded relatively rapidly, this

process has been repeated many times to produce a series of subdued ridges and swales. Progradation appears to have occurred in sheltered localities where the initial offshore gradient was gentle (e.g. west of Stony Point). Estimates of rates of progradation are inhibited by lack of drilling and dating.

At exposed sites a clear distinction can be made between sandy and rocky shores. Along bedrock margins lakeshore progradation has not taken place. On the other hand, where the Inner or Outer Barrier is reworked to form the lake shore, a sandy beach without a reed fringe is usually present. Swash bars formed by lake waves during flood levels are often preserved as sandy ridges (Fig. 7-5). Such ridges occur along the northern and eastern shores of Broadwater Lake. The sand ridges form a miniature barrier system along the northern shore with cuspate forelands enclosing areas of swamp. Longshore drifting induced by wind-generated lake waves has enabled ridges to extend laterally from their barrier source areas as spits or tombolos. For instance, the Upper Myall Inner Barrier has become connected to the Bombah Point rock outcrop in this manner (Fig. 7-4).

Along the central section of the eastern shore of Broadwater Lake, two sand ridges up to about 3 m MSL run parallel to the shore. Initial examination indicates these to be mid-Holocene lakeshore beach ridges with some possessing an eolian capping (Fig. 7-6). These ridges extend across the mouth of the west to east trending parabolic dune (Fig. 7-1b). They are composed of white sand implying reworking of leached sands of Pleistocene age. There is no evidence of fresh marine sand having been deposited in this area in the Holocene.

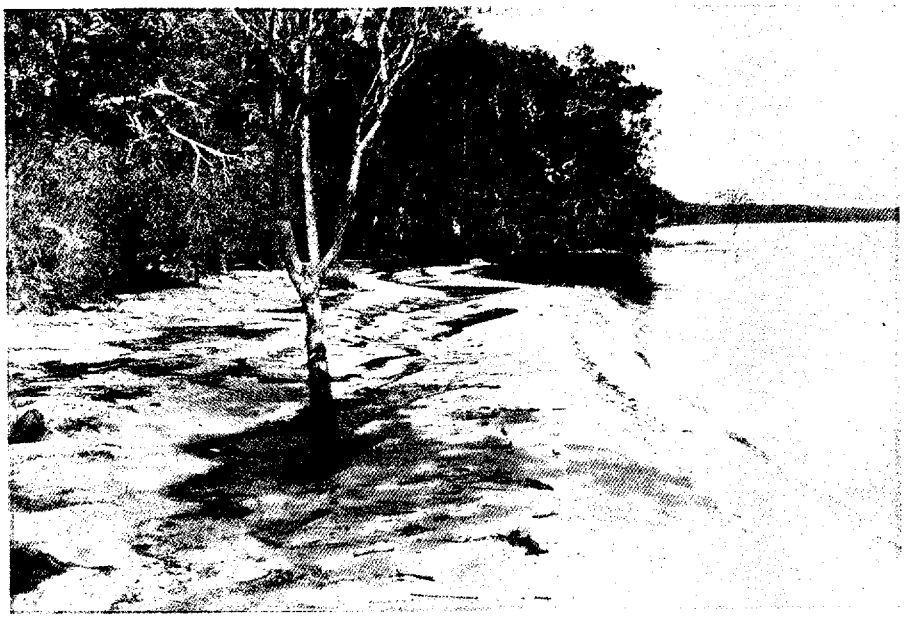

Figure 7-5: Swash bars formed of reworked Pleistocene leached sand at and above modal level (c. MSL) on the eastern side of Broadwater Lake.

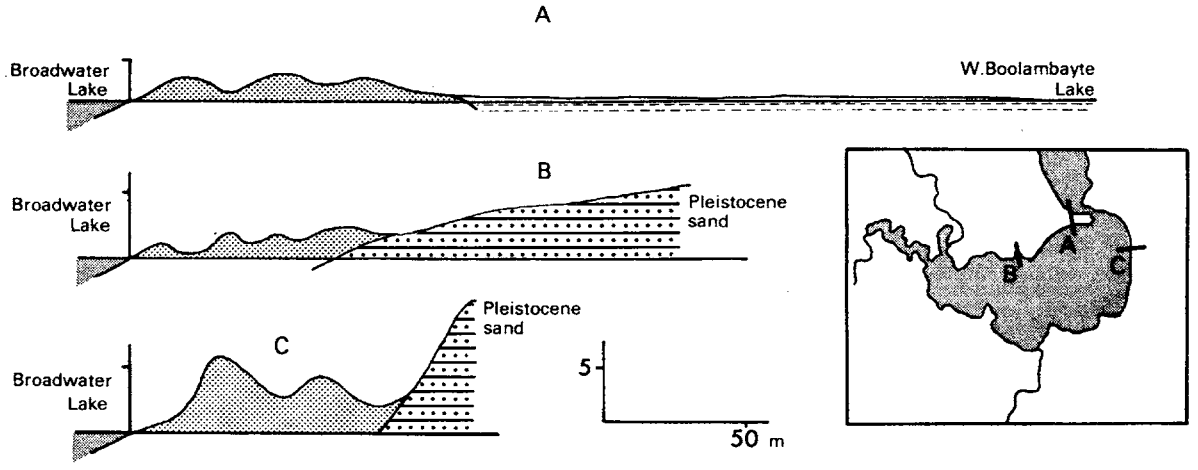

Figure 7-6: Levelled cross-sections of Holocene lakeshore ridges mainly formed by the wave reworking of Pleistocene leached sands.

The smooth outline of the lakeshore which truncates Inner Barrier deposits indicates that shoreline modification has occurred in the Holocene. At the southern end of East Boolambayte Lake, Pleistocene humate-impregnated sand outcrops on the lake bed at a distance of 100 m from the shore, indicating that at least that amount of shoreline retreat has occurred. However, shorelines adjacent to the barriers where erosion initially occurred are now fringed by progradational features. It is possible that progradation commenced when tidal currents ceased to affect the lakes (see 7.3.2.1).

7.2.6 Interbarrier Deposits

7.2.6.1 South of Broadwater Lake

The interbarrier zone extends southwards for 5 km from the southern shore of Broadwater Lake towards The Grasswater and Sandy Point. This zone is contiguous with the interbarrier depression of the Fens embayment (Figs. 2-1, 6-1, 7-1). It widens from 1.3 km near The Grasswater to 3.5 km near Broadwater Lake and covers an area of approximately 6 km^2. To the east it is bordered by a narrow Outer Barrier, while Carboniferous rocky hills and Inner Barrier deposits form the western limit (7.2.3.2). This zone is characterised by a surface which is generally swampy and less than +1 m MSL. The surface is crossed by numerous river traces which record former courses of the Lower Myall River. At least four former points of exit from Broadwater Lake can be recognized.

There is some evidence for wind-wave reworking of Pleistocene sands within the interbarrier depression. Narrow, discontinuous and curved ridges occur on the northern side of the swamp near The Grasswater. These ridges appear to have derived their sand from Inner Barrier sands of the Fens embayment. Presumably, their development coincided with an early stage of depression enclosure prior to swamp infill.

The presence of a "reverse" delta where the river enters the lake at

Tamboy demonstrates that this zone is extending northwards into the lake by the process of sediment "backtracking", i.e. the transport of sandy sediment into the lake by flood-tide currents. This process is likely to be particularly active during summer droughts when evaporation from the lakes is high, causing flood-tide currents to be dominant. Asymmetrical current ripples have been observed in the channel within the "reverse" delta at depths of 3-4 m (observations by snorkel diving in January, 1978). The orientation of the ripples strongly suggested sand transport into the lake from the south at this time.

7.2.6.2 Broadwater Lake to Eurunderee

This small area extends approximately 1 km northeastwards from the eastern shore of Broadwater Lake to the Eurunderee interbarrier zone. An elongate swamp occupies the Eurunderee interbarrier zone, and together with a small shallow lake, extends into this area. In the Eurunderee embayment the gradients of the swamp surface are very gentle, but it steepens to the southwest about 0.5 km from Broadwater Lake. At this point the altitude decreases from +2.5 m to approximately MSL at Broadwater Lake. A Cladium community, which characterizes the Eurunderee interbarrier depression, is replaced by a Melaleuca swamp near Broadwater where former lakeshore sand ridges extend across the depression. It is possible that, during the last 6000 years, the interbarrier zone has extended nearly 0.5 km towards the lake. The irregular, slightly protruding character of the shoreline bordering this zone contrasts with the smooth curve of the lakeshore further to the north. Wave energy is relatively weak at this end of Broadwater Lake. Although we have not drilled in this area, it is most likely that backbarrier sand underlies the swamp surface at shallow depths.

7.2.7 Broadwater Outer Barrier

Broadwater Outer Barrier is 10 km in length and varies in width from about 1 km at locations where a wide backbarrier flat is present, to a narrow barrier only 0.2 km wide where one or two foredune ridges separate the beach from the interbarrier zone. This barrier is continuous with the Outer Barrier of Fens embayment to the south and Eurunderee embayment to the north (Fig. 2-1). The varying morphology of this barrier is shown in Figure 7-7. Three morphological units have been recognized: mobile dunes, beach ridges-foredune and backbarrier flat.

7.2.7.1 Mobile dunes

The largest area of active dunes is located to the north of Sandy Point where a dune sheet 0.6 km in width has transgressed over beach ridges and backbarrier flats. Intermittent blowout activity occurs farther north within the foredune complex.

7.2.7.2 Beach ridges and foredune

The Broadwater Outer Barrier can be regarded as transitional between Fens Outer Barrier, which consists primarily of beach ridges, and Eurunderee Outer Barrier, which consists of parabolic dunes. Mining company records (Mineral Deposits Ltd.) indicate that the beach ridges of Fens Outer Barrier continue northeast parallel to the coast beneath the Sandy Point dune sheet. The width of the beach-ridge zone narrows



Figure 7-7: **The Outer Barrier where it is narrowest in the Upper Myall-Broadwater embayment adjacent to Broadwater Lake. An erosional established foredune and active parabolic dunes characterise the barrier (26-1-88).**

considerably to the north of Sandy Point where less than five ridges are present.

The narrow width of the barrier along this particular stretch of coastline may be attributed to lack of an adequate sediment supply, partially blocked by the effect of refracted waves in the lee of Broughton Island, and the orientation of the coastline which is here nearly parallel to the dominant onshore wind. By-passing of sands may occur on this section of shoreline due to longshore drift to the northeast (into Eurunderee and/or Seal Rocks areas). The narrow zone of beach ridges is replaced by a foredune complex one kilometre to the south of Mungo Brush. This foredune complex widens northeastwards until it joins the Eurunderee Outer Barrier. The complex increases in height from a maximum of about +20 m MSL near Mungo Brush to about +30 m MSL in the Eurunderee embayment. The foredune ridge consists of many hillocks and small depressions. Periodic eolian instability during the last 6000 years has taken place. Soil development is meagre. A buried soil, typical of eroded foredunes of the study area where exposed by deflation (e.g. Fens, Newcastle Bight), was observed in a blowout near Mungo Brush (see 7.3.2.1).

There is an increase in the frequency and size of both active and fixed parabolic dunes in a northerly direction. This can be related to increasing exposure to the dominant southerly onshore winds as the coastal trend changes from NNE-SSW at Sandy Point to NE-SW at the boundary with Eurunderee embayment.

7.2.7.3 Backbarrier sand flat

To landward of the foredune complex is a broad, poorly-drained sand surface which merges into the peaty sands of the interbarrier depression. This backbarrier surface is a continuation of the sand flats occurring behind the beach ridges of the Fens embayment. These flats are mostly vegetated by swamp forest. Figure 7-1a indicates the broad extent of the flat (and associated interbarrier depression). There is little relief on the backbarrier surface except where traces of former channels of the Lower Myall River occur (7.2.6.1). As discussed in 7.3, the backbarrier flat is a product of washover processes during and immediately following the Postglacial Marine Transgression.

7.3 STRATIGRAPHICAL CHARACTERISTICS

7.3.1 Bedrock Configuration

There are numerous drill holes in the narrow Upper Myall embayment which penetrate the sands. However, few of these bottom on bedrock or clay. The drilling has mostly been conducted for heavy mineral exploration (for instance, Rutile & Zircon Mines), but some holes have been drilled by the Department of Main Roads and by A.N.U. The D.M.R. drilling across the river at Bulahdelah, undertaken for purposes of bridge site investigation, encountered bedrock at depths of 20 m below ground surface. More recently the Water Resources Commission has been drilling in this area.

Elsewhere in the embayment some of the drill holes stop on a compact clay unit. Figure 7-8 demonstrates how this clay surface rises up-valley

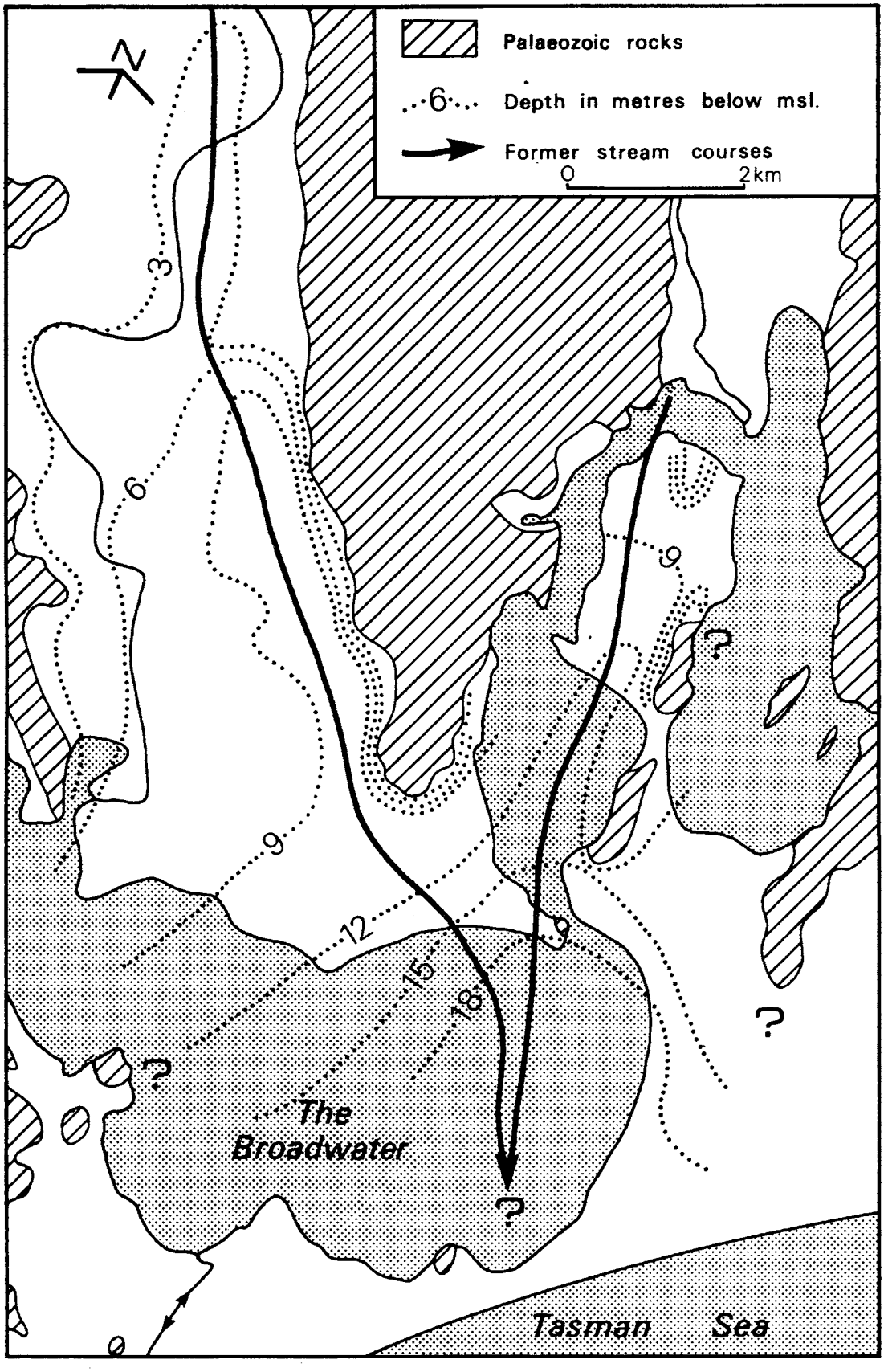

Figure 7-8: **Isopach map of surface of Pleistocene clay unit showing possible course of Upper Myall River during Last Glacial period.**

and how it contains a distinct valley morphology. In both the Upper Myall and Boolambayte valleys the clay surface is channelled. These channels appear to converge under Broadwater Lake. The old channel in the Upper Myall Valley does not coincide with the position of the present river (see Fig. 7-8).

In general, sand deposits in the Upper Myall Valley rest on a shallow clay "basement"(Figs. 7-8, 12). The basement descends to -20 m MSL beneath the Outer Barrier where it blocks Broadwater Lake. However, irregular bedrock outcrops, such as at Mungo Brush, locally interrupt the apparent smooth seaward descent of the clay as shown in Figure 7-8.

7.3.2 Stratigraphic Units

7.3.2.1 Holocene deposits

Holocene sediments within this embayment have not been the subject of detailed investigation. Five distinct environments of deposition are recognized: fluvial, estuarine, lacustrine, paludal and barrier.

Fluvial environments are associated with the Upper Myall River and Boolambayte Creek. Well-developed levees and point bars occur along the Upper Myall between Markwell and Bulahdelah. Similar features also occur downstream from Bulahdelah forming poorly drained depressions between the levees, sand ridges and "The Plains" lagoon terrace. Channel sands are poorly sorted with mixed lithic, quartz, and humate-stained quartz grains. The lithic content of the channel is surprisingly high considering the quartzose nature of the ridges through which it flows. Thus a fresh river sand input since the Holocene estuary was infilled (see below) is required to explain the sinuous belt of mixed quartz - lithic sand within a predominantly quartzose sand embayment.

Estuarine muds also occur in the Upper Myall Valley. They extend to at least 4 km downstream from Bulahdelah (A.N.U. drill hole 115). No attempt has been made to map their extent or geometry.

Martin (1987) in his drilling of Bombah Bog has demonstrated that blue grey muds occur as a wedge opening towards the river. They contain marine to brackish diatoms. Their upper surface is close to LWM. The muds extend to depths of 12 m below that datum in Bombah Bog. Here they are sandwiched between peats occupying an eroded channel (Fig. 7-9). No dates have been obtained from the clay unit. Five dates have been obtained on organic detritus at the base of the upper peat layer (see Martin, 1987, for details). They range from 2860 to 4120 ^{14}C years. Three radiocarbon ages have been determined from basal peat and wood material. The oldest date (SUA-1212) is 19,660 $\pm$ 240, the youngest is 8890 $\pm$ 130 (SUA-1211). Martin (1987) interprets the organic sequence as follows: the Postglacial Marine Transgression buried an older acid, heath-covered surface under a thick wedge of estuarine mud containing a rather impoverished diatom flora. A freshwater lake of rather short duration lies on top of the clay wedge almost directly. The marine influence was cut off by the development of a sandy levee structure next to the Myall River. Inflowing drainage into Bombah Bog remained acidic throughout enabling the water-shield Brasenia schreberi, to grow in the lake. This lake was replaced by an acidic freshwater peat bog which has accumulated c. 3 m vertically over the last 3000 years.

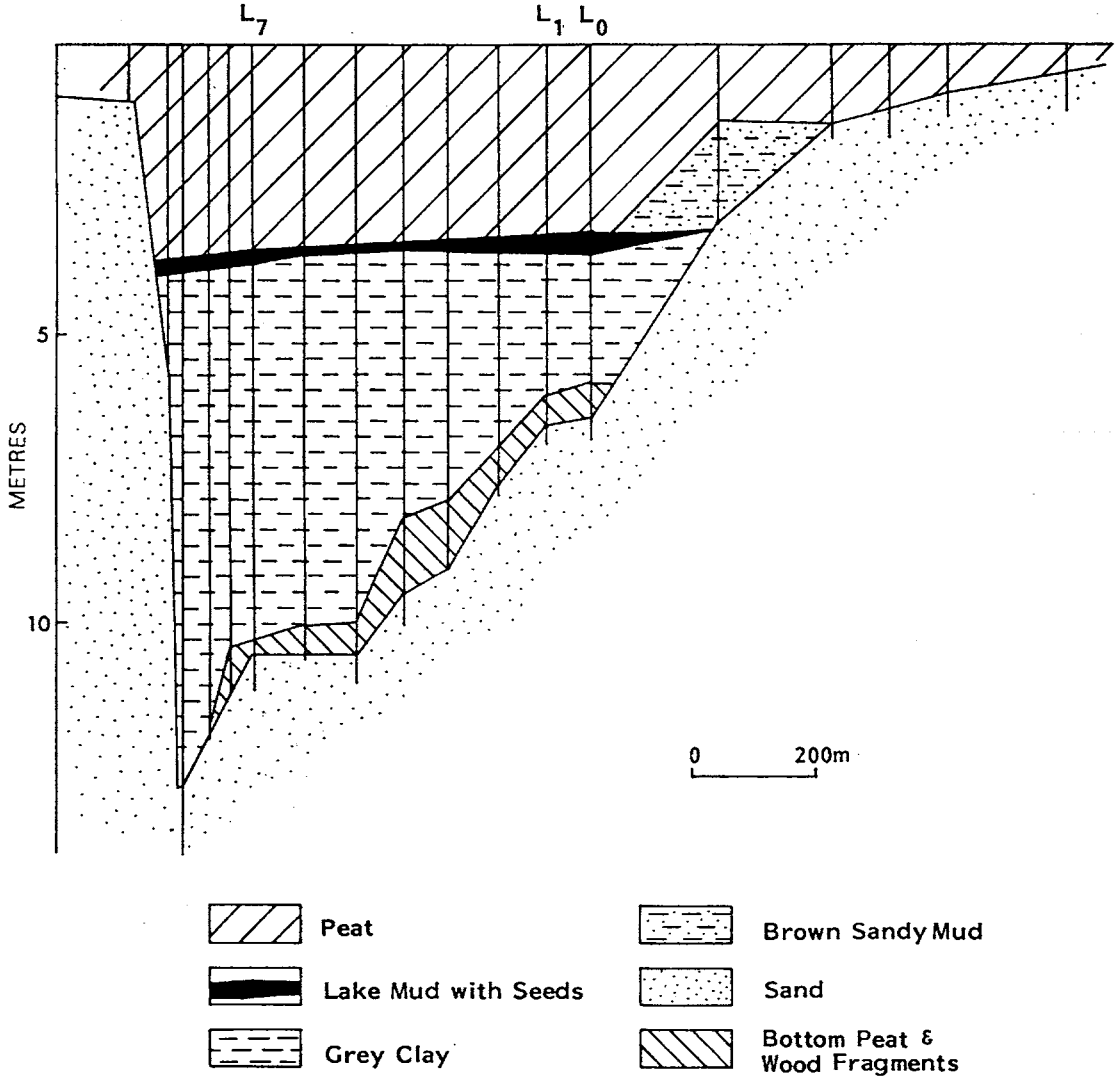

Figure 7-9: **Longitudinal section of Bombah Bog showing stratigraphy of organic and estuarine clay units (based on Martin, 1987, Fig. 1).**

Further up-valley, A.N.U. drill hole 115 encountered a shelly mud at a depth of approximately 3 m below MSL (i.e. 4.5 m below GS). This clay is rich in Notospisula parva (bivalves intact) and Nassarius sp. The Notospisula shells date 6100 + 130 ^{14}C yrs BP (ANU - 1670). This deposit is directly overlain by 50 cm of lithic coarse sand and then by 3 m of muddy sand rich in charcoal. Brown, oxidized silt of the river levee forms the surface deposit. It is 1 m in thickness.

Sandy estuarine facies occur beneath Holocene lakeshore deposits and backbarrier sands around the margins of Broadwater Lake. Near Bombah Point a shelly bed was encountered 4 m below lake level (=c. MSL) in A.N.U. drill hole 113. This unit is 3 m thick. It is rich in disarticulated Anadara trapezia, Notospisula parva and the gastropod Nassarius sp. (SUA-909, 5120 + 80 ^{14}C yrs BP). A similar shell bed occurs on the east side of the lake near Mungo Brush beneath backbarrier sands. It was dated at 6480 + 210 ^{14}C yrs BP (ANU-1543). The shells were recovered from A.N.U. drill hole 109. They occur in a dark grey sand, 2 m thick, located 5-8 m below MSL (Fig. 7-10a). The shells are reworked. This could have been in a tidally-influenced backbarrier environment associated with wave action around the sandy shores during the period when sea-level was nearing its present position. Washover and tidal delta processes may also have been involved.

A slightly muddy sand occurs at the base of the Holocene section beneath backbarrier and estuarine sand facies. A.N.U. drill hole 109 (see Fig. 7-1b for location) encountered this unit at 8 m below lake level. No organisms were observed within it. Tentatively, it is interpreted as a washover-lagoonal sand facies which accumulated as a transgressional unit associated with the last phase of the Postglacial Marine Transgression.

Estuarine muds and sands rich in molluscs tolerant of brackish waters are not today accumulating in the embayment, including Broadwater Lake. They were associated with a more open embayment involving tidal inlet and washover processes prior to or immediately following the "stillstand" in sea-level (see 7.3.3).

Lacustrine deposits include those which have accumulated in and around the lake subsequent to sealing of the Outer Barrier c. 5500 - 6000 ^{14}C yrs. The Broadwater and to a lesser extent adjacent water bodies are subjected to marked changes in water level and salinity-temperature variations from fresh to brackish (Atkinson et al., 1981). Little is known of seasonal or longer-term fluctuations in these parametres, although the study by Atkinson et al. (1981) has increased understanding of the hydrochemistry of the lake system. These authors have noted that "within the Broadwater, Boolambayte and Myall Lakes, the benthic communities are predominately freshwater communities" (p. 319).

Residents such as the late H. Legge and his son R. Legge of Bombah Point have observed up to 3 m rise in lake level and the persistence of high levels for several months. The inability of the Lower Myall to discharge flood waters permits reversal of flow from Broadwater into the Myall Lake, the latter serving as a storage reservoir (see Ch. 1). The effect of higher lake levels is to create sites for wave action above the apparent modal lake level (close to MSL). Parts of the Broadwater contain well-developed lakeshore beach ridges (see 7.2.5.2). These are

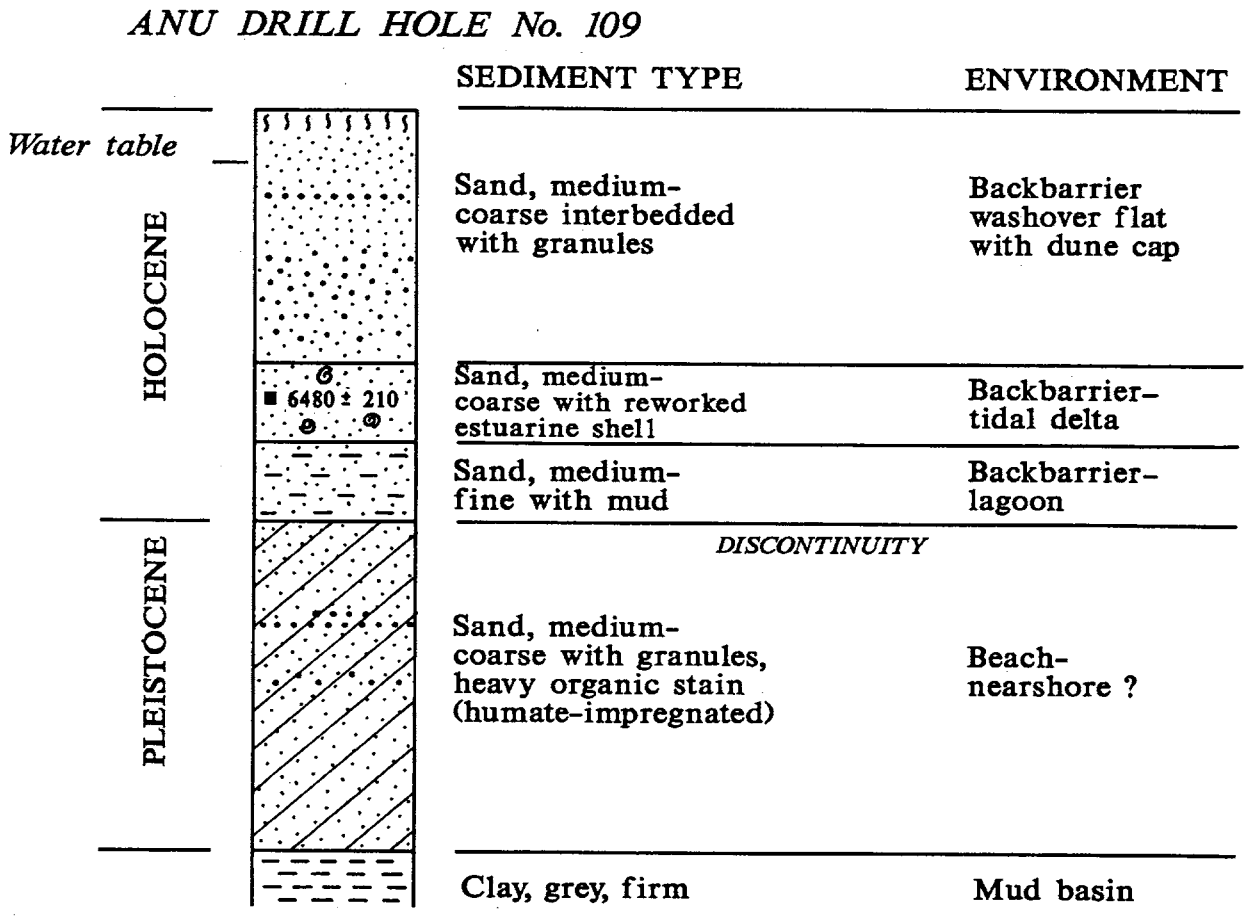

Figure 7-10a: Log of ANU drill hole 109 (GR 358996 Bombah Point 9332-I-N, 1:25,000).

ANU DRILL HOLE No. 112

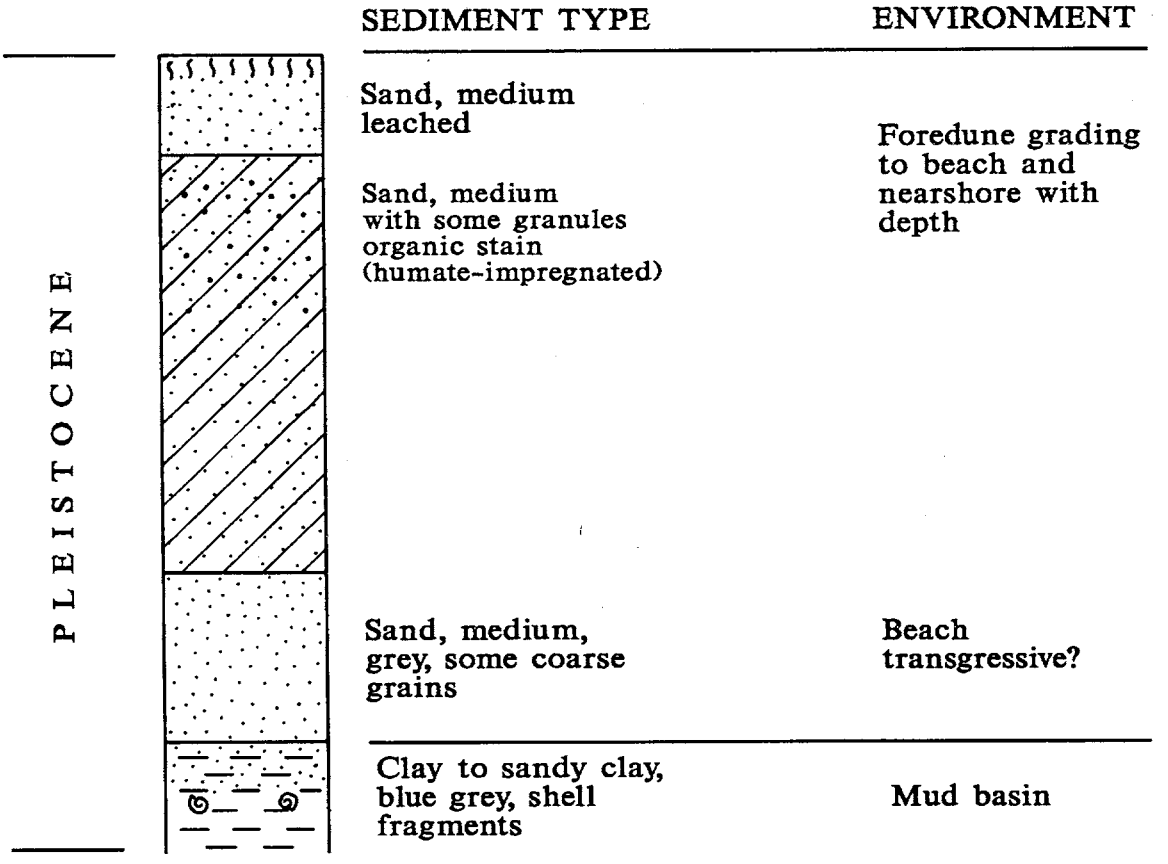

Figure 7-10b: Log of ANU drill hole 112 (GR 298047 Myall Lake 9333-II-S, 1:25,000).

composed of reworked Pleistocene sands, quite white in appearance and quartzose in composition. The slightly acidic waters of the lake margin, at least on occasions, and percolating ground waters from Pleistocene sand may be responsible for cleansing the sand of its slight iron coating. The ridge sands are well sorted but grain size varies locally. More work needs to be undertaken on these sediments, their age and relation to lake levels. As the heights of lake ridges do not usually exceed 3 m above MSL, and because they are well-vegetated even though wave swash deposition is active today, it is suggested that eolian processes were not significant in the accumulation of sand around the lake shores. However, Shepherd (1970) has recorded locally higher ridges containing finer sand and believes these sands possess an eolian component (see 7.2.5.2). An alternative view is that the higher ridges were formed within a tidally active estuary prior to sealing by the formation of the Outer Barrier.

The map of sediment type distribution and bathymetry of Broadwater in Figure 7-4 represents a preliminary attempt to show these two parameters (see also Atkinson et al., 1981, Figs. 5 and 6, and Table 8). The distribution of sand around the margins and as a broad shoal in the centre of the lake is interpreted as a reflection of both past and present processes. In water 2 m or less in depth the lake bottom is quite sandy. Mostly this is a medium to coarse sand, dominantly quartzose in composition, but containing some angular "lithic" grains similar to those of the Upper Myall channel. The sands are often highly charged in root material from the presently dense growth of aquatic plants. We consider that the distribution of sand reflects the incision by estuarine channel-forming processes in the mid Holocene when the embayment was more open to tidal action. On the basis of drilling around the margin, there is no evidence for open-ocean wave action and deposition in Broadwater Lake area in the Holocene. Backbarrier development is restricted to a narrow zone within 1 km of the present Outer Barrier shoreline. Water depths up to 4-5 m separate the central sand shoal from the barrier (Fig. 7-4).

Mud dominates the bottom of Broadwater Lake in water depths greater than 2-3 m. Except in the Dirty Creek embayment the mud is mostly inorganic. Organic matter content generally is less than 10 percent. However, quiet backwaters such as Dirty Creek are infilled with gyttja, the rich organic ooze so typical of the Myall Lake. It appears that the Broadwater is the settling basin for terrigenous silt and clay from the Upper Myall River. It is likely that Boolambayte Lakes (East and West) serve as sediment sinks for fines flushed out of Boolambayte Creek (plus some from flood overflow of the Broadwater). These fines may be steadily building up the bottom to the critical 2-3 m water depth, above which wave agitation inhibits mud sedimentation. The mud cover of the bar at the mouth of the Upper Myall River suggests limited sand influx into the Broadwater.

The flood-tidal delta at the entrance to the Lower Myall River at Tamboy (Fig. 7-4) is a feature whose degree of activity at present is uncertain. Except during river floods, measured flow at Tamboy, direction of current ripples on the bed and the well-developed "flood tide" levees all indicate that for most of the time a small net movement towards the lake must predominate (see further discussion in Shepherd,

1970, p. 209). Yet the subaqueous levees are composed of muddy sand. It is interesting to speculate whether similar sedimentation trends accompanied the accumulation of sand at Sandy Point (the lake feature not the cuspate foreland). This point forms the apex of a now defunct channel connecting Broadwater Lake with the Lower Myall near Tamboy (Fig. 7-4). It is possible that it is a relict tidal delta which was more active when the interbarrier depression of the Fens was more open.

Little need be said in this study about paludal vegetation and deposits. These will be the subject of two studies to be published soon: one by Carolin and Myerscough on the plant ecology of the valley of the Upper Myall River, the other by Martin specifically on the ecology and palynology of Bombah Bog. Accumulation of organic muds and peats in a variety of topographic situations within the embayment has already been noted. Perhaps more than any part of the study area between Newcastle and Seal Rocks, the Upper Myall-Broadwater segment offers considerable scope for research in a variety of wetland habitats. These habitats show changing ecological conditions over time (for instance, the change from estuarine to freshwater in Bombah Bog), as well as in providing sites which experience seasonal and annual fluctuations in salinity, water depth and temperature. Such fluctuations are pronounced within Broadwater and its marginal swamps whereas more constant freshwater paludal environments prevail in the Boolambayte-Myall Lake system and up the Upper Myall Valley. Encroachment successions of plants which form the lakeshore hydrosere of Broadwater (see Osborn and Robertson, 1939, for general description) contribute organic detritus to lake-margin sediments. In sites sheltered from wave action the Casuarina-Melaleuca fringe together with locally dense sedge growth constitute peat-producing communities. The thickness of these peats is limited by the shallow lake bed to less than 2 m.

Barrier sands of Holocene age can be divided into three facies: beach-nearshore, dune and backbarrier. Beach and nearshore sands are similar to those of Fens and Eurunderee and have been discussed elsewhere (Chs. 6 and 8). Similarly, little need be said in this section of sands forming the dune ridge which blocks off the Broadwater. These sands are typically well-sorted and medium-grained. A buried soil horizon separates two clear phases of foredune development at Mungo Brush. Buried Banksia stumps from this horizon date 385 $\pm$ 75 ^{14}C yrs BP (SUA-1220). This exhumed soil exhibits a clear A horizon containing abundant charcoal fragments and scattered midden shells (open-ocean species such as Plebidonax).

A backbarrier surface fringes the barrier and extends beneath the southern Broadwater Lake. This surface abuts the bedrock outcrop of Mungo Brush and continues uninterrupted into the Fens embayment. The nature of its extension into the Eurunderee segment is not clear. Drilling in the northern Fens backbarrier (A.N.U. drill hole 103) encountered 5 m of shell-free sand which is medium-coarse in texture. It becomes slightly muddy in the lower 3 m above the Pleistocene sand disconformity. At Mungo Brush, the sand is also medium to coarse with occasional granules in the upper 7 m (Fig. 7-10a). It overlies the estuarine shelly sand described above, and a slightly muddy basal sand which occurs at -7 m below lake level (A.N.U. drill hole 109). The sands in all three Holocene units of this hole probably accumulated by washover processes behind a stationary barrier. Bore logs of Mineral Deposits Ltd., indicate that south of Mungo Brush 3 to 7 m of Outer Barrier sand

overlies shelly estuarine beds at about -3 m MSL. These extend down to a brown, probably Inner Barrier, sand at a depth of about -10 m MSL.

7.3.2.2 Pleistocene deposits

Three Pleistocene sediment units have been recognized in the Upper Myall-Broadwater embayment: basal clay, subaerial fine-grained valley fill, and barrier sands.

The basal clay unit infills the entire embayment including West Boolambayte Lake and the Boolambayte Peninsula. We have no data on what lies below East Boolambayte Lake. To assume that the clay unit is also beneath these waters is reasonable as the Pleistocene clay outcrops beneath the sands of the peninsula on its western shores. Lack of deep drilling through the clay prevents us from saying anything about the geometry of the clay unit. Typically, the clay is very compact and difficult to penetrate with the power auger. A.N.U. holes, drilled in the Upper Myall Valley, recovered materials of slightly varying texture. Mostly they are quite sticky clays, but sandy clays are also present (e.g. A.N.U. drill hole 111). In all cases where the clay was overlain by Inner Barrier sands, the clay was unoxidized. It possesses a dark to light grey or blue grey colour. However, in A.N.U. drill hole 115, located on the flood plain of the Upper Myall, the basal clay is strongly oxidized. This is a site from which barrier sands, if they were once deposited across the valley, have been removed. The occurrence of shell fragments (not identifiable) and an echinoid plate and spine further supports the view that the clay was deposited under estuarine waters (A.N.U. drill hole 112 at 21 m below ground surface). However, the clay often contains organic fibres or is organic rich (e.g. A.N.U. drill hole 111). In general, the hard clays of the area are of estuarine origin as suggested in Chapter 3. This has been recently confirmed by the recovery of Anadara shells in the clay during a drilling program by the Water Resources Commission (Drury, 1982; Pickett, 1983). This hole shows 13 m of indurated Inner Barrier sand overlying 5.8 m of clay with shells. Another estuarine clay layer exists at a depth of 25.8 m below GS separated from the upper clay by "fluvial" sand. The hole bottomed in rock at 42 m (see Table 7-1 for drilling log, and Fig. 7-1b for location). Pickett (1983) has studied the Pleistocene invertebrate fauna from waterbore WRC 39275, and concluded that at the time of deposition the estuary was quite open and that the muddy sediments were emplaced before the development of the barrier ridges. However, the presence of Notospisula, which forms the largest proportion of the molluscan fauna, suggests a relatively sheltered channel environment. He indicates the possibility that "the earlier part of the Last Interglacial displayed biotapes at the same time more sheltered and more open to oceanic water than those observed at present" (Pickett, 1983, p.9).

The area known as "The Plains" behind the innermost sand ridge of the Upper Myall Valley, has a sandy clay surface. It is poorly drained and has not been drilled. The configuration of this flat surface and its relationship to barrier and valley fill deposits suggests it is a Pleistocene infilled lagoon related to a MSL of about +3 m above present.

Shepherd (1970, p. 152ff) has described the geometry and composition of the valley fill in the Upper Myall and Boolambayte valleys. He refers to the material as "colluvium". The fill generally forms a smooth, concave upward profile from the valley floor to the valley sides, and

TABLE 7-1 Bore Log 39275 Water Resources Commission NSW Upper Myall Valley (L. Drury, Geologist, published with permission, Secretary, Water Resources Commission)

From	To (in metres)	Thickness	Description of Strata	Environment of Deposition
0	0.5	0.5	Sand, light to dark grey, fine to medium, mainly clear quartz, angular and subangular, well sorted. Organic remains present	Barrier
0.5	11.5	11.0	Sand, brown to coffee brown, carbonaceous cement, no hard nodules	Barrier
11.5	13	1.5	Sand, dark grey to light brown, fine to medium grains, mainly clear quartz, minor smoky quartz, angular to subangular, poorly sorted	Barrier
13	18.8	5.8	Clay, bluish black, very sticky, foraminifera present, micro and macro shells	Estuarine
18.8	22	3.2	Clayey sand, light grey, fine to coarse sand, clay 40%, sand 60%	Fluvial
22	25.8	3.8	Sand and gravel, silty and clayey, light grey, fine to coarse sand 60%, fine to coarse gravel 30%, clay and silt 10%. Sand angular to subrounded, clear and smoky quartz. Gravel subangular to rounded, clear, smoky and rose quartz, jasper and volcanic rock fragments	Fluvial
25.8	38.8	13.0	Clay, bluish black, very sticky, no macroshells, foraminifera present	Estuarine
38.8	40.5	1.7	Fine to coarse sand, fine to coarse gravel and small cobbles, fine to coarse sand 40%, gravel 40%, cobbles 20%. Sand, fine to coarse, angular to sub-angular, poorly sorted, clear, smoky and rose quartz, jasper, chert, rock fragments. Gravel angular to subrounded, smoky and rose quartz, jasper, feldspar, volcanic rock fragments, basalt, chert and quartz feldspar porphyry, basalt, chert	Fluvial
40.5	40.8	0.3	Clay, bluish black, wet, very sticky	Estuarine
40.8	41.5	1.7	Clayey fine to coarse sand, fine to coarse gravel and small cobbles	Fluvial
41.5	42	0.5	Fine to coarse sand, fine to coarse gravel and small cobbles lithology similar to 38.8 - 40.5 m	Fluvial

displays a catenary soil sequence grading from blue-gray gleyed podzolics in clayey sediments on the valley floor to yellow podzolics in somewhat coarser and more poorly sorted sediments on the slopes. Valley fill contains both slope wash and fluvial overbank silts and clays. Alluvial terraces occur upvalley and can locally be distinguished from colluvial valley fill "flats" by a marked bluff. More intensive land use on the terraces reflects better natural drainage, superior soil fertility and younger age. It is proposed that valley-fill deposits with the exception of undisputable fluvial landforms, are polycyclic in origin developing prior to, during, and subsequent to Inner Barrier formation (Ch. 10).

