CHEMICAL AND CLASTIC SEDIMENTS
AND LATE QUATERNARY HISTORY,
PRUNGLE LAKES,
NEW SOUTH WALES

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Unless otherwise acknowledged this thesis represents my own work.

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ABSTRACT

The Prungle Lakes are part of the now dry Willandra Lakes system in semi-arid south western New South Wales. The Willandra Lakes have been a site of cyclic Quaternary sedimentation in response to the well documented global climatic fluctuations associated with the glacial-interglacial cycle.

The Prungle Lakes, being at the downstream end of the Willandra system, have been affected by hydrologic fluctuations, more often and to a greater degree than lakes higher in the system. At times of hydrologic stress, the low lake levels are associated with high salt volumes, inherited from evaporative concentration in the large shallow lakes upstream and the inflow of saline groundwaters. Thus, at Prungle, a complex array of concentric shorelines, lake floor terraces and lunettes have developed as basin-within-basin landforms which formed in response to filling and drying cycles. Sediments associated with these geomorphic units include:

Freshwater littoral, nearshore and deep water deposited laminated sands and muds, with biogenic carbonates chiefly of ostracodal and algal origin;

Evaporites comprising interbedded clay and laminated gypsum-clay couplets, which consist of discrete thin laminae of sugary white euhedral prismatic gypsum separated by detrital clay layers with a high degree of optical orientation. Primary accessory celestite (Sr SO₄) occurs as discrete patches within the gypsum laminae;

Groundwater pyramidal discoidal or lenticular gypsum crystals, grown from supersaturation produced by evaporation at the capillary fringe of
the water table, have formed displacively within the sediments and caused considerable disruption of the sediment matrix;

Aeolian deposition in irregular transverse ridges of sand-sized reworked groundwater gypsum and disrupted lacustrine clays. The gypsum crystals are predominantly discoidal pyramidal forms which are conspicuously oriented parallel to bedding, well sorted and extensively corroded. The clay pellets are well sorted and moderately well rounded. Higher in the profile, bedding becomes indistinct due to pedogenic processes, which include modification of detrital grains and secondary crystallization of gypsum and carbonate. A thin gypcrete horizon occurs at the surface.

The last cycle of sedimentation in the Prungle Lakes is believed, from correlation with lakes higher in the Willandra System, to have occurred during the period 50,000-16,000 years BP. Since then groundwaters have dropped below the zone of interaction with the lake floor and surface water no longer reaches the lakes. Sedimentation has ceased and soil formation with secondary carbonate and gypsum has continued to the present.

A range of sedimentary environments are identified which depend on strong seasonal oscillations. These environments are virtually absent from the continent today, and their occurrence during the Pleistocene supports the contention of enhanced climatic seasonality at that time.

The array of sediment types and mineralogies are almost identical to those characteristic of coastal sabkha sequences highlighting the difficulty of
relying on unusual evaporative mineralogy to differentiate marine and non-marine environments.

Detailed petrographic analyses of the Prungle sequence have been made in association with a review of theoretical, experimental and observational studies of the environmental controls of calcium sulphate mineralogy and crystal habit. This has enabled the correlation at Prungle of depositional environment with gypsum petrofacies and associated compositional, fabric or structural features. These observations are more generally applicable to other evaporite deposits. Many gypsum evaporites reported in the literature have been compared with this scheme developed at Prungle.
INTRODUCTION: Background to the thesis topic and presentation.

The Prungle Lakes are part of the now dry Willandra Lakes system in semi-arid south western New South Wales. Geological investigation of the Willandra Lakes commenced in 1967 with the work of Bowler (1971, 1973, 1986). His detailed work, over a number of years, established the lake system as a prime site for elucidating the Quaternary history of Australia. The location of the lakes in the semi-arid zone at the edge of the continental dunefield and fed by streams rising in the southeastern highlands, ensured their sensitivity to the major climatic fluctuations during the Quaternary.

Bowler's work was concentrated on the main lakes in the system particularly at Lake Mungo. In this relatively stable landscape of low relief natural exposures of the stratigraphy are rare. The exception to this limitation are the lake shore lee-side transverse dunes or lunettes which because of their high local relief and sandy nature are subject to both gullying and deflation. At Lake Mungo virtually the whole 25 km lunette is extensively deflated thereby exposing the internal stratigraphy. This enabled Bowler to devise a depositional model which related lunette sediment types to hydrologic stages in the lake, or to groundwater controlled processes. Using this model he documented a major cycle of lake oscillation from freshwater high lake level conditions, through progressive stages of hydrologic stress to the present dry-lake, soil-forming conditions. These conditions of hydrologic stress were felt first and were most effective at the downstream end of the overflow lake system. Thus the further downstream in the lake system, the earlier and more intense were the sedimentological and geomorphological processes associated with increased salinity, influx of groundwater and lake drying. This resulted in a more complex stratigraphy and basin morphology in those lakes.
It was after Bowler had established this regional stratigraphic framework, based essentially on lunette sequences, that a topic was sought for this Masters thesis. At the same time drill cores and tractor trenches were used to extend the stratigraphy to the lake floors. The Prungle Lakes were chosen for the thesis project. They had been visited previously by Bowler but not investigated in any detail as they were isolated from the main basins, at the far downstream end of the system, and lacked natural exposures of lunette stratigraphy. The complex basin-within-basin and multiple lunette topography suggested that the record of high salinity, groundwater controlled, deflationary and drying phases would be particularly well developed. Additionally, the presence on the inner lake floor of irregular aeolian ridges capped by white powdery gypsum suggested the development of high salinity environments not known from further upstream in the Willandra system. Similar ridges were known to occur in the saline groundwater discharge zones or boinkas in the northwestern Victorian Mallee (Macumber, 1980).

The availability of a tractor with a backhoe capable of digging to 3 metres, enabled the investigation of the lake floor sediments of the Prungle system, despite the total lack of natural exposures. A series of 13 trenches were dug in a transect across the lake basin, sited to sample all geomorphic units identified from aerial photography and ground surveying. Trenches in the inner lake basin exposed finely laminated lacustrine gypsum evaporites and associated aeolian and pedogenic gypsum-rich sequences in the irregular ridges. These sedimentary facies had not previously been found in the Willandra system.
The original aim of the thesis project was to examine the sedimentology and stratigraphy of the Prungle sequence and attempt to correlate the environmental record with the regional stratigraphic framework established by Bowler. Additionally, in elucidating the depositional environments of the sedimentary units, one aspect of the sedimentology would be chosen for more detailed work to be included in the thesis. The project was to be based mainly on thin section petrography with additional textural, chemical and mineralogical analyses. Once detailed laboratory analyses commenced it became apparent that the study of gypsum depositional environments was the most important sedimentological aspect of the study. This involved the correlation of gypsum crystal morphologies, sedimentary fabrics and associated components with particular depositional environments. Similar sediments occur in marginal marine lagoons (Caldwell, 1976; Arakel, 1980; Warren, 1982; Logan, 1987) and were subsequently identified in continental lacustrine settings (Lake Tyrrell, Bowler and Teller, 1986; Lake Frome, Bowler and Magee, in prep.; Lake Eyre, Magee et al., in prep.). However, detailed thin section analyses of the gypsum depositional environments had not been reported although Bowler and Teller (1986) initiated some aspects of this work at Lake Tyrrell.

Finely laminated calcium sulphate evaporites occur extensively in ancient evaporite sequences and there has been considerable disagreement as to their environment of deposition. Detailed petrographic studies of recent sequences, such as Prungle, where independent environmental information is available (such as water and solute source, climate, basin morphology etc.), can resolve many of these difficulties. Furthermore, the close similarity of sediment types and mineralogies at Prungle to those considered to be characteristic of coastal sabkha environments warns against the simple assumption of a marginal marine origin for such features in ancient
sequences. With these immediate applications for the thesis project in mind Dr. K.A.W. Crook, as supervisor, suggested that I prepare the thesis material for publication and submit the papers as the thesis.

In choosing to follow this course of action I have prepared two papers which accord with the original aims of the project. The first paper is a general treatment of the sedimentology and stratigraphy of the Prungle Lakes sequence, it then goes on to extend the high salinity phases of Bowler's generalized Willandra Lakes depositional model and attempts to correlate the Prungle sequence with Bowler's regional stratigraphy and chronology. This paper has been submitted to the proceedings of the 1988 SLEADS (Salt Lakes Evaporites and Aeolian Deposits) Conference to be published as a special issue of Palaeogeography, Palaeoclimatology and Palaeoecology. The second paper deals in detail with gypsum depositional environments in association with a review of theoretical, experimental and observational studies of the environmental controls of calcium sulphate mineralogy and crystal habit. This has allowed a correlation at Prungle of depositional environment with gypsum petrofacies and associated compositional, fabric or structural features. This correlation is believed to be more generally applicable to other evaporite deposits. Many gypsum evaporites reported in the literature have been compared with this scheme developed at Prungle. This paper has been submitted to the journal Sedimentary Geology.