Sand deposits of Pleistocene age occupy the Upper Myall-Broadwater embayment downstream from the inland limit of marine transgression. In the Upper Myall Valley and marginal to Boolambayte Lakes these deposits are expressed as beach-ridge, dune, backbarrier flat and river-channel landforms. Drilling has revealed humate-impregnated sands beneath eroded swales between sand ridges in the Upper Myall, and beneath Holocene lakeshore and Outer Barrier sands of the Broadwater portion of the embayment. Unfortunately, no drill holes have been put down in Broadwater Lake, but interpolation from holes around its shoreline indicates that sand of Pleistocene origin would underlie most of the lake bottom.

Shepherd (1970) has shown that surface sands from the Upper Myall Valley, in common with other Inner Barriers, are markedly bimodal. The major mode is medium sand (phi mean 1.5 to 2.1) with a lesser mode in the silt range. This lesser mode forms 1-2 percent of the sample; the problem of its origin is discussed in Chapter 8. Figure 7-11 shows the seaward decrease in phi mean sand size along a transect down the Upper Myall Valley. All samples used for comparison of size variation were taken from depths of 50 to 100 cm beneath sand ridge crests. This tendency for grain size in surface sediments to decrease seawards also occurs in other Inner Barriers (see Chs. 6 and 8). It may reflect a similar variation in the underlying beach sand. Drilling near the landward limit of the marine transgression revealed a coarse sand throughout the sequence (A.N.U. drill hole 114). Medium to coarse sand, plus granules, occurs below the water table down valley. Coarser, more poorly sorted and negatively skewed sands were recorded by Shepherd (1970, p. 182) at heights of 2-4 m above MSL adjacent to the Upper Myall River. Material designated in Rutile and Zircon Ltd. bore logs as "gravel" or "heavy gravel" occurs under a number of ridges on the western side of the Upper Myall Inner Barrier, a phenomenon not common from beneath other Inner Barriers. It is most likely that this "gravel" was derived from fluvial sources within the valley and later reworked by wave action. It occurs beneath the sand ridges at heights of up to 5 m above MSL.

The mineralogical character of Pleistocene sand in the Upper Myall Valley reflects a local enrichment of "lithic" grains. This is particularly marked at the head of the transgression (see Fig. 7-10b, A.N.U. drill hole 112). These grains are quite angular. In contrast, samples from the mouth of the valley are less enriched in lithics (see A.N.U. drill hole 111) except near the base. It appears that the Pleistocene transgression prior to Inner Barrier formation not only brought fresh "marine" quartzose sand into the bay, but also actively reworked a fluvial sand (and gravel) bed.

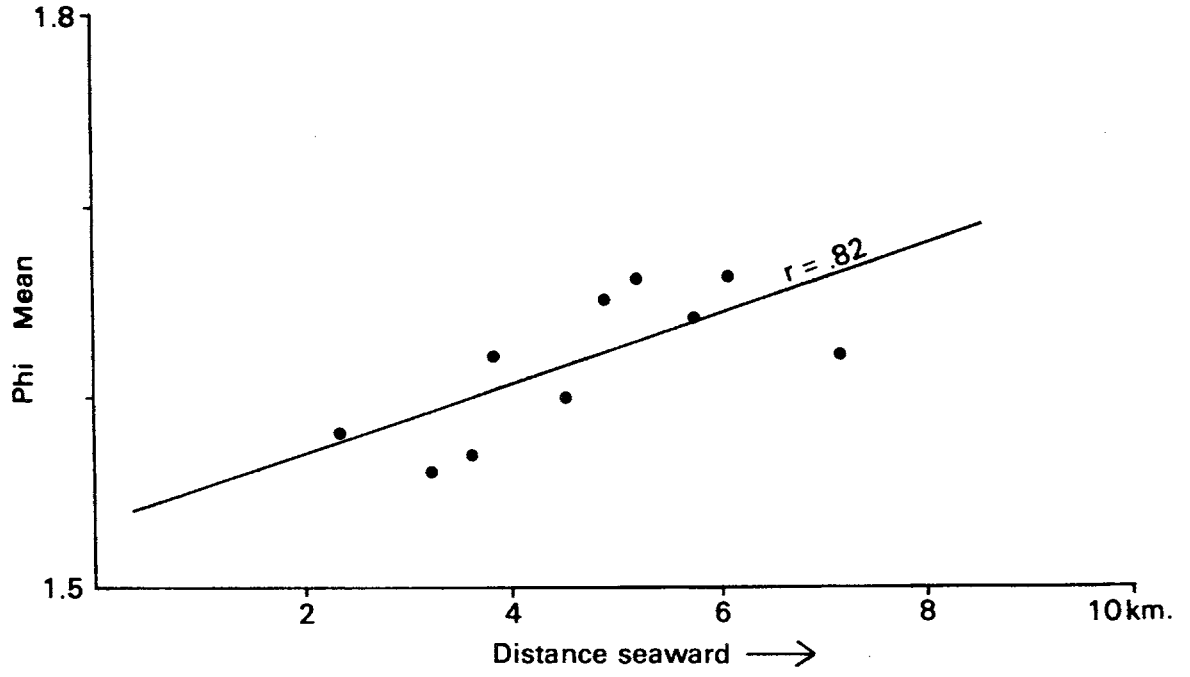

Figure 7-11: Trend in mean grain size of surface sand samples from Inner Barrier of Upper Myall Valley.

Lesser concentrations of heavy minerals occur within the Upper Myall Inner Barrier than beneath similar deposits in the study region. Highest values occur at +3 to 6 m above MSL. In spite of a strong fluvial influence upon sediments in the Upper Myall Valley, the heavy mineral suite remains dominated by rutile, ilmenite and zircon. This is further evidence for the bulk of the sand mass being derived from offshore rather than being of local origin. The relative high concentration of heavy minerals (1 percent and greater) near Boolambayte Lake and west of Johnsons Hill must be noted. This is an area which has been mined by Rutile & Zircon Mines.

Pleistocene sands in the Upper Myall-Broadwater embayment are heavily impregnated with humate (Fig. 7-10b). Drilling and heavy mineral excavation in the Boolambayte area have encountered humate-impregnated sand extending from just above to 10 to 20 m below sea-level (see Fig. 7-13). The maximum depth of humate enrichment observed in this area is shown in Figure 7-10a (A.N.U. drill hole 109). Where Pleistocene sands underlie lakeshore, paludal or Outer Barrier deposits, the strong humate stain and the increase in resistance to drilling clearly marks the disconformity.

Towards the base of the Pleistocene barrier sand unit the degree of humate-staining decreases. In some holes a thin 2-4 m layer of brownish grey to grey sand grades downwards from a more heavily impregnated dark brown, heavily stained sand (e.g. A.N.U. drill hole 111). At the base of the sand there is usually a thin 1-2 m sandy clay unit, grey to "greenish" grey in colour. Under Boolambayte Peninsula the "muddy" sand is thicker (3-6 m) and directly overlies the clay "basement" (Fig. 7-13).

It is not known whether this muddy unit represents an offshore deeper-water facies, or is part of a transgressed backbarrier environment similar to that inferred for the Holocene sequence near Mungo Brush.

There are two other Pleistocene sand deposits in the embayment. The first is the somewhat enigmatic channel sand bordering the Upper Myall River These vegetated deposits are isolated from barrier ridges by an active river channel or a former course of the river (Fig. 7-1a). A distinctive plant community and topographic position suggests some degree of reworking either by river or eolian processes during a period of lower sea-level (P. Myerscough, pers. comm.). The sands are mostly quartzose. Preliminary observations of sediment characteristics do not assist in unravelling their history subsequent to marine deposition. The second deposit consists of well-sorted quartzose sands which occur in both the parabolic ridges of the eastern Broadwater and the hummocky dune ridges on the relatively flat beach ridges of the Inner Barrier surface near Bombah Bog. These sands are deeply leached. A.N.U. drill hole 59 was drilled 0.8 km north of Broadwater Lake on the arm of the parabolic where it overlies Inner Barrier beach ridges of Eurunderee embayment. Here the parabolic ridge is 10 m above the beach-ridge plain. A well-sorted, leached sand, medium to fine in texture overlies a humate-impregnated sand 11 m below the surface. The dune sand is markedly finer.

Dateable material at the contact was not encountered. The source of these eolian sands appears to be a deflated Inner Barrier surface. Late Pleistocene peat has been recovered from beneath Bombah Bog at a depth of 5 m below MSL (Fig. 7-11). As noted above, the age of the woody peat is c. 11,000 radiocarbon years (0-1859). This radiocarbon date is historically significant as it was the first unequivocal evidence that the barrier sands of the Upper Myall, and by extrapolation other Inner Barriers, were pre-Holocene in age (Thom, 1965).

7.3.3 Stratigraphic Pattern and Depositional Sequence (Figs. 7-12, 13, 14)

The general stratigraphy of the Upper Myall-Broadwater embayment is diagrammatically presented in Figure 7-12. Details of this section require further drilling (see Pickett, 1983, Fig.2). A basal clay unit is shown as occupying the entire embayment section below sea-level. Upstream it outcrops as "The Plains", which is interpreted as a former barrier lagoon behind the Inner Barrier. The section indicates a steepening of the clay surface beneath the inner margin of Inner Barrier sands. It is possible that slope and terrace material mapped by Shepherd as "colluvium" is contiguous with the ancient lagoon, i.e. the subaerial valley slope and fluvial equivalent. A polycyclic origin is likely for both the basal clay and colluvium in the Upper Myall Valley.

The basal clay occurs at relatively shallow depths beneath the Inner Barrier sands (Fig. 7-8). There is no evidence of Pleistocene clay fill within or between the beach ridges. The clay surface dips at a low angle seaward from the Upper Myall limit of beach ridges to beneath the Outer Barrier (Fig. 7-12).

Rutile & Zircon Mines bored five sections across Boolambayte Peninsula (see Fig. 7-13). These indicate a flat clay basement at -6 to 10 m MSL. The surface of the clay horizon is closely related to the

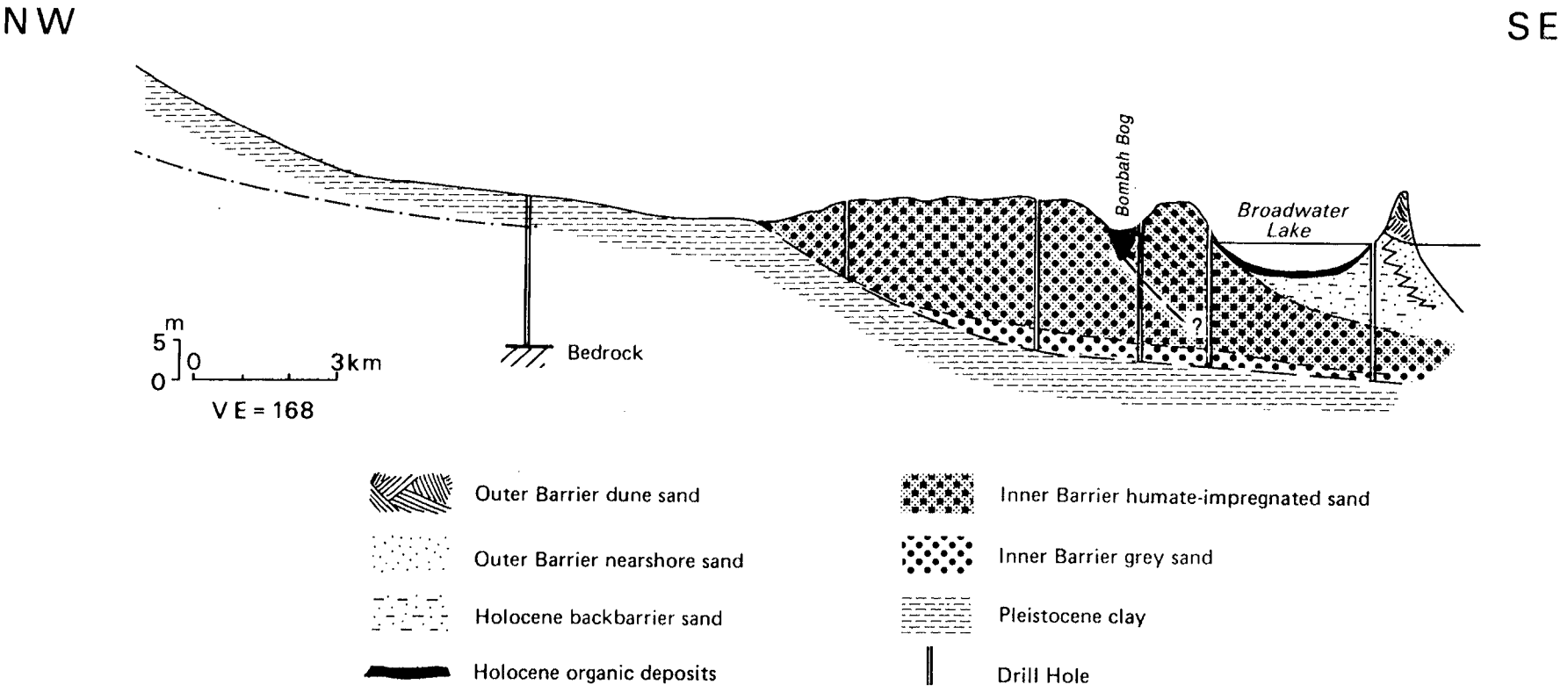

Figure 7-12: **Generalized stratigraphy of the Upper Myall-Broadwater embayment (see Fig. 7-1a for location of drill holes). The discontinuity shown beneath Bombah Bog represents a possible division of the Inner Barrier into two separate time units.**

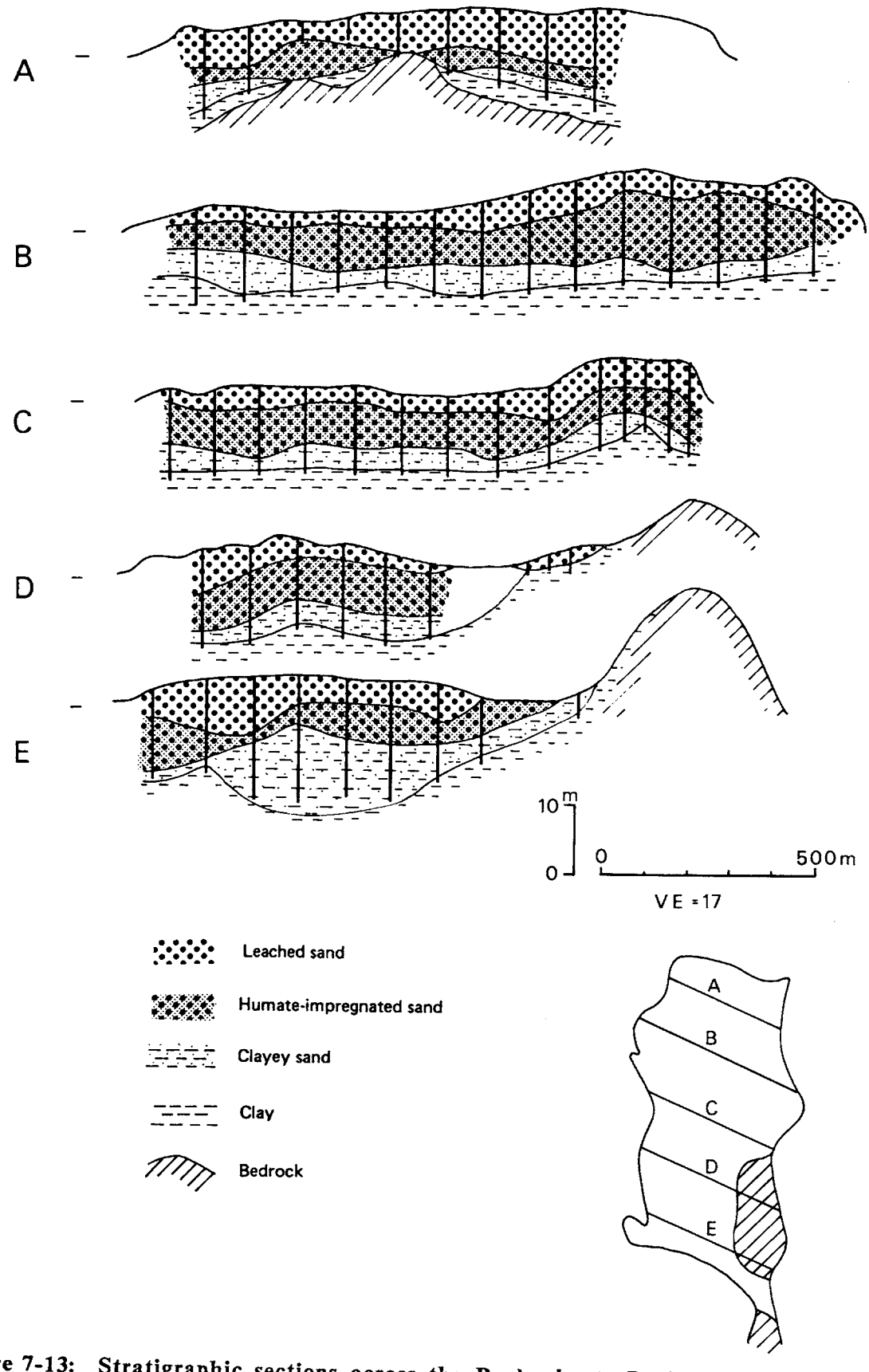

Figure 7-13: **Stratigraphic sections across the Boolambayte Peninsula (based on data supplied by Rutile and Zircon Mines).**

bedrock topography and at least some of the clay appears to be subaerial in origin, probably originating as colluvial deposits (section A, Fig. 7-13). Their easternmost hole on Profile E shows a horizon of post-Inner Barrier hillslope deposits overlying Inner Barrier sand which, in turn, overlies pre-Inner Barrier hillslope deposits. No dates are available from these sections.

Pleistocene sands of the Upper Myall show one of two characteristics: one is deep humate-impregnation beneath a shallow leached horizon, the other is a deeply leached profile. The latter is characteristic of Pleistocene dune sands such as those forming the parabolics of east Broadwater. The two characteristics are interpreted as follows:

(i) Deep humate profiles are associated with vegetated sand surfaces throughout the Last Glacial. Such surfaces have not been reworked by river and wind action.
(ii) Locally, eolian and fluvial processes have reworked Pleistocene sands in the Last Glacial producing thick, well-drained sands which have been subjected to a relatively long period of leaching.

The most spectacular product of reworking is the parabolic complex of east Broadwater. These dunes are oriented west to east and clearly have been formed by westerly winds (Q3Te). How did they originate and when? The dunes could have formed as source-bordering dunes marginal to the incised Myall River where it flowed across an exposed sand plain now covered by Broadwater Lake. Their soil morphology compares favourably with the longitudinal dunes on the Inner Barrier at Tomago, which have been dated late Pleistocene (see Ch. 10 and Appendix A). We suggest that eolian reworking took place during the later period of the Last Glacial (probably 12,000 to 20,000 years ago) when sea-level was still low and westerly winds were very strong (see Bowler, 1976, 1978).

The stratigraphy of the early Holocene fill of this embayment awaits further attention. Martin showed remarkable perception in 1958 in selecting the Bombah Bog site. Very few areas in N.S.W. show the lateral extent and thickness of both estuarine and paludal sediments such as occurs here (see Martin 1987). What appears to have happened is that freshwater swamps and alluvial channel deposits were flooded with lagoonal waters within a few kilometres of Bulahdelah during the Postglacial Marine Transgression. Clays from the river accumulated in these estuarine waters in which lived vast numbers of Notospisula. Similar conditions existed in many N.S.W. estuaries at this time (e.g. Eskdale Swamp, see Ch. 4).

In the mid-Holocene, the shelly lagoonal (pro-delta) clays of the Upper Myall Valley were either transgressed by fluvial silts and sands, or invaded and covered by freshwater organic debris. The transformation to freshwater conditions appears to have been a relatively sudden process, taking no more than 1500 years. The blocking of the Broadwater embayment by an Outer Barrier most likely took place at the time when the barrier was stabilized at Fens, i.e. about 5000 to 4500 ^{14}C yrs BP. Dates on estuarine shells below sea-level (e.g. from A.N.U. drill hole 109 See Fig. 7-10a), support the view that tidal exchange was active across a rising but low bar at the mouth of the Broadwater between 6500

and 5000 ^{14}C years ago. After the termination of the P.M.T. the foredune built upwards making it easy for fluvial discharge to be diverted south into the Fens interbarrier depression. If this depression had not been so accessible flood waters could have maintained an entrance to the sea near Mungo Brush, thereby creating a different set of ecological conditions in the lake than exists today.

In summary, the depositional history of the Upper Myall-Broadwater embayment is as follows (see Fig. 7-14):

(i) Estuarine and perhpas freshwater clay deposits and valley slope and alluvial material accumulated over a long period before the Last Interglacial (Q1). These facies most likely (see Pickett, 1983, Fig.2) contain several discontinuities which remain to be documented; the reduced uppermost portion of the clay probably formed during the transgression to the Last Interglacial high sea-level when it was buried by marine sand invading the embayment for the first time.

(ii) Inner Barrier beach ridges developed within the narrow Upper Myall embayment during the Last Interglacial (Q2Mer); lagoonal clays accumulated to form "The Plains"; it is possible that the separation of the Inner Barrier by a broad "inter-barrier" depression of Bambah Bog reflects the twin peaks of the Last Interglacial high sea-level stage (Chappell and Thom, 1978).

(iii) During the Last Glacial low sea-level period (Q3) the Inner Barrier beach-ridge plain was incised by the Myall River. Tributary streams draining the swales between beach ridges modified the primary topography by producing funnel-shaped re-entrants and gullied interconnections between swales. Some areas of the Pleistocene marine sands marginal to the incised channel were reworked by both fluvial and eolian processes, the major effect being the development of a parabolic dune complex, possibly towards the end of the Last Glacial, on the east side of the Broadwater depression.

(iv) The Postglacial Marine Transgression in the Upper Myall-Broadwater embayment (Q4) transformed the valley from a fluvial drainage system into a drowned valley in which estuarine deposits accumulated. Pro-delta clays full of estuarine shells accumulated in the drowned channels and gullies (Q4Em). As sea-level rose close to its present position the leached sands bordering the Broadwater "lagoon" were reworked and washover deposits accumulated behind a near-stationary Outer Barrier.

(v) The initial "stillstand" phase in the mid-Holocene (Q5) witnessed tidal exchange near Mungo Brush with the complete blockage of any tidal inlet across the mouth of the Broadwater bay as a result of barrier/foredune development, and diversion of Myall River and lake waters into the Fens interbarrier depression. This took place between 4500 and 5000 ^{14}C yrs ago. Freshwater to slightly brackish environments have been favoured in the Broadwater since that time, a water body which is barely tidal.

(vi) The late Holocene (Q6) has been a period in which the following has taken place: freshwater peat growth in swales and swamps around

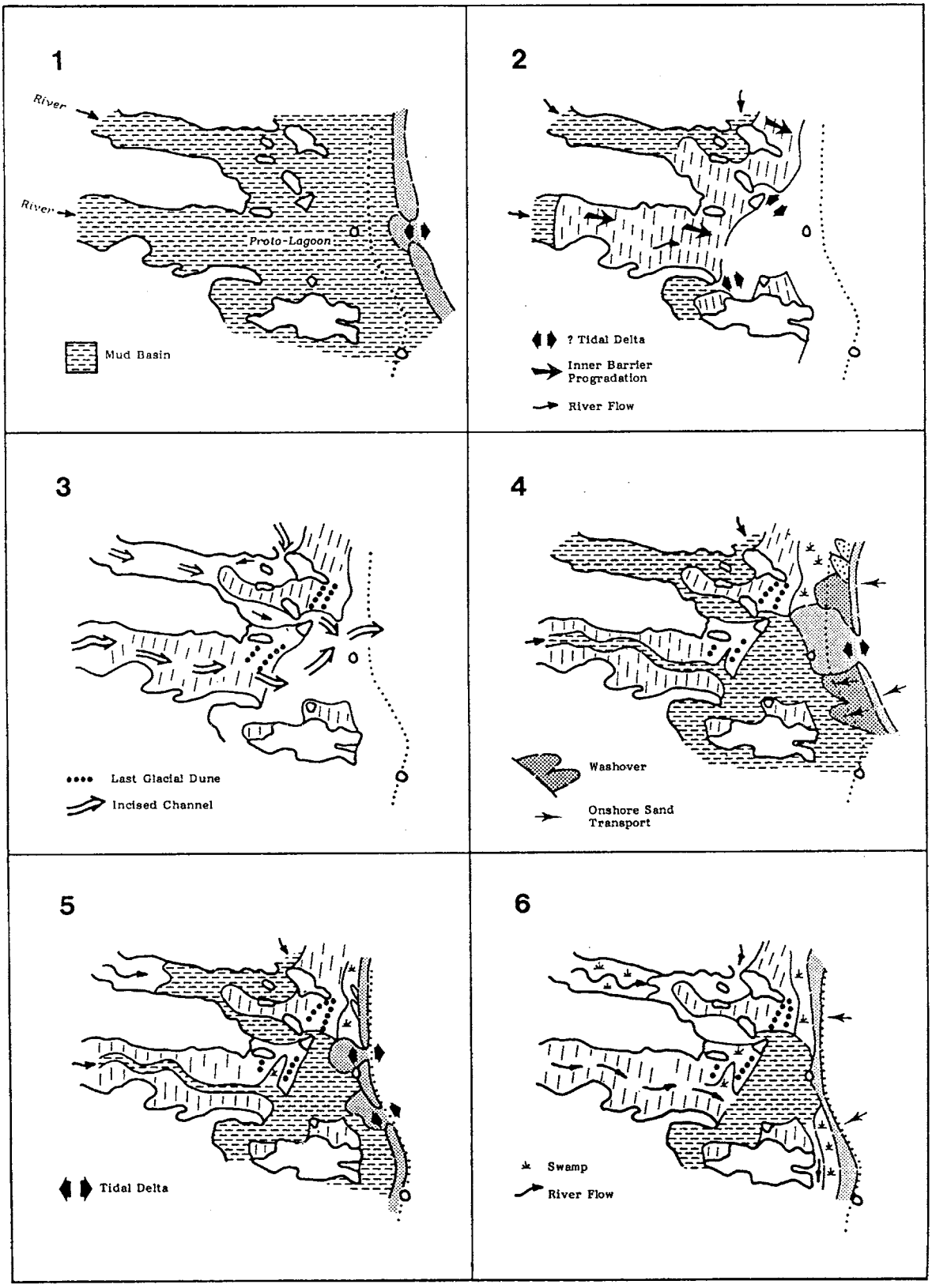

Figure 7-14: **Six stage model of the geomorphic history of the Upper Myall-Broadwater embayment (the stage numbers refer to time periods discussed in Chapter 10).**

lake shores (Q6To); further reworking of sands along lake margins into beach ridges especially during periods of high lake level; periodic instability in the foredune complex on the Outer Barrier; flood tidal delta development at the entrance to the Lower Myall River; and fluvial sedimentation of lithic sands and silts in the channel of the Upper Myall Valley and Boolambayte Creek (Q6Tc).

8

Eurunderee

8.1 REGIONAL SETTING

Eurunderee embayment is bounded in the west by a Carboniferous strike ridge which forms the western shore of Myall Lake. This ridge extends nearly 2 km southwards from Johnsons Hill (Fig. 8-1a). It plunges beneath Quaternary sediments approximately 1.5 km from the coastline so that the boundary between Upper Myall and Eurunderee embayments is taken as a line projecting southwards along the trend of the ridge and bisecting the shoreline about 2 km northeast from Mungo Brush. Although somewhat arbitrary, this boundary clearly separates Eurunderee Inner Barrier beach ridges from shore features associated with Broadwater Lake. On the other hand, the Outer Barrier of the two embayments is a continuous morphological feature. The Broadwater Pleistocene parabolic dune complex (7.2), which transgresses the beach ridges of the Eurunderee Inner Barrier, is bisected by the boundary (Fig. 8-1b).

Figures 8-1a,b show that the northeastern boundary of Eurunderee embayment is formed by Big Gibber, a small outcrop of Carboniferous Wooton Beds which barely interrupts the smooth curve of the coastline between Sandy Point and Yagon Gibber near Seal Rocks. However, a northerly extension of Big Gibber, now covered by dune sand, interrupts the continuity of the Eurunderee Inner Barrier (Fig. 8-2). A line

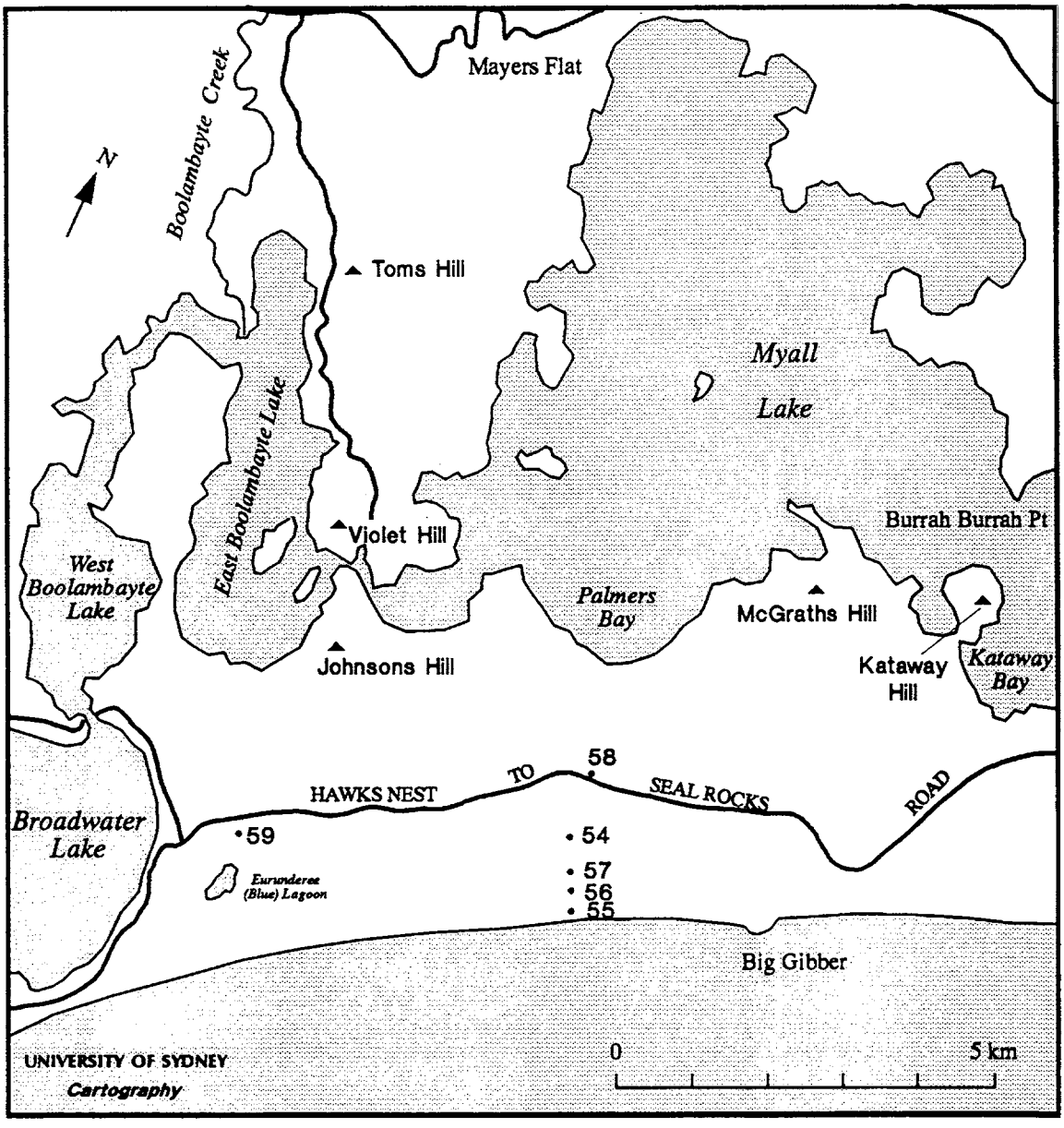

Figure 8-1a: Location map of the Eurunderee embayment.

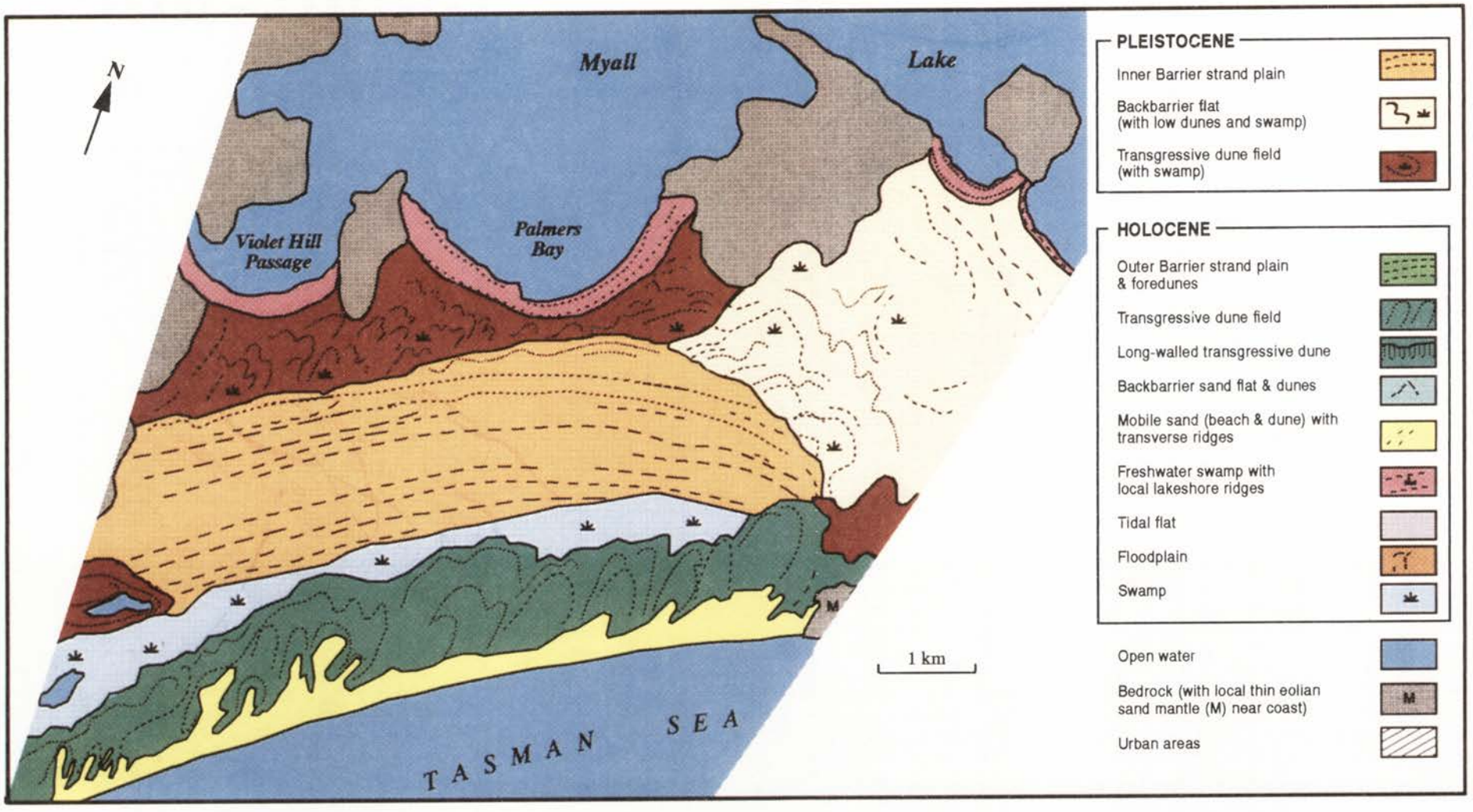

Figure 8-1b: Generalized morphological map of the Eurunderee embayment.

joining Big Gibber to outcrops at Kataway Hill and the ridge which terminates at Burrah Burrah Point should probably be regarded as the eastern boundary of Eurunderee embayment, but it is convenient to include the eastern portion of Myall Lake and the swamp to the southwest of Kataway Bay within this segment of the coast.

The rear of the embayment, which is up to 12 km from the coastline, is irregular in plan and consists of projecting strike ridges, separated by flat-floored valleys infilled with colluvium and alluvium. The bedrock margin consists of a variety of Carboniferous sedimentary and volcanic rocks: Wooton Beds, Nerong Volcanics and the Crawford Formation. The strike and fold axes trend normal to the coastline and the beds plunge below sea-level at the rear of the embayment (Fig. 1-1).

The rear bedrock margin of the embayment is separated from Inner Barrier beach ridges and dunes by Myall Lake. Isolated outcrops of Carboniferous rock occur as islands within the lake or as promontories projecting from the southern shore (Fig. 8-1). Myall Lake, which covers an area of 48 km^2, was formed when sand barriers extended across Eurunderee and Seal Rocks embayments blocking low relief drainage basins. Figure 8-2 shows the drowned bedrock shoreline on the north side of Myall Lake.

8.2 MORPHOLOGICAL CHARACTERISTICS

Eurunderee embayment is a broad embayment which is open to the southeast. Subaerial Quaternary deposits which fill the embayment cover an area of approximately 30 km^2. It can be subdivided into 4 major morphological units:

(a) Myall Lake (48 km^2)
(b) Inner Barrier (20 km^2)
(c) Interbarrier swamp (2 km^2)
(d) Outer Barrier (8 km^2)

8.2.1 Myall Lake

8.2.1.1 Subaqueous features

For the most part the lake bed is covered by a highly organic and mobile gyttja which has a gelatinous appearance. This usually supports a cover of aquatic plants of which Chara and Naias predominate (see Atkinson et al., 1981, for more detailed description of aquatic biology). Although the vegetation dies back annually, the bottom sediment is occasionally mobilised and suspended by wave-induced currents even where there is a thick vegetation cover. Bottom profiles are generally smooth and flat except where sand bars or bedrock projections are present (Shepherd, 1970). Lake depths vary according to fetch distance and direction. In areas exposed to relatively large lake waves arriving from the dominant southerly and westerly wind directions, depths of 4 to 4.5 m are reached. Elsewhere depths of less than 4 m are more common (Fig. 8-2). In sheltered bays and near the northern and western margins of the lake, depths of less than 2 m are usual, but in such locations waves associated with southerly storms occasionally tear sheets of vegetation from the bottom to produce an irregular profile. While lake depths generally appear to be related to the degree of exposure to wave-induced bottom currents, wind-induced currents cause local scouring

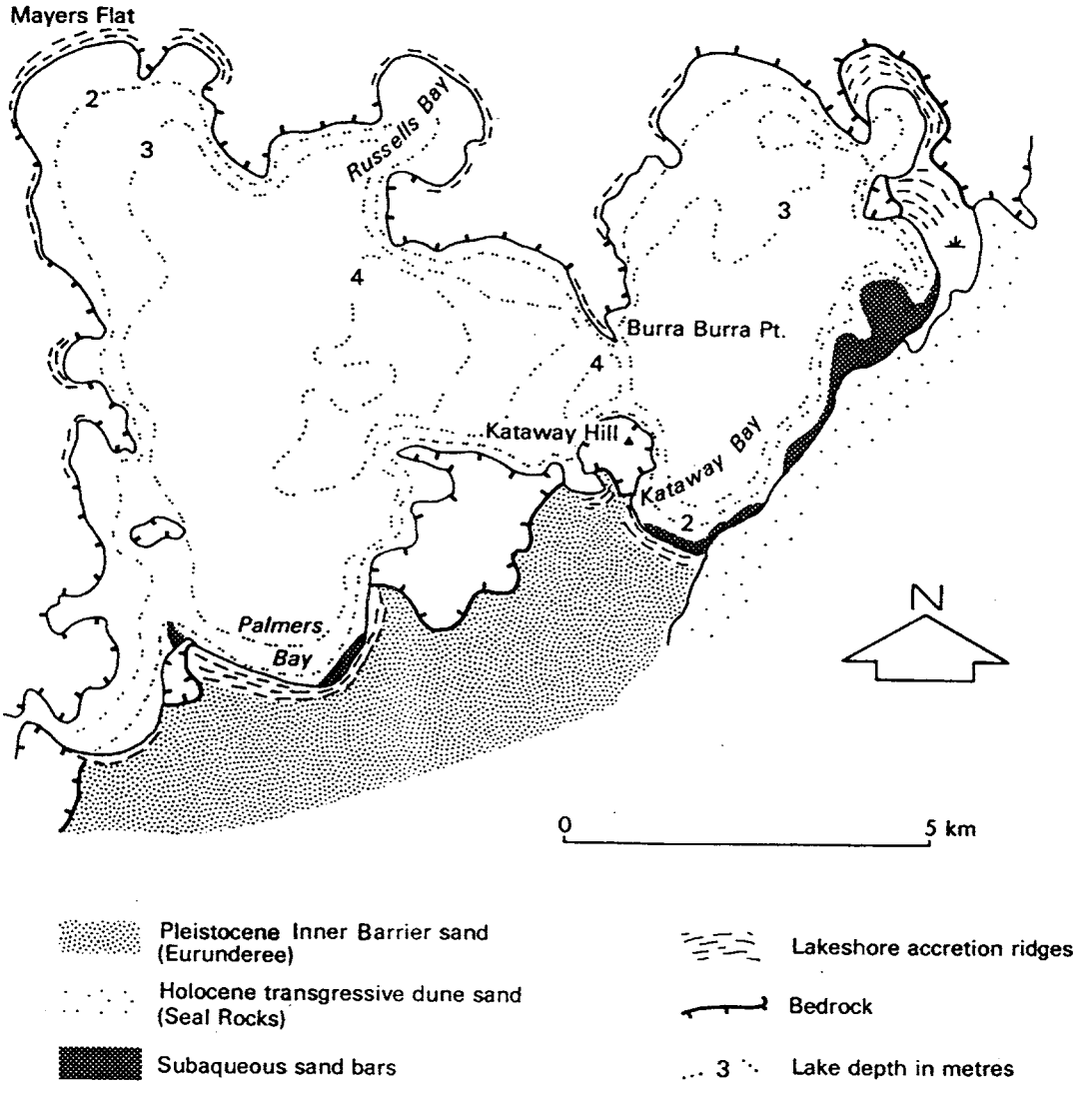

Figure 8-2: Bathymetry of the Myall Lake.

adjacent to exposed headlands while flood currents have scoured or maintained a channel up to 14 m in depth between Violet and Johnsons Hills at the entrance to the lake.