Because the papers have been prepared for separate publication each must stand alone and some duplication has been necessary, for instance the general stratigraphy paper required a summary of gypsum-rich sediments and the gypsum sediment paper needed a general stratigraphic setting. Frequent cross referencing from one paper to the other has also been necessary.
In order to accord as closely as possible with the requirements for thesis presentation, an overall abstract and table of contents have been included at the start, figures are included with captions at appropriate places within the text and a single bibliography combining references from both papers is located at the end.

Much of the data obtained in the field and laboratory has not been included in the papers although it may have been drawn on to arrive at some of the conclusions. Such data would probably have been included in a conventional thesis. In order to make the most important components of this material available I have included appendices of additional information in the thesis. Included in these appendices are profiles of trenches not treated in detail in the papers and additional analyses of profiles presented in detail already. In general these are included only in an archivial manner, with no interpretive comments. The exception is the inclusion of water level curves constructed from facies analysis of two key trenches in the inner basin. These were not included in the papers because of the lack of absolute dating in the sections and because it was not possible the correlate accurately between the sections without additional intermediary information.
LATE QUATERNARY STRATIGRAPHY, SEDIMENTOLOGY AND PALAEOHYDROLOGY OF THE PRUNGLE LAKES, SOUTH-WESTERN NEW SOUTH WALES.

A. INTRODUCTION

The Prungle Lakes are part of the Willandra Lakes system of dry lakes in semi-arid south western New South Wales. Fed by the Willandra Billabong Creek, a distributary of the Lachlan River, the Willandra Lakes are located within the Mallee region, an east-west dunefield which takes its name from the shrubby eucalypt-dominated vegetation which now stabilizes the dunes. The Mallee, and the Riverine Plain to the east of it, are the physiographic regions which form the surface expression of the Murray Basin, a major Tertiary and Quaternary sedimentary basin in south-eastern Australia (Fig. 1).

Throughout the Quaternary, aeolian lacustrine and fluvial deposition in the Murray Basin has been cyclic in response to the world-wide glacial-interglacial climatic fluctuations (Bowler, 1980; Bowler and Wasson, 1984). During interglacial periods conditions were probably similar to those of today, with a stable landscape characterized by minimal regional deposition and the development of calcareous soils.

Numerous lake basins are associated with Pleistocene and modern river channels, particularly near the Riverine Plain-Mallee boundary. These
have been sites of intermittent deposition, synchronous with formation of the aeolian dunefield (Bowler and Magee, 1978). These lakes are characterized by lee-side, crescentic dunes (lunettes, Hills, 1940) formed from material derived from the lake basin.

Using a detailed radiocarbon chronology, Bowler (1971, 1980, 1986a, b) has developed a cyclic lacustrine depositional model associated with the glacial/interglacial cycle. He has used stratigraphic, sedimentologic, and pedologic evidence from many lake and lunette sequences from the Murray Basin, but most notably from the Willandra Lakes (Fig. 2). This cycle is characterized by a hydrologically controlled oscillation from dry soil-forming conditions, to high fresh lake levels, to saline lake levels and finally a return to dry conditions. Its deposits are underlain by those of previous cycles believed to represent previous glacial episodes. At Lake Mungo in the Willandra Lakes, Bowler and Magee (1978) reported the possible presence of three such cycles. At Lake Tyrrell, Bowler and Teller (1986) also reported three cycles which they examined in more detail.

This paper is concerned with the stratigraphy and sedimentology of lake floor deposits at the downstream end of the Willandra system where, as the lake system dried up, the effects of low water levels and increasing salinity had their first impact, and persisted for longer than anywhere else in the lake system. Thus at Prungle an array of geomorphic units and evaporite sediments are preserved which do not occur elsewhere in the Willandra system and which are more typical of playa lakes of more arid areas. These geomorphic units and the sediments associated with them are described in detail and the depositional model developed by Bowler (1980, 1986a, b) for lunette-lake sedimentation is expanded to include the observed facies variations. Although restricted by the absence of isotopic dates, an attempt
FIGURE 1. Regional geomorphic map of the Murray Basin in southeastern Australia, showing the two main physiographic components, the Mallee and the Riverine Plain. The inset shows the location of Figure 2. Modified after Bowler (1971); Bowler and Magee (1978).
is made to correlate the Prungle sequence with Bowler's regional palaeohydrologic history.

1. REGIONAL SETTING.

a. Geology and physiography.

The Murray Basin is a sedimentary basin, of more than 310,000 sq. km. in southeastern Australia. It forms an area of dominantly low relief surrounded almost entirely by highlands (Fig. 1). Sediments in this shallow tectonic basin are dominantly derived from the highlands and consist of both continental and marine deposits of Tertiary and Quaternary age (Lawrence, 1975; Brown, 1986). Post-Eocene division of Tertiary sedimentation in the Basin into marine western and non-marine eastern sections has resulted in a distinctive array of lithologies and topographic forms. These early sediments are covered by an almost continuous, but relatively thin, veneer of Quaternary terrestrial sediments, the nature of which strongly reflects divisions in the underlying Tertiary. In the east, fluvial sedimentation has continued, forming the physiographic region known as the Riverine Plain (Butler et al., 1972). In the west, aeolian reworking of marine littoral sands has resulted in the widespread dunefield landscapes of the Mallee region (Storrier and Stannard, 1980).

The Riverine Plain is an extensive depositional plain of interbedded alluvial sands and clays conformably overlying Tertiary alluvium deposited by a distributary system of rivers. Superimposed on these deposits are younger palaeo-stream traces forming a tributary system draining to the west, as do the present streams. In the Mallee, redistribution of the Pliocene littoral Parilla Sands exposed by the final
marine regression blanketed the Tertiary marine sequence and the Blanchetown Clay, a widespread Lower Pleistocene lacustrine unit formed by tectonic damming of the Murray River (Bowler, 1980). The age of the initiation of this aeolian deposition is not known but An et al., (1986) suggested that all the dune sequences post-date the Brunhes-Matuyama palaeomagnetic boundary at about 730,000 BP. These extensive but now stabilized desert dunes are part of the Central Australian dunefield (Jennings 1968).

b. Climate

A strong climatic gradient exists across the Murray Basin, paralleling the topographic gradient from the southeastern highlands to the continental interior. An increase in temperature and evaporation is accompanied by a decrease in amount and reliability of rainfall. Thus the source area of the Lachlan River/Willandra Creek system lies at over 1000 metres above sea level in the relatively well-watered highlands north of Canberra, whereas the Willandra Lakes occur in the higher evaporation regime of the semi-arid zone.

The climate of the Willandra Lakes region is typically semi-arid. Annual rainfall averages about 250 mm and is distributed evenly throughout the year. Although rainfall in summer is often of higher intensity than in winter, it tends to be less reliable. Mean annual evaporation is approximately 1600 mm, exceeding rainfall in all months, especially in summer when the nett moisture deficiency is at a maximum. Temperatures in the region show the influence of continentality, particularly with respect to the extremes which can occur. In general, summers are hot, with maxima commonly above 35°C. Winters are cool,
with maxima around 15°C and frosts common at night. Winds in the region are controlled by the migrating pressure systems swinging from north westerly to south westerly or southerly with the passage of a cold front.

Even the most extreme events of present climatic variation are insufficient to reactivate the processes which, during the Pleistocene, formed the landscape we see today. Mallee vegetation is able to survive the most severe droughts, thus preventing any reactivation of the dunefield, and during the wettest of years flow along the Willandra Creek does not reach the most northern basins of the system. The landscape is essentially fossil and inherently stable under the current climate except where European settlement has affected the balance with grazing animals, clearing for cultivation and changes in the natural fire regime.

The temperature and rainfall regime which operated in the region during the Pleistocene is not known from any direct evidence. Bowler (1975) has argued, from the geomorphological processes active at the time and from assumptions about the atmospheric circulation, that whilst summers might have been at least as hot as those of today, winters were probably much colder. Lowered sea levels would have enhanced continentality, further increasing seasonal contrasts. From this presumption of similar but intensified pressure systems Bowler (1975) suggested that the Pleistocene wind pattern was similar to that of today, with a possible increase in strong winds. Hot summers and stronger winds may have resulted in higher evaporation than occurs today.
FIGURE 2. Geomorphic map of the Willandra Lakes, Southwestern New South Wales, showing lakes, lunettes river course and dunesfields. The Prungle Lakes are located at the downstream end of the system. The inset shows the location of Figure 3. Modified after Bowler (1971): Bowler and Magee, 1978.
c. The Willandra Lakes

The Willandra Billabong Creek diverges from the Lachlan River close to its point of exit from the foothills of the Eastern Highlands near Hillston and follows a course around the northern margin of the Riverine Plain (Butler et al., 1972). It leaves the Plain and enters the Mallee feeding many large and small lakes in a complex overflow system (Fig. 2). The overflow system follows a southerly course adjacent to the boundary between the Mallee and the Riverine Plain, continuing on into the Murrumbidgee-Murray confluence area (Bowler and Magee, 1978).

The origin of the lake basins is unknown. Pels (1969) suggested, for the Darling and Anabranch Lakes, an evolutionary process of origin resulting from base level impediment by rock bars causing floodout and subsequent lateral erosion and basin floor deflation. Bowler and Magee (1978) suggested that the en echelon arrangement of the Willandra Lake basins and the common NNW - SSE orientation of large tracts of the river channels (Willandra Creek, Darling River and the Murray River) are controlled by and aligned with Parilla Sand strandline ridges. They mapped the occurrence of four such ridges north of the Murray. The most prominent of these ridges has a broad flattish crest, some 3 km in width, and is situated 30 km south-west of the Prungle Lakes. The marine transgression may have extended as far as the Willandra Lakes leaving regressive littoral sands with subdued ridge and valley topography similar to the more pronounced forms known from the Parilla Sand in Northern Victoria (Lawrence, 1975). The lakes could then have been formed by damming of drainage behind ridges with subsequent basin enlargement and shoreline smoothing by lateral erosion and deflation. Bowler and Magee (1978) reported evidence supporting this hypothesis in the
occurrence of grey micaceous, well sorted sands, resembling the Parilla Sands, at a depth of 15-21 metres (unbottomed) beneath the floor of Lake Mungo. Additionally, shallow or outcropping, silcrete-cemented, beach-like sands form resistant promontories and peninsulas on the western margins of Lakes Leaghur, Mungo and Outer Arumpo.

Bowler (1970) coined the term lunette-lakes for the shallow deflation basins occurring throughout southern Australia which are characterized by regular transverse crescentic dunes (lunettes) on their eastern or lee-side margins. The nature of lunette sedimentation is directly dependent on the hydrologic regime in the basin. High or low lake levels produce characteristic source materials deflated to the lunette and dry-lake conditions permit the formation of an isochronous soil over the lunette and the lake floor. Bowler (1971, 1980, 1986a, b) recognized these variations as three distinct phases of environmentally controlled lunette-lake sedimentation and, using the succession of depositional environments recorded from the Willandra Lakes, developed a depositional model which will be discussed later. Initially Bowler's work was concentrated on studies of lunette stratigraphy as deep gullying and wind deflation provided good natural exposures of most of the sedimentary sequence.

2. METHODS OF STUDY.

In this study geomorphic units were mapped from aerial photography and field surveys. The complete absence of natural sections and exposures of subsurface units, necessitated the use of artificial profiles. A series of twelve back-hoe trenches were dug to provide a cross section of the lake sediments. Trenches were situated to sample all geomorphic units which had been
differentiated (Fig. 3). An additional trench was sited in a small sub-basin on the lake floor which appeared distinctive on aerial photographs. Sediments in this trench were identical to those of the main cross section and will not be discussed separately. Trenching depth was limited to a maximum of 3 m by the equipment available. This depth was insufficient to bottom the depositional sequences exposed. Coring equipment to provide deeper sections was not available at the time of the study. The profile across the lake was levelled and surveyed accurately.

All trench profiles were described and sampled in the field before refilling. Three trenches, which provided the best exposures of sedimentary units recognized in the field, were sampled continuously in large metal monolith boxes measuring 40x15x10 cm. These box samples were logged in detail in the laboratory, and, after sub-sampling of all observable sub-units, the remainder was vacuum impregnated with polyester resin. When cured the impregnated blocks were slabbed and used for thin sections. Thin sections were sited to provide representatives of all sedimentary subunits observed. These thin sections formed the core of the study with additional information from textural, mineralogical (XRD), and chemical analyses of bag samples collected in the field or laboratory.

B. PRUNGLE LAKES: STRATIGRAPHY AND SEDIMENTOLOGY

The Willandra Creek overflow from Lake Outer Arumpo passes through the dunefield in a generally southerly direction, feeding a number of small basins adjacent to the channel, before flowing into the Prungle Lakes (Fig. 2). The dunefield in this portion of the Mallee is dominated by subdued,
FIGURE 3. Geomorphic map of the Prungle Lake South basin showing the topographic units described in the text and the location of trench profiles in a transect across the basin. The extent of lacustrine gypsum evaporites on the inner basin floor has been mapped from colour aerial photographs with ground control provided by the transect trenches.
widely-spaced, longitudinal forms, which are relatively rich in clay and carbonate. These dunes are widely distributed over much of the region (Bowler and Magee, 1978).

The Prungle basins, with a maximum surface area of about 90 km², are less than 10% of the total Willandra system. The lakes are at the southern downstream end of the overflow system, isolated from the majority of larger basins. Some 60 km of channel separates the outflow at Lake Outer Arumpo from the inflow into Prungle. South from Prungle, a NE-SW reach of the Willandra Creek passes through four smaller basins before continuing southwards to meet the Murrumbidgee River near its confluence with the Murray, 30 km west of Balranald.

The main Prungle system consists of a large lake now divided into two distinct basins, joined by a short channel (Fig. 3). To simplify discussion these basins will be referred to as Prungle Lake North and Prungle Lake South. This study is chiefly concerned with an analysis of sediments from a transect across the basin of Prungle Lake South.

In common with lunette lakes throughout the system, the lake basins are sub-elliptical with relatively smooth shorelines and flat floors (Bowler, 1971). The western shoreline is cliffed and the eastern shoreline has a lee-side transverse dune (lunette) formed from material deflated from the lake floor. Being at the downstream end of the Willandra system, the Prungle Lakes have been affected by hydrologic fluctuations more often and to a greater degree than have lakes higher in the system. Thus at Prungle, a complex array of concentric shorelines, lake floor terraces and lunettes have developed as basin-within-basin landforms which formed in response to filling and drying cycles. A similar but less complex geomorphic sequence
has been described, on a larger scale, in the Outer Arumpo-Chibnalwood system upstream from Prungle (Bowler, 1971). Because of the complexity of lunette systems in the Prungle Lakes, the most distinctive and highest lunette will be referred to as the "Main Lunette" for ease of discussion.

At times of hydrologic stress, low lake levels are associated with high salt volumes, inherited from the evaporative concentration of waters in the large shallow lakes upstream and the inflow of saline groundwaters. The present landscape preserves the effects of this salinity in the high gypsum content of the sediments of the innermost lake basins. These sediments have been reworked by deflation, particularly in the Prungle South basin, into a network of irregular transverse ridges of white powdery gypsum, and a unit of gypsum-rich material blanketing earlier lunettes, particularly on their inner flanks. Similar aeolian gypsum ridges occur in groundwater outcrop zones in northern Victoria, such as the Raak Plain salina complex (Macumber, 1980) but are not known from elsewhere in the Willandra Lakes system.

A cross-section across the basin of Prungle South (Fig. 4) illustrates the terrace, lake floor and lunette relationships and the associated sedimentary units. These include freshwater lake sediments, gypsum evaporites, groundwater gypsum, and lunettes containing gypsum, quartz sands and pelletal clays. The most distinctive and best preserved sequence occurs on the floor of the inner basin, between the inner western cliff and the easternmost gypsum lunette. This sequence is the focus of this study and it forms a distinctive array of easily recognizable sedimentary units which are linked genetically. For ease of discussion this sequence is informally named here as the Prungle Beds, a term which will be used in discussion to
FIGURE 4. Cross section across the Prungle Lake South basin showing the relationship between topography, geomorphic units and subsurface sediments. The inner lake basin is also shown with increased vertical exaggeration to illustrate the location of trenches and occurrence of the Prungle Beds sequence.
differentiate this major stratigraphic component from the whole Prungle sequence.

1. UPPER LAKE TERRACE:

The outer cliff marks a step down from the linear dune plains to the lake floor terrace and the oldest lacustrine sediments in the basin exposed at the surface. This shoreline, when traced in plan, cannot be matched with a well defined lunette on the eastern side (Fig. 3). However, it might correspond to a degraded ancient ridge known to occur to the east of the main lunette.

Sediments exposed in a trench to 190 cms (Trench 12, Fig. 4) consist of a dark green-brown mottled clay grading at 145 cm to lighter coloured micaceous silty clay. Brown iron mottling is present throughout, becoming lighter coloured in the lower unit. No sedimentary structures are preserved. Pedogenic features include biotubules and vertical structures in clays. Secondary carbonate is strongly developed between 40 cm and 75 cm and consists of abundant hard nodules in a soft earthy matrix. The secondary carbonate horizon gradually decreases down to about 110 cm. In the lower levels carbonate concentrates around vertical soil cracks. Unionid shells are preserved at 45 cm. The sharp upper boundary at 40 cms appears to be erosional, and the upper red-brown sandy material is probably a more recent locally-derived aeolian unit, rather than a soil A-horizon. This unit might be equivalent to an aeolian erosion event, which has locally stripped and reworked soil A-horizons at the Chibnalwood Lakes higher in the system (Dare-Edwards, 1982). This event is tentatively dated, by degree of pedogenesis, to the late Holocene.
The duration of the high lake level represented by this highest shoreline is unknown. Sediments on the terrace are modified by a well-developed calcareous soil, but this soil is not as strongly developed as the pre-50,000 BP Golgol Soil occurring elsewhere within the Willandra system (Bowler, 1971). Primary carbonate, in the form of mussel shells, is still preserved within the soil carbonate horizon. Elsewhere on the terrace surface Bowler (pers. comm.) has dated mussels to beyond 38,000 BP. It is likely that the contraction of the lake marked by the formation of the inner cliff represents the onset of drying dated elsewhere within the Willandra System to about 36,000 BP (Bowler 1986b). The degree of development of the terrace soil, by comparison with soils of known age elsewhere within the Willandra system, suggests that since contraction from the terrace the lake has rarely, if ever, risen to that level again.