Rates of sedimentation in Myall Lake are probably very slow. No direct measurements are available. Only small streams enter the lake and deposit minor amounts of terrigenous sediment. During major floods, mud-rich water from the Upper Myall River and Boolambayte Creek enters the southwestern portion of the lake. Deposition of suspended sediment from these sources appears to be mainly restricted to this area.

The lake abuts sandy barrier deposits on the south side and here submarine sand bars and terraces are present. Wave scouring is far less effective over these sandy beds compared to mud or gyttja bottoms and, regardless of exposure, lake depths usually lie within the range 0.5-1.5 m. Submarine sand terraces border Palmers Bay and Kataway Bay (Fig. 8-2). The outer margins of these terraces generally rise steeply from the lake floor with characteristic convexo-concave slopes, but the terraces themselves shelve very gently towards the shore. Submarine bars formed at either end of Palmers Bay are apparently caused by longshore drifting (Shepherd, 1970).

Adjacent to the high dunes of Seal Rocks embayment, which border the northeastern end of Myall Lake, two large sand bars extend into the lake (Fig. 8-2). These could have been formed at a time when the dunes were being eroded by lake waves, or were actively transgressing into the lake. Holocene lakeshore deposits which may be contemporaneous with the bars are discussed in the next section.

8.2.1.2 Lakeshore features

As lake levels are normally close to MSL (Shepherd, 1970), the morphology of both depositional and erosional lakeshore features may be a useful indicator of sea-level change. Shepherd (1970) used MSL as datum in his surveys of lakeshore features. The majority of shore features around Myall Lake have developed with lake levels similar to the present level, but there are features which may have formed when levels were 1.5 to 2.5 m higher. In the Myall Lakes area no evidence has been found to support Pleistocene mean sea-levels more than about 2.5 m above the present level, and Holocene mean sea-levels above the present position.

Two types of lakeshore accretion have occurred in the Holocene. Parallel lakeshore sand ridges with crest heights between +1.0 and +2.5 m MSL have prograded in areas adjacent to barrier deposits along the southern shore of the Myall Lake (Fig. 8-2). The zone of ridges is usually less than 200 m in width, but near Bridge Hill at the western extremity of the lake it reaches a width of 450 m. It is considered that this extensive progradation was facilitated by an abundant supply of sand from the high dunes which abut the lakeshore. Erosion of the dunes is not occurring at the present time and it seems likely that either the dunes have been mobile during the last 6000 years (see Ch. 9), or rapid beachface progradation and bar formation occurred when equilibrium lakeshore profiles were being established at the end of the P.M.T.

In more sheltered situations, shorelines have prograded with the accretion of organic-rich mud deposits to less than +1 m MSL in altitude.

These form zones up to 300 m in width. This type of shore accretion is particularly pronounced around the shallow sheltered bays of the northern and western shores of Myall Lake. Initial shore gradient appears to have been an important factor controlling degree of progradation; bays with steep bedrock shores such as Russells Bay have prograded to a lesser degree than bays adjacent to gently sloping surfaces such as Mayers Flat (Fig. 8-2).

Rock platforms backed by cliffs in various stages of degradation occur at several bedrock locations around Myall Lake (Fig. 8-3). The platforms are relict features often covered with a thin layer of soil or gravel and mature species of Casuarina, Eucalyptus and Ficus. The platforms often reach 20 m in width. They truncate Carboniferous beds of varying lithology and dip (Fig. 8-3). These platforms generally extend a few metres offshore to -0.5 to -1.0 MSL, before terminating abruptly at their outer margins. Where best developed the platforms rise to heights of +1.5 to +2.6 m MSL at the foot of the cliff. Although platform development is particularly pronounced in locations exposed to long fetches, as around Kataway Hill, the existence of platforms along the eastern shore of West Boolambayte Lake demonstrates that large fetches are not necessarily a prerequisite for platform development (Fig. 8-3). Nevertheless, in sheltered locations rock platforms are usually less well developed and often absent.

It is considered that the platforms developed either during or before the Last Interglacial (Ch. 10). There is no evidence that platforms formed during the last 6000 years when lake levels have been close to the present level. It is suggested that conditions different from today prevailed during their formation. Absence of other marine and eolian features suggests that the western bedrock shore of Myall Lake has never been exposed to the full force of ocean waves. However, it is likely that during the period of Inner Barrier development a combination of saline water, lagoon waves and a tidal regime would have been conducive to platform formation. This presupposes that Myall Lake was more effectively connected with the sea through tidal inlets. There is some morphological evidence to indicate that a former lake outlet extended from Kataway Bay towards Big Gibber at that time.

At present, swash bars are formed along sandy shores during floods; these are preserved as lakeshore ridges when lake levels return to normal. On exposed sandy shores the crests of such ridges usually lie within the range +1.5 to +2.5 MSL (see also 7.2.5.2). However, at the rear of Palmers Bay and Kataway Bay, on the southern shore of Myall lake,

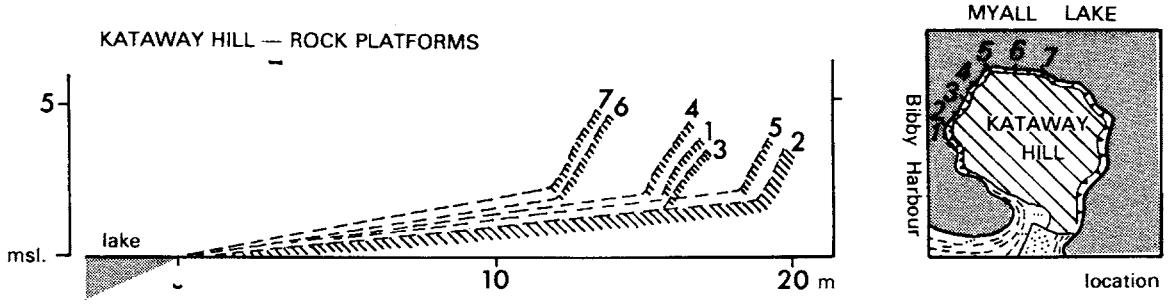

Figure 8-3: Rock platforms and cliffs around the bedrock outcrop at Kataway Hill.

more massive ridges are found parallel to the lake shoreline behind a zone of Holocene ridges (Fig. 8-2; see Shepherd, 1970, Ch. 5 for details).

The innermost lakeshore sand ridge of Palmers Bay is far wider and higher than subsequent lakeshore ridges and in places merges with Inner Barrier parabolic dunes which it appears to truncate. Eastern and western ends of the single high ridge at the rear of Palmers Bay have maximum heights of +3.2 and +4.7 m MSL respectively. These elevations are 1.8 and 2.1 m above the highest Holocene ridges at the respective ends of the bay. Size parametres of the sand in the higher ridges are similar to those of the present swash bar. However, the sands of the higher ridge are strongly podzolized. In plan, the ridge is oriented parallel to the curve of the lakeshore for a distance of nearly 3 km. It is likely that this is a Pleistocene lakeshore sand ridge and was formed when sea-levels were 1.5-2.5 m above the present level, at a time subsequent to the deposition of Eurunderee Inner Barrier parabolic dunes, and possibly during the period of Inner Barrier beach-ridge progradation (see 8.3.3). Similar ridges occur to the northeast of Johnsons Hill and to the southwest of Kataway Bay (Fig. 8-2). At the latter location two broad ridges are present approximately parallel to the lakeshore with several more ancient ridges trending north-south apparently marking a former extension of Myall Lake towards Big Gibber. Kataway Hill appears to be joined to these features by a tombolo of similar age.

The spacing of Pleistocene lakeshore sand ridges may exceed 100 m in width, whereas Holocene lakeshore sand ridges are spaced at approximately 30 m intervals. The spacing of the Pleistocene ridges may have been formed by the degradation of lakeshore ridges which were originally more closely spaced, as could be the case for spacing of beach ridges on the Inner Barrier (see 2.3.2).

A constructional shoreline feature composed of gravel occurs at Burrah Burrah Point (Fig. 8-4). The coarse material was apparently derived from a locally outcropping Carboniferous conglomerate. The feature forms a spit which continues northwards as a gravel lakeshore ridge, enclosing a shallow depression. The gravel has a thin soil cover and reaches a height of +3 m MSL. At the present time only the lowermost metre of gravel is affected by lake waves; above this level the deposit is vegetated and clearly relict. It is thought to be contemporaneous with the rock platforms and older sand ridges mentioned above.

8.2.2 Inner Barrier

In the Eurunderee embayment the Inner Barrier is very clearly demonstrated on vertical and oblique aerial photographs (Fig. 8-5). The sharp tonal contrast between the wet swales and dune depressions (black) and the low-relief ridges (speckled light grey) is evident on Figure 8-5. These contrasts reflect the zonation of vegetation communities which have developed on a landscape influenced by subtle differences in water table position and soil profile morphology (Carolin, 1971; Myerscough and Carolin, 1986, p. 437. Free-draining sands forming ridge crests are colonized by dry heath, a relatively open community in which Banksia aemula is an important species. Wet heath occurs on the margins of ridges and adjacent peat swamps. Low-growing Banksia oblongifolia, Dillwynia floribunda, and Xanthorrhoea resinosa are key species in the

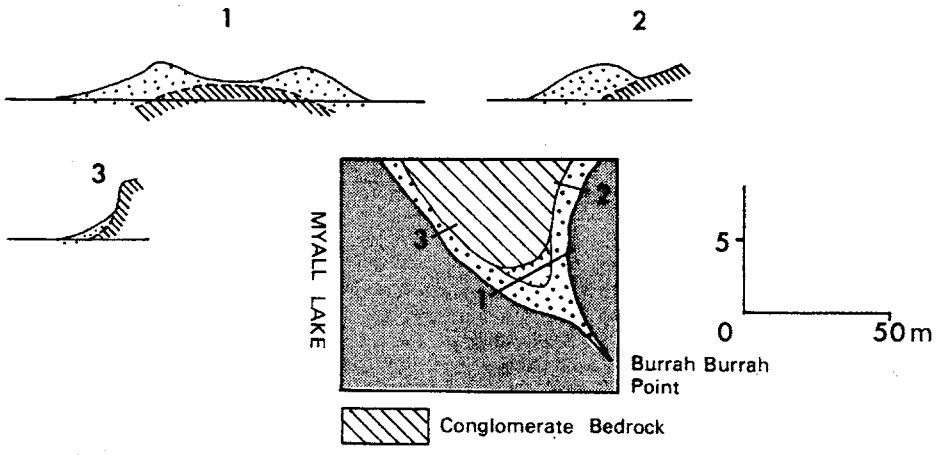

Figure 8-4: Wave-reworked gravel derived from a conglomerate Carboniferous bedrock outcrop at Burrah Burrah Point, Myall Lake.

wet heath which grades into swamp "forest" of the depressions (Fig. 8-6). Linear swales and irregular-shaped depressions are permanently wet in this area, and are colonized by a mixture of sedges, Callistemon citrinus, and rows of ghostly Melaleuca quinquenervia. These depressions are quite wet with organic detritus directly overlying humate-impregnated sand.

The Inner Barrier of the Eurunderee embayment can be divided into two morphological units: backbarrier dunes and beach-ridge plain.

8.2.2.1 Inner Barrier backbarrier dunes

Between the Inner Barrier beach ridges and the lakes is a zone 0.3 to 1.3 km wide of degraded dunes and shallow swamps (Figs. 8-1b and 8-5). The relief of the dunes is relatively flat; the microtopography of ridge and swale is barely perceptible on the ground, but in places sand ridges rise to two or more metres above adjacent swamps. The dunes are truncated by the oldest Inner Barrier beach ridge to the south and by the oldest lakeshore ridge of Myall Lake to the north (Fig. 8-1b). The higher dunes are vegetated by dry heath forest or wet heath forest (Myerscough and Carolin, 1986).

In detail, the dunes inland from the beach ridges appear as a set of imperfect arcs sometimes joined at their ends. The arcs face the SSW (Fig. 8-1b) and "nest" one inside the other. Their morphology is suggestive of a subdued parabolic dune complex opening to the SSW. The orientation of dune troughs is 208 $\pm$ 10 degrees. Migration of sand from SSW to NNE from an ancient shoreline is the most probable source.

The dune complex widens to the northeast. This is the area inland from the Big Gibber towards the Myall Lake (Fig. 8-1a). Here a broad flat sand plain is mostly vegetated by wet heath and is interrupted occasionally by low dune rises with dry heath or dry heath forest. The plain is contiguous with the low relief surface which underlies the Holocene high dunes of the Seal Rocks segment (see Ch. 9). The plain is nearly horizontal and is c. +2-3 m MSL. It has not been levelled in order to determine if it dips gently toward the Myall Lake. On air

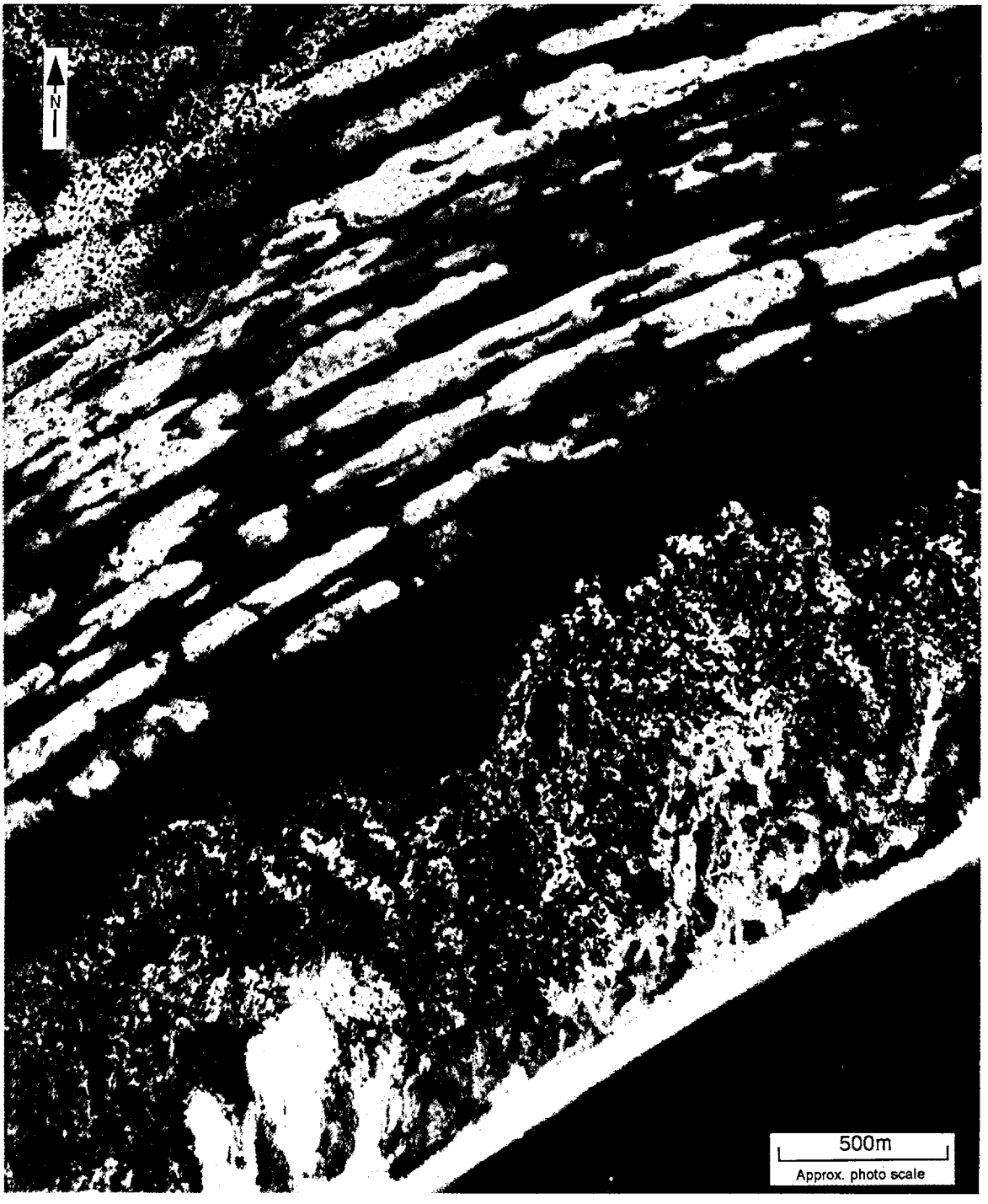

Figure 8-5: **Aerial photograph (taken in 1952) of Inner and Outer Barriers of the Eurunderee embayment highlighting the contrast between parallel, degraded beach ridges and dunes of the Inner Barrier and the vegetated parabolic and active blowout dunes of the Outer Barrier.**

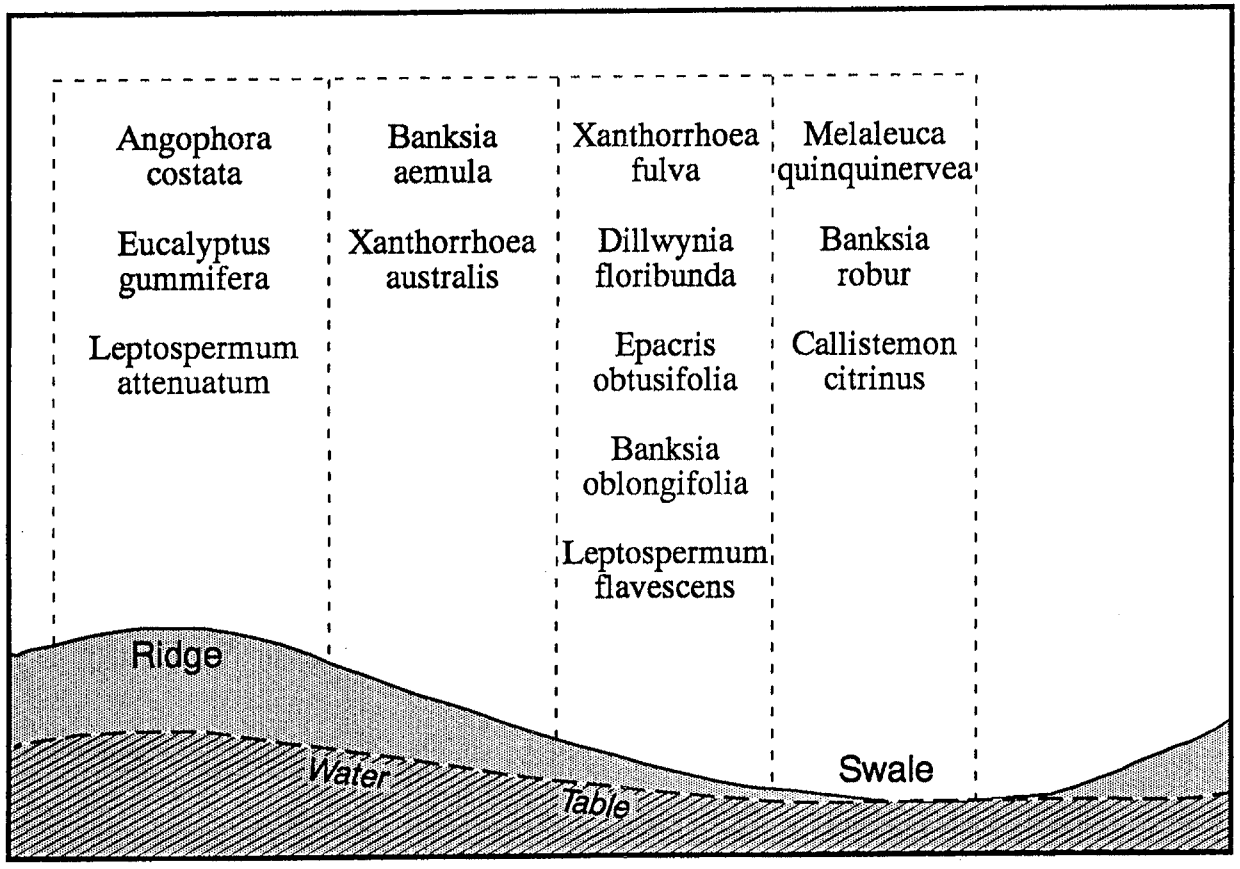

Figure 8-6: **Plant species characteristic of ridge and swale sites of the Eurunderee Outer Barrier (after Carolin, 1969, 1971, and Carolin and Myerscough, 1986). Average difference in relief between ridge crest and swale is 1 to 1.5 m.**

photographs two morphologic patterns are evident (Fig. 8-5). First, there are the crescentic dune forms contiguous with the subdued parabolics behind the Inner Barrier. However, the pattern is not as clearly parabolic north of the Big Gibber. In fact, the ridges have a curved wriggly appearance similar to "banner dunes" described by Price (1958) from the coastal plain of Texas. They are very low in relief. It is possible that they formed as low free-moving sand dunes on a broad backbarrier plain and subsequently degraded with time. They may have been little influenced during their accumulation by sand-binding vegetation.

The second morphologic pattern in the northeast part of the Eurunderee segment is a near-featureless sand plain. Over 3 km in length, this plain merges with Pleistocene lakeshore ridges of Palmers Bay (Fig. 8-1b). The long-walled transgressive ridge of the Seal Rocks segment has buried the eastern part of this plain (Fig. 8-1b). In the absence of drilling and levelling, the plain is tentatively interpreted as a backbarrier flat formed by washover and perhaps deflation processes from both the south (i.e. Eurunderee side) and southeast (i.e. from the Seal Rocks side).

Immediately to the north of, and attached to, Big Gibber, is a ridge of sand whose existence is difficult to explain (see Fig. 8-1a for location). It was originally mapped by Thom (1960, 1965) as part of the Holocene sand mass. Independently, Carolin and Myerscough (1986) on the basis of vegetation type, and the authors after an inspection of exposures in a mining pit concluded that the sand is of Pleistocene age. The ridge is slightly less than 1 km in length and up to 30 m high. The mining excavation showed a deeply leached soil profile. The A2 horizon is 3-4m thick overlying a thick (+4m) B horizon rich in humic colloids and sesquioxides. Although the B horizon is well-developed, it does not possess the heavy induration characteristic of pre-Last Interglacial paleosols. The ridge is relatively rich in heavy minerals and may be a relict foredune or transgressive ridge which was somehow connected or asociated with the "Yagon strandline" (to be discussed in Ch. 9).

8.2.2.2 Inner Barrier beach ridges

A sequence of beach ridges forms the major portion of Eurunderee Inner Barrier (Fig. 8-1b and 8-5). The sequence extends from the vicinity of Bombah Point to the backbarrier plain inland from Big Gibber. The inner part of the series is partly interrupted by a bedrock outcrop which extends southwards from Johnsons Hill.

The ridges are oriented parallel to the present coastline except near their northeastern extremity where the curvature is sharper behind the Big Gibber (Fig. 8-5). The innermost ridge extends across the "limbs" of the parabolic dunes apparently truncating them. There is a drop of 1-3 m from the crest of this ridge to the troughs of the parabolics. This particular ridge divides into two parts. To the southeast it is a broad single ridge vegetated by dry heath forest. In the centre of the embayment it splits into an inner straight ridge 2 km in length containing two and possibly more curved "hooks" to the north, and a gently curved outer ridge which extends towards the Big Gibber. These features are shown in Figure 8-1b. The inner ridge is covered by dry heath forest whilst the outer ridge is an open dry heath cover. The outer ridge closely parallels the remaining set of beach ridges to

seaward. Littoral drift to the northeast may have been important in the establishment and development of the inner beach ridge with the recurved ends.

Figure 8-6 shows characteristic vegetation types and Figure 8-7 shows the relief between ridge and swales to be little more than 1 to 2 m at present. The slight dip of the surface to seaward means that wide surfaces are slightly perched one above the other. This "terraced" effect is not apparent to the observer in the field. There is a distinct gradient across the beach ridge series; the elevation of the innermost ridge averages about +11 m MSL and subsequent ridges to seaward descend to a height of about +3 m MSL where the system abuts the interbarrier swamp. The gradient across the system averages about 1:200 except at the northeastern end where the ridges converge and the gradient is steeper (Fig. 8-7). To the east of Johnsons Hill the ridges are clearly defined, being separated by narrow elongate swamps. The ridges are usually continuous and parallel except towards the eastern extremity of the system where they converge. Although the beach ridges appear to average about 150 m in width, many are composite features; in places, narrower ridges only 30-50 m wide amalgamate to form a single broad ridge. Major swales contain permanently standing water, however, the shallower swales may be dry for much of the year. Up to 2 m of peaty sediment fills some of the swales. The development of transverse surface drainage linking adjacent swales has resulted in the division of beach ridges into rectangular blocks. The connecting channels are rarely as deep as the swales and are probably zones of concentrated surface flow during periods of high watertable and heavy rainfall.

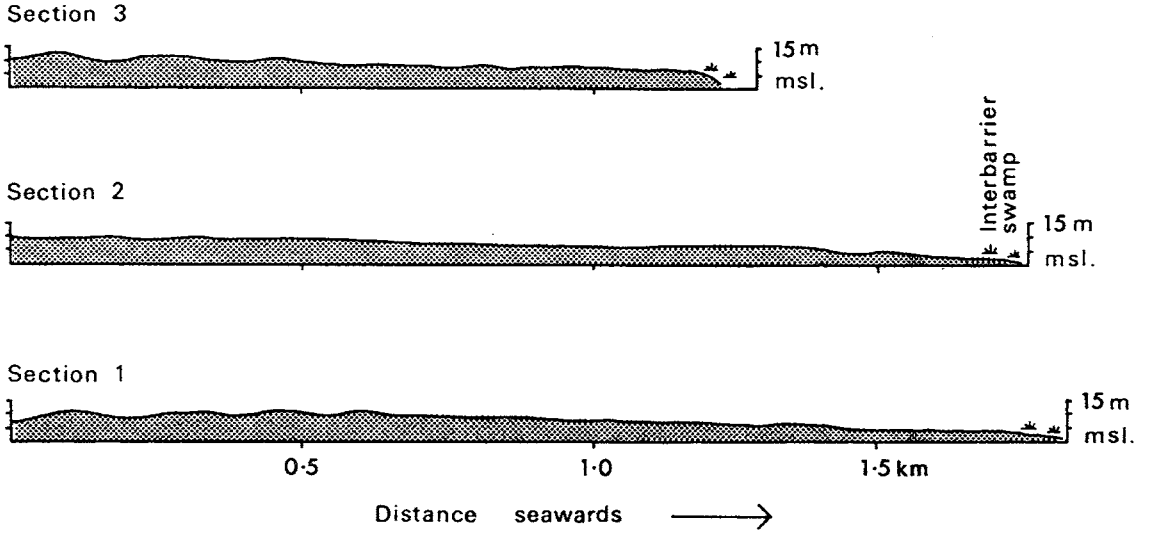

Figure 8-7: Topographic sections across Eurunderee Outer Barrier showing gentle inclination of surface to seaward (see Fig. 8-1a for location of sections).

Figure 8-1b depicts a smaller set of beach ridges to the west of Johnsons Hill; these ridges are of similar altitude (+6 to +9 m MSL) to the main series, but are less clearly defined. Further seaward, the beach-ridge topography has been destroyed by eolian action subsequent to barrier development (see Ch. 7).

The apparently level nature of the beach-ridge plain led Osborn and Robertson (1939, p. 289) to conclude that the surface was the sandy bottom of a former lake bed. However, these "heaths" or "moors", as they are referred to by locals, can be best interpreted by use of air photos, a facility not available to Osborn and Robertson at the time of their Rover Scout Expedition in 1936. Today the parallel ridge and swale topography can be best explained as beach ridges formed on a prograding shoreline of the open ocean (Thom, 1960, 1965).

8.2.3 Interbarrier Swamp

The zone between the Inner Barrier beach ridges and Outer Barrier is occupied by an elongate Cladium swamp at an altitude of +2.5 to +3 m MSL. Swamp mahogany (Eucalyptus robusta) forms a distinctive fringe on the Outer Barrier side of the depression. A small body of open water occurs near the south end of the swamp (Blue or Eurunderee Lake), and is actively being encroached upon by reed swamp from all directions (Fig. 8-1b).

The interbarrier swamp is 8 km in length and averages 400 m in width. It drains southwestwards toward Broadwater Lake. The swamp appears to rise in altitude towards the northeast end of the Inner Barrier where it has encroached over the two outermost beach ridges (Fig. 8-5).

8.2.4 Outer Barrier

One of the fascinating aspects of the geomorphology of the Port Stephens-Myall Lakes region is the diversity of landform types within the framework of the basic repetition of two barrier structures. The Outer Barrier of Eurunderee lacks the distinctive marine-eolian topography of Fens, but possesses instead a set of parabolic dunes and blowouts (Fig. 8-1b). Collectively these dunes comprise an elongate bay barrier linking the foredune ridge of the Broadwater embayment with the Big Gibber (Fig. 2-1). As will be shown in Chapter 9, the Big Gibber headland separates what is clearly Outer Barrier of Eurunderee from a high transgressive dune complex of the Seal Rocks segment which has buried most of the Pleistocene surface to landward.

8.2.4.1 Outer Barrier parabolic dunes

The Outer Barrier of Eurunderee is 10 km long and 1.5 km wide. No beach ridges or backbarrier flats are evident in the Outer Barrier. Figure 8-1b shows an array of parabolic dunes developed side by side and "nested" within each other. These dunes are well vegetated by a dry sclerophyll forest dominated by Eucalyptus pilularis, Angophora costata, and Banksia serrata. In many cases, the troughs of vegetated parabolics and bottoms of steep "ravines" separating the lateral walls of adjacent parabolics, are colonized by a swamp forest consisting of Melaleuca quinquenervia and E. robusta.

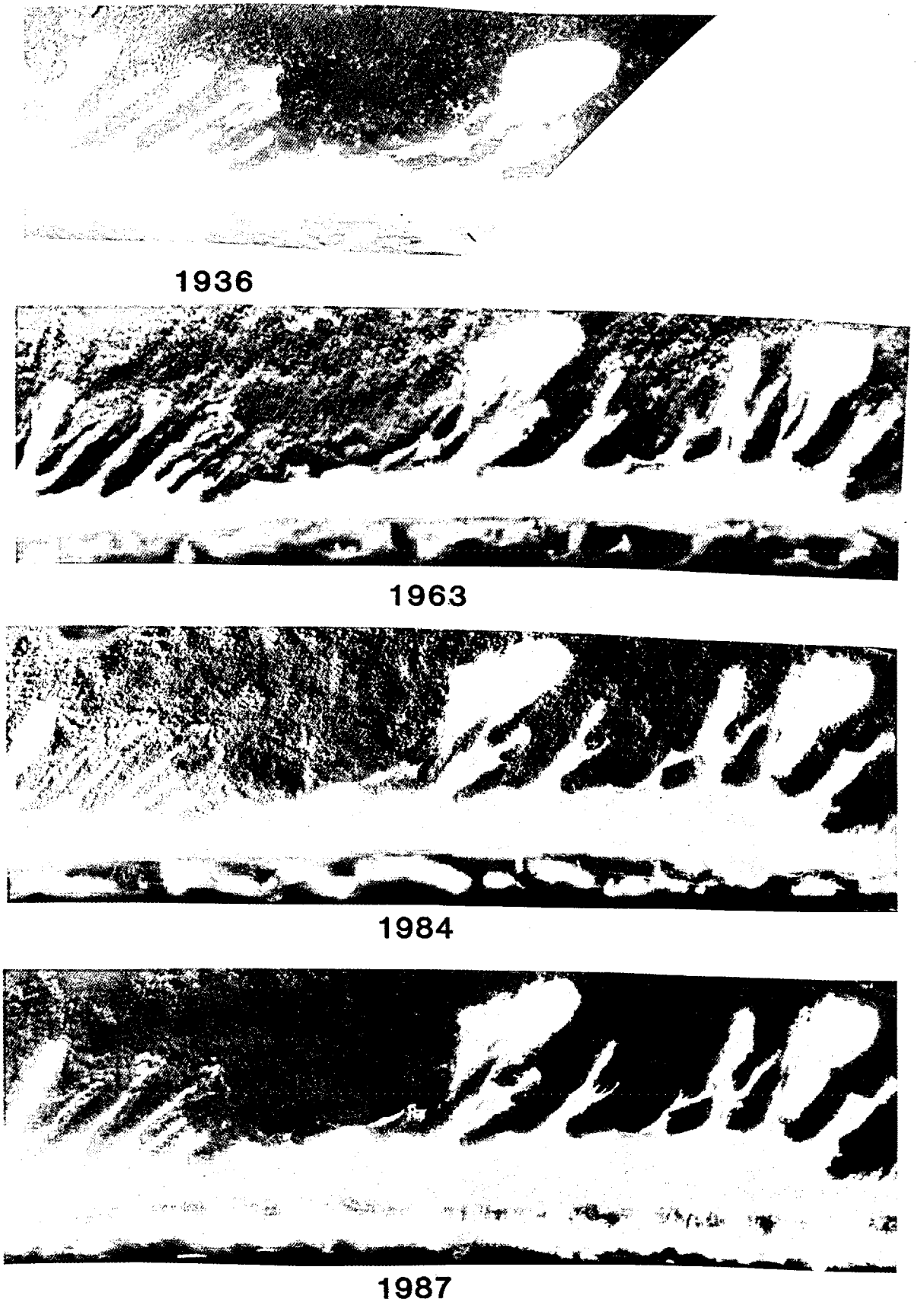

Figure 8-8: **Vertical air photographs of the southern portion of the Eurunderee Outer Barrier showing active blowouts and parabolics advancing into a vegetated set of parabolic dunes.**

Dune relief is quite variable. Lateral arms and terminal walls may attain elevations close to 40 m. Part of the area has been mined (1971-1976) by Mineral Deposits Ltd. Detailed contour maps were prepared for mining operations. Figure 8-9 is an example of a portion of the parabolic dune complex.

Individual parabolics vary in length, height of terminal walls and lateral arms, and the degree to which the form has been preserved from later eolian reworking or burial. However, three aspects of the parabolics are consistent: (i) they all open towards the ocean; (ii) they are not "blown-through", but occur as spoon-shaped lobes with high terminal walls; and (iii) they are aligned approximately north-south (182 $\pm$ 2 degrees). The largest individual parabolics occur towards the eastern end of the embayment (Fig. 8-1b). Here lateral arms are up to 1 km in length. In the southwest part of the embayment the lateral walls lose much of their identity as nesting of smaller parabolics within older features is more common. In fact, two sets of vegetated dunes can be recognized in central and southern parts of the embayment.

Soil profile studies confirm relative age differences between nested sets of parabolics. Innermost dunes form well-drained forested sites which show well-differentiated podzol profiles with A_2 horizons. Parabolics to seaward have A horizons less than 1 m thick, overlying a poorly defined B horizon (Type 6 soil, Appendix A).

8.2.4.2 Blowouts and foredunes

The seaward portion of the Eurunderee Outer Barrier is composed of a high, discontinuous foredune ridge. Locally exceeding 20 m in height, this ridge is vegetated by a typical foredune flora of woody shrubs, trees and grasses. The sheared nature of the vegetation attests to exposure to high onshore wind velocities.

The foredune is not straight. Its indented outline corresponds to the troughs of many stabilized parabolics. In many places the established foredune is cliffed. Here poorly vegetated surfaces are exposed to wind erosion. A buried soil within the cliff section attests to periodic instability during construction. This soil is similar in profile morphology to that observed in blowouts and mobile dune sheets at Newcastle Bight, north Fens, Broadwater and Seal Rocks (see Ch. 10).

A carpet of Spinifex covers a hummocky incipient foredune up to 5 m above present sea-level in front of the established foredune. This surface is also discontinuous, being partly destroyed by waves during south to east storms.

Well-developed blowouts within the Outer Barrier cut through the high established foredune, and are locally contiguous with the modern beach where the incipient foredune has been breached. Two types of blowouts are evident on the photographs (Fig. 8-8). One is club-shaped with a narrow throat, widening and rising inland to a broad terminal wall of transgressive sand. The second type is elongate and narrow (to 200 m wide) sometimes branching into "fingers" or tongues of sand at the downwind end. Both types are not clearly represented in the stabilized parabolic dune state where the lateral walls are generally quite parallel and the terminal wall V-shaped or rounded. Trough blowouts in some cases

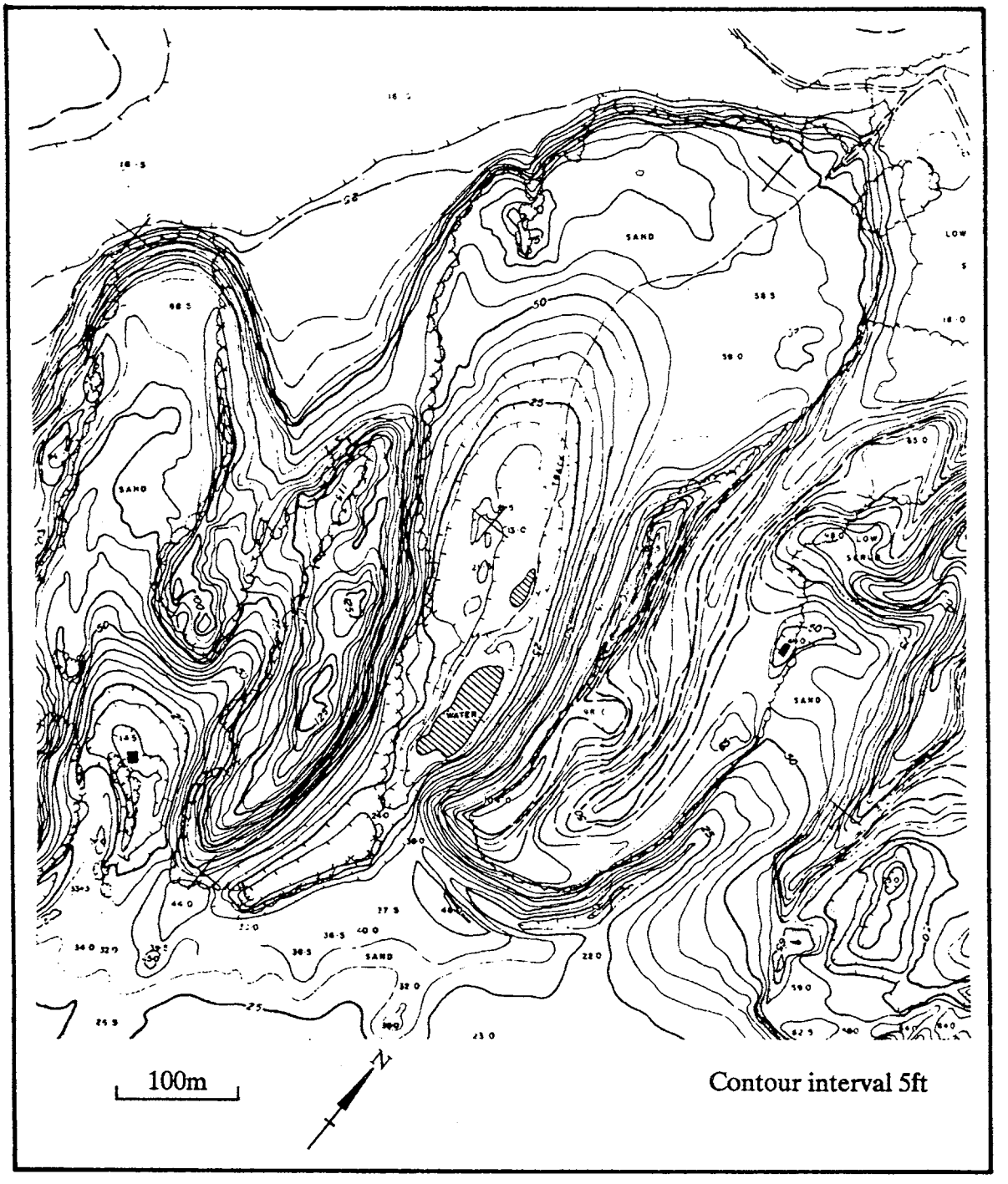

Figure 8-9: **Contour map of the central portion of the Outer Barrier parabolic dune field at Eurunderee (contour map was supplied by Mineral Deposits Ltd).**

are advancing across lateral walls of the stabilized parabolics, especially near Big Gibber (Fig. 8-1b). Here the axial direction of the blowouts is 192 ± 4 degrees, whereas the parabolics trend almost north-south. To the southwest of the embayment blowout orientation is more meridional coinciding with the parabolics (185 ± 3 degrees).

Figure 8-10 is a view up a blowout from the foredune. The most active portion today is the windward facing slope of the terminal end. The west-facing wall exposed to winter westerly and south-easterly winds is less vegetated than the east-facing side. Frequently, deflation troughs are wet and vegetated by Scirpus nodusa, Hydrocotyle and Spinifex hirsutus. In many cases colonization of the trough plus the active growth of the incipient foredune inhibits the supply of sand from the south. Lateral expansion of the "throat" area by wind erosion of unstable walls of the cut foredune is a ready source of sand for the blowout. Nevertheless, it is possible that the blowouts are being colonized by plants at a rate faster than their active sand surface is expanding.

Commander Sidney recorded "remarkable sand hills" as a landmark from the Eurunderee Outer Barrier on his 1865 chart. Aerial photographs taken in 1936 when compared with prints in 1963, 1984 and more recently show little change in the general configuration and area of mobile sand (Fig.8-8). There are some areas of extension and some areas of revegetation. Areas of revegetation since 1936 include the southern set of blowouts shown in Figure 8-8. The blowouts are probably features which pre-date European occupance, and in such a remote area, European activities prior to mining have had little apparent impact on the stability of these dunes.

8.2.4.3 Modern beach

The steady increase in grain size of sands composing the modern beach from Fens to Eurunderee has already been noted (Fig. 3-4). Carbonate content decreases in the sands towards Big Gibber, but it is common to find swash concentrations of large bivalves (e.g. Glycmeris sp.) and other species on the berm.

Given the exposed nature of the beach to southerly storm and swell waves and the coarse grain size, it is not surprising to find steep beachface slopes in Eurunderee (Shepherd, 1970, Fig. 3-2). Typically, this beach possesses a distinctive rhythmic nearshore bar morphology and as a result the beachface is strongly indented (Fig. 8-5; see also Wright et al., 1979; Short and Hesp, 1982). It is possible to associate sites where foredunes are eroded and semi-permanent beachface indentations; such an association is considered to be of genetic significance in the development of parabolic dunes on high energy coasts (see Short and Hesp, 1982).

8.3 STRATIGRAPHICAL CHARACTERISTICS

8.3.1 Bedrock Configuration

The Carboniferous strike ridges, which so clearly delineate the northern and eastern boundary of the Eurunderee segment, dip to the



Figure 8-10: View into an active blowout in the Eurunderee embayment.

southwest beneath Quaternary embayment fill. No drill holes penetrate this fill to bedrock, and no seismic profiles are available to delineate the buried bedrock surface. Drilling by H.D.W.B., various mining companies and A.N.U. either bottomed in a heavy clay, or stopped within the sand deposit. As shown in the generalized section for the embayment (Fig. 8-11) the basal clay surface dips gently to the south. There is no evidence that this surface, at least in the centre of the Eurunderee embayment, has been dissected by river flow during a period of low sea-level.

8.3.2 Stratigraphic Units and Sediment Properties

8.3.2.1 Holocene deposits

As in other embayments, quartz sand is the most abundant mineral in Holocene deposits with minor (less 5 percent) amounts of other constituents, including economic proportions of rutile and zircon. Mineral Deposits Ltd. mined Outer Barrier eolian sands over the period 1971-76. Shell carbonate is restricted to contemporary beach and nearshore shelly sand facies. However, a relict beach (?) sand occurs beneath the high foredune (see 8.3.3). Organic accumulations have developed in the interbarrier depression, in swales of Inner Barrier beach ridges and dunes, as well as within and bordering the Myall Lake.