2. PRUNGLE BEDS SEQUENCE:

The inner cliff marks the step down to the lowest lake floor. This shoreline can be traced around the lake to the sandy Main Lunette formed primarily by deflation from sandy beaches. These younger lake sediments are much less affected by pedogenesis, and this sequence appears in all trench profiles on the floor of the inner lake basin (Trenches 5-11, Fig 4) The sequence is best preserved on the western side of that basin in trench profiles 10 and 11, and consists of laminated sands and muds, often calcareous, which represent littoral, nearshore and occasionally deep water sediments. Biogenic carbonates are common, chiefly derived from ostracod shells and algal mats. In trench profiles 8, 9 and 10 thin beds of laminated gypsum evaporites occur.
FIGURE 5. Log of trench profile 11 (see Figs. 3, 4 for location) at the western margin of the inner lake basin. The profile shows calcareous sands and clays of the Prungle Beds sequence. Algal mat carbonates occur commonly. Relative abundance of sand, silt and clay (finer than 2 μ) and carbonate mineralogy and abundance (weight %) are shown. Proto-dolomite mineralogy is assumed from the non-stoichiometric nature of dolomites (Mg44-48).
a. Terrigenous sediments

The terrigenous components of the sequence are best exposed in trench 11 (Fig 5). At the base of this 290 cm profile is an unlaminated sandy-clay unit which becomes sandier towards the base. This unit shows weakly developed pedogenic features such as iron mottling, biotubules and the development of stress and grain argillans (Brewer, 1976). In thin section the unit consists of equant, sub-angular to sub-rounded quartz sand grains (0.3-0.5 mm) in a matrix of red-yellow clay containing fine sand or coarse silt quartz grains (0.03-0.1mm). Feldspar and muscovite grains occur occasionally. Pedogenic matrix reorganization, in the form of grain and stress cutans, occurs discontinuously. This lower unit has a sharp uneven upper boundary marked by vertical cracks infilled with clean sands. This sequence indicates a drying episode in which surface cracking and pedogenesis occurred, quickly followed by a lacustrine interval which truncated the lower unit before burying the disconformity under transgressive sands.

Textural analysis of the trench 11 sequence (Fig. 5) shows that it consists dominantly of sandy sediments, with a mean size generally around 4Ø or coarser, reflecting its near-shore location. Irregularly cyclic, clay-rich phases of deposition at 180 cm, 112 cm and 77 cm, suggest the periodic onset of deeper water conditions. The mean size of these phases is generally finer than 6Ø with the finest at about 9Ø. The coarser horizons are generally muddy sands or clayey sands, poorly to very poorly sorted. The poor sorting and fine sand size of the coarse fraction suggests that these sediments are near-shore but below wave base. The silt content is low, generally less than 20%, but uniform throughout the sequence (mean 15.88 ± 4.12 %). Sand and
clay content, by contrast, is more variable and dependant on depositional environment.

The terrigenous components of Trench 10 (see later Figs. 8, 9a, b) are similar to those in trench 11, with a basal sandy clay overlain by transgressive sands and a number of deep water clay phases. As might be expected from its location more towards the basin centre, the mean particle size tends to be finer and the deep water phases are more marked and characterized by finer grainsize. The silt content shows more variation than in the trench 11 profile.

Clay mineralogy from a number of horizons in both profiles, was examined by X-ray diffraction. In particular, the clay fraction associated with evaporites was studied to test for the occurrence of authigenic magnesium clays (palygorskite), known to occur in saline lake deposits elsewhere (Singer and Galan, 1984). In the Prungle sequence all clay minerals were found to be mixtures of kaolinite and illite with no evidence for assuming anything but a detrital origin for the clay fraction.

b. Carbonates:

The carbonates were examined by bulk chemical analysis of CO$_3$ content, X-ray diffraction analysis of mineralogy and petrographic analysis by thin section. Carbonates occur throughout most of the Prungle Beds sequence. They are absent from the basal (pedogenically modified) sandy clay, from most of the laminated gypsum zones and from the upper leached horizon of the surface soil. The carbonate content of the lower transgressive sands overlying the basal sandy clay is low. Higher carbonate content is found in the near-shore shallow water sequence. This pattern, common in many
lacustrine systems (Dean and Fouch, 1983), reflects the increased activity of photosynthetic bio-induced carbonate production, and the greater variability of environmental conditions in shallow waters. A complex petrographic and mineralogic variety of carbonates, have been identified at Prungle, including detrital and in-situ materials of both allogenic and more commonly authigenic origin. The authigenic components include biogenic (e.g. skeletal parts) and bio-induced (e.g. by photosynthesis) carbonates.

i. Detrital carbonate components:

Many of the deep-water phase, clay-rich horizons in the Prungle sequence are weakly calcareous. In thin section these carbonates are discrete microcrystallites (1-3 μ) scattered throughout the clay matrix (Fig. 6a). Such microcrystalline carbonates, forming marls when in abundance, are known from a great number of lakes in a variety of environments (Strakhov, 1970; Reeves 1968; Muller et al., 1972). The origin of this material has been variously suggested as: a direct precipitate from solution (Neeve and Emery, 1967); precipitation from colloidal suspension (Strakhov, 1967); fine, clastic, allogenic deposition; finely comminuted authigenic components; and by anaerobic desulphatizing and denitrifying bacteria. The difficulty of examining such fine material by light microscopy has prevented any resolution of these possibilities for the Prungle materials. However, the absence of carbonate in the clay fraction of the evaporite units, when detrital input into the basin was still occurring but high salinities had suppressed biological activity, suggests that the allogenic component might be minimal and that comminution of biogenic and bio-induced carbonate is the dominant source. Scanning electron microscopy might resolve this problem.
FIGURE 6a. Photomicrograph of deep water phase clays at 175 cm depth in trench profile 11. The Lower third shows uniform fine grained clays, virtually non-calcareous, overlain by highly calcareous clay with quartz silt grains (q). Crossed polarizers.

FIGURE 6b. Photomicrograph of algal mat carbonate sediment at 248 cm depth in trench profile 11. The algal mat has trapped many quartz grains (q) as well as valves and fragments of ostracod shells (of). Crossed polarizers.

FIGURE 6c Photomicrograph of fine sands at 105 cm depth in trench profile 11. Detrital components include quartz grains (q), whole ostracod (o), ostracod shell fragments (of), clay aggregates (c) and algal tubules (a). Plane light.
ii. Biogenic carbonates:

Biogenic components, whilst occasionally abundant, consist entirely of ostracod remains. These occur as fragments and occasionally as whole valves which are clearly reworked before final deposition. They have been detected in thin section in all environments except the evaporite units. One specimen was identified in thin section by Dr. P. De Deckker as *Leptocythere lacustris*, an indicator of permanent water of moderate salinity (19-28%). They are less common and more fragmented in sandier shallow water units. In the algal mat carbonates and the deep-water calcareous muds they are often better preserved and occasionally form micro-coquinas containing many entire valves when observed in thin section (Fig. 6b).

The small size, and low concentration of ostracod fragments renders them virtually invisible in hand specimen. Field examination of trench sections in the Prungle Lakes revealed little evidence of lacustrine algae or invertebrate fauna, contrasting dramatically with other lakes in the Willandra system. The only mollusc recorded was a small, unidentified planorbital gastropod found on the spoil heap of one of the trenches. No charophyte stems or gyrogonites (calcareous outer cover of female reproductive structure or oogonium) or *Coxiella* gastropods were observed despite the abundance of these forms in many brackish and saline Australian lakes (De Deckker, 1983; 1988) and in Pleistocene sedimentary sequences (Bowler, 1971).

iii. Bio-induced carbonates:

Bio-induced carbonates (Dean and Fouch, 1983) are precipitated when algae and macrophytes alter physico-chemical conditions (particularly by
withdrawing CO$_2$ from the water) during photosynthesis, causing precipitation, usually as an encrustation. Tubular stem encrustations have been reported as a common component of beach and near-shore sediments of other lakes in the Willandra System (Bowler, 1980). They are found at Prungle as occasional detrital components in sandy shallow water sediments (Fig, 6c) and rarely in algal mat carbonates.

Algal mat sediments are the commonest bio-induced carbonates in the Prungle sequence, indeed they are the richest and most important carbonate sediments in the sequence. They generally form thin continuous horizons 1-2cm thick and can be soft earthy marls or hard, cemented "biscuits". In thin section they show many features characteristic of algal mat carbonates (Shinn, 1983). Micritic crystallites form a dense fabric, rarely micro-laminated, but commonly cementing detrital fragments including poorly sorted quartz, shell fragments, algal tubules, algal mat intraclasts and clay aggregates (Fig, 6a). Fenestrae, generally elongate and sub-parallel to bedding can be common, rare or absent (Fig. 7a). Boundaries, particularly upper boundaries, are usually abrupt and irregular (Fig, 7b), apparently erosional with the overlying unit commonly containing clasts of reworked algal mat. Where clay-rich sediment directly underlies the mats it often exhibits vertical cracks refilled with sands, indicating shallow to ephemerally dry conditions during growth of the mats, as is typical of many modern occurrences in intertidal situations and ephemeral lagoons (Shinn, 1983). The lack of associated pedogenic features suggests that such dry phases were not prolonged and that groundwaters probably remained close to the surface. The common occurrence within the mats of lenticular voids (Fig, 7c), formed by displacive gypsum, grown within the groundwater capillary fringe (see discussion later, and Magee, in prep.) strongly supports a
FIGURE 7a. Photomicrograph of algal mat carbonate sediment at 183 cm depth in trench profile 11. Quartz sands (q) are cemented by dark fine micritic carbonate. The upper boundary is irregular and fenestrae (f) are present. Plane light.