Eolian processes have dominated sedimentation above sea-level during the Holocene. The Outer Barrier is clearly composed of wind-deposited landforms. Exposures observed at the time of mining revealed massive accumulations of steeply dipping sand. Bedding properties were not

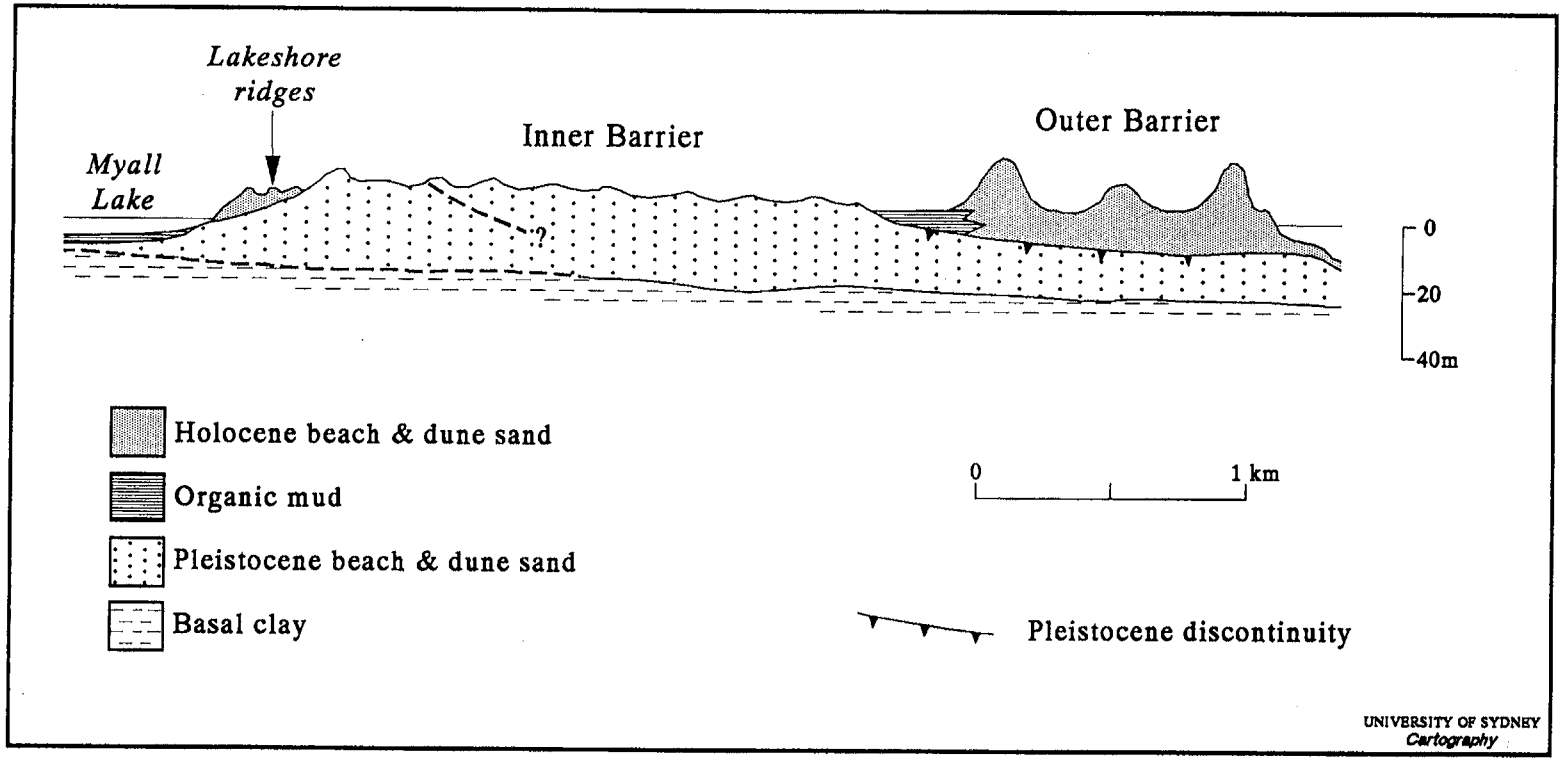

Figure 8-11: Generalized stratigraphic section of the Eurunderee Inner and Outer barriers (see Fig. 8-1a for location of drill holes).

studied in detail, but typical cross-bedding associated with migrating transgressive sand lobes was observed. Grain-size characteristics of Outer Barrier sands have also not been studied in any detail. Well sorted, medium to fine sands characterize the dune environment (see Section 8.3.3). Beach and incipient foredune sands are noticeably coarser.

Organic accumulations consist of either fibrous peat or gyttja. The interbarrier depression contains both materials. Swale peats of the Inner Barrier are more woody; lakeshore organics are quite fibrous in character. Organics on the bed of the Myall Lake form gyttja, the soft oozy character of which is quite distinctive. Loss on ignition from sediments collected on the lake bed is close to 100 percent.

8.3.2.2 Pleistocene deposits

The Inner Barrier has not been extensively drilled by us. However, our one hole through the Inner Barrier (A.N.U. drill hole 58; see Fig. 8-1a for location of drill holes), and several of our holes in the Outer Barrier, bottomed on basal clay. All of the old H.D.W.B. holes terminated in this clay. Only the upper 2-3 m has been drilled into and sampled. The basal clay is typically dark grey, compact, with less than 5 percent sand. Fine organic fragments may be present. A black, organic rich clay was observed at the base of A.N.U. drill hole 55. Nowhere was oxidized clay encountered.

Pleistocene sediments above the basal clay are mostly quartzose sands locally enriched in heavy minerals (to 3 percent). Shepherd (1970) has investigated the size characteristics of surface samples from the Eurunderee Inner Barrier. A distinctive bimodal character of the grain size distribution is apparent in many samples. The major mode is medium sand (phi mean 1.5 to 2.1), but a lesser mode (1 to 2 percent) is composed dominantly of silt (<4.0 phi). Size analysis by means of the hydrometer method of the silt and clay fraction taken from ridge samples of the Eurunderee Inner Barrier showed 62 percent to be within the range .06 to .02 mm (4 to 5 phi), 32 percent between 0.02 and .002 mm (5 to 9 phi), and 5 percent less than .002 mm. The silt fraction mainly consists of angular to subrounded quartz, plus small amounts of green tourmaline, zircon and rutile.

In the five locations where drilling to depths of 2 m was possible, the highest percentages of silt and clay material occurred at depths of c. 1 m, with lower values above and below this depth. There was no apparent relation to water table position. It is possible that much of the fine sediment was introduced at the surface and illuviated. The silt to clay size of the quartz fraction suggests it was not derived from in situ weathering of less stable minerals. The subrounded character of many grains supports the possibility of an eolian origin, but the question is from where? Assuming the fine material post-dates the development of Inner Barrier beach ridges (similar fine fractions do not occur on Outer Barriers), there are three possible sources: (i) local alluvial materials deposited by rivers such as the Upper Myall graded to lower sea-levels; (ii) a seaward source, possibly exposed tidal flat, transported by east to south winds during low sea-level periods; and (iii) a distant source to the west from inland Australia with the material being deposited from dust en route to the sea. The third

alternative is favoured in part because westerly winds are now known to be stronger and more effective transporting agents during full glacial conditions than now (Bowler, 1976), and fine terrigenous sediment including silt-size quartz has been noted in Tasman Sea cores and related to an Australian eolian source (Thiede, 1979). The minor heavy mineral component is most likely derived from the finest grains deposited by wave action during barrier formation.

On the Eurunderee Inner Barrier, as with Fens and Upper Myall, there is a definite tendency for sand to become finer in a seaward direction. Trends for the surface samples at the three Eurunderee sections are depicted in Figure 8-12a. The phi mean values using Inman's statistic in this case was calculated with the fine mode included (Shepherd, 1970, p. 178). All samples used for comparison were taken from 0.4 to 0.8 m beneath ridge crests. The seaward decrease in mean grain size is consistent with trends on the Fens Outer Barrier (Ch. 6) and at Seven Mile Beach (Wright, 1970).

Longitudinal differences in barrier sediment size were examined by correlating the mean diameter of samples collected at one mile intervals from the innermost Eurunderee ridge with distance from south to north. Without exception a northward decrease in size was noted (Fig. 8-12b). Shepherd (1970) suggests that this correlation may apply to the barrier as a whole.

In A.N.U. drill hole 58, which extends from the Pleistocene beach-ridge surface to the basal clay, the typical fine-coarse-fining downwards trend in grain size was observed. This trend is well documented in Newcastle Bight (Chs. 3 and 4), and is associated with changing environments of deposition: eolian cap on top, beach, inner nearshore,

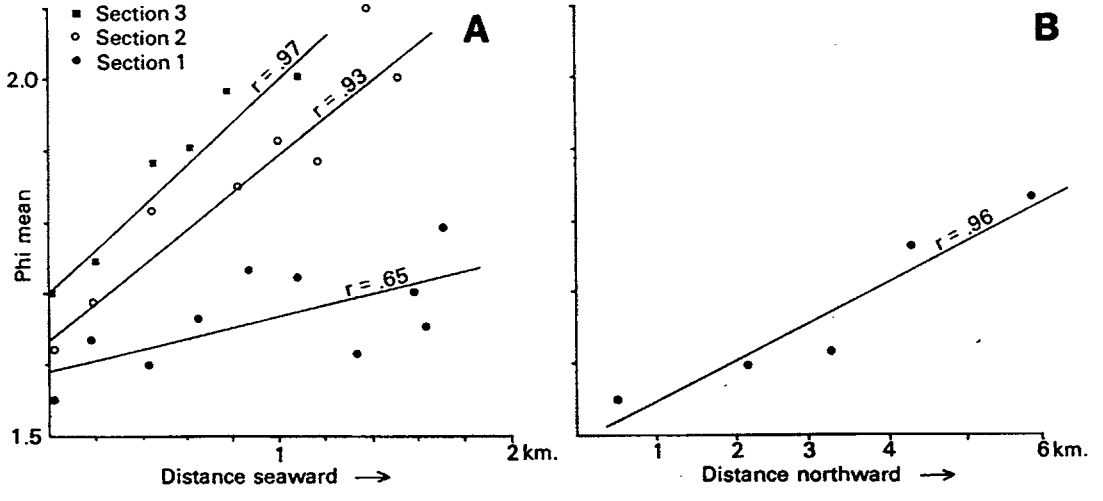

Figure 8-12: Grain size trends on the Inner Barrier at Eurunderee (after Shepherd, 1970): (a) transverse trends involving three sections 1, 2, 3 (see Fig. 8-7); and (b) longitudinal trend for inner-most ridge.

outer nearshore. A coarse transgressive sand facies was not observed at Eurunderee overlying the basal clay.

8.3.3 Stratigraphic Pattern and Depositional Sequence (Figs. 8-11, 13)

The stratigraphy of the Eurunderee segment is depicted in a generalized section in Figure 8-11. Although many hundreds of holes have been drilled by mining companies on both Inner and Outer Barriers in this embayment, they are rarely deep enough or are logged in sufficient detail to show whether the surficial sands are of a certain minimum thickness, if they are indurated, and to give the heavy mineral content (usually confidential information).

The deeper holes by the H.D.W.B. were mostly drilled in 1942, and provide more information on the thickness of humate-impregnated sand and depth to basal clay. Only the few A.N.U. holes provide data on lithology, granulometry, fauna (if any) and organic constituents. Observations were made on the walls of water-filled dredge pits excavated in the Outer Barrier between 1971-1976; however, it was not possible to visit the area regularly during this period so that a thorough description of internal properties of mined dunes cannot be made.

The pattern shown in Figure 8-11 is of a basal clay of unknown thickness gently dipping seawards and overlain by Inner Barrier sand. It is not possible to distinguish the extent of various sedimentary facies in the Inner Barrier. However, it is clear that finer grained sands grade upwards into coarser sands. In the absence of deep drilling north of the innermost ridge the facies relationship between dunes, backbarrier Pleistocene lake ridges (and swamps), and open-ocean beach ridges is unknown. The dashed lines in Figure 8-11 represent speculations on facies relationships behind the Inner Barrier. The basic assumption is that the sand flat on which the parabolic and "banner" dunes have formed represents a washover accumulation formed during and at the termination of the marine transgression which preceded the growth of Inner Barrier beach ridges.

The development of humate within Inner Barrier sands is most marked in this embayment. In Figure 8-13, a more detailed section is presented. It shows humate +10 m thick at A.N.U. drill hole 58 extending below sea-level. In some localities the humate is quite hard with 2-3 percent humic colloid content diminishing with depth. Where the Inner Barrier surface underlies Outer Barrier sand, the extent to which the humate-impregnated surface has been reworked is uncertain.

What is so different about Eurunderee in comparison with Fens and Newcastle Bight is the shallowness of the Pleistocene surface beneath the modern beach. Outer Barrier sands extend to no more than 8 m below MSL, compared with up to 40 m at Newcastle Bight and 30 m at Fens. The Outer Barrier sand mass forms a thin wedge widening seaward over this gently dipping Inner Barrier surface (1:200, Fig. 8-13).

The Outer Barrier section as drawn in Figure 8-13 shows 3 relict eolian time units (I to III) and one modern unit (IV). The oldest unit (I) is defined by a radiocarbon date on buried fibrous roots (7280 $\pm$ 220 ^{14}C yrs BP, SUA-252). This unit occurs just below MSL and appears to have been eroded by wave action on the seaward margin during the period

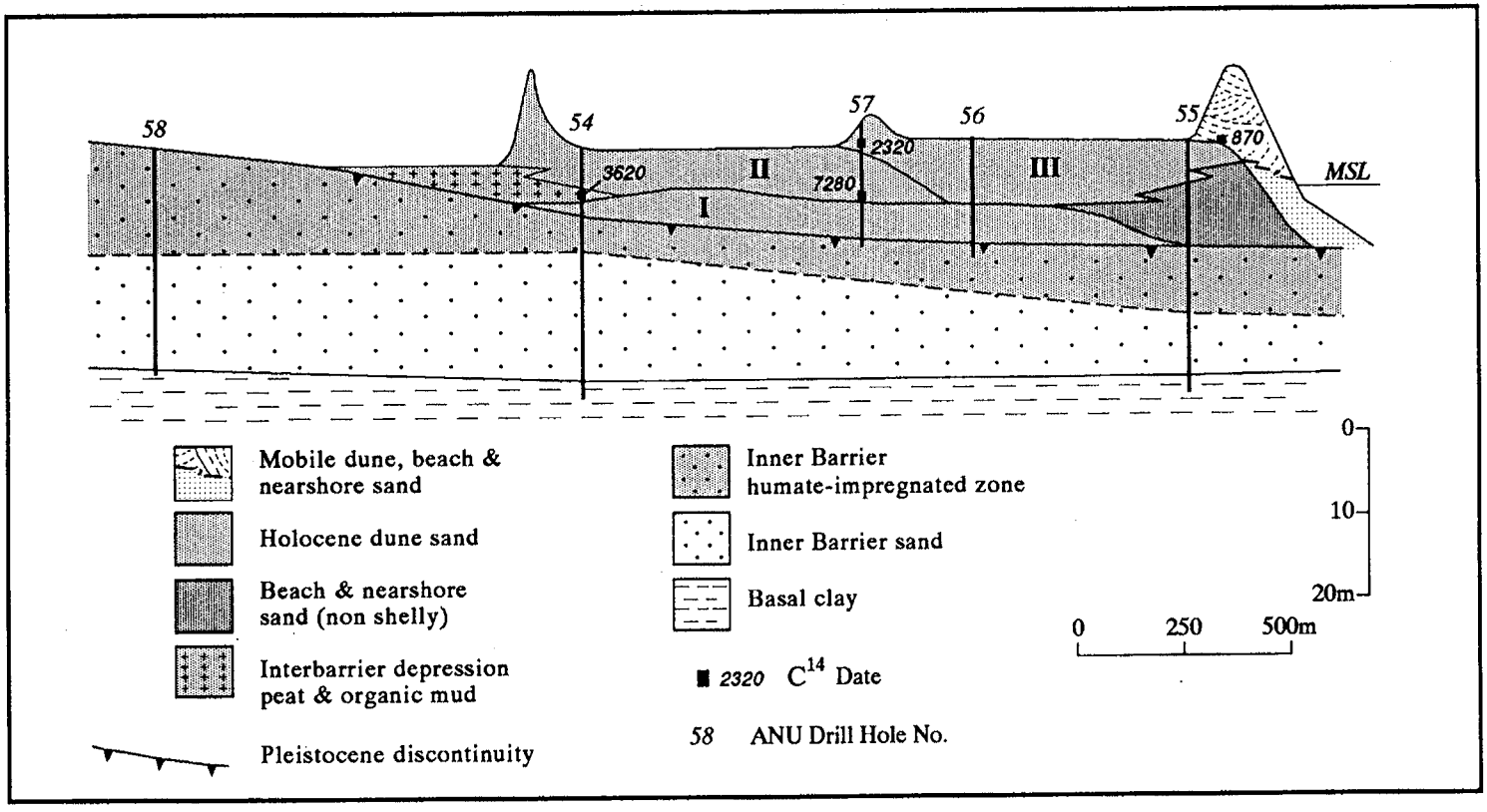

Figure 8-13: Stratigraphic section for the central portion of Eurunderee Outer Barrier.

that sea level has been at its present position. Although not precisely defined by drilling a sharp contact is postulated between unit I and a coarse non-shelly sand (beach?) which underlies the youngest stabilized dune unit (III) (see Fig. 8-13). Dune units II and III are manifested at their landward ends by pronounced terminal walls of parabolic ridges. Unit II the most landward, overlies peats of the interbarrier depression (3620 ± 130 ^{14}C yrs BP, ANU-1673). Unit III buries the charcoal-rich soil, and thus must be younger than 2320 ± 110 ^{14}C yrs BP (SUA-251). The youngest dune sand unit in the sequence (IV) includes the modern blowout and foredune complex. One of us (P.H.) has obtained a date of 870 ± 65 (SUA-1056) on a Banksia stump found in situ in a buried soil profile on the erosion face of a large blowout lobe (see Fig. 8-1a for location). There is only one clear buried soil horizon in this blowout-foredune complex. However, analysis of this soil horizon indicates an older rather than younger Holocene age for this surface. Thus the stump date provides the age at which the modern blowout migrated over a Banksia thicket growing at this location. The modern erosional phase was probably initiated 1000 or less years ago, perhaps slightly earlier than the similar dated phase in Newcastle Bight and Broadwater.

Relationships shown in Figure 8-13 are presented here as a morphostratigraphic model requiring confirmation. The model implies initiation of each phase of transgressive (parabolic) dune development behind an eroding shore line (Fig. 8-14). Differences in soil development between vegetated surfaces of units II and III, and the morphological "nesting" shown in Figures 8-1b and 8-13, provide evidence for separate "major" episodes of eolian development. However, the few radiocarbon dates on transgressed surfaces are inadequate in any attempt to relate these episodes to any model of mid to late Holocene environmental change (Thom, 1978).

In summary, the depositional history of the Eurunderee embayment is as follows (see Fig. 8-14):

1. Estuarine clay deposition prior to the Last Interglacial (Q1Em); the uppermost unit of the basal clay probably formed during the transgression to the Last Interglacial high sea-level and was buried by marine sand invading the embayment for the first time (Q2E).

2. Backbarrier sands accumulated at the rear of the embayment during the transgression (Q2Mbb), and as sea-level approached its high level (+5 m above MSL) the surface of the backbarrier deposits was partially reworked into parabolic and "banner" dunes (Q2Met).

3. Inner Barrier beach ridges and lake shore ridges (and perhaps rock platforms) were initiated after sea-level reached close to its maximum level in the Last Interglacial. Progradation continued as sea level fell extending the Inner Barrier shoreline beneath MSL (Q2Mer).

4. During the Last Glacial low sea-level period (Q3) the western end of the Eurunderee Inner Barrier was reworked into a large parabolic dune complex by westerly winds (see Ch. 7). Elsewhere the surface remained vegetated and humate was precipitated at the water table. It is possible that "loess"-like sediments were added to the Inner Barrier surface during this period from dust travelling from west to east.

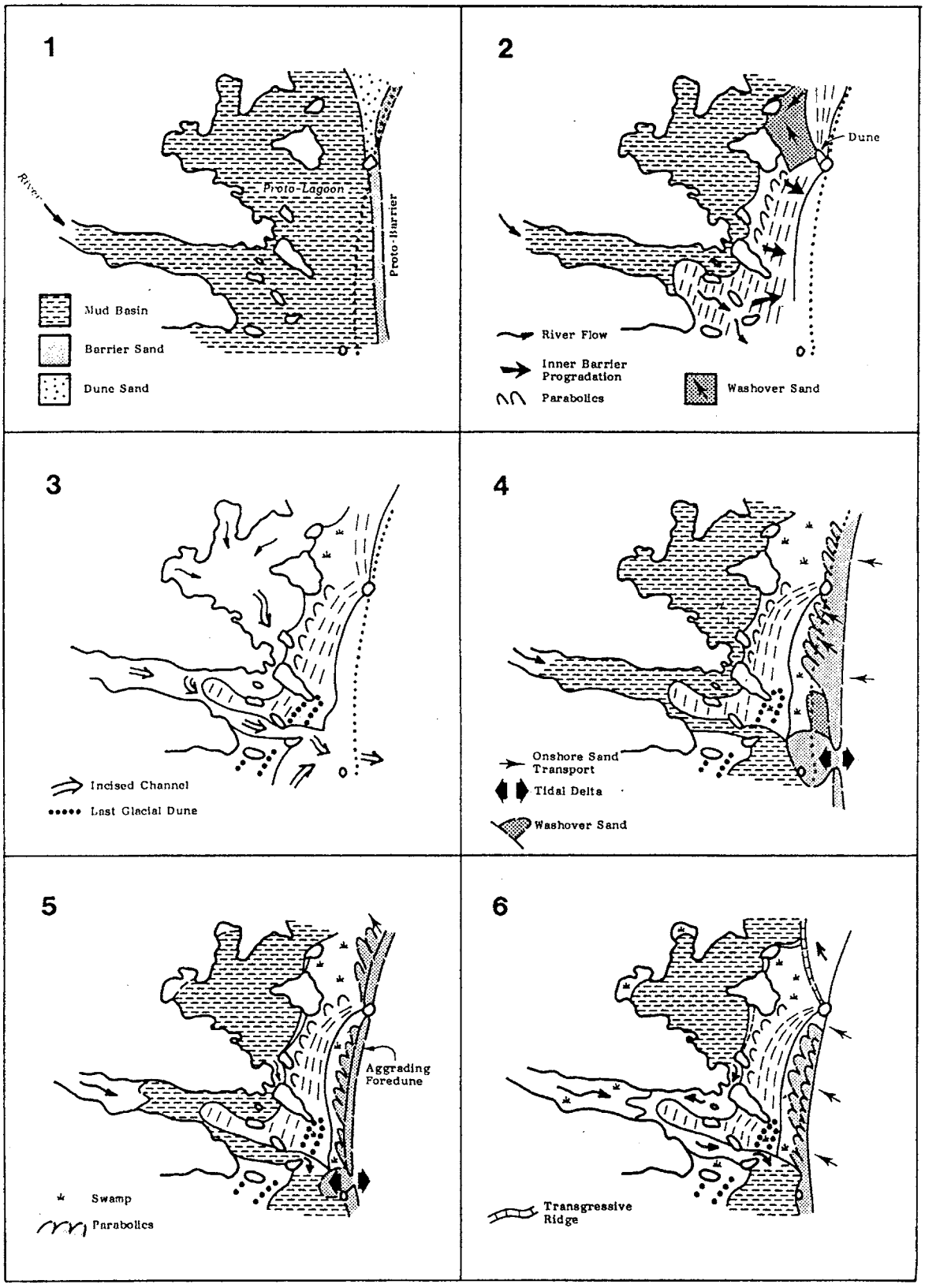

Figure 8-14: **Six state model of the geomorphic history of the Eurunderee embayment (the stage numbers refer to time periods discussed in Chapter 10).**

5. During the Postglacial Marine Transgression parabolic dunes were initiated along the receding open-ocean strandline. Phase I of Outer Barrier transgressive dunes formed just prior to sea-level reaching its present position blocking off an interbarrier depression (Q4Met).

6. During the Holocene "stillstand" it is postulated that there have been at least three distinct phases of eolian transgression. Two of these parabolic dune sets have been stabilized (II and III). Phase IV represents modern blowouts and foredune features which are being reworked by eolian and to a lesser extent marine processes (Q6Met). However, the degree of instability appears to have declined in recent decades suggesting that Phase IV was initiated prior to European settlement and is currently undergoing stabilization.

9

Seal Rocks

9.1 REGIONAL SETTING

9.1.1 Bedrock Properties

The coastline extends to the ENE from the Eurunderee embayment, a slight eastwards deviation from the general NE-SW alignment between Hawks Nest and Sugarloaf Point (Fig. 1-1). Sand deposits link bedrock outcrops forming the Seal Rocks segment of the study region. This segment is bounded on the southwest by the Big Gibber headland, on the northeast by Sugarloaf Point, on the north by Smiths Lake, and on the west by Bridge Hill and Myall Lake (Fig. 9-1a). The configuration of depositional landforms in the Seal Rocks segment is to a large extent controlled by the distribution of relatively small, detached bedrock ridges.

The bedrock is entirely composed of lower Carboniferous strata, the Wootton Beds (Engel, 1962). In the region between Smiths Lake and Bungwahl these sedimentary rocks consist of black, indurated mudstones interbedded with coarse, medium and fine grain lithic arenites (ibid, p. 201). Locally, coarse dacitic conglomerates occur, for instance immediately west of Bungwahl. Structurally, the beds dip steeply west at 40 to 60 degrees and appear to be part of a faulted limb of the Bungwahl Anticline which strikes NW-SE. The steeply dipping, indurated beds have been eroded by waves to form irregular cliffs cut by caves and tunnels (e.g. near Sugarloaf Point Lighthouse).

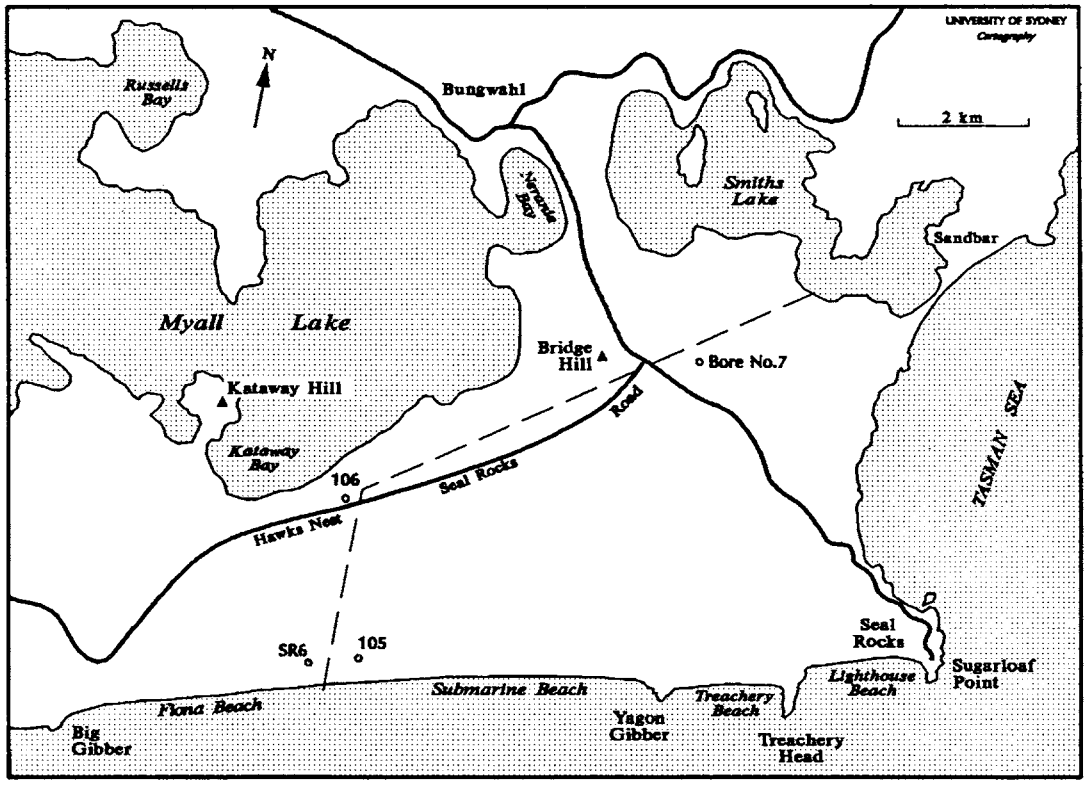

Figure 9-1a: Location map of Seal Rocks segment of the study area from Big Gibber to Smiths Lake.

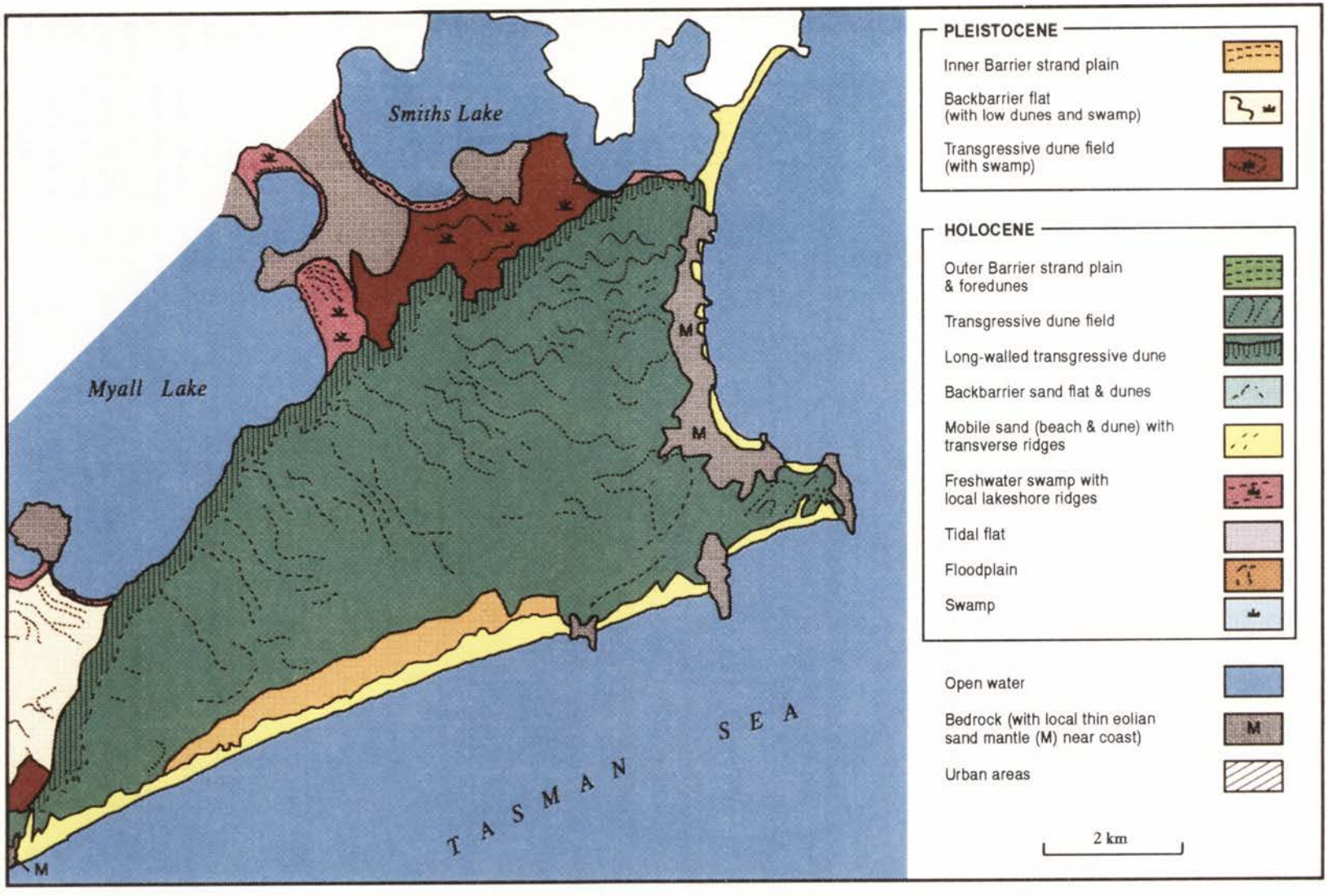

Figure 9-1b: Generalized morphological map of the Seal Rocks area showing the dominance of dune topographies.

Although rock outcrops form a small proportion of the total area of the segment, their occurrence as strike ridges trending NNW-SSE in the eastern part of the segment has given rise to the development of natural "groynes" (e.g. Treachery Head). These ridges extend below present sea-level and thus may have functioned as sediment traps during low sea-level stages of the Quaternary. This is particularly likely to be the case for the ridge which extends seawards of Sugarloaf Point and includes the Seal Rocks (Fig. 9-1a). Drilling near Bridge Hill reveals the extension of the bedrock ridge below sea-level towards Treachery Head. Except for occasional outcrops and the rocky coast north of Sugarloaf Point, the bedrock surface lies beneath a sand cover (see 9.3.1).

9.1.2 Dynamic Environment

Specific data on wave and wind regimes derived from recording systems are lacking for the Seal Rocks segment. However, rainfall data have been collected at the Sugarloaf Point Lighthouse. Temperature-precipitation information has already been discussed (Ch. 1). Inspite of variable rainfall from year to year (Fig. 1-3), conditions appear favourable for the growth of dune vegetation. It is estimated that at least 35 percent (or 445 mm) of the average annual rainfall for Seal Rocks is available for groundwater recharge (Mineral Deposits Ltd., 1973; see also Fox, 1981). For the period 1923 to 1972 the extreme range in annual rainfall was from 723 mm (28.41") in 1965 to 2135 mm (84.20") in 1963. Heaviest rainfalls for periods lasting a day or more are associated with strong onshore winds from the south or southeast generated by cyclonic depressions in the Tasman Sea (see Ch. 1).

The easterly trend of the "embayment" at Seal Rocks creates a condition of maximum shoreline exposure to the force of southerly winds and waves. Assuming that Nobbys Lighthouse (Newcastle) data are appropriate to the Seal Rocks segment, the occurrence of effective southerly winds is related to the relative dominance of westerly compared to easterly circulation patterns in winter (Ch. 1). In those years when deep depressions frequently develop in the Tasman Sea region (e.g. 1974), strong south to east winds (in excess of 30 knots) are maintained for several days. These winds are responsible for not only inland eolian sediment transport, but also wave erosion of exposed beach and foredune areas under extreme conditions of wave energy dissipation (Thom, 1974; Chapman et al., 1982). It is apparent from the depositional morphology, to be discussed below, that during Holocene times this embayment has been subjected to considerable eolian reworking of sand derived for the most part from an exposed south-facing shoreline. Furthermore, wave approach from south or southwest directions, particularly at lower sea-levels, appears to have transported sediment into the embayment, the rocky headlands at these lower levels serving as sediment traps (Roy and Thom, 1981). It is this interaction of bedrock configuration providing the potential to trap sediment moving alongshore, and exposure to winds and waves from the southerly quadrant, which has resulted in the distinctive morphostratigraphy of the Seal Rocks segment.

9.2 MORPHOLOGICAL CHARACTERISTICS

9.2.1 Major Morphological Features

The Seal Rocks segment is somewhat comparable in its morphology with

the Tomaree Hills area (Ch. 5). The landscape is dominated by eolian landforms, but unlike Tomaree the dunes have not been markedly deformed or re-oriented by the occurrence of bedrock outcrops. On the contrary, the dunes at Seal Rocks tend to obliterate underlying terrain.

The depositional complex which defines the Seal Rocks segment is roughly triangular in shape, mimicing in miniature the shape of the dune barrier islands of southern Queensland (Hails, 1964; Bird, 1973). The ENE-WSW coastal side of the triangle is 14 km in length. It stretches from the Big Gibber in the west, a low headland separating Eurunderee from Seal Rocks "embayments", to Sugarloaf Point. This coastal stretch can be divided into three beaches. The longest is Fiona Beach between the Big Gibber and Yagon Head (Fig. 9-1a). Yagon Head, Treachery Head, and Sugarloaf Point are steepsided, elongate Carboniferous outcrops which contain two relatively small beaches (Treachery and Lighthouse) backed by high stabilized dunes.

The short north-south side of the triangle extends for 6 km between Sugarloaf Point and Sandbar at Smiths Lake. Rocky cliffs up to 50 m high dominate this stretch with narrow pocket beaches confined between the cliff face and the sea (Fig. 9-1b). Sand dunes mantle the cliff top. Well-developed rock platforms occur at the base of these cliffs.

Smiths Lake and the Big Gibber are connected by a southwest to northeast trending sand ridge which extends uninterrupted for 15 km. Known as the Bridge Hill sand ridge, this eolian structure could be regarded as one of the most striking vegetated dune landforms in the world. Rising 110 m above sea-level, its steep vegetated slopes overlook Smiths Lake and adjacent swamps to the north and Myall Lake to the northwest. The highest point of the ridge occurs where it crosses older dunes mantling the Bungwahl bedrock ridge at Bridge Hill. At its northeast end the ridge merges with sand deposits which cover the bedrock cliffs. To the southwest, the ridge is attached to older Pleistocene dunes which occur in the lee of the Big Gibber. Figure 9-2 is a perspective drawing which shows how the ridge encloses a vast vegetated sand plain composed of asymmetric dunes, parabolics and irregular dune hills.

There are six major depositional features in the Seal Rocks segment: "old" dunes and adjacent swamps, Bridge Hill sand ridge, Treachery Head parabola, Seal Rocks sand plain, Fiona Beach swamp plain, and modern beach and foredune areas (Fig. 9-1b).

9.2.2 "Old" Dunes

As shown in Figure 9-1b, the surface expression of what are referred to as "old" dunes in this segment is quite limited. Besides the small area discussed in Chapter 8 near the Big Gibber, the only occurrences of these dunes are between Smiths Lake and Bridge Hill and a small locality on Sugarloaf Point where the "old" dune surface mantles the Carboniferous ridge and lacks distinctive morphology. South of Smiths Lake "old" dunes form a parabolic ridge open to the west. The eastern end of the ridge, or terminal wall, rises up to 20 m above lake level and has been locally eroded by wave action on the lake. The surface relief is otherwise subdued and vegetated by a *Eucalyptus-Angophora* woodland.

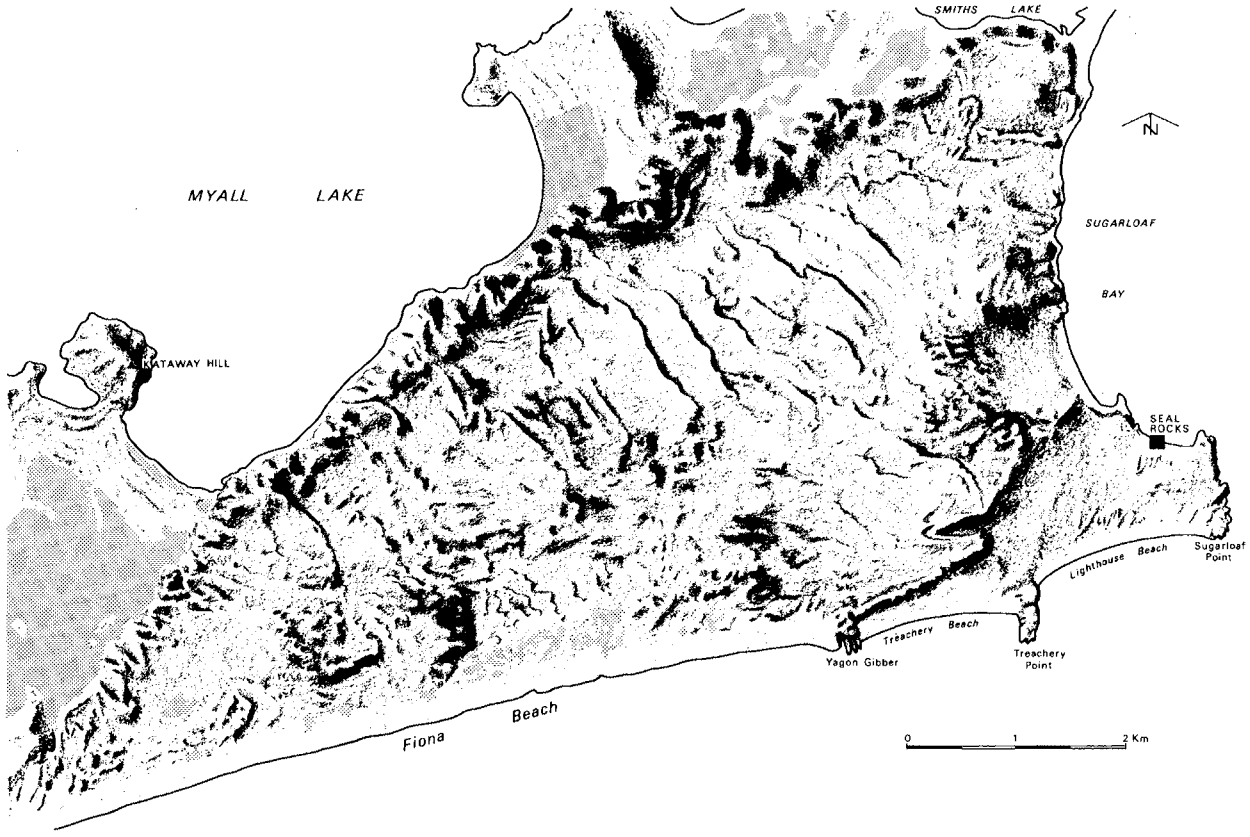

Figure 9-2: **Perspective sketch of the Seal Rocks dune field based on aerial photographs (prepared by Cartography Section, Department of Geography, University of Kansas). This figure highlights the array of asymmetric vegetated dunes occurring within the embrace of the giant parabola of the Bridge Hill long-walled transgressive dune. Wrap-around ridges can be seen on the windward flanks of the Bridge Hill dune.**

A distinctive characteristic of the "old" dunes is their deeply leached soils. A white, leached A horizon, several metres thick, overlies a well-indurated, iron-humic B horizon. The profile is similar to that described in Chapter 5 for the "old" dune exposure at the Nelson Bay Bowling Club. An exposure cut into a hillslope on the south shore of Smiths Lake (east of Horse Point, GR 5115, Myall Lake topographic sheet 9333-II, 1:25000) revealed a truncated leached horizon and a very compact, cliffed B horizon locally enriched with bands of iron oxide. Similar B horizon properties may be observed in shallow exposures on the east side of the Bungwahl-Seal Rocks road to the north of Bridge Hill. As discussed below (see 9.3), the "old" dunes are believed to underlie much of the Holocene dune complex.

Swamp surfaces flank the high sand ridge along the southern side of Smiths Lake. Although we have not investigated these areas in detail three attributes suggest Pleistocene age for the surfaces: (i) they are "perched" in elevation above the lake level (to 3-4 m) with swamp water draining into Smiths Lake: (ii) shallow drilling by Mineral Deposits Ltd. indicates the presence of "indurated" sand of shallow depth (c. 1 m) below peat; and (iii) the plant community which dominates the swamp surfaces both east and west of Bridge Hill is very similar to that associated with swamp surfaces of known Pleistocene age in the Eurunderee and Upper Myall embayments (Myerscough and Carolin, 1986, and in press; see also Fox, 1981, for detailed discussion of forest vegetation in the Seal Rocks embayment). Stratigraphic data and radiocarbon dates, to be described below, also support a Pleistocene origin for the swamp surface.

9.2.3 Bridge Hill Sand Ridge

This 15 km long feature is classified as a long-walled transgressive dune. Its topography is graphically depicted in Figure 9-2. The ridge stretches from near sea-level at Big Gibber to overlook Smiths Lake. For 5 km of its length the Bridge Hill ridge forms a towering wall along the SE shore of the Myall Lake. The section north of the Bungwahl-Seal Rocks road has been mined for heavy mineral by Mineral Deposits Ltd.

In common with long-walled transgressive ridges of Newcastle Bight (Ch. 4), the crest line of the Bridge Hill Ridge exhibits considerable variation in relief. Figure 9-2 drawn from aerial photographs indicates that the ridge is composed of a multitude of fused hillocks or sand lobes separated by steep-sided amphitheatres ("constructional gullies"). Each hillock resembles a high-angle cone especially when viewed from the Myall Lake (see Fig. 2-4). The summit areas of the hillocks are sharply rounded. Smooth, straight slopes plunge to the north at angles of 20-27 degrees. Near Bridge Hill these "lee" slopes are up to 100 m high. South-facing slopes are lower, discontinuous, and of variable declivity (10-25 degrees). Frequently they enclose depressions facing southwest to southeast.

Although the general alignment of the Bridge Hill sand ridge is relatively straight with a tendency to curve eastwards near Smith Lake, in detail the plan form of the crestline is quite disjointed (Fig. 9-2). The displacement of one hillock farther to the north relative to adjacent highs probably reflects differential rates of dune migration during the active phase of dune construction. Cols are up to 50 m lower than flanking hillocks. Relative relief increases towards Bridge Hill. The

spacing between hillocks along the massive transgressive ridge is quite regular at c. 200 to 400 m.

There is no evidence of significant fluvial erosion on the slopes of the transgressive ridge or in the steep-sided valleys which separate the hillocks. These valleys clearly represent the unfilled depressions between merging lobes of sand. Under the cover of a Eucalyptus-Angophora woodland sand movement is restricted to localized sheet-wash accumulating behind fallen logs (Fig. 9-3). Soil development is limited on the steep slopes implying more-or-less continuous slope instability since stabilization. However, on crests and low declivity south-facing slopes soil development is more marked (similar to Type 6 soil in Appendix A).

9.2.4 Treachery Head Parabola

Treachery Beach is backed by a towering dune ridge which extends from Yagon Gibber to behind Treachery Head (Figs. 9-1 and 2). Viewed from the beach, it appears to be a hooked ridge resembling a parabolic dune with one long and one short side. The parabola opens towards Fiona Beach; the sand mass appears to have been blown towards the eastern bedrock (or Pleistocene dune) high from the WSW or SW.

Within the Seal Rocks embayment the overall morphologic impression is that the Treachery Head parabola constitutes the southern "arm" of a massive transgressive dune complex with the Bridge Hill ridge being the northern "arm". The "receptive shore" for this complex is Fiona Beach.* Continuity of the transgressive complex is interrupted by bedrock or Pleistocene dune topography north of Sugarloaf Point, where there exists an extensive eolian mantle.

In detail, the morphology of the Treachery Head parabola resembles the Bridge Hill Ridge. The ridge is 4 km in length and is composed of fused hillocks. Steep slopes (20-30 degrees) are characteristic of both sides of the ridge. It ranges in elevation from 40 to 70 m above sea-level with relative relief along the crest of at least 20 m. Soils have not been investigated systematically on this feature, except that auger holes revealed a profile morphology similar to that of the Bridge Hill Ridge.

9.2.5 Seal Rocks Sand Plain and Asymmetric Ridges

Another remarkable feature of the Seal Rocks segment is the timbered sand plain which is enclosed by the Bridge Hill ridge and Treachery Head parabola. Within this sand plain are dune ridges aligned approximately at right angles to the Bridge Hill ridge. The general pattern of these ridges is depicted in Figure 9-2. These ridges are concentrated on the northern side of the sand plain. They reach elevations of 50-60 m above MSL. The southern half of the plain is of lower relief, with less well

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* Cooper (1958, p. 86) defines "receptive shore" as follows: "Maintenance of dune activity requires access to a favourable shore frontage: a beach for reception of sand from the sea, with low-lying or gently sloping country behind it over which the wind-propelled sand can move easily. Such a situation may be conveniently termed a receptive shore".

organized hummocky dune terrain.

Dune ridges of the northern sand plain are quite asymmetrical in section. Slopes facing northeast are the steepest. Averages of 234 measurements of northeast and southwest slopes show the former to be 24.9 degrees, while the latter is 6.6 degrees. Slope angles were measured on straight mid-slope positions using an Abney level. Slopes facing northeast range in elevation from less than 5 to 20 m (average = 14 m). The ground cover of shrubs and herbs is less dense on the steep slopes and this is reflected in a lighter tone on air photos. On steep slopes sand can easily be displaced by walking, but unlike unvegetated slopes at the angle of repose (33 degrees), movement is confined to the surface around one's feet. No signs of gully erosion were observed, but sheet wash is important in maintaining surface instability. Sand and organic debris "pile up" behind log dams on these steep slopes (Fig. 9-3). These accumulations are rarely more than 20-30 cm high and may form discontinuous steps parallel to or even slightly across the contour. However, we have never actually observed sheet flow during heavy rain on these slopes.

In plan, the asymmetric ridges are sub-parallel trending NW-SE to NNW-SSE (Figs. 9-1b,2). They are up to 3 km in length and slightly sinuous in general form. However, micro-relief is characterized by conical-shaped hillocks, which tend to be less pronounced than those which form the Bridge Hill long-walled transgressive ridge. The hillocks have projecting slopes on the steep northeast side of asymmetric ridges where they enclose "constructional gullies". The elevation of the crestline of these ridges is also variable (5-10 m), but again much less



Figure 9-3: Steep "slipface" of a forested asymmetric dune in the Seal Rocks area showing localized effects of sheetwash behind a fallen log with sand moving from top right to bottom left.

so than transgressive ridges, such as the Bridge Hill ridge. The asymmetric ridges may merge with the Bridge Hill ridge forming steep-sided, enclosed depressions. They also tend to grade into the ill-defined sand plain to the southeast. However, there are several ridges which terminate more abruptly at both ends. The gentle southwest slope in almost all cases descends into the trough surface between ridges. It is often difficult to define the base of the southwest slope due to low slope angles and local hummocky relief. A spacing of 1-2 km exists between the major asymmetric ridges shown on Figure 9-2.

Besides these major asymmetric dunes, the southern side of the Bridge Hill ridge is also flanked by several smaller dune ridges which appear to be partially wrapped around the "windward" sides of the massive hillocks. The crescentic form of these small ridges, or "wrap-around" dunes, mimics the shape of the hillocks. They bear little relation to the alignment of the asymmetric dunes. A good example of a set of "wrap-around" dunes occurs southwest of Bridge Hill (Fig. 9-2). Slopes on both sides of these ridges are steep (20 degrees). They form narrow gorge-like troughs, which are completely enclosed and up to 15-20 m deep. Another example of "wrap-around" dunes to the east of Bridge Hill exhibits a terraced sequence of four encircling ridges at successively lower levels.

The southern half of the Seal Rocks sand plain lacks the spectacular dune morphology just described. The mass of sand above sea-level decreases towards Fiona Beach. Low, irregularly-shaped sand mounds and ridges occur in the sand plain. There are several localities where these hills are quite prominent as at Slide Hill behind Fiona Beach (Fig. 9-1a,b). This hill is 60 m in elevation. It may be composed of a bedrock or Pleistocene sand "core".

Detailed vegetation mapping in the southern sand plain area by M. Fox has revealed bands of a Eucalyptus. gummifera and Casuarina, and a relative absence of Angophora costata (Fox, 1981). These patterns could be associated with a shallower Holocene sand cover and relatively flatter terrain. The remainder of the sand plain is covered by a E. pilularis A. costata forest community. Except for very small areas in the southern half, the sand plain is free of freshwater swamps and plant communities suggestive of a high water table. Soils are poorly developed. Minimum profile development is encountered on steep slopes. Elsewhere the permeable sands are slightly leached with A_1 horizons less than 0.5 m, over a weakly stained and cohesionless B horizon. Profile characteristics similar to that described on Ridge II in Newcastle Bight (Type 6 in Appendix A) are apparent (see also Ch. 10).

9.2.6 Fiona Beach Swamp Plain

A flat-lying strip behind the foredune and mobile dune sand at Fiona Beach is quite swampy. On aerial photographs a mosaic pattern is evident with rudimentary "L" or "T" shapes trending north to northeast. These patterns represent shallow depressions within the swamp plain; they carry standing water at least 1 m deep. The water-table is at or very close to the surface for other parts of the plain, rising above the surface after periods of heavy rain.

The swamp plain lies parallel to Fiona Beach between Yagon Head and Big Gibber. It is 12 km long and up to 0.7 km wide (Fig. 9-1b). Its

elevation above sea-level is less than 5 m. Except for shallow depressions, the surface is quite flat rising gradually to the north as it grades into the sand plain.

The vegetation association is "wet heath", but the floristic composition has troubled Myerscough and Carolin (1986) in their mapping. Many of the components of the "wet heath" characteristic of Pleistocene surfaces in Eurunderee embayment are present in this swamp plain. However, these authors queried the direct comparison between wet heath communities of Fiona Beach and Pleistocene areas in Eurunderee, because the former contains an admixture of species not fully represented at the older sites (P. Myerscough pers. comm). The reason for the similarity is apparent in the substrate. Unlike the sand plain terrain to the north, the swamp plain is directly underlain by relatively impermeable humate-impregnated sand. Excavations by Mineral Deposits Ltd. in their mining behind Fiona Beach exposed "sandrock", often with thin gravel layers. It is noticeable that the leached horizon which normally underlies the humate-impregnated sand is generally absent. A thin discontinuous layer of relatively unleached sand overlies the sandrock. This cover sand is of Holocene age.

In the section on stratigraphy (9.3), it will be shown that the sandrock forms the upper surface of a buried Pleistocene sand body. Behind Fiona Beach, the Pleistocene surface appears to have been exhumed by eolian deflation during the period when Holocene sand was transported inland to form the transgressive ridges and sand plain dunes. Thus the swamp plain is a relict deflation surface across which great masses of sand from the "receptive shore" were transported during the Holocene to form the high dunes of the embayment.

9.2.7 Modern Beach and Foredune Areas

Between Big Gibber and Sugarloaf Point the beaches are backed by partially stabilized foredune complexes. At Fiona Beach there is evidence (see Fig. 9-4) for a recent period of vegetation stabilization since the sand plain was a mobile sand surface. "Remanie" dune knobs occur containing a weakly podzolized soil and kitchen midden materials (shell detritus and chert flakes). The soil is similar in character to that exposed in blowouts in Eurunderee, Broadwater, Fens and Newcastle Bight localities. However, the foredune surface today is partially mobile with sand penetrating landwards across the swamp plain (Fig. 9-4). It is clear that the sand mass is moving inland roughly parallel to the shore, although in detail there are localities where the sand mass is advancing as tongues in a manner similar to the Fens and Newcastle Bight mobile dune sheets.

Figure 9-4 shows the same view along Fiona Beach from Yagon Head at different times. It is clear that the incipient foredune has developed over this period on stabilized parts of the mobile dune sheet. A similar tendency towards plant colonization of mobile sand surfaces in the last decade or so has been noted elsewhere in this study.

The continuity of the established foredune is more pronounced behind Treachery and Lighthouse beaches. However, there are major trough blowouts within these large foredunes (Fig. 9-5). The blowout at the eastern end of Lighthouse Beach was marked by Captain Sidney on his 1862 chart (Sheet 1, 1862, Sugarloaf Point to Crowdy Head) as a "Remarkable



Figure 9-4: **Fiona Beach (or Submarine Beach) viewed from Yagon Headland in 1962 (top), 1975 (middle) and 1988 (bottom).**



Figure 9-5: Lighthouse Beach viewed from Sugarloaf Point in 1973. The established foredune is cut by a blowout at the eastern end (see Short and Hesp, 1982, Fig 6b (ii) for a view of eroded scarp in 1978).

white sand patch". Sless (1958) stated that activation in this area was due to foot traffic and cutting timber. However, blowout development prior to 1862 suggests either natural factors and/or the impact of Aboriginal fires were more likely causes.

The high foredune ridge at Lighthouse Beach, except for the blowouts, is well vegetated by trees, shrubs and grasses. A remarkable dune structure rising to 30 m in height on the seaward side, it is composed of a series of fused lobes of sand. These lobes have penetrated only a short distance inland, thus forming a high, continuous, well-rounded ridge. There is a marked difference in height between the north side (inland) and south side of the foredune. The ridge descends no more than 10 m on the north side. The mode of development of the ridge is evident from stratification on the eroded seaward face. Severe wave erosion in 1974 cliffed the foredune and exposed the bedding. Primary sedimentary structures are mostly low angle cross strata with localized high angle foreset beds associated with foredune lobes. Organic layers no more than 20 cm thick sub-divide the foredune into separate "pieces". These layers are quite discontinuous, and although sub-horizontal, they occur at different levels. Unfortunately, bedding and soil surfaces become quickly obscured by slumping and are hard to document. It is inferred that this high ridge grew incrementally, and is a more complex feature than eroded foredunes containing the single

immature soil noted further south. As sand was added to one part and stabilized, more sand was accreted around sand-binding plants and/or small blowouts or other (lower?) parts of the ridge. It probably extends back in time to the mid-Holocene.

Beaches of the Seal Rocks embayment have not been systematically studied. The exposed open-ocean beaches between Big Gibber, Yagon, Treachery and Sugarloaf Point headland beaches show similar morphology. Broad dissipative inshore systems are characteristic of the three high-energy, south-facing beaches. In contrast, the two beaches north of Sugarloaf Point experience lower energy. The swell wave spectrum is filtered by the headland and offshore rock outcrops. It is of interest to note that beach grain size is slightly finer along Fiona Beach than to the south of Big Gibber in Eurunderee. Fiona, Treachery and Lighthouse beaches are noticeably flatter than the beach at Eurunderee.

9.3 STRATIGRAPHICAL CHARACTERISTICS

9.3.1 Bedrock Configuration

Unfortunately, few drill holes in this embayment penetrate to bedrock. In the absence of seismic refraction studies it is not possible to delineate bedrock configuration.

Ten holes have been drilled in the area for water pumping tests or production. Only one of these holes encountered bedrock above present sea-level. H.D.W.D. Seal Rocks hole No. 6 struck bedrock at -120 feet (40 m). The production bores drilled for Mineral Deposits Ltd. by the Bill Finn Drilling Company encountered bedrock at varying depths below sea-level ranging from 3 m to 30 m.

9.3.2 Stratigraphic Units and Sediment Properties

9.3.2.1 Holocene deposits

Sediments which have accumulated in the Seal Rocks segment during the Holocene are predominantly of eolian origin. Quartz sand is the most abundant mineral with very minor amounts (less than 5 percent) of rock fragments, feldspar, ilmenite, rutile and zircon. The last two are of economic significance. Concentrations of heavy minerals of about 1 percent occur in Bridge Hill Ridge (Mineral Deposits Ltd., 1973). Shell carbonate is only important within the contemporary beach and nearshore shelly sand facies. Holocene swamp deposits occur in shallow depressions of the swamp plain behind Fiona Beach and bordering Smiths and Myall Lakes.

The eolian origin of the sand deposits of Holocene age is manifested in several ways besides the distinctive geomorphology. In the deep dredge pit of Mineral Deposits Ltd. in the Bridge Hill Ridge, magnificent steeply dipping foresets typical of eolian environments are well expressed. These structures are evident in Figure 9-6. Observations by geologists of the mining company and N.S.W. Geological Survey have revealed two bedding sets. The greater mass of sand is contained in steeply dipping foresets. These beds commonly possess a dip to the north. Variations in dip reflect the inclination of the advancing lobe of the transgressive ridge. The other bedding set is a narrow (less than

5 m) zone of topset beds. These are sub-horizontal with perhaps a slight inclination to the south in some outcrops. Unfortunately, continuous slumping on working faces of the excavations made it too dangerous to undertake a comprehensive study of bedding. There have been no excavations in the asymmetric, "wrap-around", parabola or sand plain dunes, so it is not possible to describe their sedimentary structures.

In general, grain size parametres reveal a distinctive sand population which is medium size, well to very well sorted, and positively skewed. As part of a program to investigate the granulometric variability of a coastal sand body of apparently uniform age, 92 samples were collected from the dunes of the Seal Rocks area. The distribution of these samples is shown in Figure 9-7. Samples were collected below the A soil horizon at a depth of 20-30 cm. An attempt was made to sample dune crest as well as north and south-facing slopes on a transect at right angles to the dune crest.

Figure 9-8 shows mean and standard deviation data for 28 samples from dune ridges in the asymmetrical dune field. The majority of samples cluster in the medium sand range between 1.50 and 1.80 phi. Only a few samples (2 are from Bridge Hill) are classed as fine sand (finer than

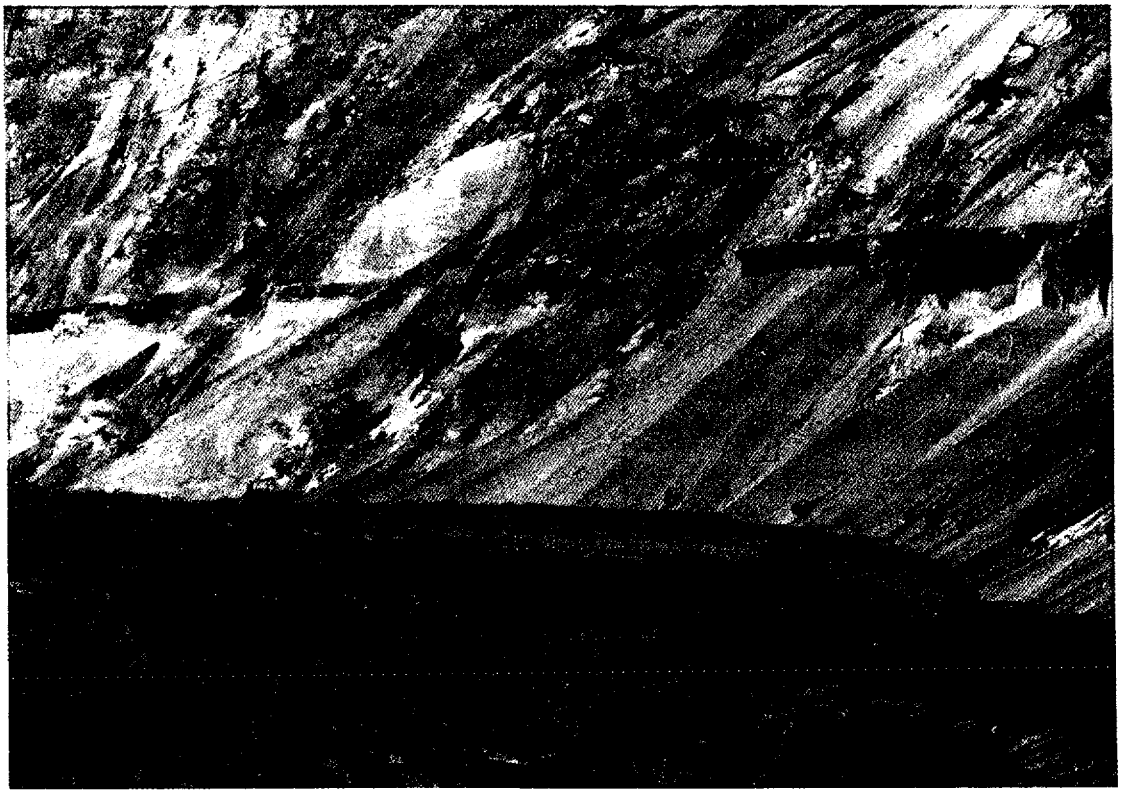

Figure 9-6: Buried Pleistocene soil surface beneath Bridge Hill Ridge. This paleosol dips northward beneath yellow dune sands containing heavy mineral. The dredge pit was excavated by Mineral Deposits Ltd (photo by K. Winward, Geological Survey of NSW, in 1975, see Byrnes, 1975).

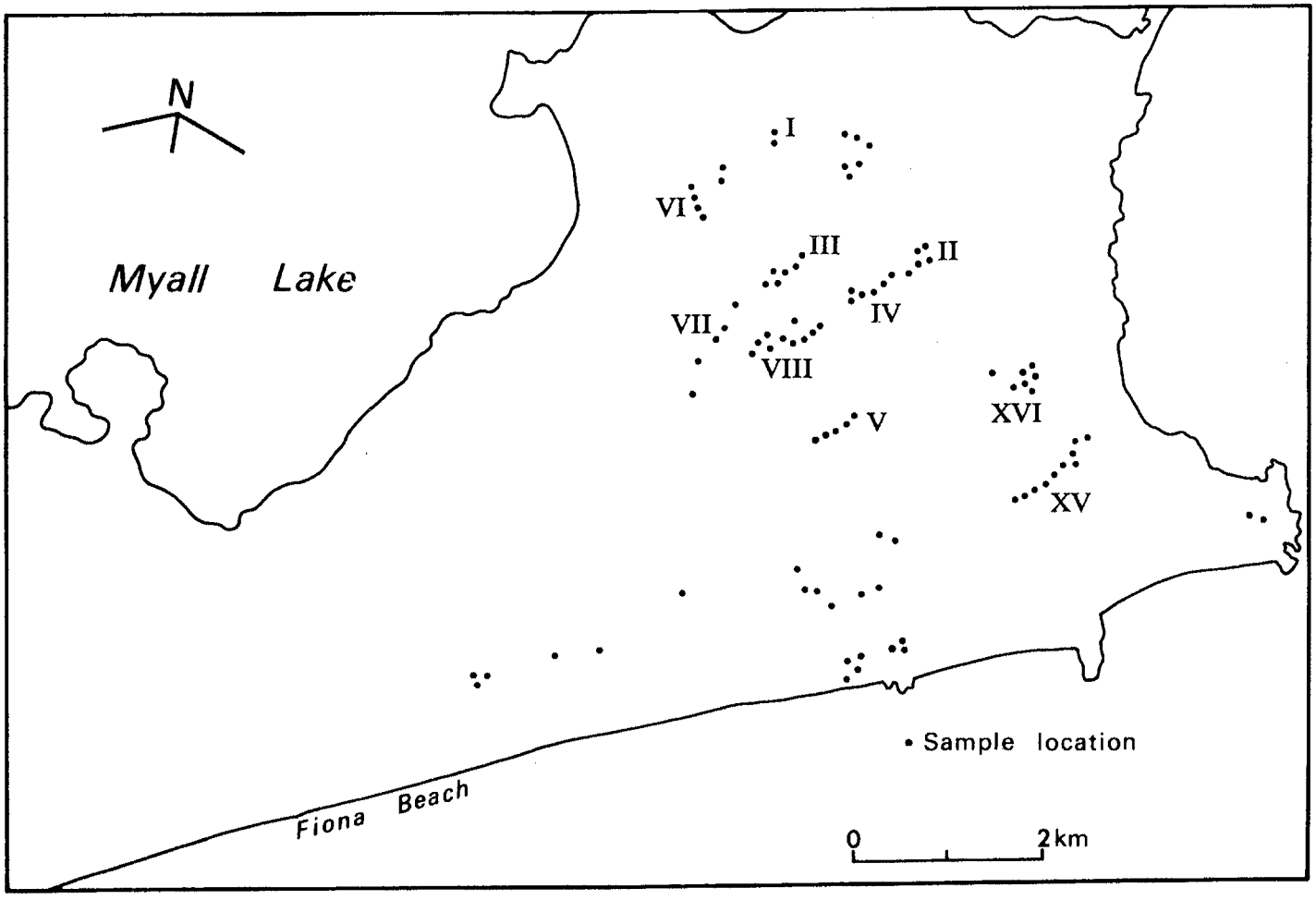

Figure 9-7: Location of surface sand samples for grain size analysis from Seal Rocks dunefield.

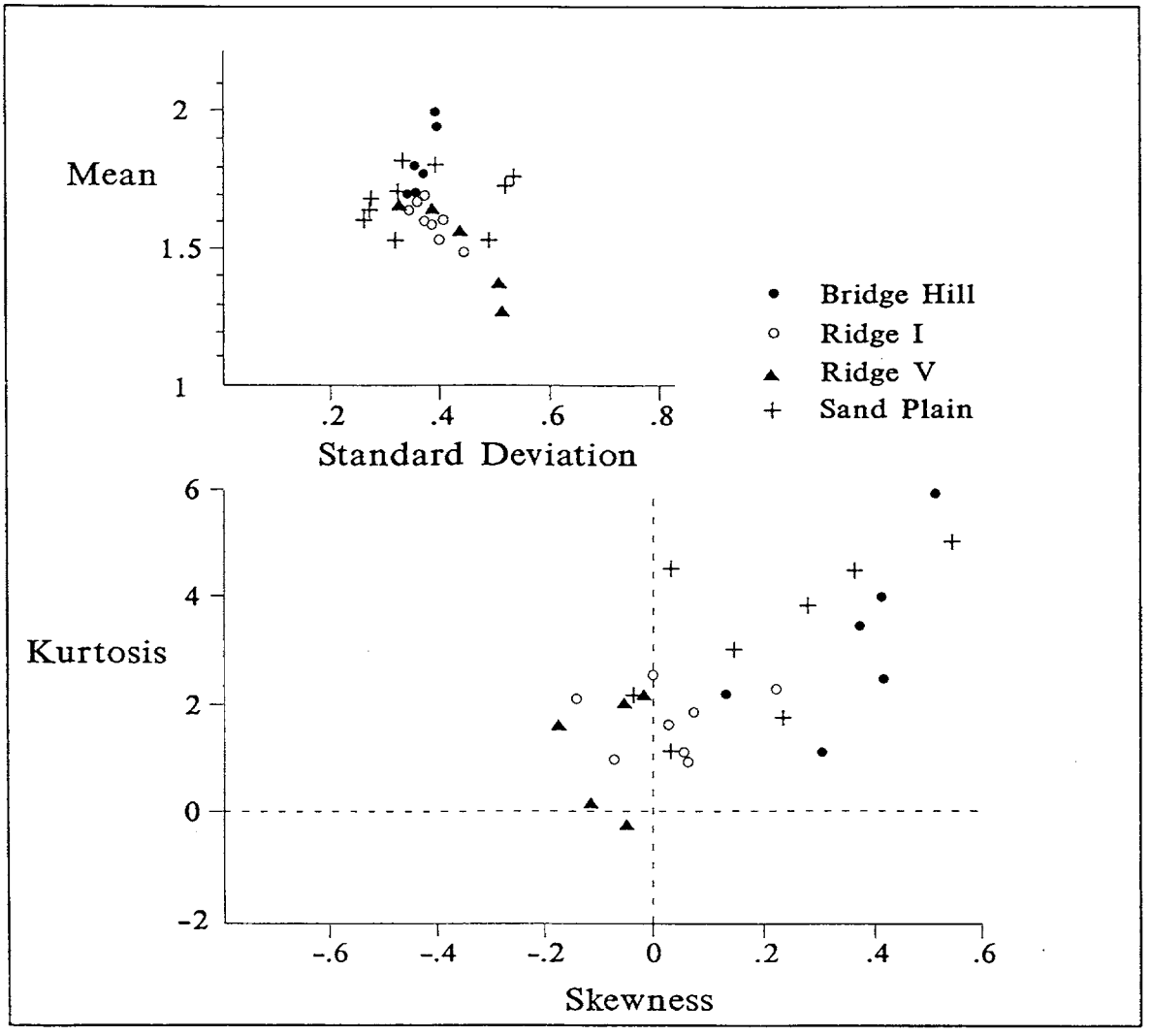

Figure 9-8: Grain size mean and standard deviation for selected samples from the Seal Rocks dunefield.

TABLE 9-1 Seal Rocks Dunefield - Grainsize Properties (in phi units)

Ridge No.	No. Samples	Mean	Max.	Min.	Mean S. Dev.
XV	8	1.63	1.75	1.57	.37
XVI	6	1.53	1.65	1.33	.40
IV	4	1.48	1.53	1.39	.44
VII	5	1.52	1.67	1.23	.39
V	5	1.50	1.65	1.30	.43
I	8	1.62	1.73	1.50	.38
II	3	1.58	1.62	1.52	.35

2 phi). The samples are mostly well to very well sorted (0.3 to 0.5 phi standard deviation). However, there are some samples, especially from the sand plain, which are more poorly sorted. Predominatly Seal Rocks sands are positively skewed and possess kurtosis values ranging from 0 to +6.

The sand population available for eolian distribution is quite uniform. This has inhibited any selective differentiation in relation to distance transported and elevation. There is little evidence for variation in grain size parametres within and between individual dunes (see Table 9-1). In comparison with moment measure data from Newcastle Bight (see Fig. 3-18), it is quite apparent that the Seal Rocks dunes possess sands which are not as fine or as well sorted (Fig. 9-8). This is suprising given the elevation of dunes at Seal Rocks. The implication is that the two dune fields have been derived from distinctively different sand populations.

Another sediment characteristic of the Holocene dune sands of the region is their grain surface texture using the SEM. In A.N.U. drill hole 106, selected quartz sand samples from the Holocene dune sheet were compared with samples from within the Pleistocene sand unit. The differences are shown at Figure 9-9. The Holocene grains are noticeably smoother but still etched. In contrast the Pleistocene samples are chipped, angular and show little impact of diagenetic change. This is puzzling considering the strong imprint of diagenesis noted by Ly for Pleistocene sands in Newcastle Bight (see Ch. 3). A non-eolian origin for the Pleistocene sands is suggested; in contrast, the Holocene dune sands show more rounding and the presence of small pits associated with eolian processes and post-depositional solution (Margolis and Krinsley, 1974).

9.3.2.2 Pleistocene deposits.

As in the case of Holocene deposits, Pleistocene sediments in the Seal Rocks embayment are predominantly composed of quartz sand. They are basically differentiated from overlying Holocene sands by their soil characteristics. The Holocene sands are yellow to buff-coloured with soil profile differentiation confined to the upper 2 to 3 m, however the Pleistocene sands are highly variegated in colour and degree of humate-impregnation for thicknesses up to 20 to 30 m.

Very few holes penetrate the Pleistocene sand section of this segment. However, those that do reveal one startling feature in comparison with other embayments to the south. The thick basal clay unit so characteristic of bay fill beneath Pleistocene Inner Barrier and dune sands is apparently absent in the Seal Rocks segment. Clay has been recovered in the production bores in the north as layers within the Pleistocene sand unit, or as a thin layer directly overlying bedrock. Unfortunately, these production bores were not precisely logged, and samples were not available to the author. However, it is clear that in the Seal Rocks' area clay occurs as thin beds up to 4 m thick.

Sedimentologic characteristics of the Pleistocene in the Seal Rocks area were studied from drill holes and excavations. The best natural outcrop occurs on the south side of Smiths Lake where a Pleistocene parabolic dune has been eroded by lake waves. An example of a production bore sequence is depicted in Figure 9-10 (Bore No. 7). Bedrock occurs at

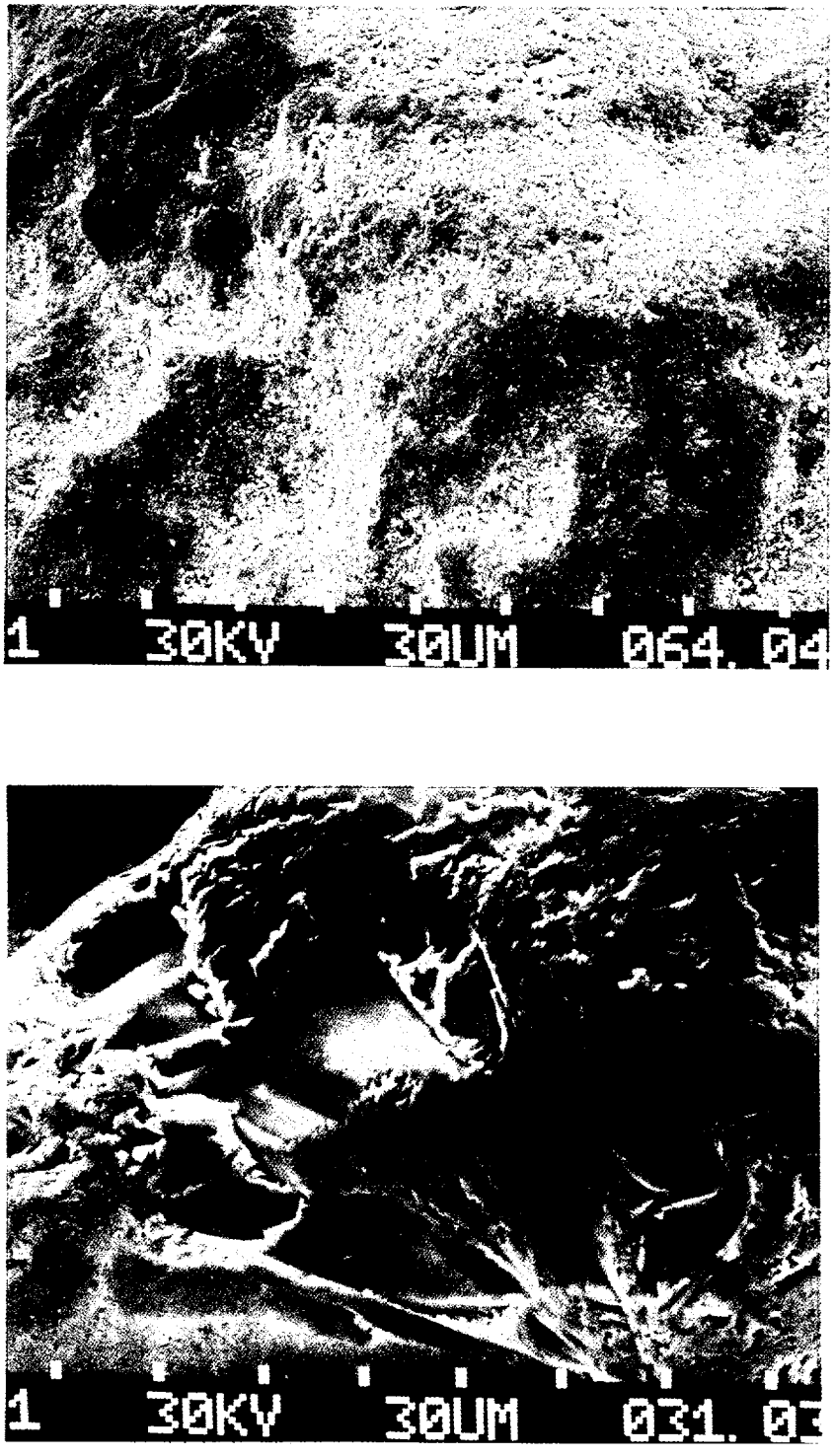

Figure 9-9: **Scanning electron micrograph of grain surface texture of Holocene (top) and Pleistocene (bottom) dune sands from Seal Rocks dunefield (ANU drill hole 106, see text for discussion).**

69.5 m below ground surface (-28 m below MSL). The upper unit is a weakly podzolized (top 2 m), yellow to light brown sand, up to 13.7 m thick, and is of Holocene age. As is the case in many of these production drill holes, the uppermost Pleistocene unit, commencing here at -13.7 m below GS, is a "white sand". This unit has also been observed at the base of the mining dredge pit on occasions (see below). In Bore No. 7 it is described as a "coarse" sand 6.7 m thick. It overlies 8.8 m of "indurated brown sand". This is one of five "indurated" horizons on the hole (Fig. 9-10). These horizons vary in thickness from 3.3 to 8.8 m and are separated by relatively thinner "soft dirty sand" or "soft brown sand" layers. The problem is interpreting these layers: are they paleosols, or do they represent a form of sub-surface organic accumulation?

Some light on these questions can be shed by comparing Bore No. 7 with an adjacent hole No. 6 (see Fig. 9-1a for location). Indurated horizons do not correspond to the same elevation. There are six "indurated" horizons in No. 6, the basal layer being overlain by 3 m of "fine white sand". Furthermore, a clay layer occurs at -5 to 7 m below sea-level in No. 6, in a "dirty sand" (= paleosol?) horizon. The ground elevation is higher at No. 6 by 5 m and this may explain the variation in elevation and thickness of the indurated horizons and possible paleosol horizons. Without detailed drilling and sampling, it is not possible to be more definitive about the nature of the units within the Pleistocene sand mass at the north end of the Seal Rocks segment. What is clear, however, is that the multiple bands of "indurated" and "dirty sand" are quite different from what has been logged by various drilling operators and ourselves elsewhere in the study area, with the possible exception of the Tomaree Hills. Indurated or humate-impregnated sand is observed in the production bores over a thickness of nearly 60 m of sand. This far exceeds the 9-12 m thick horizon encountered beneath the Inner Barrier surface.

Farther south in the Seal Rocks embayment three drill holes penetrate a humate-bearing sand (see Fig. 9-1a for location of drill holes). Shallow pits excavated in the sand plain expose the upper part of this sandrock. The old hole by the H.D.W.B. (SR 6) has many characteristics in common with A.N.U. drill hole 105. This hole is located behind the swamp plain (Fig. 9-1a). A humate-impregnated sand at least 9 m thick characterizes the upper part of a medium to coarse sand. This sand grades into a grey brown, gravelly sand which abruptly changes to a creamy grey, slightly clayey sand at 24 m below GS (i.e. c. -20 m MSL). No basal clay or bedrock was observed in this hole. The lighter clayey sand is correlated with the multi-banded Pleistocene sand with clay unit to the north (see 9.3.3).

The mining company, Mineral Deposits Ltd., has recognized the "Yagon strandline" within the top 3 m or so of the indurated portion of humate sand unit. (L. Bennett, pers. comm., Sept. 1973). This band of indurated sand is adjacent to the swamp plain and extends parallel to Fiona Beach between Big Gibber and Yagon. In places it underlies a yellow to light brown Holocene sand mantle with heavy mineral values of 3 percent. The "Yagon strandline" locally possesses heavy mineral values closer to those found in beach deposits (i.e. c. 3 to 5 percent). Dredge excavations into these sands have revealed bands of pebbles. Mining is now finished in this area.

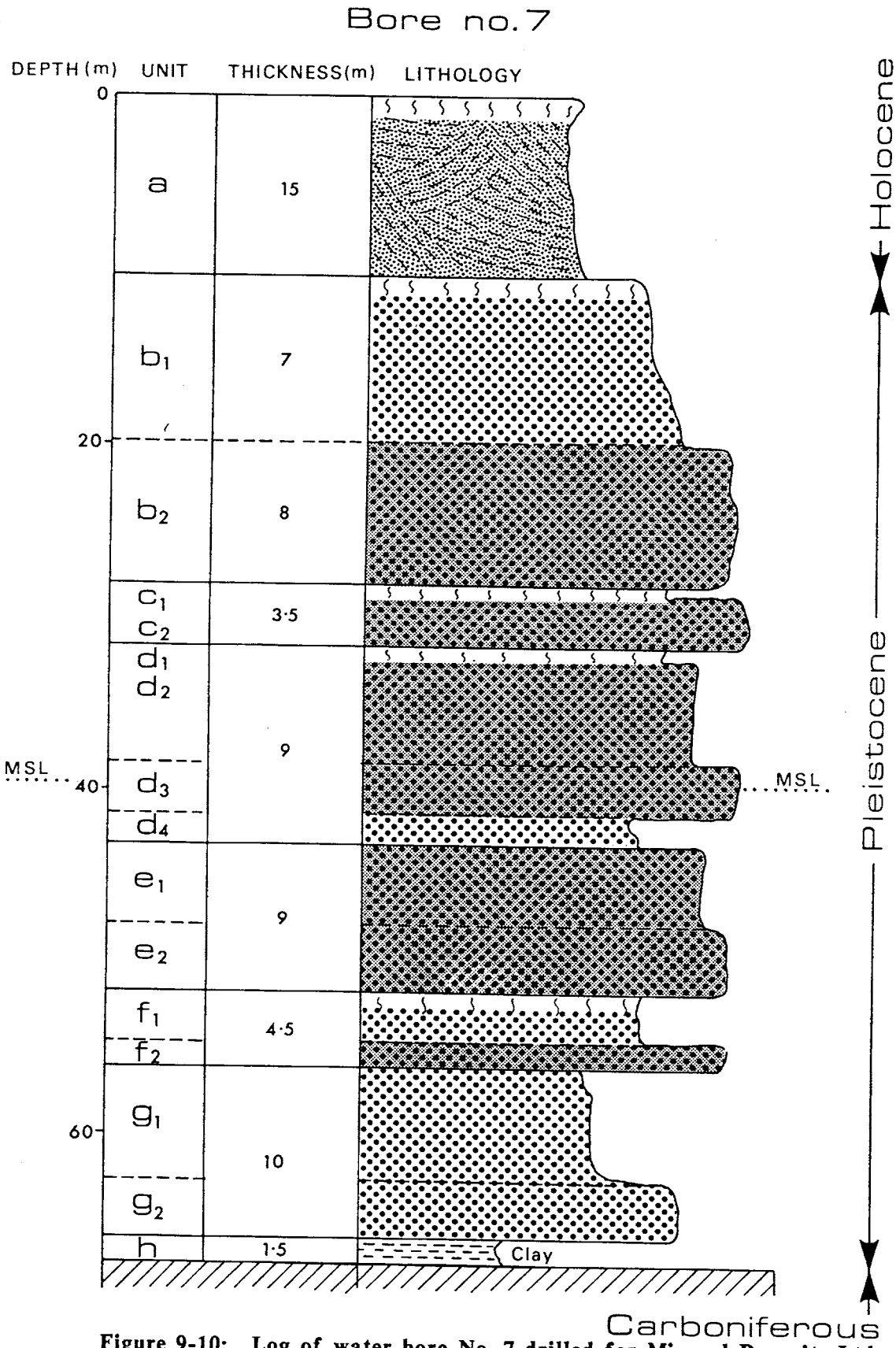

Figure 9-10: **Log of water bore No. 7 drilled for Mineral Deposits Ltd (see Fig. 9-1a for location). Several discontinuities are represented in this sequence.**

In summary, three major sediment units are recognized in the Seal Rocks embayment.

(i) A multi-layered indurated and leached sand in the north, up to 60 m thick and locally containing clay and brown (organic?) sand layers of unknown origin; this unit is believed to be continuous with a basal creamy-grey clayey sand in the southern part of the segment (see below):

(ii) A medium to coarse sand in the southern part of the embayment, impregnated with humate for thicknesses of up to 9 m and rich in heavy minerals in the top 3 m unit; this unit is mostly of late Pleistocene age and nearshore-beach in origin (Q2Mer).

(iii) A well-sorted, yellow sand which virtually blankets the entire embayment above sea-level; this will be shown to be Holocene in age and is clearly eolian in origin (Q4-6Met).

9.3.3 Stratigraphic Pattern and Depositional Sequence (see Fig. 9-11)

Only a generalized stratigraphic section can be constructed for the Seal Rocks embayment at this stage. Although mining company drilling and excavations have provided very useful data on the surficial geology, there are few holes to bedrock so it is difficult to show clearly the relations between Holocene and Pleistocene units, and especially within the Pleistocene.

Figure 9-11 attempts to convey the stratigraphic relations between depositional units on a line from Fiona Beach to Smiths Lake. This section is based on the deep holes shown on the section, numerous unplotted shallow drill holes (especially those along the mining company road between Big Gibber and Bridge Hill), drilling along Bridge Hill by Mineral Deposits Ltd. and mining excavations by Mineral Deposits Ltd. at two localities behind Fiona Beach and on Bridge Hill. The section is schematic and only follows the approximate location indicated on Figure 9-1a. It does not include those areas to the north of the Seal Rocks Road where Holocene sand attains elevations of c. 100 m with "yellow sand" being reported to the water table at a depth of 84 m below ground surface (e.g. Mineral Deposits Hole Ltd. 48N-7 1/2SE).