FIGURE 7b. Photomicrograph of algal mat carbonate sediment at 261 cm depth in trench profile 10 (Fig. 8). Quartz sand grains (q) are cemented by dense micritic carbonate. The upper boundary is sharp and irregular and a large vertical crack extends down into the carbonate from that boundary. The crack contains fine sands from the overlying sediment. Crossed polarizers.

FIGURE 7c. Photomicrograph of partially disrupted algal mat carbonate sediment at 112 cm depth in trench profile 11. Quartz sand grains (q) are cemented by dense micritic carbonate. The large lenticular void in the centre of the photograph was formed by the growth of a displacive gypsum crystal from the capillary fringe of the water table. Since removal of the gypsum, by solution, quartz grains and fragments of algal mat carbonate have penetrated the void. Other voids also contain these detrital particles. Crossed polarisers.
model of deposition within an ephemeral lake with subaerial exposure of
the lake floor with local groundwaters close to the sediment surface.

iv. Carbonate Mineralogy:

X-ray diffraction analysis of the carbonate fraction identified a number of
mineral species. No aragonite was identified, probably due to the lack of
molluscan fauna in the lakes. Calcites are common, generally with a high
magnesium content (ranging from 4 to 17%, most commonly in the 5-9% range). Dolomites also occur commonly with magnesium content from 40-
47%. Detailed analysis of the dolomite ordering was not carried out,
however the non-stoichiometric nature of the dolomites suggests that they
are probably proto-dolomites.

Calcite tends to be dominant over dolomite, though overall abundances are
more nearly equal in the shallow water sequence (Trench 11, Fig. 5).
Relative abundances can fluctuate markedly throughout the profile, with
very different ratios occurring in adjacent sediments. No obvious pattern is
discernable with the exception of trench 10 where dolomite is clearly
restricted to the upper portion of the profile, above the lowest groundwater
gypsum zone. Clearly the petrographic analysis of carbonate origin, which
suggests that most of the carbonate is derived from a biogenic or bio-induced
source, does not favour direct precipitation of dolomite as the origin of that
mineral. This suggests that early diagenetic dolomitization of calcites has
occurred, but in an irregular manner. Whilst a detailed discussion of the
dolomite question is beyond the scope of this paper, some suggestions as to a
controlling mechanism will be discussed in a later section.
Below 200 cm the profile shows calcareous terrigenous sediments deposited during the higher fresher-water phases of the Prungle Beds sequence. Above this are zones of prismatic gypsum/clay evaporite couplets interbedded with terrigenous sediments and algal mat carbonates. Displacive pyramidal groundwater gypsum occurs above 180 cm. Relative abundance of sand, silt and clay (finer than 2 φ), carbonate mineralogy and abundance (weight %) and gypsum abundance (weight %) are shown. Proto-dolomite only occurs above the lowest groundwater gypsum zone strongly suggesting a relationship between evaporating groundwaters and dolomitization.
c. Lacustrine sub-aqueous gypsum evaporites:

Gypsum sedimentation in the Prungle Lakes is examined in detail elsewhere (Magee, in prep.) and is summarized here in sufficient detail in order to understand the stratigraphy and sedimentology of the Prungle Beds. Calcium sulfate mineralogy and crystal morphology are dependant on the environmental growth conditions and a review of experimental and observational evidence for the correlation of particular crystal forms with particular environments is presented elsewhere (Magee, in prep.). In summary, gypsum crystals growing from supersaturation in an aqueous medium (either at the brine/air interface, within the brine or on the substrate) grow as prismatic crystals as a result of preferential adsorption of H+ and OH− ions on the prism (011) and pinacoid (010) faces respectively. Crystals growing within a host sediment, as a result of supersaturation at the capillary fringe of the water table, are pyramidal forms due to adsorption of foreign ions and more particularly organic matter on the (111) pyramidal faces. During slow prolonged growth of these pyramidal crystals interference by (102) and (103) forms results in characteristic curved faces and disc or lens shaped crystals. Growth is almost always displacive.

The sub-aqueously deposited lacustrine evaporites are exposed in trench profiles 8, 9 and 10 (Fig. 4) with the thickest sequence in the westernmost trench 10 (Fig. 8, 9 a & b). The evaporites consist of laminated gypsum/clay couplets approximately 1mm thick. White sugary gypsum laminae are separated by slightly thinner detrital clay layers. Sedimentary structures include pinch and swell, clay draping and wavy laminae which tend to pinch out regularly, usually within one metre. Combinations of thickness, colour and structure can be correlated across these interruptions to individual laminae.
FIGURE 9a. Photograph of trench profile 10 showing calcareous sandy terrigenous sediments at the base. Finely laminated gypsum/clay couplets show up clearly in the centre of the trench. Upper homogeneous material is modified by pedogenesis.

FIGURE 9b. Photograph showing gypsum/clay couplets in the centre of trench profile 10, in detail. Three major zones of laminites are visible with occasional thicker individual gypsum laminae.

FIGURE 9c. Photomicrograph of a gypsum layer from the gypsum/clay laminites at 186 cm in trench profile 10. Gypsum crystals (g) are prismatic forms and are reverse graded. Patches of primary celestite (c) occur in the lower portion of the layer. Plane light.

FIGURE 9d. Photomicrograph of a gypsum layer from the gypsum/clay laminites at 178 cm in trench profile 10. Gypsum crystals (g) are prismatic forms and prolonged growth attached to the substrate has produced large bladed forms (sedentary gypsum of Bowler and Teller, 1986). Plane light.
In thin section the gypsum crystals are prismatic forms occurring in a dense fabric of euhedral crystals lying with their long axes horizontal. Most crystals show an equant polygonal outline with occasional grains oriented to show the prismatic form (Fig. 9 c). Reverse graded bedding is very common within the gypsum layers (Fig. 9 c). Occasionally the upper crystals of the laminae become large bladed forms with long axes oriented sub-vertically (Fig. 9 d). Celestite (SrSO$_4$) occurs as a relatively abundant primary accessory mineral in discrete patches within the gypsum laminae (Fig. 9 c). The celestite forms fan-like bundles of acicular crystals, a few microns in length, which are often arranged radially in a circular (or perhaps spherical) pattern, much too delicate to survive reworking. Bulk strontium analyses of laminite samples, including detrital layers, occasionally reach nearly 1% by weight.

The interbedded detrital laminae consist of small amounts of fine sand or silt in a matrix of non-calcareous clay sized particles. They are often graded and occasionally multiply graded (Fig. 10 a). The clay sized particles of these detrital laminae are preferentially aligned parallel to bedding, resulting in a high degree of optical orientation (Fig. 10 b). The clays are mixtures of kaolinite and illite, of poor crystallinity and apparently of detrital origin.

The regular repetition of thickness and lithology in the gypsum/clay laminites is reminiscent of varves and it is probable that they are the product of a seasonal cycle. As outlined above, seasonality and climatic gradients between the southeastern highlands and the semi-arid Mallee are believed to have been enhanced during the Pleistocene. Winters were colder with widespread periglacial activity in the highlands, and summers were similar to those of today but with evaporation enhanced by increased
FIGURE 10a. Photomicrograph of a portion of a thick multiply graded layer at 151 cm trench 10. View shows a graded sub-lamination with quartz fine sand (q) and silt at the base grading through silty clay to clay with an abrupt transition to the overlying fine quartz sand of the next graded sub-lamination. Crossed polarisers.

FIGURE 10b. Photomicrograph of a multiply graded detrital layer in the gypsum/clay laminites, showing optically oriented clay (oc), at 162 cm trench profile 10. The detrital layer is oriented at 45° to show the oriented clay in maximum illumination. Clay orientation is best developed in the lower right corner. Quartz fine sand and silt are evident in the centre of the detrital layer, where a crack has opened up at the textural contrast. Crossed polarisers.
wind strength (Bowler, 1975). Spring thaw in the periglacial highlands would have resulted in a flood of sediment-charged water into the Prungle Lakes which were at gypsum saturation. The inflow, even with its sediment load, would have been considerably less dense than the brine at gypsum-saturation salinity and would have spread over the lake water body. In this manner the inflow would have been able to spread between Prungle North and South Lakes. Eventually mixing and flocculation caused the silts and clays to settle out draping and blanketing the gypsum deposited during the previous high evaporation season. Despite the criss-crossing orientation of clay particles known to be characteristic of flocculation, these detrital layers show a remarkable preferred orientation parallel to bedding. This is believed to be a result of suppression, by high salinity, of bioturbation by benthic organisms as suggested by Bowler and Teller (1986).