It is suggested in Figure 9-11 that the bedrock is covered by a Pleistocene sand unit containing numerous humate-impregnated horizons and some clay layers. The sand unit thickens northwards towards Smiths Lake. In the south this unit is a pasty white or creamy grey sand very similar to the lower sand unit of Pleistocene age from the Tomaree area (Ch. 5). In the deep production holes to the north (e.g. Bore No. 7), similar white sands ("very hard") may occur at the base of the section. It is possible that such sands represent a former leached horizon which was later buried by one or more phases of sand into which humic colloids have been precipitated. The unit is therefore composite. Apparently sands of different age form the sand body which thickens into a ridge or hills of sand along the south side of Smiths Lake.

The undulating surface of the Pleistocene sand body was sometimes visible in the Bridge Hill dredge pit. Here a thick white sand horizon (+10 m?) is buried by tens of metres of Holocene yellow sand (Fig. 9-6).

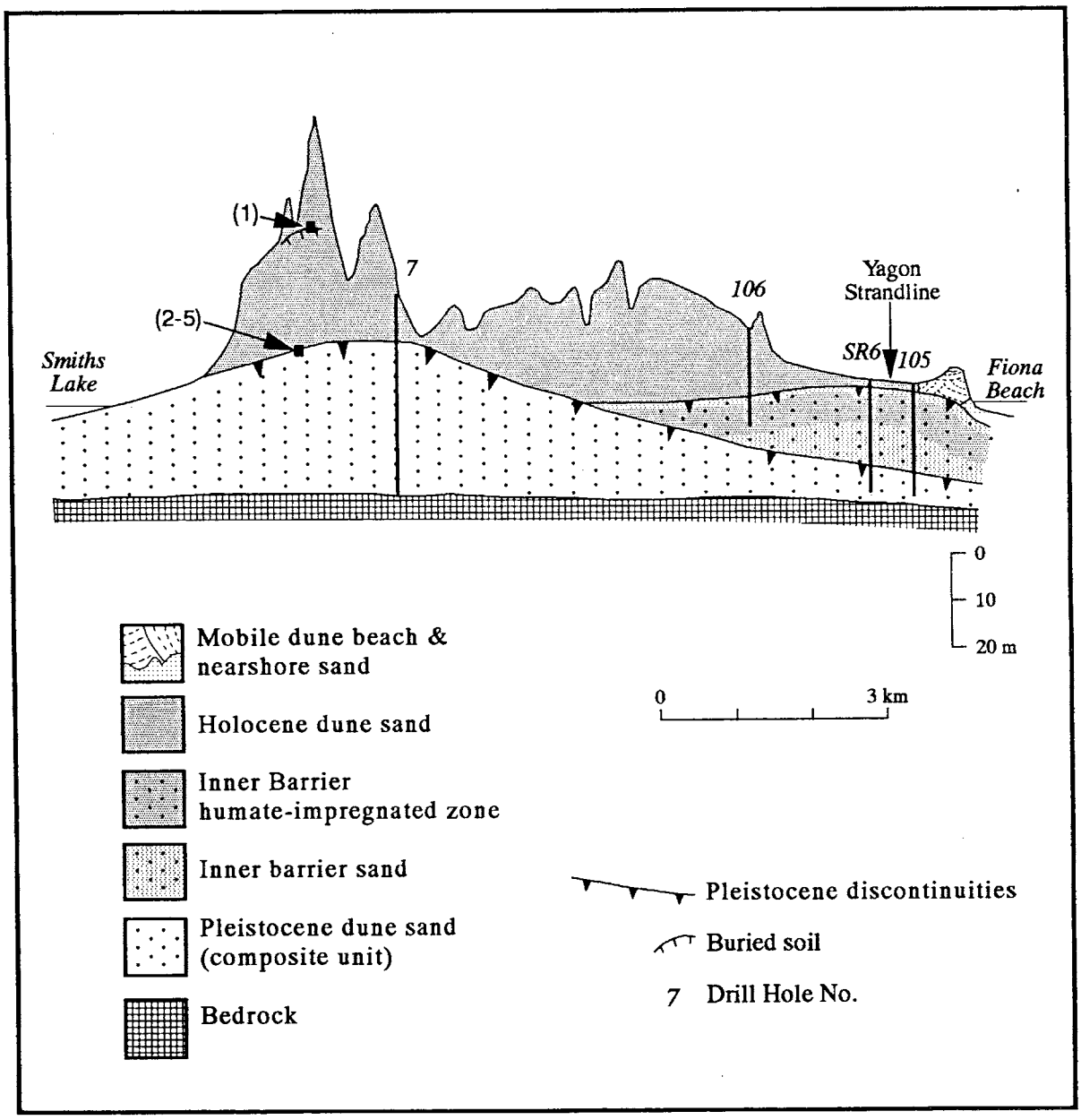

Figure 9-11: **Generalized stratigraphic section along an approximate N-S transect from Fiona Beach to Smiths Lake. The composite structure of the Bridge Hill Ridge is indicated. Radiocarbon dates are on charcoal pieces sampled from buried soil surfaces in sand-mining excavations: (1) 1265 ± 135 yr B.P. (GX-5295); (2) 3025 ± 135 yr B.P. (GX-5294); (3) 2485 ± 135 yr B.P. (GX-4833); (4) 1975 ± 110 yr B.P. (GX-4112); and (5) 2600 ± 110 yr B.P. (SUA-648) (See Figure 9-13). These dates suggest late Holocene phases of transgressive dune construction for the bulk of the large sand ridge.**

Studies by Mineral Deposits Ltd. and the N.S.W. Geological Survey have determined the sedimentological differences between these two units. The white sand is much finer than the over-lying Holocene sand. The white sand contains very little heavy mineral (Byrnes, 1975). A charcoal-rich layer at the top of the white sand separates the two units (Fig. 9-6). Six sections provided by Mineral Deposits Ltd., which are based on closely spaced drilling and pit exposures, show in detail the configuration of the surface of the Pleistocene sand under the massive Holocene ridge (Fig. 9-12).

The pit has also cut into swamp deposits adjacent to Smiths Lake. These organic deposits have been overridden by the Holocene transgressive dune. They are of variable age from Pleistocene to Holocene (see Appendix B). As the samples were recovered from below the water table, precise stratigraphic relations are not known. The samples were collected by the N.S.W. Geological Survey on the north or Smiths Lake side of the pit (Fig. 9-13). Swamp deposits appear to overlap the Pleistocene dune sand.

In the southern half of the embayment a second and perhaps younger Pleistocene unit is inserted in Figure 9-11 between the two main sand bodies. This unit is locally very heavily indurated. Sediment characteristics, including heavy mineral concentration ("Yagon strandline") and SEM properties (Fig. 9-9), suggest a beach-nearshore environment of deposition. This inference is supported by the geometry of the sand body, its surface rising to elevations similar to that of the Inner Barrier and dipping landwards perhaps as a relict backbarrier surface. It suggests that the Myall Lake was blocked off from the sea by a Pleistocene barrier to the northeast, as well as southwest (Eurunderee Inner Barrier), of Big Gibber. As discussed above, there is nothing in the stratigraphy or morphology of the Myall Lake which would suggest it was open to the sea during the Holocene as was the case with the Broadwater, and as is the case today at Smiths Lake.

The Pleistocene age of the surface is proved by dating materials in A.N.U. drill hole 106 (Fig. 9-11). Two dates have been obtained (Appendix B). Just below the cover of yellow sand which is 15 m thick, is a thin (1 m) indurated sand which overlies a 2 m thick, muddy sand, grey to dark grey, and rich in charcoal fragments. This is possibly a backbarrier facies. The charcoal dated >37,000 ^{14}C yrs BP (ANU-1533). Humic colloids from the heavily impregnated layer 20 m below ground surface dated "background". This layer was so indurated that the power auger drill could not penetrate it.

The Holocene sand unit which mantles the area clearly thickens to the northwest and north (Fig. 9-11). To the north it has accumulated against a composite bedrock and Pleistocene dune "ridge" (Thom et al., 1981a). However, to the northwest it forms a high transgressive sand mass across a low relief Inner Barrier surface (see Fig. 9-1b for contact with Eurunderee Inner Barrier terrain), and into Myall Lake. Dates from the Bridge Hill pit show it to be as young as 1900 years in places, although older dates imply variable periods of accumulation between 1900 and 4000 years ago. The location of dated samples is depicted in Figure 9-13. So far only one thin soil layer has been discovered within the relatively homogeneous "yellow sand". Charcoal from it dated 1265 $\pm$ 135 ^{14}C yrs BP (GX-5295). The relation between the two dated surfaces of Holocene age in the soil pit is shown in Figure 9-11.

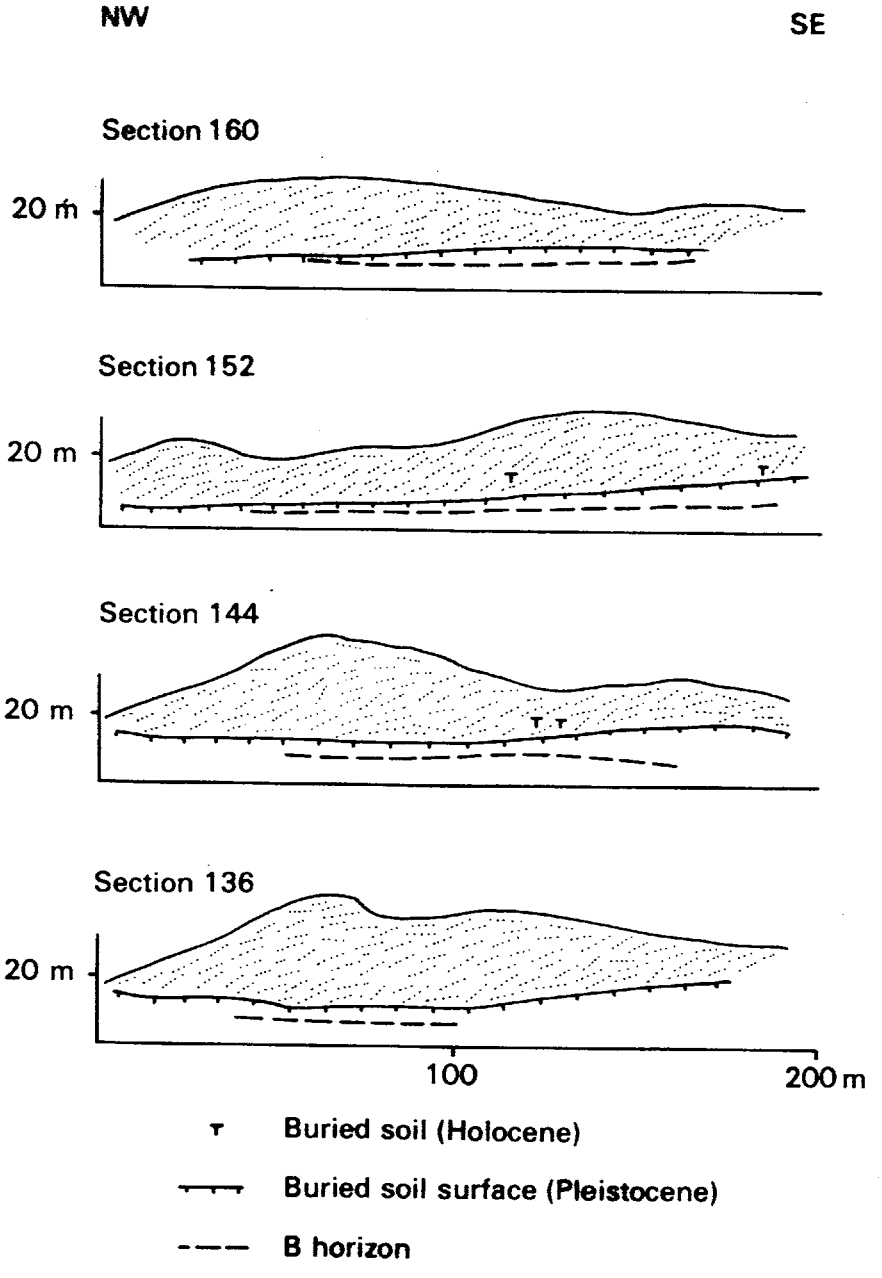

Figure 9-12: Cross-sections of Bridge Hill Ridge where mined by Mineral Deposits Ltd. The sections show the thickness of Holocene dune sand (data provided by Mineral Deposits Ltd. and N.S.W. Geological Survey).

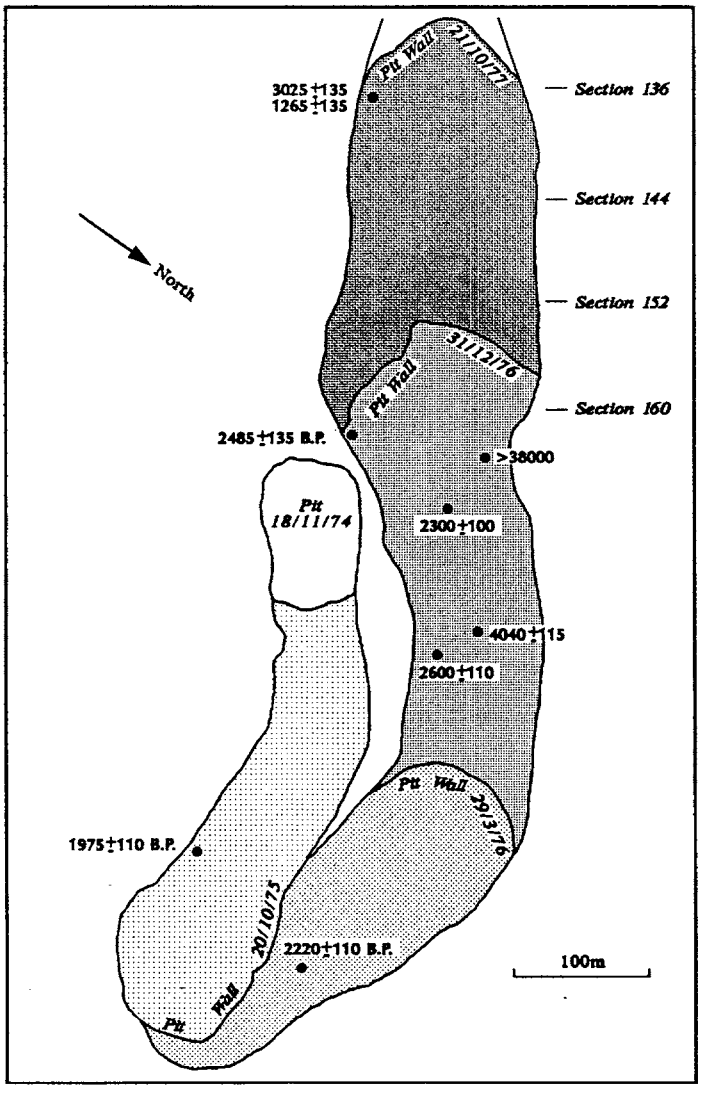

Figure 9-13: Map of Bridge Hill Ridge showing location of radiocarbon dates.

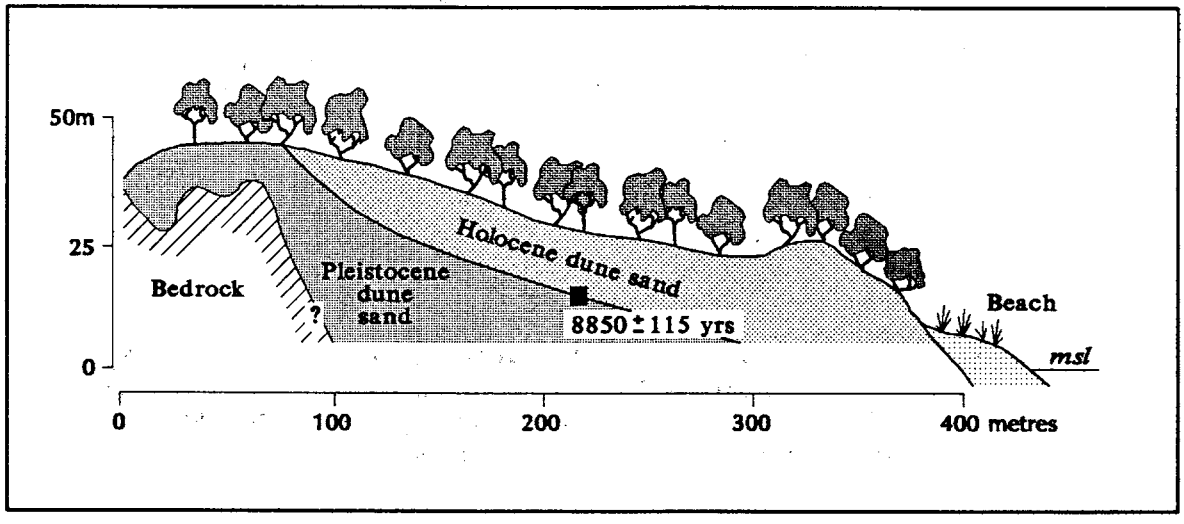

Figure 9-14: Stratigraphic section at Sandbar, Smiths Lake.

At Sandbar on the north side of Smiths Lake, an exposure in 1972 revealed a well-podzolized dune sand which buried a humate-impregnated sand (Fig. 9-14). The two units were separated by a charcoal-rich sand dating 8850 ± 115 ^{14}C yrs BP(SUA-41). This date agrees with several others on the Central N.S.W. coast (e.g. at Eurunderee and at Kurnell and Jibbon south of Sydney) suggesting eolian instability prior to sea level reaching its present position. A similar age has not been established within the Seal Rocks segment.

In summary, the depositional history of the Seal Rocks area is as follows (see Fig. 9-15):

1. Some "estuarine" clay deposition at depths below MSL of >30 m; this unit is poorly expressed in this area with further exploration being required.

2. Several episodes of marine-eolian deposition with mostly eolian sand accumulating as a ridge on the south side of Smiths Lake (Q1Met); clay deposits (estuarine?) accumulated as discontinuous lenses in depressions between dunes at depths ranging from a few metres above to below present MSL.

3. Inner Barrier marine deposition blocked off the Myall Lake during the Last Interglacial (Q2Mer). This morphostratigraphic unit is apparently continuous with Inner Barrier features of the Eurunderee embayment. Swamp deposits adjacent to Smiths Lake and onlapping the Pleistocene dune ridges developed since the Last Interglacial (Q3To).

4. Eolian instability in the Holocene led to the accumulation of the high transgressive ridge and the sand plain burying Inner Barrier Pleistocene dune, and Pleistocene swamp surfaces. Several episodes are probable with sand accumulating above present sea-level prior to 6000 BP at Sandbar (Q4Met). The main mass of sand forming Bridge Hill ridge attained its present configuration about 2000 years ago, but was initially formed about 4000-4500 years ago. A final, perhaps very local, phase of instability is recorded by a buried soil dating c. 1200 ^{14}C yrs ago within this ridge (Q6Met).

5. Very recent eolian instability behind the south-facing beaches (last few hundred years) has led to mobile sand forming at Fiona Beach and in blowouts (e.g. at Lighthouse Beach). There is some indication of vegetation of mobile sand in the last 20 years.

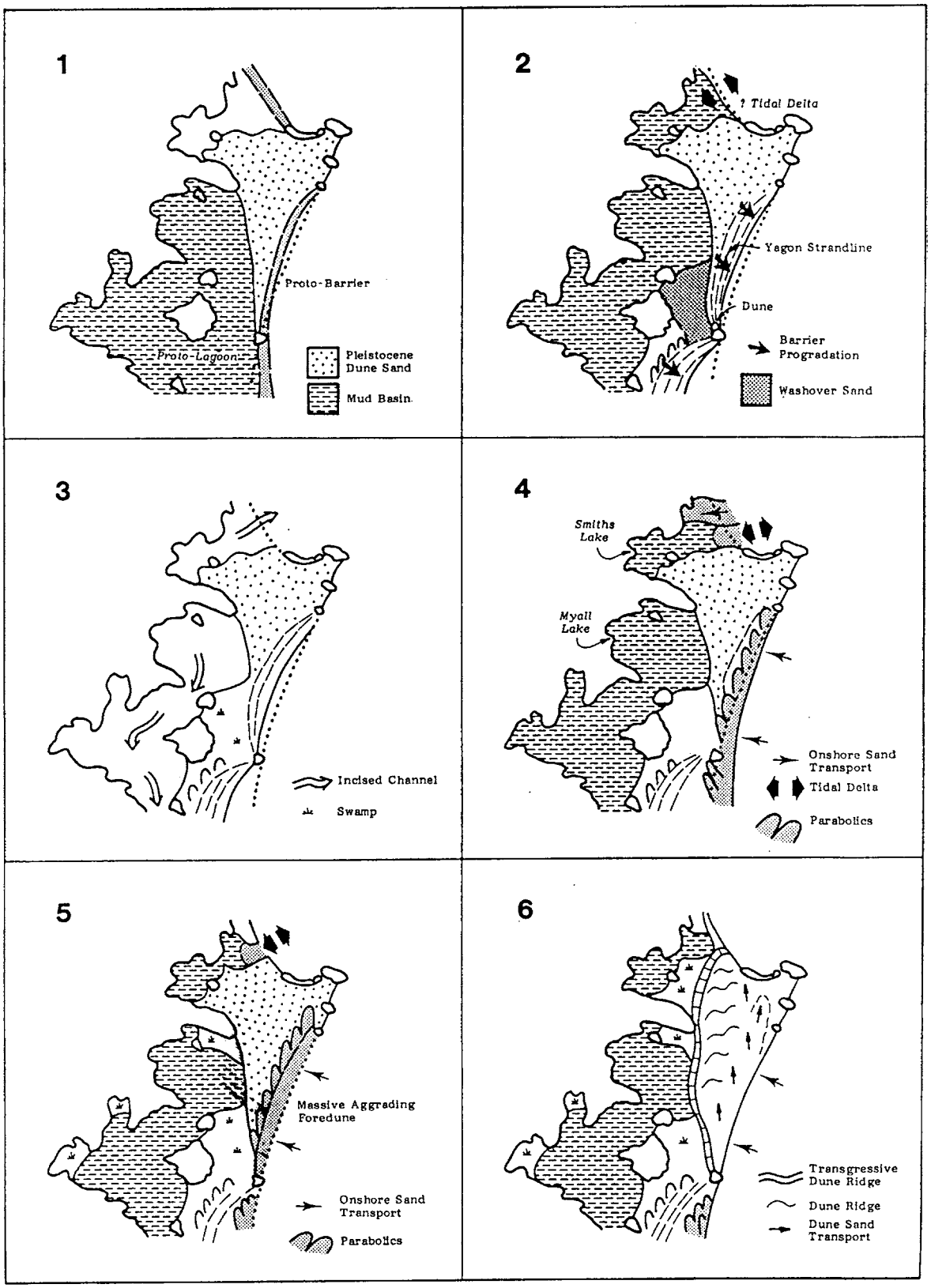

Figure 9-15: **Six stage model of the geomorphic history of the Seal Rocks area (the stage numbers refer to time periods discussed in Chapter 10).**

10

Correlation and Chronology

In this final chapter, it is our purpose to compare depositional sequences and histories of the six segments described and discussed in Chapters 4 to 9. Information available within each segment provides the necessary detail for regional correlation and chronology. It is now important to establish a classification system by which depositional units can be compared before proceeding to correlate.

10.1 CLASSIFICATION OF THE LATE QUATERNARY SEDIMENTARY SEQUENCE

10.1.1 Principles of Subdivision of Late Quaternary Coastal Deposits.

Lithofacies, surface morphology, shell assemblage and radiocarbon dating constitute the criteria for the subdivision of the Quaternary deposits in the Port Stephens-Myall Lakes region. Table 10-1 illustrates the different sedimentary units recognized in the Quaternary for this area. The units are divided on both a chronological basis (Q1 to Q6) and according to facies type (upper and lower case letters). Figure 10-1 illustrates by means of a generalized cross-section the relationship between units identified in the study area, and Figure 10-2 shows the distribution of these units throughout the study area.

10.1.2 Subdivision of the Pleistocene (Q1, Q2, Q3).

The Pleistocene sequence of the Newcastle-Myall Lakes area is

divided into Pre-Last Interglacial (Q1), Last Interglacial (Q2) and Late Pleistocene or Last Glacial (Q3). The basal sand and gravel and the clay unit interbedded with sand beneath the Inner Barrier have been regarded as Pre-Last Interglacial in age as radiometric dating (radiocarbon and uranium series) on marine carbonates including corals has established that the Inner Barrier is Last Interglacial in age (c. 120,000 to 140,000 years; Marshall and Thom, 1976). During the Last Pleistocene stage the sea-level dropped so much that the shoreline lay beyond the present-day coast, and marine sediments were not deposited. A possible exception was localized interstadial deposition in Newcastle Bight at c. -40 m (see 4.3). Reworking of former stranded deposits by wind with the formation of parabolic and longitudinal dunes was the main process of accumulation of sediments, although fluvial and freshwater swamp deposits together with soil processes also took place during the low sea-level interval.

10.1.2.1 Marine sequence (Q2M).

The Pleistocene marine sequence developed during the Last Interglacial stage when the sea-level was slightly higher than the present position (+4-6m). At the lowest parts of the sequence occurs transgressive sand; it is moderately to poorly sorted, polymodal, sometimes contains a mixed mineral suite and possesses locally abundant mollusc shells, particularly Bankivia as well as corals (Marshall & Thom, 1976). A regressive nearshore sand (Q2Mnr) is overlain by a medium to coarse sand, well to moderately sorted, unimodal, negatively skewed and quartzose composition which is of beach to surf zone origin (Q2Mbr). A medium sand, very well to well sorted, positively skewed, and quartzose terminates the marine sequence (Q2Mer). A beach-ridge plain forms the surface morphology of the Last Interglacial marine sequence in several embayments and has been designated Inner Barrier (Thom, 1965).

10.1.2.2 Estuarine sequence (Q1E, Q2E).

In a number of locations deep borings have encountered a thick estuarine clay unit. This clay unit is interbedded with sand and either overlies directly the Permian-Carboniferous bedrock or a basal sand and gravel of fluvial origin (Q1T) which is the lowest unit of the Pleistocene sequence. The clay unit is interpreted as onlapping estuarine deposits formed behind sand barriers as the result of successive transgressions during the mid Quaternary (see below). It appears to be a composite unit in that the clay contains several discontinuities of pre-Last Interglacial age; however, the uppermost part of the unit (Q2E) is interpreted as the time-equivalent of the Pleistocene marine sequence Q2M. A fossiliferous outcrop of Q2E occurs at Largs in the lower Hunter Valley (see David and Etheridge, 1890; Langford-Smith and Thom, 1969). Application of amino acid racemization to Anadara shells at this site confirms the age designation (C.V. Murray-Wallace, pers. comm.).

10.1.2.3. Terrestrial sequence (Q1T, Q2T, Q3T).

Drilling has revealed the presence of sediment units similar to those of the present day fluvial deposits, which become coarser with depth. The units appear to fill channels (Tc) cut into the bedrock or older sediments. The material is quite gravelly and the sand fraction is lithic in composition with angular to sub-angular grains. The unit Q1Tc

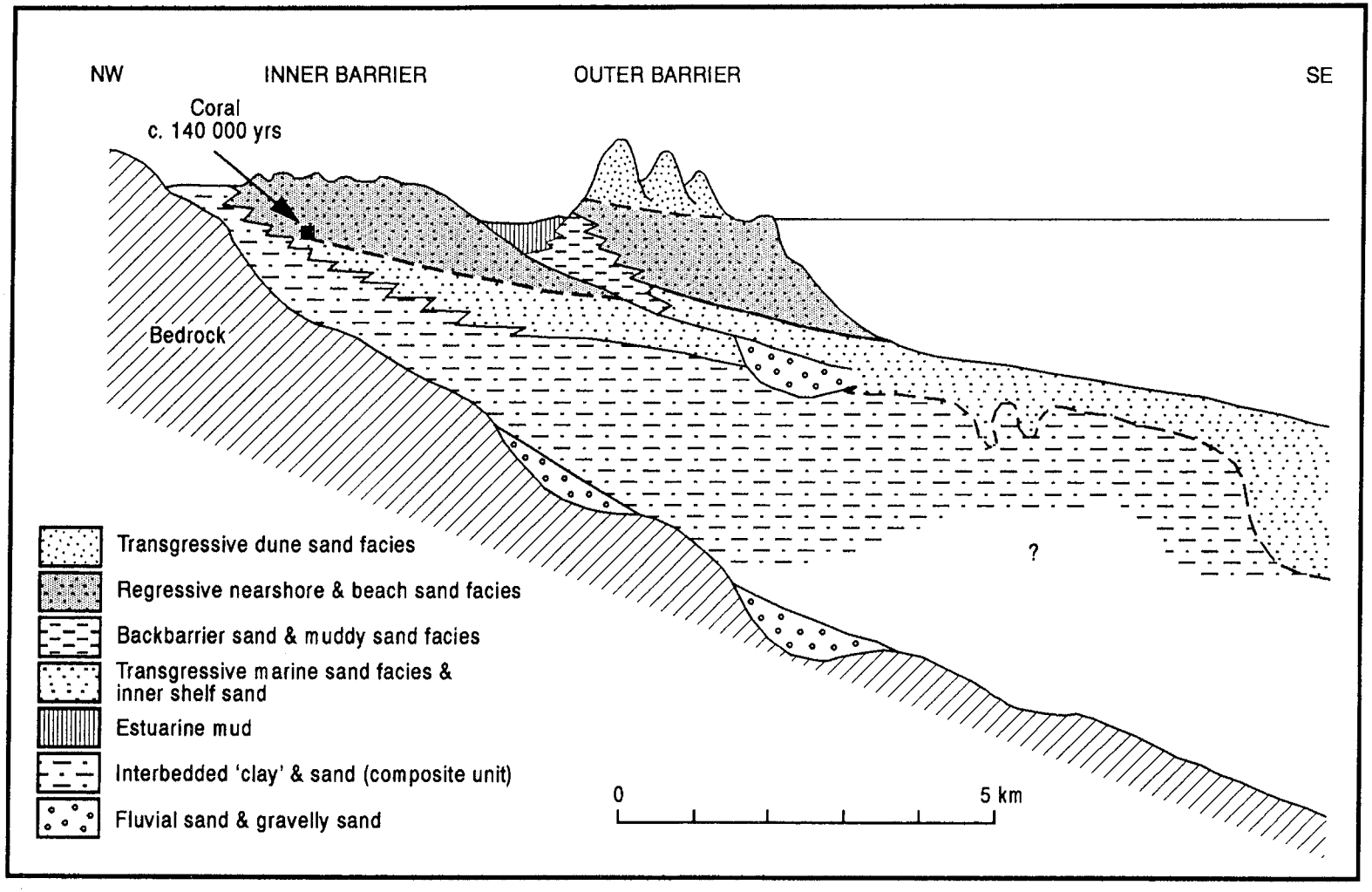

Figure 10-1: **Generalized stratigraphic section of the Newcastle Bight embayment containing an Inner and Outer Barrier showing most of the stratigraphic units as listed in Table 10-1. The relationship of one unit to another in this section is idealized in order to depict possible sequences of deposition in any given embayment.**

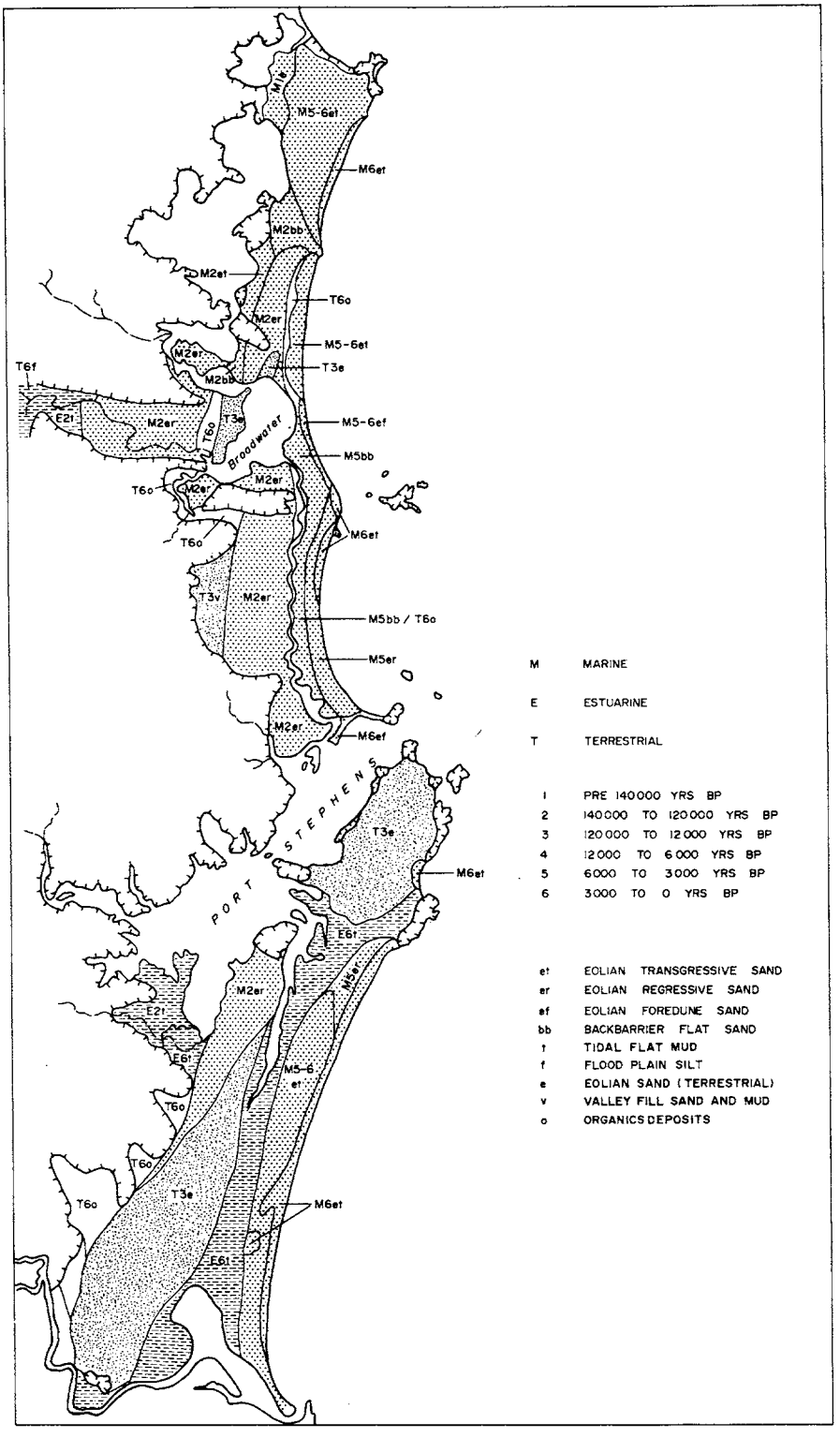

Figure 10-2: **Port Stephens-Myall Lakes area showing distribution of sedimentary units listed in Table 10-1.**

underlies the thick estuarine clay sequence (Q1E). During the Last Interglacial and Last Glacial periods fluvial deposition also occurred in several embayments (Q2Tc and Q3Tc). Wind action during the low sea-level period of the Late Pleistocene stage thick terrestrial dune sand sequences interbedded with thin fresh water swamp deposits in many localities of the Newcastle-Myall Lakes area (see Ch. 4). The dune sands are labelled Q3Te and the freshwater organics Q3To (Table 10-1).

10.1.3 Subdivision of the Holocene

10.1.3.1 Pleistocene-Holocene boundary.

The Pleistocene-Holocene boundary is placed between the Inner Barrier and Outer Barrier (Thom, 1965). An unconformity marks the beginning of the Postglacial Marine Transgression which caused the "drowning" of older coastal deposits. During episodes of low sea level, fluvial sediment was carried seaward and reworked northwards by littoral drift on the inner continental shelf (Roy and Thom, 1981). Soil formation on exposed Pleistocene marine and dune deposits resulted in the impregnation of these sands with humic colloids (humate) (see Fig. 4-18). During the Holocene transgression some of the continental shelf sediment was transported landward over the older surfaces of the Pleistocene deposits. In most drill holes, a distinct horizon separates Holocene from the Pleistocene deposits. This contact is exhibited by sharp sedimentological breaks, and often the presence of humate or a leached grey sand devoid of carbonate.

10.1.3.2 Marine sequence (Q4M, Q5M, Q6M).

The Holocene sequence is divided into early (Q4), middle (Q5) and late (Q6) (Table 10-1). During the early stage of the Holocene, part of the coastal area was affected by rising sea-level, and older surfaces were covered by transgressive marine sediments. Radiocarbon dating on molluscan fragments and peats has indicated that early Holocene deposits were partially reworked. Much of this material was transported landward to the present-day coast for the formation of the Outer Barrier (Roy and Thom, 1981).

Sea-level became stable at a position very close to the present sea-level between 6500 and 6000 years BP (Thom and Chappell, 1975; Thom and Roy, 1985). Since that time, a marine regressive sequence has formed with the development of beach ridges, transgressive dunes, backbarrier flats and lagoons. Most coastal accretion appears to have occurred in the mid-Holocene (6000 to 3000 years ago).

The late Holocene of the study area is characterized by phases of transgressive dune formation and a relatively stable or eroding shoreline. Filling of interbarrier depressions by marine, eolian and estuarine materials has occurred either by direct transportation from the marine to the dune environment, or by erosion of sand barriers, particularly the Outer Barrier.

The Holocene regressive marine sequence is composed at the base of fine quartz sand, moderately sorted, unimodal or bimodal and with abundant mollusc shells (Q4Mnt or Q5Mnr). This sand of nearshore marine origin is overlain by coarser and better sorted unimodal sand and negatively skewed sand of beach (and surfzone) origin (Q5Mbr). The

Table 10 - 1

Stage	Q1	Q2	Q3
Age (yrs BP)	>140,000	c.120,000	120,000-10,000
Dominant processes	Multiple transgressions and regressions induced by glacio-eustatic cycles leading to deposition of estuarine mud in lagoonal basins behind "proto-barriers" located seaward of present shoreline	High sea stand(s) +4 m; marine transgression to head of embayments leading to formation of strand plain composed of multiple beach ridges (Inner Barrier)	Lower sea levels than present with river channels incised into Pleistocene sands within embayments; river sands transported seawards of present shore; eolian reworking of Pleistocene sands; humate accumulation in sands
Environments of Deposition M - MARINE	e dune sand	nt nearshore transgressive sand bt beach transgressive sand nr nearshore regressive sand br beach regressive sand er eolian regressive sand bb backbarrier sand	
E - ESTUARINE	mm estuarine clay	mm estuarine clay t tidal flat mud	sbb shelly sandy bay?
T - TERRESTRIAL	e dune sand	c channel sand dsm deltaic sand and mud f floodplain silt	c channel sand e dune sand hu humate-impregnated sand o swamp?

Stage	Q4	Q5	Q6
Age (yrs BP)	10,000-6,500	6,500-3,000	<3,000
Dominant processes	Marine transgression enters embayments with shoreline recession involving extensive backbarrier deposition and tidal delta formation into lagoons with mud basins	Termination of transgression close to present sea level (± 1m); development of Outer Barrier at mouth of embayments involving strandplain formation, foredune and transgressive dune growth; estuarine mud accumulation in drowned valleys	Cessation of shoreline progradation; phases of eolian instability with formation of transgressive dunes; infill of estuaries and lagoons
Environments of Deposition M - MARINE	nt nearshore transgressive sand bt beach transgressive sand bb backbarrier sand	nr nearshore regressive sand br beach regressive sand er eolian regressive sand et transgressive dune sand ef foredune sand bb backbarrier sand	ef foredune sand et transgressive dune sand b beach sand n nearshore sand
E - ESTUARINE	d tidal delta sand m estuarine mud s bioherm shell sbb shell sandy bay	d tidal delta sand m estuarine mud sh estuarine shoreline s bioherm shell t tidal flat mud l lagoon organic mud	d tidal delta sand m estuarine mud sh estuarine shoreline sand t tidal flat mud lsm lagoon shore sand and mud l lagoon organic mud
T - TERRESTRIAL	c channel sand o swamp	c channel sand dsm deltaic sand and mud o swamp	c channel sand dsm deltaic sand and mud f floodplain silt o swamp

Table 10-1: **Environments of deposition and facies types for the Port Stephens-Myall Lakes area. Q1 to Q6 designate specific Quaternary events that have been identified in this area.**

sequence is terminated at the top by a fine to medium-grained well to very-well sorted, unimodal, and positvely skewed sand (Q5Mer).

Landward of the Holocene marine sequence are backbarrier deposits (Q4 or Q5Mbb). These form an elongated, shore-parallel sandy to muddy sand lithofacies (Fig. 10-1). Backbarrier sands tend to thin landward and grade into estuarine sediments. The sands have accumulated in shallow water or intertidally behind a low relief barrier by washover and eolian processes; shells are sparse except adjacent to estuaries where rich estuarine faunas occur in sandy bay (Q4 or Q5Esb) or tidal channel (Q4 to Q6Ec) environments.

10.1.3.3. Estuarine sequence (Q4E, Q5E, Q6E).

The Postglacial rise of the sea-level promoted the development of estuarine-lagoonal environments, where both sandy and clayey sediments have been deposited. A marine transgression followed by a stable sea-level close to its present position since 6,000 years BP has permitted throughout the Holocene (Q4 to 6) transport of a large quantity of marine sand into the estuaries to form tidal deltas (QEd), sandy bays (QEsb) and channel sands (QEc). In addition to marine sand, varying amounts of terrigenous material have been brought down by the rivers and waves (QEsh). Estuarine muds have generally been deposited in deep, quiet basins (QEm), whilst some amounts of fine terrestrial sand have accumulated in the upper parts of estuaries to form deltaic and hillslope colluvial deposits (QTd, QTv).

10.1.3.4 Terrestrial sequence (Q4T, Q5T, Q6T).

Fluvial channel deposits composed of sand and gravel have accumulated throughout the Holocene (Q4-Q6Tc) whereas the flood-plain silt deposits within the coastal area are only of Late Holocene age (Q6Tf). Flood-plain deposits have prograded over the estuarine deposits which formed as pro-delta silts and clays in estuarine basins during the transgression (Q4 to Q6Em).

The P.M.T. and the associated rise of the ground water level produced swampy areas in which freshwater peat developed (Q4-Q6To). Peats occur in depressions between some beach ridges or behind sand barriers, and in swales blocked by wind-blown sands.

10.2 CORRELATION OF QUATERNARY DEPOSITS

10.2.1 Principles of Correlation.

In this study several criteria have been used to correlate morphostratigraphic units and buried stratigraphic units from one embayment to another. Along a compartmentalized coast such as this, with bedrock ridges separating depositional bodies (Fig. 1-1), it is necessary to apply a number of criteria to the process of correlation. Continuity of sequence from one locality to another is rare. In the following discussion six criteria have been applied:

(i) topographic position within an embayment, including elevation of surfaces related to water deposition;

(ii) degree of geomorphic development including impact of morphologic modification as defined by Thom (1975);
(iii) stratigraphic sequence of lithofacies and biofacies;
(iv) degree of soil development;
(v) vegetation association expressing the effects of (ii) and (iv) following the work of Myerscough and Carolin (1986); and
(vi) radiometric dates of primary and secondary materials associated with a particular depositional unit.

10.2.2 Correlation of Marine Deposits

Table 10-2 subdivides each embayment into two time units Holocene and Pleistocene. The above criteria can be successfully used to differentiate between marine sediments of Pleistocene age and those that are associated with the Postglacial Marine Transgression and subsequent "stillstand". Thom (1960, 1965) made the distinction between a Pleistocene Inner Barrier and a Holocene Outer Barrier on the basis of applying all the criteria listed above in Newcastle Bight, Fens, Upper Myall and Eurunderee embayments. This interpretation differed from the initial views of Bird (1961) for a similar morphostratigraphic sequence from Gippsland, Victoria, but agreed with the Pleistocene-Holocene identification of barrier types in central Texas (Le Blanc and Hodgson, 1959). Bird (1965, 1978) later revised the sequence at Gippsland where there is a clear distinction between Holocene and Pleistocene barriers (see also Jenkin, 1968; Ward, 1977; and Thom 1984).

In the four embayments of the study area mentioned above, there is little doubt that a major marine transgression and regression occurred sometime in the Late Pleistocene. In each case a single barrier complex, called the Inner Barrier, formed in a bayhead position blocking narrow valleys and diverting rivers (e.g. Hunter). The morphologic pattern of ridge and swale topography, subsequently "subdued" by slope processes, is very distinctive in Newcastle Bight, Fens and Eurunderee. However, the more deeply inset Upper Myall Valley contains a beach-ridge pattern which is more broadly spaced and eroded by river and gully action. These ridges are correlated with the Inner Barriers of the other localities on the basis of topographic position and soil development. The stratigraphic sequence of lithofacies, as far as it can be determined for Pleistocene marine sediments, appears to be similar in all four Inner Barriers.

Marine deposition of Pleistocene age is difficult to document in the Tomaree Hills area and near Seal Rocks. There are no exposed sand barriers of the Inner Barrier type in these areas. Furthermore, buried sand units did not yield unequivocal evidence of biofacies which could be related to marine environments of deposition. At Tomaree, the thick sands enveloping bedrock hills appear to be eolian in origin. Whether all or only part can be classed as "coastal" dunes in the sense of being drived from a "receptive shore", or whether they are "terrestrial" in origin (i.e. reworked marine sands during low sea-level phases), is difficult to determine. For this reason a query is shown against both Met and Te in Table 10-2. Near Seal Rocks the deeply leached dunes are more likely to be of the "coastal" type, but again there is some degree of uncertainty. In this area, a Pleistocene Inner Barrier equivalent was recognized beneath Holocene transgressive dunes (see Ch. 9).

Table 10-2

Stage	Q1	Q2	Q3
Age (yrs BP)	>140,000	c.120,000	120,000-10,000
Event	Pre-LIG high sea level(s)	LIG high sea level(s)	Last Glacial low and oscillating sea levels
Newcastle Bight	Periods of mud infill of embayment behind "proto-barriers"	Inner Barrier progradation associated with backbarrier and mud basin infill	Eolian reworking of west portion of Inner Barrier; Hunter River entrenched
Tomaree	At least one phase of eolian deposition post a period(s) of mud infill	Local eolian deposition and mud basin infill in Port Stephens	Eolian reworking from west
Fens	Periods of mud infill of embayment behind "proto-barriers"	Inner Barrier progradation (possibly in two phases)	Alluvial fill behind barrier minor fluvial incision
Upper Myall-Broadwater	Periods of mud infill of embayment behind "proto-barriers"	Inner Barrier progradation (possibly in two phases) and backbarrier formation	Entrenchment of Upper Myall River; eolian reworking of small part of barrier from west
Eurunderee	Periods of mud infill of embayment behind "proto-barriers"	Inner Barrier dune and beach ridge formation and back-barrier formation	Minor eolian reworking from west
Seal Rocks	At least one, possibly more, phases of eolian deposition with local mud infill	Local eolian deposition and mud basin deposition in Myall Lake; Yagon strandline formed	No data

Stage	Q4	Q5	Q6
Age (yrs BP)	10,000-6,500	6,500-3,000	<3,000
Event	PMT within embayment	Early "stillstand"	Late "stillstand"
Newcastle Bight	Marine transgression involving extensive backbarrier deposition and mud basin infill	Initial progradation of Outer Barrier and first phase of eolian transgression (Ridge I); further mud infill	Second and third phases of eolian transgression and foredune development
Tomaree	Minor marine deposition, eolian reworking and some organic accumulation	Local foredune development and shoreline erosion; organic infill	Local foredune development and erosion; continued organic infill
Fens	Marine transgression involving extensive backbarrier and tidal delta deposition	Progradation of Outer Barrier	Some erosion of Outer Barrier with development of foredune and local transgressive sand sheet
Upper Myall-Broadwater	Minor estuarine deposition in Upper Myall; onshore sand transport to form back-barrier flats	Continued estuarine deposition and shoreline reworking until closure of tidal delta and diversion of Lower Myall River; organic accumulation	Fluvial infill of river valley and lake with continued organic accumulation
Eurunderee	Eolian reworking of sand onshore to form transgressive sand sheet	Phases of dune formation involving formation of parabolic dunes and their stabilization	
Seal Rocks	Eolian reworking of sand onshore	Phases of dune formation involving development of massive long-walled transgressive ridge; at least one major phase of vegetative stabilization	

Table 10-2: Summary of depositional and morphological events which have taken place in each embayment in the Port Stephens-Myall Lakes area.

Holocene deposits are more easily correlated from one embayment to another. Radiocarbon dating enables a firmer age structure to be established within each area; the age sequence will be discussed in the next section. Morphology and facies relationships are clearly interpreted in the Holocene marine record. For instance, there is much less difficulty in distinguishing nearshore transgressive from nearshore regressive facies in Newcastle Bight particularly when supported by radiocarbon dates. Late Pleistocene transgressive materials are shown with a query in Table 10-2. Foredune and backbarrier sediments are well-developed in a number of embayments in the Holocene. Again in four bays (Newcastle Bight, Fens, Upper Myall-Broadwater and Eurunderee), a single bay barrier (Outer Barrier) can be recognized. The composite character of the Outer Barrier in Newcastle Bight has been demonstrated (see Fig. 4-1b). In Fens, beach ridges with similar characteristics to the remnant in Newcastle Bight, dominate the Outer Barrier. Langford-Smith and Thom (1969) used this locality as a type for Outer Barrier development. Parabolic dunes at Eurunderee constitute a distinctively different bay barrier morphology, yet soil development, vegetation associations as well as topographic position point to a coastal barrier origin in the Holocene. Linking Eurunderee and Fens is a complex foredune, or stationary barrier (Thom, 1974) formed across the mouth of Broadwater Lake. Here is one area where continuity between localities assists in correlation.

The Holocene section at Tomaree is restricted to narrow bedrock bays. Transgressive dunes and foredunes form "mini" barriers, the best developed being the dune complexes at One Mile Beach and Fingal Bay (Ch. 5). Eolian deposits of Holocene age dominate the Seal Rocks embayment. The massive long-walled dune and asymmetric dunes are of undoubted Holocene age. This was first evident on the basis of comparative soil development with beach-ridge areas, but has been more recently confirmed by ^{14}C dates. Morphologic "freshness", soils and vegetation are similar for dunes on the Newcastle Bight and Eurunderee Outer Barrier, and the Seal Rocks vegetated transgressive dunes. Complex foredune development at Lighthouse Beach is not unlike that observed at Broadwater and One Mile Beach. More detailed correlation of phases of eolian activity in the mid and late Holocene largely depends on radiocarbon dating (see below.)

10.2.3 Correlation of Estuarine Deposits

A feature of Table 10-2 is the recognition of estuarine mud basin deposits of Pleistocene age in all embayments with the possible exception of Seal Rocks. This unit is interpreted as a composite clay lithofacies with interbedded sand and shell layers. An undetermined number of discontinuities occur within the unit. In this study it is classed as one stratigraphic unit underlying barrier deposits of Pleistocene and Holocene age, and beneath younger estuarine muds and tidal delta sands in Port Stephens. The thickness of the unit is quite remarkable reaching 70 m in Newcastle Bight. Its only surface expression is the "lagoonal" flats behind the Inner Barrier in Newcastle Bight and perhaps Fens. Other Pleistocene lithofacies of estuarine origin are difficult to recognize.

In the Holocene there has been a relatively clear differentiation of facies units. Such units are absent in the Eurunderee and Seal Rocks

areas. Tidal delta sands are predominant in Upper Myall-Broadwater Bay, but at Fens it is the shell-rich sandy bay facies which is the most abundant unit (listed as common in Table 10-2). Shell bioherms are a unique feature of Port Stephens in the study area. This complex "barrier lagoon" contains a diverse array of depositional environments which span the Holocene period. Newcastle Bight embayment is also a diverse area for estuarine sediments, but with the exception of the tidal flat mangrove swamps of the delta, most of the estuarine material is buried by fluvial sediments.

10.2.4. Correlation of Terrestrial Deposits.

For completeness Table 10-2 contains an evaluation of the relative abundance of terrestrial environments of deposition of Pleistocene and Holocene age within each embayment. It must be made clear that these environments have not been the subject of detailed investigation. There appears to be considerable diversity in type and abundance of major terrestrial facies in each area.

Two embayments contain diverse terrestrial sediment records: Newcastle Bight and Upper Myall. In the former, the Hunter River has produced an array of features and deposits ranging in age and type from pre-Last Interglacial (e.g. basal gravels and sands of Fig. 10-1), to the modern delta silts which are burying tidal flats near Hexham. Included in the terrestrial group of this embayment are the longitudinal and parabolic dunes of late Last Glacial age near Tomago. These extend eastwards into the Tomaree Hill dune area. In the Upper Myall there is also the effect of a river on the sediment record. This effect is behind, within and in front of the Inner Barrier. Here peat swamps have accumulated in "drowned" swales incised during lower sea-levels (Thom, 1965). Eolian activity on the north side of Broadwater is intermediate in age between Inner Barrier and Holocene sand surfaces as suggested by morphostratigraphic position, soil development, and quite interestingly, also by vegetation association (Myerscough and Carolin, 1986, p. 424).

In Fens bay, the extensive basin behind the Inner Barrier remains an enigma. Here clays cover sand ridges preserving the ancient strandline alignment. These patterns are observed on air photos but not on the ground. It is possible that the restricted catchment behind the Pleistocene barrier was dammed and the clays deposited over the low-lying innermost sand ridges. Details of alluviation in this basin and on adjacent slopes remain to be determined. Likewise in the Eurunderee segment, in particular in the Myall Lake, there are no details on the sediment sequence of lacustrine (and estuarine) materials. The organic oozes have been simply sampled at the surface.

Soil development on vegetated surfaces in the period following deposition is a useful criterion for correlation. This is a "terrestrial" process, and for purposes of correlation certain assumptions need be made about the role of soil-forming factors other than time (see Bowman, 1979). Table 10-3 summarizes the properties of six soil types recognized widely in the study area (see Appendix A for soil profile descriptions). Each type is associated with sandy depositional surfaces of a certain age range (see 10.3).

Table 10 -3

Stage	Q1	Q2	Q3
Age (yrs BP)	>140,000	c.120,000	120,000-10,000
Environment of Deposition	Dune sand	Beach ridge sand	Parabolic or linear dune sand
Topography	Moderate relief, moderate drainage	Low relief, swampy, poor drainage	Moderate to high relief, moderate to free drainage
Vegetation	Dry heath to mixed forest	Wet heath or wet heath forest	Dry heath forest or mixed forest
Profile Thickness (m)	A_1 0.5-1 A_2 1.5-3 B_h +7	A_1 0.5-1 A_2 1 B_h to 10	A_1 0.5 A_2 1-3 B_h +5
Profile Characteristics	Deeply leached light grey sand (A_2) with sharp contrast to semi-indurated B horizon containing thick humate-rich columns or concentrations with bands of iron oxide; various colours	Water table usually perched on top of B horizon close to ground surface. Deeply indurated, locally hard, humate impregnated B horizon (up to 3% OM), becoming less indurated with depth	Sharp, convoluted contact between A_2 and B. Light gray, A_2 horizon. Dark brown to black, humic rich distinct columns in B containing leached white sand "pipes" up to 10 cm diam; mottled; quite cohesive along columns

Stage	Q4	Q5	Q6
Age (yrs BP)	10,000-6,500	6,500-3,000	<3,000
Environment of Deposition	Transgressive dune sand	Beach ridge or transgressive dune sand	Transgressive dune sand
Topography	Moderate to high relief, free draining dune sands	Moderate to high relief, free draining dune sands	Moderate to high relief, free drainage
Vegetation	Dry sclerophyll forest	Dry sclerophyll forest	Dry sclerophyll forest of Banksia woodland
Profile Thickness (m)	A_1 0.3 A_2 1-1.5 B_h 3-4	A_1 0.3 A_2 0.5-1 B_h 3	A_1 0.2 A_2 0.5 B_h 1
Profile Characteristics	Sharp convoluted contact between A_2 and B. Incipient columns and "pipes" in B, which varies in colour from light yellow to dark brown; mottled and locally cohesive nodules	Moderate to sharp contact between A_2 and B. B_h well mottled with slight column development but no "pipes"; some cohesion in B_h	Diffuse contact between A_2 and B. Light gray to gray A_2 grading to loose sand B horizon, slightly stained by colloids with weak brown mottles

Table 10-3: Soil environments and characteristics associated with each Quaternary event (Q1 to Q6) in the Port Stephens-Myall Lakes area.

10.3 LATE QUATERNARY CHRONOLOGY

10.3.1 Principles of Chronologic Sub-division of the Study Area

Several attempts have been made to interpret the region's geomorphic and geologic history (Thom, 1960, 1965; Shepherd, 1970; Ly, 1976; Roy, 1980, 1982; Thom, et al., 1981a). The initial attempt by Thom was regarded as both "tentative" and a "first approximation" (Thom, 1965, p. 33). The basis for this interpretation was "the geomorphic and pedogenic contrasts between the two sand barriers", supported by a few radiocarbon dates and a conceptual framework derived from barrier studies in the Gulf of Mexico (e.g. Le Blanc and Hodgson, 1959) and coastal dune studies in Oregon (Cooper, 1958). Four stages were recognized in the 1965 paper: (i) Late Pleistocene High Sea-Level Stage; (ii) Late Pleistocene Lowering and Low Sea-Level Stage; (iii) Early Recent Rising Sea-Level Stage; and (iv) Recent Standing Sea-Level Stage (Thom, 1965, p. 33-34).

The present study elaborates upon these earlier attempts. Two specific studies have aimed at unravelling problems of the age structure of Pleistocene and Holocene sand deposits. Marshall and Thom (1976) applied the uranium-series dating technique to corals recovered from the rear of the Inner Barrier at Grahamstown. Radiocarbon dates from Eurunderee, Fens and Newcastle Bight were used to interpret the age structure of bay barriers at those localities (Thom et al., 1978; 1981a,b).

Numerous additional radiocarbon dates from all embayments are reported in this monograph for the first time. The complete suite of radiometric dates on a variety of materials from an array of depositional environments is used in this section to arrive at what could be regarded as a "second approximation" to the late Quaternary depositional history. These dates are reported in the regional chapters of this study. Attempts have been made, where appropriate, to qualify certain dates due to inadequate understanding of stratigraphy, possibility of reworking, problems of post-death contamination, and other factors. Undoubtedly, new dates will result in modifications to the chronology outlined here. The fine detail of the Holocene record, in particular, deserves elaboration beyond what is presented in this section. However, it is our purpose to document what is known of the "established" chronology at this stage.

It is now possible to provide more detail on each one of the stages recognized by Thom (1965). A further stage is added to the sequence to cover depositional events prior to the Last Interglacial, and the last 6000 years ("stillstand") is divided into two stages. Each stage is renamed and subdivided on the basis of our interpretation of morphostratigraphic and radiometric data. Table 10-1 summarizes the age relations of major units using the classification scheme developed in this chapter for each embayment.

10.3.2 Pre-Last Interglacial Stage 1.

Inadequate stratigraphic and chronologic control severely limits any attempt to document time units in sediments earlier than the Last Interglacial. No sand barrier deposits of pre-Last Interglacial age have been recognized in the study area. However, Roy and Stephens (1980)

conclude that sands on the inner continental shelf in Newcastle Bight could form a "protobarrier" of mid-Quaternary age. A possible relationship of this shelf sand body to later coastal deposits is shown schematically in Figure 10-3.

Thick estuarine clays fill most bays in the study area. Drilling in Newcastle Bight and Port Stephens has revealed several apparent disconformities, the lateral continuity of which is not yet established. In the Upper Myall Valley two clay units have been observed separated by a fluvial sand layer (see 7.3.2.2). Figure 10-4 presents a model for the accumulation of these sediments in estuaries or lagoons behind reworked sand barriers. This model is discussed by Roy and Thom (1981). It would be useful to have a core or cores from these sediments to determine the paleomagnetic properties and possibly correlate at least the older units by using the magnetic reversal time scale. Amino acid dating of Anadara shells is another possible technique which could be applied to the dating of the clay unit. Similar clay sequences have been found in other embayments in N.S.W.; Drury and Roman (1982) report two dated interglacial clay units from the Richmond River Valley.

At Tomaree and Seal Rocks there are deeply podzolized dunes which appear to be older than Last Interglacial. Again, we have no way of establishing the absolute age of these old deposits. Their degraded morphology, thick A soil horizons, highly impregnated and thick B horizons, and morphostratigraphic positions are clear evidence of their relative antiquity (type 1 soil, Table 10-3). Deep drilling at Seal Rocks has established several possible time units (Fig. 9-10). We are uncertain as to whether these old Tomaree and Seal Rocks dunes are true coastal dunes or terrestrial reworked dunes. Nevertheless, it is clear that bedrock promontories protruding from an easterly direction onto the inner shelf have at these two localities served to trap sands. Roy and Thom (1981) have argued that coastwise movements of sand by littoral processes during periods of lower sea-level are locally interrupted by bedrock barriers. Southerly winds in these areas of abundant sand may be invoked to rework the sand into the bedrock hills. Thus, Seal Rocks and Tomaree form sediment sinks for eolian sands.*

Degraded, fossil cliffs and rock platforms occur landward of the Inner Barrier at Medowie (Newcastle Bight) and along the shores of Myall Lake (Galloway, 1965; Shepherd, 1970). The age of these erosional features is unknown. Roy and Thom (1981) have argued that similar features in central and southern N.S.W. may have been initiated prior to the Last Interglacial at sea-levels close to the present. Could they have been resculptured during an early phase of the Last Interglacial, or in the case of those bordering the Myall Lake, for a longer period associated with lake waves?

10.3.3 Last Interglacial Stage 2

Until 1976 it was not clear whether marine deposits of Pleistocene age, such as the Inner Barrier, were associated with interglacial or

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* Recent offshore sampling and drilling has revealed that headlands may also serve as "anchors" for sediment transport during periods of high sea-level (see Field and Roy, 1985).

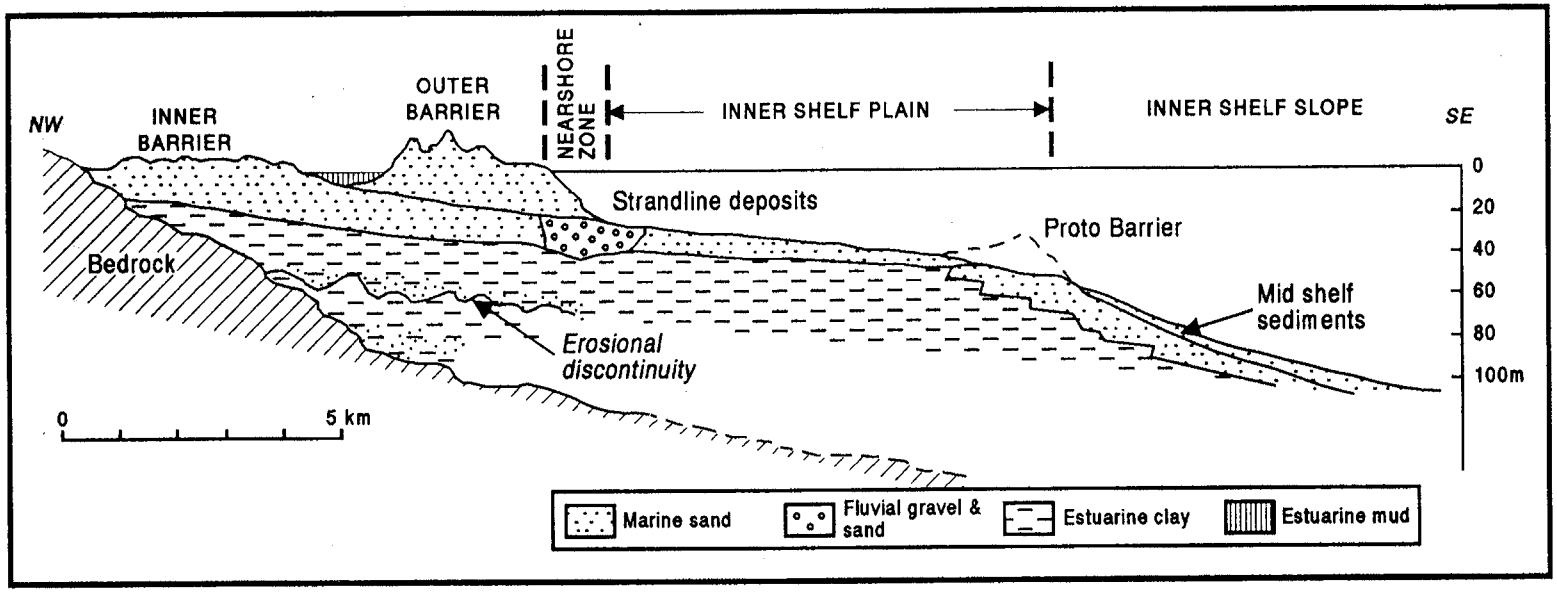

Figure 10-3: **Possible "protobarrier" on inner continental shelf formed prior to the Last Interglacial which is considered responsible for lagoonal-estuarine sedimentation within and seaward of present-day embayments during periods of lower sea level.**

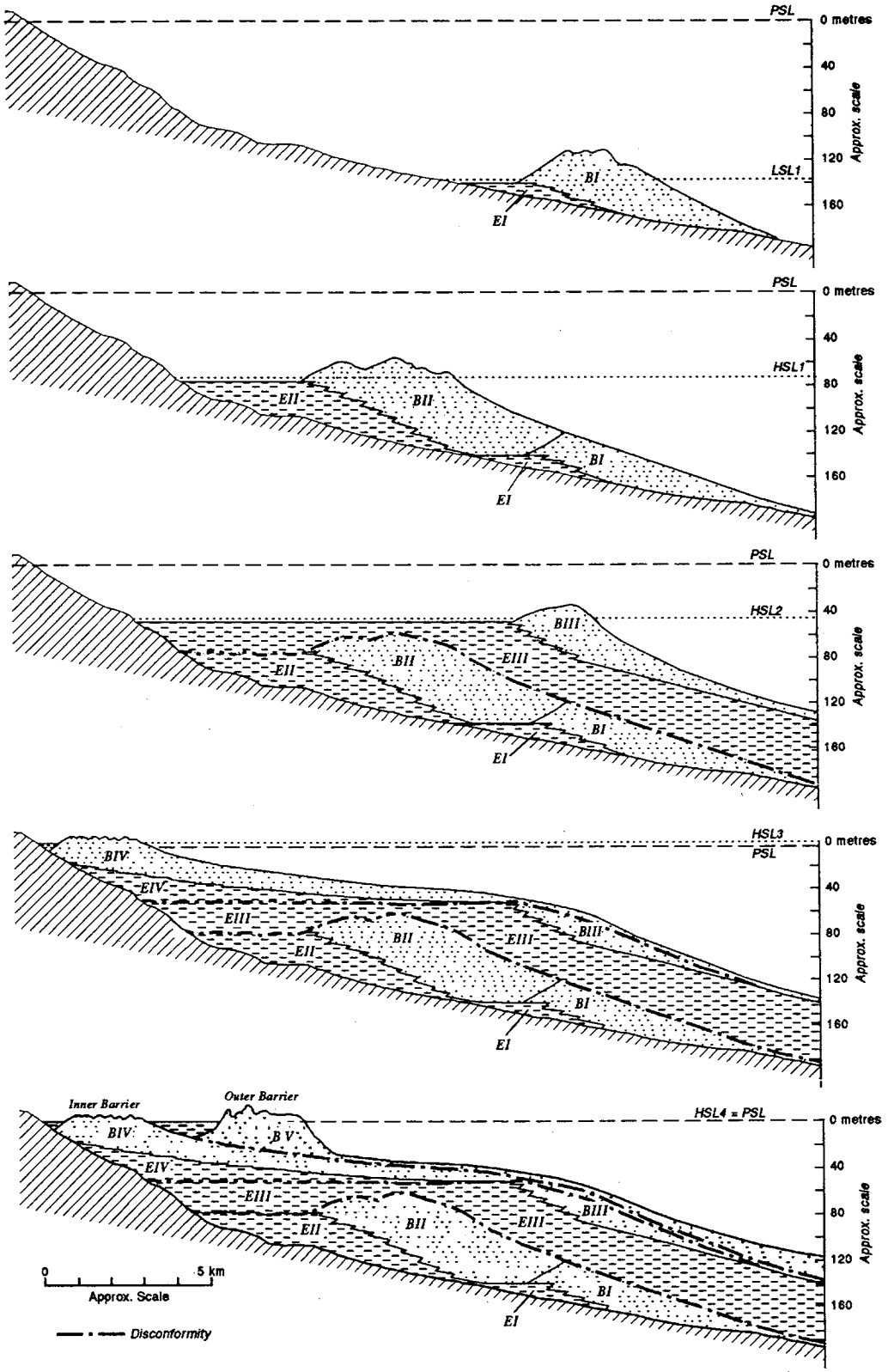

Figure 10-4: Model of episodic Pleistocene estuarine and lagoonal clay formation involving mud accumulation in paleoestuaries which reformed during glacial and interglacial low and high sea levels prior to and including the Last Interglacial. Mud deposition took place behind ephemeral proto-barriers during periods of high sea level (HSL 1 to 2) prior to the Last Interglacial. The Inner Barrier is shown as forming during a period of sea level higher than present in HSL3. The period shown as HSL4 is the Holocene. For simplicity barriers and estuaries BI/EI to BIII/EIII represent many barrier/estuarine complexes and are schematic only.

interstadial events (Thom, 1965, p. 33; Langford-Smith and Thom, 1969). In the early 1970s, a series of ^{14}C dates suggested an interstadial age within the Last Glacial at c. 30,000 to 40,000 yrs BP (Shepherd, 1970; Langford-Smith, 1973). This high sea-level event was correlated with interstadial shoreline features reported from a number of localities elsewhere (e.g. Hoyt et al., 1968). However, these dates imply a full glacial retreat, and they have not gone unchallenged (Morner, 1971; Thom, 1973. Post-depositional humate impregnation was responsible for contamination of old wood material incorporated in Inner Barriers (Polach and Thom, 1973). The discovery of unaltered corals at Grahamstown, and also near Evans Head on the northern N.S.W. coast, led to a more accurate evaluation of the age of these Pleistocene deposits using the uranium series dating technique. Marshall and Thom (1976) showed that the Last Interglacial, which is now globally recognized as a high sea-level event (Veeh, 1966; Shackleton and Opdyke, 1973; Ku, et al., 1974; Chappell and Veeh, 1978) was the period when widespread deposition took place within embayments north of Newcastle (see also recent work of Drury and Roman, 1982, in the Richmond River Valley). There is no radiometric evidence for a high sea-level depositional event at 105,000 years ago as recognized in southern Queensland (Pickett et al., 1985).

Unfortunately, coral samples have only been discovered in the study area in Newcastle Bight. Thus, it is not possible to use uranium-series dating to correlate Pleistocene marine deposits from one embayment to another. In the previous section, it was indicated that major marine facies of Pleistocene age are associated with the same depositional event (Table 10-2). In Table 10-1 these facies are designated as being formed in stage 2 (Last Interglacial).

The Last Interglacial high sea-level stage encompasses the immediately preceeding marine transgression phase which terminated close to 135,000 BP (Chappell and Veeh, 1978). It represents a period of c. 15,000 yrs of apparently oscillating sea-level following the termination of the transgression (ibid; see also Chappell and Thom, 1978). The marine regression which followed the Last Interglacial is only included in stage 2 until sea-level descended below its present position. The length of this stage in relation to the "eustatic" sea-level curve of the last 150,000 years derived primarily from New Guinea and Timor raised coral evidence, is shown in Figure 10-5.

The transgressive phase of stage 2 is expressed in two facies units (Table 10-1). In Newcastle Bight, the corals of Grahamstown were recovered at a depth of -7 m below MSL. This is a sandy unit rich in shell and some clay, and together with its stratigraphic-position, it is inferred that an open estuarine-backbarrier environment existed here as sea-level was rising c. 140,000 years ago. By c. 135,000 yrs BP the rapidly rising sea-level had transgressed this surface slightly reworking the shells and corals and transporting quartz-rich sands onshore to fill the embayment and initiate the Inner Barrier.

The history of marine transgression in other embayments at this time is nowhere near as clear. However, in Eurunderee there is a broad backbarrier surface behind the beach-ridge plain and a field of subdued parabolic dunes (see Ch. 8). Table 10-2 shows a clay unit (Met?) as forming in stage 2. It must predate the formation of the Inner Barrier beach ridges. The dunes appear to be "coastal" parabolics and are best

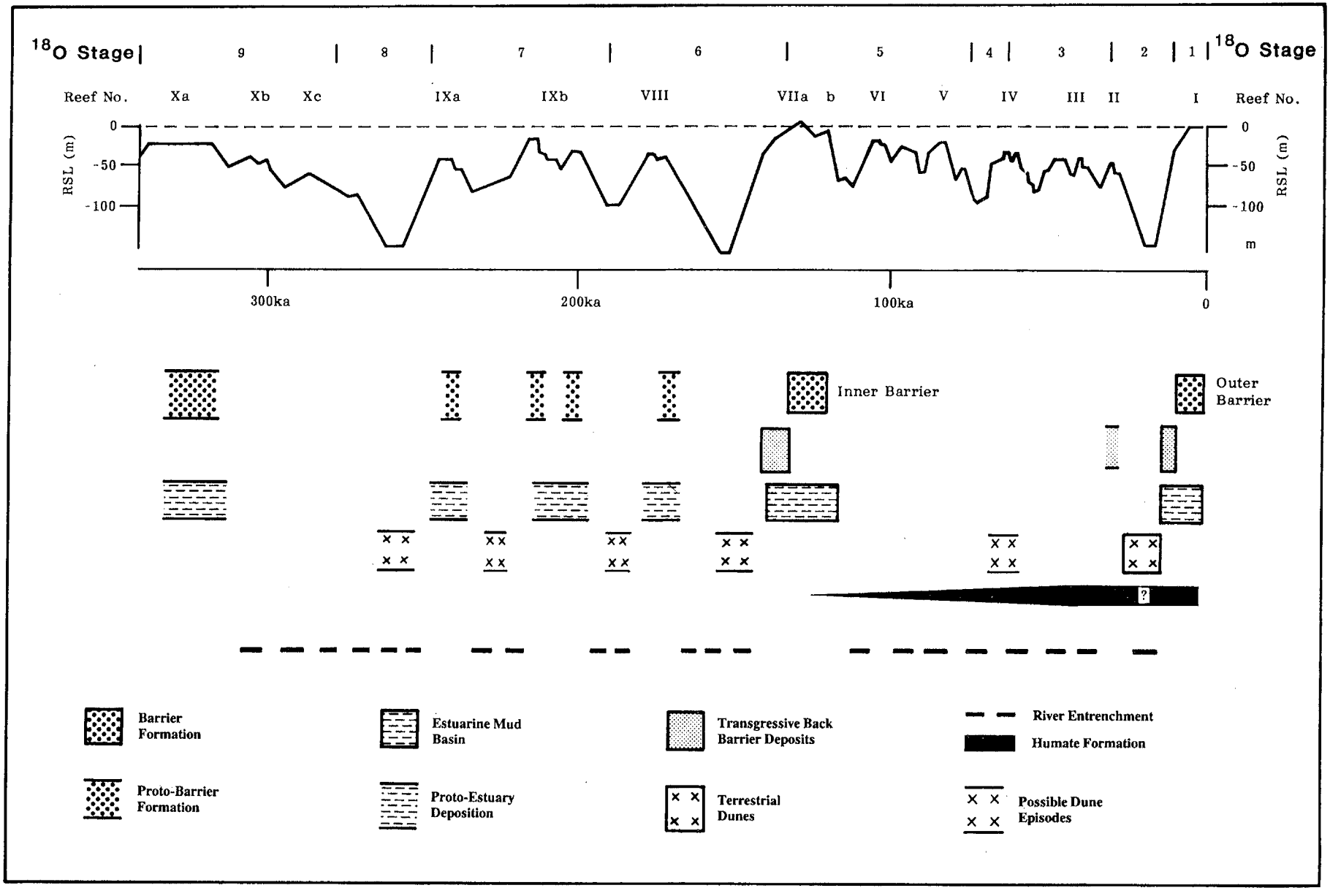

Figure 10-5: General relationships of late Quaternary sea levels (following Chappell, 1983; and Shackleton and Opdyke, 1973) and major sedimentary units in the Port Stephens-Myall Lakes area.

explained as developing from a receptive shore associated with the marine transgression of the Last Interglacial. Interestingly, the Pleistocene parabolics are oriented more towards effective winds from a southwest direction than similar dunes on the Holocene Outer Barrier.

At Evans Head, Chappell and Thom (1978) suggested that a plan unconformity in the beach ridges could represent two phases of the Last Interglacial. No similar discontinuity is evident in the beach-ridge plains of the study with the possible exception of the Inner Barrier in the Upper Myall Valley. In Chapter 7, it was noted that the seawardmost ridge of the series was broader than the rest and separated from other beach ridges by a very wide swale (Bombah Bog). It is possible that the outer ridge was formed during the second "peak" of the Last Interglacial high sea-level stage, but this is no more than conjecture at the moment. Similarly, the division of the Inner Barrier into a "buried" inner set and a more elevated outer set could be related to two events in the Last Interglacial (Ch. 6).

The question also arises as to the true age of shells recovered in drilling from beneath exposed and buried Inner Barrier surfaces in Newcastle Bight, and of estuarine shell beds at Largs in the Hunter Valley and in the Upper Myall River area (L. Drury, pers. comm.). No Pleistocene shells were sampled at other localities. Radiocarbon ages of these shells are either "Background" or are close to the limit of the method. The one date on articulated Anadara trapezia from Largs, is greater than 37,000 ^{14}Cyrs BP (0-1843). These shell deposits are assumed to be Last Interglacial in age: they are from near the maximum of the transgression at +4 m MSL; recent amino acid racemization by Colin Murray-Wallace on Anadara valves confirms the estimate of c. 125,000 years before present.

Figure 10-5 shows "eustatic" sea-level during the Last Interglacial to have risen above its present position. The Largs shell deposits, the fine-grained muds forming relict lagoon-tidal flats behind the Inner Barrier in Newcastle Bight, and the general elevation of the beach-ridge plains, suggest sea-level maxima in this stage of no higher than +6 m on present MSL. The error on this estimate is probably close to 1 m, but not greater than 2 m. Exactly when (and for how long) during the period of the Last Interglacial high sea level was it at this elevation, cannot be ascertained. It is suggested from the age range of corals on the N.S.W. coast (Marshall and Thom, 1976), and the size of depositional units associated with the event (Inner Barrier and equivalent lagoonal facies), that the length of the "stillstand" or "stillstands" exceeded that of the Holocene by a factor of 2 or 3.

It is difficult to identify a specific soil type as being Last Interglacial in age. In Table 10-3 those which occupy flat beach-ridge plains of Inner Barriers are assigned this age. These are ground-water podzols with thick Bh horizons (see Fig. 4-18).

10.3.4 Last Glacial Stage 3.

The period from close to 120,000 years ago until the early part of the Postglacial Marine Transgression (15,000 to 12,000 BP) is referred to here as the Last Glacial stage. This stage is characterized by oscillating sea-levels on the continental shelf. The levels were concentrated in the depth range -20 to -70 m MSL (the "modal" zone of Roy

and Thom, 1981), but they descended to depths of below -100 m especially during the maximum of the Last Glacial c. 20,000 yrs BP (see Fig. 10-5).

In this monograph we are primarily concerned with geomorphologic change in the present coastal zone and not continental shelf sedimentation. Growing interest in shelf morphology, stratigraphy and evolution is resulting in a rapid expansion of offshore knowledge. Roy and Thom (1981) have tried to combine shelf and coast processes and histories in a general model of Quaternary continental margin development. More recent drilling on the shelf in Newcastle Bight during the Sonne Cruise of 1980 has led to a further revision of much of what has been published in the papers cited above (von Stackelberg, 1982).

The coastal region has been differentially affected by a variety of processes during the Last Glacial period (stage 3). All these processes are referred to as "terrestrial" in Table 10-1. However, the impact of a "minor" marine transgression has been observed in Newcastle Bight (see below).

Eolian reworking of pre-Last Glacial marine sands was an important process in stage 3. Four embayments possess an eolian sedimentation record which can be best explained by sand transport associated with strong westerly winds during the Last Glacial. Longitudinal and parabolic dunes of the western part of the Inner Barrier in Newcastle Bight, near Tomago, are excellent examples of such features. The only ^{14}C dates which could assist in the age determination of the dunes indicate that sand was in motion c. 12,000 years ago (see Ch. 4). Large dunes such as the Duckhole ridge were probably initiated at least several thousand years before this. It is tempting to correlate these dunes with the last major phase of eolian activity in western N.S.W. Bowler (1976, 1978) estimates that dunes were formed in the Willandra Lakes 17,000 to 12,000 years ago. The absence of buried soils within the Tomago dunes suggests that only one phase of dune building occurred in this area late in the Last Glacial stage. However, some differences in soil development (types 3 and 4 in Table 10-3) suggest that dune stabilization was spread over a period of several thousand years.

Soil development has been used to correlate dunes of Tomago portion of the Inner Barrier Newcastle Bight with eolian sheets and dunes in Tomaree, Upper Myall and Eurunderee areas. A characteristic type 3 profile (Table 10-3) occurs on these moderate to well-drained sands. The problem of the age of the sandy swampland in the Tomaree region cannot be resolved at this time. The absence of finite radiocarbon dates on buried peats indicates that the deeper sand layers are older than the Tomago longitudinal dunes. On the other hand, it seems reasonable to postulate that active reworking of the surface of the dune sand mass took place in the Tomaree Hills-Salamander Bay area during the later part of the Last Glacial stage. Small areas of reworking in Eurunderee and Upper Myall are similarly considered to be of this age (see Chs. 7 and 8).

Fluvial erosion and deposition were also characteristic of the Last Glacial period stage when Hunter, Karuah and Upper Myall rivers incised their channels below present sea-level. It has not been possible to document or date alluvial fill of this period from the study area except for one date on wood near Hawks Nest (Ch. 6). Near Fullerton Cove there is some evidence of fluvial deposition (Roy, 1980). Incision of swales

and organic growth have been noted in the Upper Myall valley.

A prominent characteristic of the Last Glacial stage was the accumulation of humate in the B horizon of "giant" groundwater podzols of Inner Barriers (type 2 soils in Table 10-3). It was the recognition that these colloids were the product of illuviation and not primary deposition, and that they extended to depths of 10 m or more below present sea-level, which led Thom (1960, 1965) to argue that Inner Barriers must be Pleistocene and not Holocene in age. Radiocarbon dates referred to in Chapter 4 support the concept of vertical accumulation of humate from the base up as water tables rise during the later part of the Last Glacial (Fig. 4-18). Continued vegetation cover throughout the Last Glacial is not necessary as is shown beneath the "terrestrial" dunes of the Tomago area of the Newcastle Bight Inner Barrier. Here humate occurs below sea-level with similar properties to that beneath beach ridges in the eastern part of the barrier.

There is some evidence for a marine transgression dated close to 28,000 ^{14}C yrs BP. A.N.U. drill hole No. 84 in Newcastle Bight encountered a shelly sand facies at c. -40 m MSL. This unit is tentatively interpreted as the product of an interstadial high sea-level which reached about that level 28,000 years ago (Chappell and Veeh, 1978). Is it coincidental that the depth of this unit corresponds with the estimate of a Last Glacial high sea-level derived from uplifted coral terraces? Caution must be exercised in accepting the correlation, but both the stratigraphy and the one radiocarbon date are tantalizingly suggestive.

10.3.5 Postglacial Marine Transgression Stage 4.

As far as the coastal part of the study area is concerned, the P.M.T. did not commence until the invading sea reached into the embayments at depths of -30 to -40 m MSL c. 10,000 to 12,000 years ago. Of course, on the continental shelf the transgression commenced much earlier probably close to 17,000 yrs BP. The P.M.T. ceased when sea-level reached its present position between 6000 and 6500 years ago (Thom and Chappell, 1975).

Table 10-1 lists the major facies of this age which occur in each segment of the study area. All these stratigraphic units are buried below sea-level except for the transgressive dunes in Eurunderee and near Smiths Lake. Buried dune sands in the Eurunderee Outer Barrier and at Smith Lake date more than 7000 ^{14}C yrs BP. At Smiths Lake there are dunes burying a well-podzolized sand surface from which charcoal fragments have been dated 8815 $\pm$ 150 ^{14}C yrs BP (SUA-41). This area is included in the Seal Rocks Segment. Whether similar aged dunes exist at Tomaree is likely but not yet documented. Coastal dunes associated with the P.M.T. have been reported south of Sydney at Kurnell and Jibbon (Thom, 1978). Such local surges of eolian instability appear to be restricted to areas of strong exposure to southerly winds and waves. Beachface and frontal dune erosion during the period when the rising sea-level enters the bedrock compartments is suggested as the mechanism for releasing sand for inland movement behind a "receptive shore". This view agrees with the mechanism proposed by Cooper (1958). He argued that in Oregon, with a well-watered and vegetated coast, dune erosion required a rising, eroding sea-level (see also Pye and Bowman, 1984).

Remnants of nearshore and beach transgressive sediments occur in Newcastle Bight, Tomaree, Fens and Upper Myall areas. Reworking of shelly sands during the regressive phase following the termination of the P.M.T. probably results in the incorporation of much nearshore material into dune, beach and nearshore facies of younger ages. However, radiocarbon dates on marine molluscs of 6500 to 9000 ^{14}C yrs BP confirm stratigraphic data on the origin of the facies. Some of these dates were used by Thom and Chappell (1975) in the construction of the eastern Australia sea-level "envelope".

A facies associated with the P.M.T. is the backbarrier sand unit. Although observed elsewhere, particularly behind stationary barriers (Thom et al., 1978), it was in the Newcastle-Seal Rocks area that the nature of the facies was first defined. Sands were deposited as washover fans behind a narrow retreating barrier similar to that operating at present along parts of the Gulf and east coast of the U.S.A. It is envisaged that these sands spread into and rework deeper sandy bay sediments rich in shell (e.g. southern Fens bay). A relatively high proportion of backbarrier sands is preserved landward of and beneath present-day bay barriers. The process of backbarrier accumulation by the washover mechanism ceased soon after sea-level reached its present position (within 500 years?), because of the growth of high foredunes or beach-ridges to seaward.

Estuarine and alluvial valley deposition took place during the P.M.T. The Hunter River estuary, Port Stephens, Upper Myall and Broadwater were areas of both coarse and fine-grained sedimentation during the transgression as the sea "drowned" valleys incised during the Last Glacial. Only the upper part of the estuarine fill record of these localities has been dated in the study. The general pattern of sedimentation in estuaries along this coast is described more fully in Roy et al. (1980).

Organic colloid precipitation continued into the early Holocene as water tables rose in the Pleistocene sand barriers in association with sea-level rise. Thom (1965) over-emphasized this period as the main time for humate formation. We now know from ^{14}C dates near Tomago that illuviation was initiated in the Last Glacial and has continued to the present.