Summer evaporation re-concentrated the brine allowing gypsum precipitation to re-commence. The gypsum crystals, precipitating sub-aqueously, are prismatic in form. Prismatic crystals known elsewhere to grow attached to the substrate are universally reported to be oriented vertically or sub-vertically (Hardie and Eugster, 1971; Schreiber, 1978; Warren, 1982). As there is a lack of sedimentary structures such as ripple cross bedding and crystals are not damaged it seems likely that reworking has been minimal. It therefore seems more likely that the gypsum crystals have formed at the brine/air interface and settled to the lake bottom as reported from salt evaporation ponds by Schreiber et al (1982). Magee (in prep) has termed these gypsum deposits settled. Reverse graded bedding is produced as individual crystals are enlarged by continued growth after settling, occasionally producing large sub-vertical bladed crystals (Fig, 9 d) when such growth is prolonged and occurs upwards into the brine. Similar enlarged bladed crystals at Lake Tyrrell were termed sedentary by Bowler
and Teller (1986) to differentiate them from reworked or clastic precursors. Celestite precipitates as an accessory phase within the gypsum laminae as a result of an increase in the Sr\(^{2+}/Ca^{2+}\) ratio due to the removal of Ca\(^{2+}\) by gypsum precipitation as Sr\(^{2+}\) substitutes very poorly for Ca\(^{2+}\) in gypsum. The normally high rate of removal of Sr\(^{2+}\) by biological activity (incorporation in hard and soft parts of invertebrates and algae) is lessened by the exclusion of biota by high salinities. In the presence of NaCl celestite is slightly more soluble than gypsum and should occur after the onset of gypsum precipitation (Butler, 1973).

In the trench profile 10 (Fig. 8, 9a, b) there are three major zones of gypsum/clay laminites at 184-174 cm, 162-155 cm and 125-112 cm. In the uppermost of these zones the laminites are interbedded with centimetre scale beds of non-oriented calcareous clay, representing prolonged phases with lower salinity and higher lake levels than during the gypsum/clay seasonal oscillations. Thickened reverse-graded gypsum laminae with bladed sedentary gypsum crystals and more particularly beds rich in enlarged (3-4 mm) prismatic gypsum crystals probably represent conditions favouring gypsum growth prolonged beyond a single seasonal cycle. Beds 1-2 cm thick with enlarged prismatic gypsum crystals occur at 160 cm and 176 cm in trench profile 10.

d. Groundwater Gypsum:

During periods when the lake was drying and peripheral mud flats were seasonally exposed, gypsum precipitated as a result of evaporative concentration of groundwater at the capillary fringe. Most of this groundwater-derived gypsum occurs within the sediments overlying the gypsum/clay laminites in the Prungle Beds sequence, often at textural
breaks. Gypsum crystal forms are universally pyramidal and growth has disrupted the matrix of the sediment. Crystals vary in size from less than 1mm up to 4 cm and occur most commonly at 1mm and 1 cm sizes. They tend to be subhedral and discoidal with curved faces better developed in larger crystals (Fig. 12 a). Growth is always displacive.

Similar gypsum occurrences have been reported from coastal sabkha or lagoon settings (Masson, 1955; Shearman, 1966; Caldwell, 1976; Arakel, 1980) and from a lacustrine setting (Teller et al., 1983; Bowler and Teller, 1986) and the gypsum crystals are pyramidal forms in all cases. At Prungle this near-surface growth of lenticular gypsum and more soluble salts (such as halite and thenardite) disrupts the dry lake muds on the seasonally exposed lake floor as has been documented by Bowler (1973, 1983) from other lakes in the Willandra System and elsewhere. This disruption produces pelletal aggregates which can be reworked, with the lenticular gypsum, by subsequent water or wind action. This results in a common association of pyramidal groundwater gypsum with disrupted clays. Sorting is poor and the clay pellets retain a ragged outline unless water or wind reworking has occurred.

3. AEOLIAN GYPSUM:

Significant deflation and reworking of clay aggregates and gypsum crystals, during periods of oscillating lake levels, has provided sufficient sand-sized material for construction of a number of irregular gypsarenite dunes on the inner lake floor and a lunette on the eastern margin of the inner basin. Dune building on topographic highs and deflation from the hollows has enhanced any slight irregularities on the inner basin floor producing the
FIGURE 11. Log of trench profile 6 (see Figs. 3 & 4 for location), located on the gypsum lunette on the eastern (lee-side) margin of the inner lake basin. Below 225 cm are terrigenous sediments deposited during the higher fresher-water phases of the Prungle Beds sequence, partially disrupted by the growth of pyramidal displacive gypsum. Between 225 and 125 cm are plane bedded and cross bedded clay pellet rich gypsarenite layers. Above 125 cm is powdery pedogenic gypsum developed from the gypsarenite. A thin gypcrete horizon occurs at the surface. Relative abundance of sand, silt and clay (finer than 2 μ), carbonate mineralogy and abundance (weight %) and gypsum abundance (weight %) are shown.
irregular topography seen today (Fig. 4). During any high lake level phases the dunes were trimmed and smoothed by wave action, probably with 
reworking by water of aeolian components, as has been reported from 
Holocene levels in cores at Lake Tyrrell (Bowler & Teller, 1986).

Trench profile 6 (Fig. 11, 12 b) is sited on the gypsum lunette and shows a 225 
cm-thick clay pellet-rich gypsarenite sequence which overlies lacustrine clays 
and sandy clays. Primary aeolian sedimentary structures are preserved from 
125 cm to the base of the gypseous sediments. Above 125 cm bedding has 
been destroyed by pedogenesis although traces are still observable in thin 
section above this level. On the surface of the lunette a thin gypcrete crust 
has developed. Between 225 and 195 cm the gypsarenite is horizontally 
laminated, as in typical lunette sequences where hygroscopic salts stabilize 
clay pellet laminae preventing the development of sand slip faces (Bowler, 
1973, 1983). Above 195 cm the lamination is more typical aeolian cross-
bedding reflecting a higher gypsum/clay pellet ratio and consequent 
reduction in cohesion.

In thin section the lamination is seen to be due to a combination of three 
factors: variation in the gypsum/clay pellet ratio; different mean grain size 
of adjacent well sorted laminae; and a preferred orientation of gypsum 
crystal long axes parallel to bedding (Fig. 12 c). Gypsum crystals are well 
sorted within individual laminae but can vary in size from fine to very 
coarse sand (0.1-2 mm), with fine to medium sands (0.1-1 mm) most 
common. Almost all crystals are hemipyramidal discoidal forms and many 
are significantly corroded by dissolution (Fig, 12 c) and occasionally have a 
discontinuous coating of calcareous non-oriented clay. These clay coatings 
are identical in nature to the clay pellets and are preserved where abrasion
FIGURE 12a. Photomicrograph showing pyramidal displacive gypsum crystals (g) grown from evaporation at the capillary fringe of the water table at 118 cm in trench profile 10. The crystals clearly show the curved faces and lens or disc-shaped outline characteristic of this form of gypsum. Plane light.

FIGURE 12b. Photograph of the plane and cross bedded portion of the clay pellet rich gypsarenite (ga) between 225 and 125 cm and the overlying pedogenic gypsum (pg) unit in trench profile 6.

FIGURE 12c. Photomicrograph of laminated gypsarenite at 187 cm in trench profile 6. The lower laminae consists of a bimodal population of coarse sand sized gypsum (g) and medium sand sized gypsum and clay pellets (cp). The upper layer contains fine to medium sand sized gypsum crystals and clay pellets with a much higher clay pellet/gypsum ratio. Gypsum crystals are pyramidal discoidal forms and show evidence of corrosion and abrasion (especially in larger crystals). Clay pellets are non-oriented calcareous clay and are well sorted in this layer. Plane light.

FIGURE 12d. Photomicrograph of a large pyramidal discoidal gypsum crystal at 47 cm in trench profile 6. The crystal shows well developed pyramidal overgrowths in optical continuity with the corroded detrital core which can be seen clearly outlined by a zone of included impurities. Plane light.
during transport has been incomplete leaving remnant traces of the host lake sediment, in which displacive growth originally occurred. Small prismatic crystals (0.1-0.15 mm) occur rarely.

Most clay pellets (Fig. 12 c) consist of a slightly calcareous non-oriented clay matrix containing silt to fine sand sized quartz and minor muscovite. Rarely red-brown iron/manganese soil nodules also occur. The pellets vary in size from coarse silt to coarse sand (0.05-2 mm). The sorting and rounding of clay pellets is variable and they are not generally as well rounded, sorted or as uniform in composition as those reported by Bowler (1971, 1973) from upstream in the Willandra system, perhaps reflecting the smaller lake size and a shorter transport distance and consequent reduction in abrasion.

The fabric of the clay pellets is identical to that of the lacustrine clays of the Prungle sequence and clearly they have been derived by disruption and subsequent deflation of those sediments. More rarely occurring are highly calcareous fragments of algal mat sediments and reworked sediment lithoclasts, with micro-laminations and oriented clays, which might be either fragments of the detrital component of the gypsum/clay laminites or reworked mud curls.

During the major phases of gypsum lunette construction considerable quantities of gypsum and clay were also deflated beyond the gypsarenite lunette to blanket the flank of the Main Lunette to the east (Fig. 3, 4). At the same time an unknown quantity of sub sand-sized gypsum, clay and soluble salt must have been lost from the lake basin as dust. Bowler (1983, 1986b) has demonstrated the regional extent and profound effect on the landscape, of this saline groundwater controlled deflationary event, which occurred between 18,000 and 16,000 BP over much of southern Australia.
a. Pedogenesis on gypsarenite dunes:

Since deposition on the lunette ceased, pedogenic processes of leaching, translocation and precipitation by meteoric water have resulted in the destruction of sedimentary lamination above about 125 cm in the gypsum lunette profile, and the formation of a surface gypcrete. In thin section some traces of lamination are still visible up to 72 cm, but above this level all primary sedimentary structures disappear. Primary gypsarenite sediment grains, both gypsum and clay pellets, are modified in this process and secondary precipitation of gypsum and carbonate occurs especially near the top of the profile.

Primary corroded gypsum crystals develop pyramidal discoidal overgrowths in crystallographic continuity with the original detrital core which is often clearly outlined by zones of included impurities (Fig. 12 d). Twins occur frequently. The original sub-horizontal orientation becomes random or sub-vertical. Generally the clay pellets remain relatively unaltered. Only in the top 20 cm of the profile where secondary precipitation is very well developed are clay pellets completely broken down to form a secondary pedogenic clay fabric. Elsewhere only the most ragged clay pellets show any evidence of coalescence and pellet breakdown similar to that reported by Dare-Edwards (1982) from the genesis of lunette soils of the same age, at the Chibnalwood Lakes higher in the Willandra sequence.

In addition to detrital grain overgrowths, secondary gypsum nucleates and grows as densely intergrown aggregates of very small (0.01 mm) crystals and as larger (0.05-0.1 mm) discrete sub-vertical crystals. Both of these types are pyramidal forms and become progressively more common higher in the
profile. Eventually they form a massive intergrown felted mass of secondary gypsum in the gypcrete.

Secondary carbonate appears above about 60 cm in the profile and is closely connected with gypsum crystals. Carbonate occurs adhering to the gypsum crystals or replacing the gypsum, with preferential location along cleavage planes. This replacement along cleavage planes becomes particularly well developed near the surface where very small (3-20 m) isolated equant rhombs of carbonate are scattered throughout the massive secondary gypsum fabric. The carbonate is low magnesium calcite (Mg$_{2.5}$). Similar replacement of gypsum by low magnesium calcite in a pedogenic profile developed on gypsarenite was reported by Warren (1982). The implications of this phenomenon are discussed further by Magee (in prep).

4. MAIN LUNETTE:

The style of deposition on a lunette directly reflects the sedimentary processes operating in the lake. Lunette sequences preserve a sensitive record of lake levels and salinities in their stratigraphy, sedimentary structures, mineralogy, faunal assemblages and pedogenic history (Bowler, 1973, 1983). Elsewhere in the Willandra System and at other lakes in southeastern Australia deflation and gullying of lunettes has enabled detailed observation of their internal characteristics. However, the main lunette at Prungle, which stands some 35 metres above the lake floor is essentially uneroded, thus limiting access to its internal structure.

Trenching to 3 m depth near the crest and on the upper slopes of the lunette (Trenches 1 & 2, Fig. 4) did not penetrate the surface pedogenic
horizons to expose unmodified sediments. The surface soil shows a secondary carbonate horizon between about 40 and 100 cm overlying a secondary gypsum horizon below about 190 cm. This soil is developed on a substrate of well sorted medium sand and together with the steep western back-slopes of the Prungle main lunette, which resemble degraded sand slip faces, suggests that most of the main lunette consists of sand deflated from high lake level beaches. On the western (lake) side of the main lunette, overlying the sands, is a unit of aeolian gypseous pelletal clay which forms a low wide shoulder on the flanks of the lunette and is exposed in trenches 3 and 4 (Fig. 4). The secondary gypsum horizon is higher in these profiles, reflecting both the greater abundance of primary gypsum and the reduced permeability of the more clay rich substrate. Where this gypsum-rich aeolian material overlies dense lacustrine clays at shallow depth (Trench 5, Fig. 4), a massive secondary gypsum horizon forms a hardpan at the texture contrast. Smaller amounts of gypsum deflated beyond this zone, to a position higher on the sandy main lunette would have been the source for the secondary gypsum horizons developed there.

D. ENVIRONMENTAL RECONSTRUCTION AND PALAEOHYDROLOGY

The detailed stratigraphic, petrographic and mineralogical analyses of the array of facies types represented in the Prungle Beds allows an interpretation of the depositional environment of each facies in some detail. The irregular cyclic occurrence of those facies in the sequence can be used to construct the depositional model for the Prungle beds and to reconstruct a Late Quaternary environmental history of the Prungle Lakes. The lack of isotopic dating restricts the detail with which comparisons can be made between the Prungle sequence and other sites in south-eastern Australia.
However, correlation of the major changes at Prungle with the major changes documented and securely dated from other lakes in the Willandra system (Bowler 1970, 1971, 1980, 1986b) allows a tentative chronological structure to be established. When viewed from within this framework the position of the Prungle Lakes at the downstream end of the Willandra Lakes system has implications for the interpretation of Late Quaternary palaeoenvironments and climates.

1. DEPOSITIONAL MODEL:

The depositional model proposed here to explain facies variations in the Prungle Lakes sequence is based on the generalized lunette-lake model developed for lakes higher in the Willandra System by Bowler (1980; 1986a, b). It is presented diagrammatically in Figure 13. The model has been expanded to accommodate the greater complexity of stages in the contraction of the Prungle Lakes from full, fresh and overflowing, through oscillating and saline phases to dry lake conditions. Five phases are recognized and discussed sequentially below. Phases A and E are identical to the initial and final phases of Bowler (1986b).

A. HIGH LAKE PHASE- FRESH WATER: This phase is characterized by deep, freshwater, overflow conditions in the lakes and recharge of regionally high water tables. Deep water, fine textured sediments, occasionally calcareous, occur in the basin centre and coarsen laterally to littoral sands. Shallow depths and wave action prevent prolonged stratification and the resulting oxidizing conditions allow lake organisms such as ostracoda, mollusca, soft bodied crustaceans, fish, algae and macrophytes to flourish. Wave action erodes the western margin and,
through longshore transport of sands and gravels, forms beaches on the eastern lee-side. Where lake size permits sufficient wave action and sand is plentiful, thick beach sands and gravels accumulate during this phase. The westerly winds then blow these into a foredune of well sorted quartz sands with steep foreset bedding. The foredune deposits are often calcareous due to the inclusion of fragments of shell and calcareous algal material from the lacustrine environment.

B. INTERMEDIATE LAKE LEVELS- OSCILLATING FRESH AND BRACKISH WATER: This phase is characterized by a reduction in lake levels and a consequent contraction to form an inner lake basin. Overflow is still predominant, maintaining fresh conditions, but periodic oscillations and lake contractions might lead to brackish conditions and begin the cutting of small inner depressions into the basin floor. Lake levels remained high enough to recharge regional water tables. During the higher overflow stages, sediments deposited would be identical to those of Phase A, with fine-textured, usually calcareous sediments in the centre, coarsening laterally to littoral sands. Periodic oscillations would produce transgressive and regressive sands while ephemeral exposure of mudflats would lead to sub-aerial shrinkage cracking and extensive development of algal mats. Lunettes would continue to receive quartz sands, but in reduced quantities, as the effects of reduced wave action and beach building are felt. Due to the reduced lake volumes, variations in inflow are more effective in causing oscillations in lake level and sediment supply. Individual flood events may be preserved in the sediments as coarse and fine micro laminations.