10.3.6 Mid Holocene Stillstand Stage 5

The period immediately following the termination of the P.M.T. was one of marked geomorphological change in the study area. Up until the commencement of this stage sea-level was rising at a rate of 10 mm/yr or greater, thereby creating, in the open-ocean depositional environment, the impetus for shoreface erosion and washover deposition. A new set of equilibrium conditions was initiated when the transgression ceased. These new conditions varied from one embayment to another, depending on the energy regime and available supply of sand in the nearshore zone.

At Newcastle Bight and Fens the morphological response to the new conditions was shoreline progradation. Outer Barriers were initiated within 500 to 1000 years of sea-level reaching its present position. Thom et al., (1978, 1981b) have demonstrated that prograded bay barrier formation occurred at this time at other localities in central and

southern N.S.W. Onshore sediment movement characterized the early part of stage 5. The beach-nearshore system attempted to adjust its configuration to a condition in which transfer of sediment from subaqueous to subaerial environments was minimized. A sedimentary regressive sequence of beach ridge, beach, and nearshore environments of deposition which dates from close to the termination of the P.M.T., is interpreted as a response of wave energy conditions to the relatively flat slope of the reworked transgressed surface, or "ramp" (Davies, 1974), once sea-level ceased to rise. It is envisaged that this slope (the nearshore gradient) was in disequilibrium with the energy conditions; in other words, excess sediment exists at this time as a temporary offshore reservoir or store. It is this material which was available for onshore transport by shoaling waves in the mid-Holocene period. Modes of strandline accumulation included beach ridges (Newcastle Bight and Fens) and large foredune development, such as occurred at Broadwater Lake.

Radiocarbon dates from within the regressive sediment wedge strongly suggest that progradation in the mid Holocene was episodic (Thom, 1978; Thom et al., 1978). There are insufficient dates from the study area to make a strong case for episodicity on the basis of dates from the nearshore shelly sand facies. However, the Outer Barrier at Newcastle Bight is a composite feature. The innermost, long-walled transgressive dune (Ridge I) dates older than 4000 ^{14}C yrs (see Ch. 4). It overlies beach ridges which are older than 5000 ^{14}C yrs. Soil development on Ridge I is consistent with a mid Holocene age (type 5, Table 10-3). Thus an episodic history of sedimentation is proposed for the mid Holocene stage at Newcastle Bight: (i) initial progradation and beach-ridge formation; (ii) eolian instability and transgressive dune development (Ridge I); and (iii) about 3000 to 3500 ^{14}C yrs ago, further beachface and foredune accumulation involving some degree of shoreline progradation with a vegetative cover developing on mobile dunes (Ridge I) to landward.

The radiocarbon history at Fens is more elaborate in stage 5 than elsewhere in the study area (see Ch. 6 for details). In summary, a narrow, highly mobile barrier first accumulated at present sea-level c. 6000 ^{14}C yrs behind which formed extensive washover deposits and low relief dunes. Close to 5000 ^{14}C yrs ago, the Outer Barrier commenced progradation and deposition continued, perhaps intermittently, until at least 3300 ^{14}C yrs. No transgressive dune episodes are evident in this embayment during stage 5.

Elsewhere in the study area along the open-ocean coast other modes of deposition can be recognized in the mid Holocene. High foredune development at Broadwater has already been noted blocking the lake and diverting the Upper Myall River into Port Stephens. Narrow bay barriers with foredunes, were formed in the small bays of Tomaree. Many of these possess well-developed soils which are now exposed in cliffs in eroding foredunes (e.g. at Fingal Bay and Shoal Bay).

At Eurunderee and Seal Rocks, the mid Holocene is characterized by episodes of eolian instability. Here there is little evidence of marine sedimentation. Various types of transgressive dunes occur, all of which appear to have been initiated behind a "receptive shore". However, once initiated, southwest to southeast winds have reworked the sands landwards. The few radiocarbon dates available from buried soils suggest several phases of eolian activity with at least one major event in the

mid Holocene. Buried peat at Eurunderee beneath the innermost parabolic dune, and part of the buried surface beneath the massive Bridge Hill transgressive dune near Seal Rocks, falls into the period 3700 to 4400 ^{14}C yrs BP. Certainly the soils of these surfaces are suggestive of a mid Holocene age (type 5 in Table 10-3). The few dates and the soils imply correlation of this eolian activity with Ridge I in Newcastle Bight (Table 10-2). Synchroneity of eolian activity between embayments, if firmly established, will provide further support to the climatic model for explaining secular variation in shoreline development, as proposed by Thom (1978).

During the 3000 years of the mid Holocene, estuarine, lacustrine, paludal and deltaic sedimentation continued. However, base level during this period was fixed ($\pm$1 m?) at present sea-level permitting, not only vertical accumulation, but also lateral spread of flood plains and tidal flats. There are some distinctive aspects of quiet-water sedimentation in each embayment. Early in the period, before a barrier completely sealed the embayment, estuarine muds and sands containing abundant Notospisula parva and Anadara trapezia, continued to be deposited in the incised Upper Myall Valley and around the sandy bay shores of the Broadwater. However, by 5000 to 5500 ^{14}C yrs lake waters were diverted south along the interbarrier depression of the Fens Embayment and estuarine shells ceased to live in the Myall-Broadwater Lakes. In Port Stephens, pro-delta muds continued to accumulate in deep basins throughout the period, but one radiocarbon date reported by Peat and Roy (1975) indicates that perhaps by 3000 ^{14}C yrs most of the shell bioherms had ceased upwards growth. Whether this change was induced by different water conditions in the estuary, or simply because the bioherms had reached close to present sea-level, is unknown. In the Hunter Delta, the broad estuary soon began to infill once the sea-level stopped rising. Estuarine shells recovered from the Eskdale Swamp on the lower Williams River, a tributary of the Hunter River, dated 5900 $\pm$ 145 ^{14}C yrs BP (0-1844). These shells are now covered by fluvial silts.

10.3.7 Late Holocene Stillstand Stage 6.

In comparison with the mid Holocene, the last 3000 years has been a period of much less geomorphic activity. There is no evidence for shoreline progradation during this period in the study area. Estuarine, lacustrine, paludal and alluvial valley sedimentation continued from the mid Holocene. Extensive tidal flats around Port Stephens and in the interbarrier depression of Newcastle Bight probably achieved their present configuration by the beginning of stage 6.

The most dramatic geomorphic phenomenon of the late Holocene are the surges of eolian activity behind open-ocean beaches. Two distinct phases are inferred from dated sequences and soils at Newcastle Bight, Eurunderee and Seal Rocks. The first is older than 1500 yrs but younger than 3000 yrs., the other less than 500 yrs. Even at Tomaree, Fens and Upper Myall-Broadwater there is evidence for at least one phase of coastal dune instability.

Newcastle Bight and Eurunderee both possess eolian events which can be interpreted as dating from these periods. A stabilized long-walled ridge, Ridge II, lies nested within Ridge I in Newcastle Bight (Fig. 4-1b). Unfortunately, it has not been dated directly, but its poorly developed soil type is consistent with the middle set of

parabolics of Eurunderee. A date of 2320 ± 110 ^{14}C years BP (SUA-251) was obtained on charcoal contained in a buried soil beneath the wall of one of these parabolics.

The sequence at Seal Rocks, where it has been dated, shows the progressive build-up of the massive Bridge Hill ridge. There are no Holocene dates from within the sand plain to the south. There are six dates from the Mineral Deposits Ltd. excavation at Bridge Hill which are less than 3000 yrs old. It is probably premature at this stage to classify the grouping of these dates into distinct events. However, it is tempting to divide the dates into two groups at 3100 to 2600 and 2300 to 1800 ^{14}C yrs BP. One date of 1265 ± 135 ^{14}C years BP (GX-5295) does not fit this division. Perhaps a more cautious interpretation is required of the Bridge Hill sequence, one that stresses the possibility of recurrent localized dune sand mobilization during the period from 4000 to about 1200 years ago. This area may be too exposed to southerly winds to be sensitive to minor climatic changes in the mid to late Holocene.

It is clear that sometime between 1200 to 1800 years ago mobile dune surfaces of the study area underwent stabilization by vegetation (see Ch. 9). The mechanism of stabilization remains a mystery, although it is probably a recurrent process which in Newcastle Bight and Eurunderee also followed the mid Holocene phase of dune instability. A model of Holocene climatic oscillation was proposed by Thom (1978) to explain the alternate and apparently synchronous phases of dune sand mobilization followed by vegetation stabilization.

The initiation of a new and contemporary phase of dune instability occurred by about 400 to 500 years ago. All open-ocean parts of the study area seem to have been affected by this phase. Beachface retreat and foredune erosion are characteristic of the event. Extensive wind erosion and landward migration of transgressive dunes also took place at this time, especially where sand supplies were abundant (c.f. Ridge III in Newcastle Bight). Thom (1978) has tentatively correlated the event with global climatic deterioration during the Little Ice Age, speculating that this was a period of higher intensity east coast storms and stronger onshore winds. However, this interpretation must be treated with caution. A tendency noted throughout the study area over the last 20 years for sand-binding plants to spread across the mouths of blowouts, within deflation hollows and over slipfaces may be more associated with a decline in grazing of cattle in the dunes than any other factor.

10.3.8 Summary

Figure 10-5 summarizes major geologic events over the last 700,000 years in the study area. It indicates that little is known of eolian-marine-estuarine sedimentation prior to the Last Interglacial (LIG in Fig. 10-5). In fact the record is so patchy before then that there is little chance of obtaining a useful chronology with the possible exception of the thick estuarine deposits. There are still many problems associated with the chronology of terrestrial eolian activity in the Last Glacial, especially in the Tomaree area. However, extensive drilling, morphologic mapping, soil studies and ^{14}C dating have enabled a reasonable Holocene chronology to be determined. Factors responsible for changing environmental conditions and process regimes in the mid to late

Holocene are not clearly understood. Further detailed studies of this and similar areas are needed before a more comprehensive understanding is achieved of how spatial and temporal variations in physical and biologic environments lead to different energy regimes and landform responses.

Epilogue

In the course of final preparation of this monograph a number of recent studies have been undertaken which have modified or clarified our thinking in some areas. These are briefly outlined below.

Two relatively new dating techniques have been used on materials from the Port Stephens-Myall Lakes region. Thom and Murray-Wallace (1988) reported on the application of amino acid racemization dating on samples of the estuarine mollusc, Anadara trapezia, collected near Largs in the lower Hunter River valley (GR 693805 Maitland 1:25000). It has long been suspected that this shell bed, elevated at +2 to 3 m AHD, was Last Interglacial in age. The racemization technique supported this conclusion, and demonstrated the time equivalence of the sediments at Largs with other Last Interglacial marginal marine strata in southern Australia (Murray-Wallace, et al., 1988).

In association with Dr. Edward Bryant of the Department of Geography, University of Wollongong, a number of thermoluminesence (TL) ages have been obtained on dune sand at sites on the Newcastle Bight Inner Barrier, and in the Tomaree Hills region. The TL dating provided ages ranging from 14,000 years to 20,000 years for the most recent phase of linear and parabolic dune building in the Williamtown, Lemon Tree Passage and Nelson Bay areas. At some locations these dunes overlie a stratigraphically older eolian deposit dated close to 30,000 years BP. The TL results support earlier conclusions derived from radiocarbon dating by Shepherd (1970) and subsequent morphostratigraphic research pointing to a period of active dune formation during the Last Glacial maximum (Thom et al., 1981a; Thom

et al., in prep). Furthermore, there is confirmation of a period of dune development prior to the Last Interglacial in the Tomaree Hills area (section 5.3.2.2).

Roy (1982) mapped discontinuities in the Inner Barrier beach ridges of the Fens and Tuncurry embayments (see Fig. 2.1). In the latter area recent research coupled with TL dating by Dr. Peter Roy and Dr. Edward Bryant indicates that the Inner Barrier in the Tuncurry embayment is a composite landform, part of which formed in the penultimate Interglacial. Whilst "Inner Barriers" have commonly come to be considered by some as Last Interglacial in age, we have often wondered if this is so. In fact, the greater degree of small stream and drainage development on the surface of the Upper Myall River-Broadwater Inner Barrier (Fig. 7-2), and the complex morphological pattern of the Boolambayte Peninsula (Fig. 7-3), have led us to suspect that these deposits may be older than the adjacent Eurunderee Inner Barrier. In addition, the morphology of the Inner Barrier in the Upper Myall Valley and position of Bombah Bog suggests that this barrier may comprise two separate phases or events (see Fig. 7-12).

Deep drilling by the Water Resources Commission in the Upper Myall embayment (WRD hole 39275) has yielded a diverse Late Pleistocene dinoflagellate microflora (McMinn, 1987). The composition of the assemblage reported by McMinn bears little resemblance to any previously described assemblage. It was inferred that the "assemblage was deposited in a subtropical estuarine/shallow marine environment" (McMinn, 1987, p.178). Pickett and others have suggested that the biota in the clays beneath Inner Barrier sediments accumulated prior to barrier emplacement (Pickett, 1981; McKenzie and Pickett, 1984). Further paleoecological work

is continuing on these sediments including those recently recovered from a deep drill hole by Roy in Newcastle Bight. Our interpretation is that the clays were deposited in deep estuarine waters, slightly warmer than present, that formed behind a trangressive barrier that was frequently being breached and overwashed by storm waves as sea level continued to rise. Full barrier development, which restricted access of marine waters to the estuaries, took place during stillstand and/or falling sea level periods (see Fig. 10-4).

Considerably more research on the offshore region has been conducted along the N.S.W. coast since this monograph was conceived and largely completed. In this regard Ferland (1990) has conducted a study of shelf sand bodies along the south-eastern coast of Australia. Shelf sand bodies are relativelly well defined, asymmetric convex sand lobes attached to headlands on the inner shelf (Roy, 1985). They are present in the Cape Hawke to Sugarloaf Point area in water depths of 30-70 m and sediment thicknesses of up to 30 m, and in the Port Stephens to Morna Point area in similar water depths. The evolution and age structure of these shelf sand bodies has been determined in the Sydney region (Field and Roy, 1984; Roy, 1985) and will be the subject of further publication by Ferland and Roy.

Independent research by Roy in connection with offshore mineral exploration has focussed on exploring the nature of large drowned barrier systems on the inner shelf in the Forster-Tuncurry area. These features were first recognised in northern NSW by Schluter (in Von Stackelberg, 1982) and some preliminary TL dates suggest that they formed during the marine regression leading to the Last Glacial maximum.

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Appendices

APPENDIX A

SOIL PROPERTIES: Newcastle Bight and Tomaree Areas

NELSON BAY PROFILE (Type 1)

Location:
Behind Nelson Bay Bowling Club (GR 196787; Port Stephens 1:25,000)

Vegetation:
Mixed *Eucalyptus - Angophora - Banksia* woodland on hillslope which has been partly cleared

Elevation:
c. 35 m msl

Profile description (in cm):

0-40 Sand; dark grey speckled; abundant particulate organics (including charcoal especially in top 2 cm) and roots; medium to fine, well sorted; slightly moist with some granular cohesion; grades

40-270 Sand; very light grey to whitish grey; roots penetrate; fine to medium, well sorted; single grains slightly moist; sharp contact to

270-360 Sand; yellow brown with orange brown mottles plus whitish grey sand patches; at contact see wavy dark brown to black discontinuous layer of organic stained sand, fine to medium, well sorted with grains coated with organic and iron stain; very slight cohesion of particles; this horizon contains columns of more cohesive dark brown organic stained sand (as face of exposure retreats the more stained patches stand out as miniature pedestals and pinacles); grading

360-860 Sand; variegated colors from yellow brown with orange brown to red brown to dark brown and black; fine to medium, well sorted; organic and iron oxide staining of grains and cementation of grains to form complex horizontal, vertical and circular (cell-like) patterns in the exposure; there are some organic-cemented columns and pipes; this horizon possesses thin iron hard pan layers quite discontinuous laterally and up to 10 cm thick; some suggestion that iron and organic staining follows primary bedding surfaces. Base of soil not observed.

Horizon	Depth (in cm)	"Particulate" organics %	"Colloidal Organics" %C	% 1.7C	Oxalic-extract hydrates Soluble % Fe_2O_3	Soluble % Al_2O_3
A_1	15-20	3.42	.80	1.4	.04	.008
A_2	50-55	.49	.11	.19	.04	.002
A_2	230-235	.02	.04	.07	.04	.002
B_1	280-285	nil	.10	.17	.80	.22
Bh_1	430-435	nil	1.20	2.0	.72	.28
B_2	500-505	nil	.84	1.4	5.17	.25
B_2	670-680	nil	.16	.27	.44	.23
B_2	710-720	nil	.12	.20	4.02	.23
B_2	850-860	nil	.09	.15	.62	.18

SALAMANDER BAY PROFILE (Type 3)

Location:
Adjacent to A.N.U. Drill Hole 67 in a borrow pit alongside Anna Bay to Salamander Bay-Soldiers Point Road (GR 127759 Morna Point 1:25,000)

Vegetation:
Mixed *Eucalyptus - Angophora - Banksia* woodland on dune hillock partially cleared.

Elevation:
c. 10m msl

Profile description (in cm):

0-14 Sand; grey, speckled; medium to fine, well sorted; abundant organic fragments including live roots; slight cohesion of grains; grading

14-94 Sand; grey; medium to fine, well sorted; abundant roots live and dead plus organic particulates; moist and slight cohesion; grading

94-217 Sand; light grey; medium to fine, well sorted; fewer roots some quite large; moist but single grained loose sand; sharp wavy contact to

217-282 Sand; mottled yellow with dark brown; medium to fine, well sorted; organic stained grains with some cementation into friable vertical columns quite black and indurated, 5-10 cm in diameter, containing in places light grey loose sand centres or "pipes"; few roots; grades

282-392 Sand; mottled light yellow brown with less marked darker mottles than horizon above; medium to fine, well sorted; columns persist into this horizon; also note weak horizontal organic layering 1 to 3 cm thick; very few roots; grades

392-700 Sand; mottled light yellow with brown; medium to fine, well sorted; black columns persist up to 1 m in length but less well indurated and more mottled with grey sand centres in places; pattern of mottling less well defined with depth; some signs of primary bedding, sub-horizontal, has been observed in this horizon. Base of soil profile not determined from exposure.

Horizon	Depth (cm)	"Particulate" Organics %	"Colloidal Organics" % C	% 1.7C	Oxalic-Extract Hydrates Soluble % Fe_2O_3	Soluble % Al_2O_3
A_1	7	.98	.42	.71	.03	.006
A_1	45	.24	.20	.34	.06	.004
A_2	184	nil	.09	.15	.04	.001
Bh_1	220	.05	.15	.25	.23	.15
Bh_1	243	nil	.65	1.1	.40	.25
Bh_2	304	.40	.14	.24	.10	.16
Bh_2	404	nil	.10	.17	.08	.090
Bh_3	650	nil	.13	.22	.10	.10
Bh_3*	650	nil	.54	.92	.16	.24
Bh_3	650	nil	.22	.37	.14	not enough sample

* Column at same depth

TOMAGO PROFILE (Type 3)

Location:
Exposure on flank of longitudinal dune in borrow pit near intersection of Tomago and "Masonite" Road (GR 848685 Williamtown 1:25,000).

Vegetation:
Partly cleared surface with remnants of *Eucalyptus - Angophora - Banksia* woodland. Bracken fern surface cover.

Elevation:
c. 8m msl

Profile description (in cm):

0-25 Sand; dark grey; rich in particulate organics and roots; medium, well sorted, slight cohesion; grades

25-60 Sand; light grey; few fine particulate organics; medium, moderately well sorted, single grained; grades

60-180 Sand; light grey to white; few fine organic particles; medium, well sorted, single grains;

180-190 Sharp contact, wavy whitish sand tubes penetrate below 190 cm. Sand; very dark brown to black forming vertical columns; moderately hard (friable in fingers); grades laterally, into brown sand containing orange brown nodules (Fe-rich?) with slight clay content; columns 5-15 cm wide; grades

190-260 Sand; yellow to orange brown; medium; coating of iron oxide or humate on grains; mottled, firm, friable in fingers; this horizon is penetrated by white sand "pipes" and dark brown columns; grades

260-350 Sand; yellow brown (lighter colour than above); medium; mottled orange and dark brown to black forming lower ends of columns locally enclosing very light grey sand "pipes", 5 cm thick; nodules, 3-7 cm wide, friable; grades

350-430 Sand; light yellow brown; medium, well sorted; weakly mottled, but slight staining of grains by iron or humate; slight granular cohesion.

Horizon	Depth (cm)	"Particulate" % C	"Colliodal" % C	Oxalic-Extract Soluble % Fe_2O_2	Soluble % Al_2O_3
A_1	10- 15	.80	1.75	.20	.044
A_2	40 -45	.18	.14	.04	.002
A_2	100-105	.13	.07	.06	.0007
A_2	160-165	nil	.08	.02	.0005
Bh_1	180-190	nil	.14	1.61	.12
Bh_1	220-230	nil	.07	.08	.002
Bh_1	240-245	nil	.10	.81	.15
Bh_2	240-245	nil	.13	.42	.19
Bh_2	360-370	.01	.17	.22	.16
Bh_3	420-430	nil	.12	.21	.15

ANNA BAY PROFILE (Type 5)

Location:
Exposure into innermost beach ridge of Outer Barrier at eastern end of Newcastle Bight near intersection Nelson Bay and Soldiers Point road (GR 125737 Morna Point 1:25,000).

Vegetation:
Cleared site for sand mining: *Eucalyptus* woodland

Elevation:
c. 6 m msl

Profile description (in cm):

0-20 Sand; dark grey; rich in organic particles (charcoal and living roots); medium to fine, well sorted; single grained to slightly cohesive; grades

20-97 Sand; light grey; medium-fine, well sorted; few charcoal particles and abundant roots; single grained; sharp change to

97-120 Irregular wavy contact zone with weak columnar structure; mixture of bleached sand, cohesive nodules 1-2 cm wide, dark brown, and columnar-cylindrical mottles, dull brown not cemented; some living roots; grades

120-177 Sand; dark brown to very dark brown; fine to medium, well sorted; organic stain on grains; nodules very friable, irregular shape to 8 cm wide some cylindrical with signs of vertical penetrating columns; mottles bright yellow brown and brown; grades

177-280 Sand; becoming more yellow orange; fine-medium, well sorted; mottled brown and dark brown slightly cemented but very friable; becoming more single grained with depth.

Horizon	Depth (cm)	"Particulate" % C	"Colloidal" % C	Oxalic-Extract Soluble $\%Fe_2O_2$	Soluble $\%Al_2O_3$
A_1	2-3.5	1.23	.30	.03	.018
A_2	25-26	.51	.10	.04	.004
Bh_1	38-39	.10	.17	.24	.055
Bh_1	55-56	.50	.29	.35	.17
Bh_1	62-63	.10	.11	.21	.11
Bh_2	95-96	.41	.09	.15	.052
Bh_2	95-96	nil	.17	.25	.10

SALT ASH PROFILE (Type 5)

Location:
Exposure on south-facing slope of Ridge I (GR 020718 Williamtown 1:25,000)

Vegetation:
Eucalyptus - *Banksia* woodland with patchy cover of bracken fern.

Elevation:
c. 23 msl

Profile description (in cm):
0-35 Sand; dark grey, speckled under thin discontinuous leaf-bark-twig-charcoal cover; living roots and charcoal particulates abundant;
35-180 Sand, grey to light grey: few charcoal pieces and abundant roots; fine, well-sorted; single grained; sharp change to
180-195 Undulating-wavy contact with small columns grade laterally to mottles in between columns with less humate cement of sand.
195-275 Sand; dark brown to brown; fine, well-sorted; friable, vertical columns weakly developed; elongate mottles yellow to dark brown; grades
275-520 Sand, brownish yellow; fine, well-sorted; becoming poorly brown mottled below 300 cm; single grained.

Horizon	Depth (cm)	% "Colloidal" C	$\%Fe_2O_3$
A_1	25	1.27	0.029
A_2	100	0.026	0.064
Bh_1	245	0.102	0.148
Bh_2	275	0.093	0.122
C	510	0.060	0.116

ANNA BAY PROFILE (Type 5)

Location:
Pit dug into swale of beach ridges of Outer Barrier at eastern end of Newcastle Bight adjacent to A.N.U. Drill Hole 53 (GR 113730 Morna Point 1:25,000)

Vegetation:
Eucalyptus pilularis - Banksia serrata woodland with abundant shrubs, bracken fern and *Imperata*.

Elevation:
c. 6m msl

Profile description (in cm):
0-20 Sand; dark grey; abundant roots and particulate organics; fine, well sorted; grades
20-110 Sand; light grey; roots; fine, well sorted; single grained; sharp too
110-130 Wavy contact, mottled dark brown cemented sand with light yellow loose sand, irregular mottle shape.
130-165 Sand; light yellow brown to dark brown; fine-medium, well sorted; irregular mottles elongate to 10 cm with incipient humate columns, dark brown with sharp contacts laterally to tan cemented sand; grades
165-235 Sand; light yellow; medium-fine, well sorted; becoming less cohesive, fewer mottles (brown) elongate downwards with depth.

Horizon	Depth (cm)	% "Colloidal" C	% Fe_2O_3
A_1	10	0.42	0.017
A_2	35	0.11	0.006
A_2	75	0.035	0.009
A_2	95	0.090	0.035
Bh_1	115	0.048	0.10
Bh_1	130	0.11	0.15
Bh_1	155	0.11/0.27*	0.22/0.11*
Bh_2	195	0.15	0.14
Bh_2	215	0.13	0.11
C	285	0.028	0.066

* column at same depth

SALT ASH PROFILE (Type 6)

Location:
Exposure on crest of Ridge II near A.N.U. Drill Hole 85 (GR 011705 Williamtown 1:25,000)

Vegetation:
Eycalyptus - Banksia woodland with abundant shrub cover.

Elevation:
c. 31 m msl

Profile description (in cm):
0-20 Sand; dark grey to speckled grey, fine, well sorted; abundant organic matter including roots and charcoal; grades
30-80 Sand; light grey to yellow grey; roots present; fine, well-sorted, single grained; grades
80-150 Sand; light brown; fine, well sorted; weak mottled brown, some cohesion with very friable nodules quite irregular; grades
150-200 Sand; yellow brown; fine, well-sorted; very few mottles, single grained.

Horizon	Depth (cm)	% "Colloidal" C	% Fe_2O_3
A_1	10	0.330	0.043
A_2	45	0.062	0.079
Bh_1	100	0.077	0.179
Bh_1	140	0.076	0.219

METHODS OF SOIL ANALYSES

Soil analyses were undertaken by Jim Caldwell, Department of Biogeography and Geomorphology, A.N.U. on dried samples.

(a) "particulate" organics by air-dry weight of material caught on 22 mesh sieve and material picked up by charged nylon where applicable.

(b) "colloidal" organics by Cr oxidation of sieved material, using arrowroot starch standards.

(c) iron by 3% warm $(COOH)_2$-extraction and spectrophotometric measurement of thircyanate complex at 480 u.

(d) aluminium by 48 hour cold 3% $(COOH)_2$-extraction, and A/A abs at 3093 A in N_2O/C_2H_2 flames of soln spiked with $i\text{-}C_3H_7OH$ for enhancement, 2000 ppm to suppress ionization K^+, and 50-5000 ppm Fe for iron match of standards to unknown.

(e) silicic acids freed by $(COOH)_2$, spectrophotometric measurement of silicomolybdenum complex at 415 u.

RADIOCARBON DATES: PORT STEPHENS-MYALL LAKES REGION

LAB NO.	FIELD NO.	MATERIAL	ENVIRON. CORRECTED ^{14}C AGE	CALIBRATED ^{14}C AGE	TRANSECT OR LOCALITY	ENVIR.
EMBAYMENT: Newcastle Bight						
SUA-1023	LL-1	S:Notospisula	3120±80	3380±270	Lavis Lane	Em
ANU-1525	83-7	S:fragments	6070±125	6890±310	Anna Bay	Mnr
ANU-1526	83-10	S:fragments	8260±295	-	Anna Bay	Mnt
ANU-1671	120-5	S:fragments	6440±170	-	Lavis Lane	Mnr
ANU-1672	120-7	S:fragments	7110±130	-	Lavis Lane	Mnt
ANU-1330	71-11	S:fragments	9520±1320	-	Anna Bay	Mnt
SUA-1148	AB-1	S:fragments	3040±90	3280±280	Anna Bay	Mnr
ANU-1331	NB-X	Wood	300±70	360±160	Anna Bay	Banksia
SUA-249	53-27	S:fragments	Bkg	-	Anna Bay	Mnt
ANU-1675	84-6	S:fragments	6770±220	-	Salt Ash	Mnr
ANU-1676	84-8	S:fragments	8500±145	-	Salt Ash	Mnt
ANU-1677	84-10	S:fragments	8100±165	-	Salt Ash	Mnt
ANU-1678	84-14	S:fragments	9280±130	-	Salt Ash	Esbb
ANU-1679	84-22	S:fragments	27730±2100	-	Salt Ash	Mbb
ANU-1332	78-4	S:est.frag.	4310±100	4990±340	Salt Ash	Em/t
ANU-1669	89-4	S:est.frag.	5410±190	-	Lavis Lane	Em
0-1844	-	S:Notospisula	5900±145	-	Eskdale Swamp	Em
ANU-1481	74-7	Woody Peat	8310±110	-	Bobs Farm	Et
ANU-1334	81-5	S:fragments	7780±330	-	Bobs Farm	Mnt
0-1843	-	S:Anadara	37000	-	Largs	Em/t
SUA-254	-	S:Anadara	Bkg	-	Largs	Em/t
SUA-104	-	S:fragments	8980±160	-	Stockton	Mnt
SUA-248	53-10	S:fragments	5380±105	6190±260	Anna Bay	Mnr
SUA-253	53-13	S:fragments	16280±360	-	Anna Bay	Mnr
Gak-1700	-	Peat	11300±250	-	Williamtown	To
Gak-1701	-	Peat	13700±600	-	Williamtown	To
NZ-197	-	S:Anadara	33000	-	Tomago	Mnt/nr
ANU-1333	69-12	S:fragments	37100+2950 -2150	-	Bobs Farm	Mnt
GX-3599	SK3529-3	Peat	32000	-	Lemon Tree	To

LAB NO.	FIELD NO.	MATERIAL	ENVIRON. CORRECTED ^{14}C AGE	CALIBRATED ^{14}C AGE	TRANSECT OR LOCALITY	ENVIR.
ANU-1482	SK3524	S:Bankivia	30800+3600 -2500	-	Salt Ash	Mnr
ANU-1492	SK3523-3	Humic acid	10450±140	-	Salt Ash	Humate
ANU-1494	SK3523-5	Humic acid	24100±600	-	Salt Ash	Humate
ANU-1495	SK3523-5	Fulvic acid	12580±270	-	Salt Ash	Humate
ANU-1496	SK3523-7	Humic acid	25350±800	-	Salt Ash	Humate
ANU-1497	SK3523-7	Fulvic acid	14100±380	-	Salt Ash	Humate
ANU-1575	SK3523-9	Humic acid	21260±1040	-	Salt Ash	Humate
ANU-1576	SK3523-9	Fulvic acid	19470-1060	-	Salt Ash	Humate
ANU-1535a	SK3523-4	Humic acid	18900±670	-	Salt Ash	Humate
ANU-1535b	SK3523-4	Fulvic acid	8980±870	-	Salt Ash	Humate
ANU-1524	88-4	S:fragments	5370±220	-	Oakfield Lane	Em
ANU-1544	121-3	Peat	6280±160	-	Cox's Lane	To
ANU-1668	119-4&5	S:Glycymeris	7030±100	-	Cox's Lane	Mnr
EMBAYMENT: Tomaree and Port Stephens						
ANU-1577	FB-Y	Humic	5890±160	-	Fingal Bay	Humate
ANU-1578	FB-Y	Humic acid	3950±60	-	Fingal Bay	Humate
ANU-1579	FB-Y	Fulvic acid	4270±90	-	Fingal Bay	Humate
ANU-1580	FB-Z	Humic acid	2170±70	-	Fingal Bay	Humate
ANU-1581	FB-Z	Fulvic acid	3140±120	-	Fingal Bay	Humate
0-1257	-	Stump	3150±115	-	Fingal Bay	Melaleuca
0-2158	-	Stump	5700±140	-	Fingal Bay	Melaleuca
0-2161	-	Stump	6550±150	-	Fingal Bay	Melaleuca
ANU-1327	80-3	Sandy org. clay	Bkg	-	Anna Bay	To
ANU-1328	66-8	Sandy peat	Bkg	-	Salamander Bay	To
SUA-246	50-13	Organic clay	Bkg	-	Salamander Bay	To
SUA-247	52-4	Peat	Bkg	-	One Mile Beach	To
SUA-366	-	S:Proxichione	2070±100	-	Bioherm P/S	Es
SUA-367	-	Peat	Bkg	-	Dutchies Bay P/S	To

LAB NO.	FIELD NO.	MATERIAL	ENVIRON. CORRECTED 14_C AGE	CALIBRATED 14_C AGE	TRANSECT OR LOCALITY	ENVIR.
EMBAYMENT: Fens						
ANU-1527	94-6	S:fragments	6590±220	-	Central Fens	Esbb
ANU-1666	94-3	S:fragments	5110±110	5930±280	Central Fens	Mnr
ANU-1529	95-8	S:fragments	6820±200	-	Central Fens	Mnt
ANU-1665	RZ-1	S:Prothalotia	4980±110	5950±280	Hawks Nest	Esbb
SUA-881	Fens N-2	S:fragments	5800±80	6660±240		Mnr
ANU-1530	96-6	S:fragments	5650±100	6490±190	Central Fens	Mnr
Gak-1469	-	S:Veletuceta	4930±80	5710±230	Northern Fens	Mnr
Gak-1470	-	S:Veletuceta	4950±80	5730±230	Northern Fens	Mnr
ANU-1528	95-6	S:est.frag.	4550±100	5280±300	Central Fens	Esbb
ANU-1336	60-13	S:fragments	4540±330	5180±820	Central Fens	Mnr
SUA-882	HN-1	S:fragments	4090±90	4680±320	Hawks Nest	Mnr
ANU-1531	93-4	S:fragments	3800±180	4290±550	Central Fens	Mnr
ANU-1532	93-6	S:fragments	3700±80	4130±310	Central Fens	Mnr
ANU-1335	60-7	S:fragments	5580±530	-	Central Fens	Mnr
Gak-1468	-	S:Anadara	5830±140	6700±330		Em/t
Gak-1702	-	Wood in peat				
Gak-2128	-	Wood fragment	13200±250	-	Hawks Nest Bridge	Tf
EMBAYMENT: Eurunderee						
SUA-252	57-7	Organic fragments	7280±250	-	Central Eurunderee	Soil
ANU-1673	54-4	Peaty sand	3620±130	4030±390	Central Eurunderee	To
SUA-251	-	Charcoal	2320±110	2420±340	Central Eurunderee	Soil
SUA-1056	-	Wood	870±65	-	Eurunderre blowout	Banksia
SUA-250	55-11	Organic	Bkg	-	Central Eurunderee	To

LAB NO.	FIELD NO.	MATERIAL	ENVIRON. CORRECTED ^{14}C AGE	CALIBRATED ^{14}C AGE	TRANSECT OR LOCALITY	ENVIR.
EMBAYMENT: Upper Myall-Broadwater						
0-1854	Hole L1	Organic mud	3675±120	-	Bombah Bog	To
0-1859	Hole L1	Wood	11075±230	-	Bombah Bog	To
ANU-1670	115-5	S:Notospisula	6100±130	-	Upper Myall R.	Em
SUA-909	113-4	S:fragments	5120±80	5930±260	Broadwater Lake	Esh
ANU-1543	109-6	S:fragments	6480±210	-	Broadwater Lake	Mbb
SUA-1220	-	Wood	385±75	-	Broadwater Lake	Banksia
SUA-1207	Hole L7	Organic mud	2860±90	-	Bombah Bog	To
SUA-1208	Hole L7	Organic mud	3810±150	-	Bombah Bog	To
SUA-1209	Hole L0	Organic mud	3500±90	-	Bombah Bog	To
SUA-1210	Hole L0	Organic mud	4120±110	-	Bombah Bog	To
SUA-1211	Hole L0	Charcoal & Wood fragments	8890±130	-	Bombah Bog	To
SUA-1212	Hole L0	Charcoal & Wood fragments	19860±240	-	Bombah Bog	To
EMBAYMENT: Seal Rocks - Smiths Lake						
SUA-41	-	Charcoal	8850±115	-	Smiths Lake	Soil
ANU-1533	106-7 & 8	Charcoal	>37000	-	Central Dunefield	Soil
ANU-1534	106-11	Humic acid	Bkg	-	Central Dunefield	Humate
GX-5295	-	Charcoal	1265±135	-	Bridge Hill Pit	Soil
GX-5294	-	Charcoal	3025±135	-	Bridge Hill Pit	Soil
GX-4833	-	Charcoal	2485±135	-	Bridge Hill Pit	Soil
GX-4122	-	Charcoal	1975±110	-	Bridge Hill Pit	Soil
SUA-647	-	Peat	2600±110	-	Bridge Hill Pit	To
SUA-648	-	Charcoal	3080±110	-	Bridge Hill Pit	Soil
SUA-649	-	Peat	4040±115	-	Bridge Hill Pit	To
SUA-650	-	Peat	>38,000	-	Bridge Hill Pit	To
SUA-651	-	Peat	2300±100	-	Bridge Hill Pit	To

NOTES ON RADIOCARBON DATING

1. Radiocarbon dates in Appendix B are listed in two ways: environmentally corrected ^{14}C age and calibrated ^{14}C age.

2. Environmentally corrected ages are based on conventional radiocarbon ages which are calculated using the Libby half-life of 5568 years and 0.95 times the activity of NBS Oxalic acid as the modern standard. The modern standard value was obtained by measuring a secondary standard (ANU Sucrose), applying an isotopic correction and using the conversion factor of Currie & Polach (Radiocarbon 22, p 933-5, 1980). The error is expressed at ± one standard deviation. To obtain an environmentally corrected age, a reservoir correction has been applied to offset the lower initial ^{14}C concentrations of surface ocean water. For pre-1955 A.D. marine shells from the Australian coast, the current best estimate is -450 ± 35 years (see R. Gillespie & H.A. Polach, p 404-21 in: Radiocarbon dating, Proceedings of the Ninth International Conference, R. Berger & H.E. Suess, eds., University of California Press, 1979). Conventional ages are equivalent to environmentally corrected ages except for shell samples.

3. Calibrated ^{14}C ages are based on the need to correct for past variations in ATMOSPHERIC ^{14}C CONCENTRATION so that events can be compared on a linear time-scale. For the last 7240 radiocarbon years, the calibration curve of J. Klein, J.C. Lerman, P.E. Damon and E.K. Ralph, 1982, (CALIBRATION OF RADIOCARBON DATES: Tables based on the consensus data of the Workshop on Calibrating the Radiocarbon Time Scale: Radiocarbon, v24, No. 2, p. 103-150) can be used. A rough guide to atmospheric ^{14}C concentrations before 7240 b.p. is given by M. Barbetti (Radiocarbon,, v22, p. 191-9, 1980); early Holocene conventional radiocarbon dates are likely to be around 800 years too young. Not all samples have been calibrated in Appendix B.

APPENDIX C

ANU DRILL HOLE NO.	GRID REF.	MAP SHEET 1:25000	APPROX. ELEVATION (MSL)	DEPTH (M)	TRANSECT/LOCATION
50	157769	Port Stephens	2	30.5	Salamander Bay
51	154769	Port Stephens	6	15.2	Salamander Bay
52	177755	Morna Point	7	12.2	Anna Bay
53	113730	Morna Point	6	45.1	Anna Bay
54	408045	Myall Lake	2	32.3	Eurunderee OB
55	407034	Bombah Point	2	30.5	Eurunderee OB
56	407036	Bombah Point	5	14	Eurunderee OB
57	407037	Bombah Point	6	15.8	Eurunderee OB
58	407052	Myall Lake	2	26.8	Eurunderee IB
59	369025	Bombah Point	8	14	Eurunderee IB
60	263904	The Branch	5	30.5	Fens OB
64	150782	Port Stephens	1.5	37.8	Salamander Bay
65	134773	Port Stephens	1.5	7.6	Salamander Bay
66	144770	Port Stephens	2	39.6	Salamander Bay
67	127759	Morna Point	2	32.3	Salamander Bay
68	113741	Morna Point	1.5	25	Anna Bay OB
69	079758	Morna Point	1.5	28.6	Bobs Farm OB
70	988715	Williamtown	1.5	26.8	Salt Ash OB
71	114737	Morna Point	7	23.1	Anna Bay OB
72	114739	Morna Point	2.5	14	Anna Bay OB
73	115745	Morna Point	1.5	21.3	Anna Bay OB
74	084747	Morna Point	1.5	23.8	Bobs Farm OB
75	076737	Morna Point	1.5	28.6	Bobs Farm OB
76	002716	Williamtown	1.5	28.6	Salt Ash OB
77	004711	Williamtown	2.5	14	Salt Ash OB
78	007714	Williamtown	1.5	6.7	Salt Ash OB
79	161736	Morna Point	1.5	39.6	Anna Bay OB
80	125749	Morna Point	1.5	14	Anna Bay IB
81	069728	Morna Point	2.5	35.3	Bobs Farm OB
82	009708	Williamtown	2	35.9	Salt Ash OB
83	114732	Morna Point	4.5	25	Anna Bay OB
84	015698	Williamtown	3	39.9	Salt Ash OB
85	011705	Williamtown	31	43.3	Salt Ash OB
86	972708	Williamtown	1.5	21.3	Oakfield Lane OB
87	972701	Williamtown	1.5	23.1	Oakfield Lane OB
88	974695	Williamtown	2	33.2	Oakfield Lane OB
89	937672	Williamtown	2.5	34.7	Lavis Lane OB
90	922680	Williamtown	1.5	29	Lavis Lane OB
91	908653	Williamtown	2.5	37.2	Cox's Lane OB
92	918644	Williamtown	7	32.3	Cox's Lane OB
93	265902	The Branch	7	36.6	Fens OB
94	255905	The Branch	3	25	Fens OB
95	258905	The Branch	7	29.9	Fens OB
96	259903	The Branch	8	25	Fens OB
97	241906	The Branch	1.5	23.1	Fens IB
98	224915	The Branch	2.5	22.2	Fens IB
99	209923	The Branch	3	17.7	Fens IB

ANU DRILL HOLE NO.	GRID REF.	MAP SHEET 1:25000	APPROX. ELEVATION (MSL)	DEPTH (M)	TRANSECT/LOCATION
100	224857	Port Stephens	1.5	30.5	Hawks Nest
101	240891	Port Stephens	1.5	17.7	Fens OB
102	242888	Port Stephens	1.5	4.9	Fens OB
103	317943	Bombah Point	1.5	28.6	Fens OB
104	317939	Bombah Point	2	10.4	Fens OB
105	488077	Myall Lake	3	37.8	Seal Rocks
106	474095	Myall Lake	10	21.3	Seal Rocks
109	358996	Bombah Point	2	21.3	Broadwater
110	357030	Bombah Point	2	20.4	Broadwater
111	331035	Bombah Point	2	19.8	Upper Myall IB
112	298047	Myall Lake		20.4	Upper Myall IB
113	344028	Bombah Point	1	16.7	Broadwater
114	270100	Bulahdelah	2	10.1	Upper Myall IB
115	277099	Bulahdelah	1.5	8.5	Upper Myall
116	694806	Maitland	6		Largs
117	219795	Port Stephens	3	31.7	Shoal Bay
118	222766	Port Stephens	4	30.5	Fingal Bay
119	915646	Williamtown	2.5	30.5	Cox's Lane OB
120	944662	Williamtown	1.5	35	Lavis Lane OB
121	911652	Williamtown	7	9	Cox's Lane OB