C. LOW LAKE LEVELS; OSCILLATING BRACKISH AND SALINE WATER: As lake levels drop further the lakes become restricted to smaller inner depressions which may have been initiated in Phase B. The lakes are fed by
discharge from saline groundwaters and periodic (probably seasonal) inflow of floodwaters. Oscillations are more regular than in Phase B as the low lake volumes now respond to each seasonal inflow, with attendant changes in depositional conditions. Thin detrital clay laminae are deposited as couplets with gypsum, precipitated subaqueously as evaporation raises the salinity. These couplets form rhythmic varve-like deposits with many characteristic sedimentary features (Magee, in prep.). Seasonal exposure of mud flats, coupled with high saline water tables, allows the crystallization of displacive discoidal gypsum and the efflorescence of salts (particularly sodium sulfates and chlorides) which break up the lake muds allowing deflation of clays as sand sized pelletal aggregates to the lunette (Bowler, 1973; 1983). This process has been reported occurring today in hypersaline lagoons of the Gulf of Mexico (Price, 1963, Bowler, 1973), a lagoon adjacent to Lake Tyrrell (Bowler, 1980) and at Lakes Tyrrell and Eyre (Bowler, 1983). Each seasonal layer is stabilized by hygroscopic absorption during high humidity phases; this allows accretion by conformable sub-horizontal layers preventing the generation of mobile sand slip faces (Bowler, 1973). As evaporation from the capillary fringe proceeds the precipitation of gypsum progressively raises the Mg/Ca ratio of the groundwaters. Seasonal repetition of this process and interchange between groundwaters and lake waters, which are also precipitating gypsum, could add an inheritance factor to this process. Such high Mg/Ca ratio groundwaters in contact with carbonate sediments would provide ideal circumstances for dolomitization to occur. The greater degree of dolomitization of carbonates in the basin margin sequence (topographically higher and more often exposed as mud flats) in trench 11 (Fig, 4), rather than in the higher salinity basin centre sequence of trench 10 (Fig, 4), is probably explained by this mechanism.
D. OSCILLATING LOW TO DRY LAKE LEVELS; SALINE GROUNDWATER PHASE: This phase is characterized by very low saline lake levels fed by discharge from saline ground waters with overflow rare or absent. Irregular seasonal floods still reach the basin but deposition is controlled by groundwater processes. Much of the inner lake floor is exposed seasonally and salt efflorescence from the capillary fringe breaks up the sediment allowing considerable quantities of clay pellets and gypsum to be deflated to the small rises on the basin floor between the final inner basins, where they accumulate as small irregular lunettes. The dominance of sand-sized, discoidal crystal forms in these gypsum lunettes suggests that groundwater engendered efflorescence features similar to those known occur in Lake Amadeus ("gypsum ground" of Chen and Bowler, 1986), may have existed on the floor of the lake during during this phase. Subsequent deflation and pedogenesis have removed all evidence of these features. Occasional flooding would temporarily raise lake levels in the inner basins, transforming the irregular gypsum lunettes into islands which would be locally trimmed by erosion. Where the gypsum content of aeolian deposits is high, slip faces with high angle bedding can form as the sand-sized gypsum crystals are much less cohesive than clay pellets.

E: DRY LAKE; PEDOGENIC PHASE: The final phase is characterized by dry lakes and regionally lowered water tables which no longer affect the lakes. Deposition in the lake basin and on the lunette ceases and vegetation colonizes these zones. Meteoric water gradually flushes soluble salts through the sediments and a soil develops over both the lunette and the lake floor.

In the depositional model outlined above, the stages A-E clearly form an evolutionary sequence whereby particular landforms and sediments are
produced in response to hydrological variations. Whilst the Late Quaternary depositional history follows that evolutionary sequence, from an initial high level fresh water phase, through lower more saline phases and eventually reverting to an inactive dry phase, the progression is not simple. Whilst the long term trend is from A to E, minor perturbations in the hydrological evolution can cause the lake basin to oscillate between phases. In particular, the small volume of lake water in the oscillating lake phases B, C and D, in relation to inflows and evaporation, implies a delicate hydrological balance in those phases. Thus minor variations in hydrology would cause oscillations between phases. Bowler and Teller (1986) present a model which details a similar delicate hydrological balance for a Late Quaternary evaporite sequence from Lake Tyrrell, to the south. By contrast the transition from phases A to B and from D to E are of greater magnitude and require a larger hydrologic change. Consequently once these changes have occurred they tend not be reversed by minor oscillations of hydrology, and represent significant thresholds crossed in the Late Quaternary evolution of the Prungle Lakes.

The effect of oscillation between phases should be clearly evident in the sedimentary record as irregular repetitive depositional cycles. Irregular cycles are evident in the Prungle Beds sequence (Trenches 10 & 11, Figs. 5 and 8) which represent the deposits of phases B, C and D. Additional factors complicating the sedimentary record of these hydrologic oscillations are erosion and redeposition during lake transgressions and regressions and the disruption and removal of material by deflation during groundwater controlled phases. The quantity of sediment contained in the lunettes indicates the considerable volumes which have been removed from the basin. Thus individual sequences do not contain a complete record and exact correlation between sequences within the basin is not possible.
2. LATE QUATERNARY DEPOSITIONAL HISTORY:

Figure 14 shows an idealized profile from the Prungle Lakes sequence with a palaeohydrologic interpretation. This sequence is correlated with the dated Willandra Lakes sequence and palaeohydrologic curve modified from Bowler (1980, 1986b).

Prior to the filling of the Willandra Lakes some time before 50,000 BP, conditions were similar to those of today (Phase E above). Both the lake floors and the lunettes had well developed red calcareous soils, the result of a long period of pedogenesis. Bowler (1971) named this soil the Golgol Soil. None of the trenches in the Prungle Lakes sequence encountered an equivalent to this soil.

a. 50,000-36,000 BP:

The Willandra lakes filled prior to about 50,000 BP and lake levels remained high (Phase A above) until about 36,000 BP. Bowler (1980) named this phase the Lower Mungo Lacustral. Sediments on the upper terrace at Prungle Lake South are related to this phase, but have been greatly modified by pedogenesis. No unmodified sediments of this phase were exposed by trenches to 3 m in the Prungle Beds sequence. The sandy clays (slightly modified by pedogenesis) below the Prungle Beds at the base of trenches 10 and 11 are tentatively correlated with this phase. East of the gypsum lunettes are thick beds of blue-grey and green-grey deep-water clays, underlying the aeolian gypseous pelletal clays which mantle the lower slopes of the main lunette (Trench 4, Fig. 4). These clay units, although not
FIGURE 14. Correlation of the Prungle sequence with the detailed chronologically controlled sequence from higher in the Willandra Lakes System. Willandra Lakes data from Bowler (1980, 1986b)
examined in detail, were most probably deposited during the Lower Mungo Lacustral phase.

b. 36,000-25,000 BP:

At about 36,000 BP the first signs of lake drying appeared in the Willandra Lakes. Evidence of clay deflation, from lake floors, is found at Lake Mungo and at Lake Outer Arumpo (Bowler, 1986b). Although Bowler (1986b) reports that the lakes had risen again by at least 32,000 BP, he suggests that the former high levels were not re-established. The contraction from the early high lake shoreline at Prungle to the inner basin is tentatively dated to this time. The presence, close to the surface of the upper terrace, of unionid shells in growth position which date to greater than 38,000 BP (Bowler, pers comm) and the degree of pedogenesis developed on the terrace sediments both support this contention. The slight pedogenesis developed on the sediments underlying the Prungle Beds, which are also attributed to the Mungo Lacustral phase, is consistent with only a short period of exposure before burial due to a return to high water levels filling the inner basin, by 32,000 BP.

The transgressive sands at the base of the Prungle Beds are correlated with the 32,000 BP rise in lake levels and the major deep water clays at 160-175 cm in trench 11 probably correlate with this last major event of the Lower Mungo Lacustral phase. During this time the Prungle Lakes were in Phase A or B of the depositional model.
c. 25,000-16,000 BP:

Bowler (1980, 1986b) places the end of the Mungo Lacustral phase at around 25,000 BP with the onset of falling lake levels and significant clay deflation and lunette building. A number of minor oscillations are recorded prior to the onset of the major clay deflation phase between 17,500 and 16,000 BP (the Zanci Aeolian phase) and the drying of the system. The period between 25,000 and 16,000 BP of oscillating lake levels on a trend towards eventual desiccation of the Willandra System, is correlated with the deposition of the Prungle Beds. As the minor oscillations in water level occurred, the lakes would have alternated between phases B, C and D of the depositional model, producing the complex interbedding of shallow and deep water detrital units, algal carbonates and evaporites preserved in the Prungle Beds sequence today. Dolomitization of carbonates in this sequence occurred during groundwater-controlled low lake phases. Because of the lack of detailed sections available and the complexity of lateral facies changes, it is not possible to accurately correlate individual events within the Prungle Beds. Additionally, the lack of absolute dates in the sequence does not allow correlation of such events with episodes elsewhere in the Willandra Lakes. The exception to this last condition is the probable correlation of most of the groundwater gypsum growth and clay pellet and gypsum deflation with the Zanci Aeolian phase between 17,500 and 16,000 BP.

d. 16,000 BP-Present:

A brief but significant return of water to the upper Willandra System at around 15,000 BP, which corresponds with rises in other inland Australian lakes (Bowler, 1986b), is not recorded at Prungle. Since the final drying at
16,000 BP, the lakes have been in Phase E of the depositional model with the development of soils on the lake floor and lunette deposits.

E. CONCLUSIONS:

The Willandra Lakes are uniquely situated in the climatically sensitive semi-arid zone, near the summer rainfall-winter rainfall boundary and fed by streams draining the periglacially affected elevations of the highlands. The longevity and preservation of the stratigraphic record and the variety of sedimentary environments recorded probably reflects that unique setting. Recent extensive drilling of lakes in diverse Australian locations during the SLEADS programme (Salt Lakes Evaporites and Aeolian Deposits, Chivas et al., 1986) has not discovered sites richer in preserved environmental history. This study of the sedimentology and stratigraphy of the Prungle Lakes, by concentrating on the expanded sequence at the saline end of the hydrologic cycle, has added to the already considerable environmental history of the Willandra Lakes.

The sequence at Prungle contains a complex array of geomorphic forms and sedimentary units which have developed in response to a hydrologic cycle from lake full fresh-water conditions, to the current dry conditions. As it dried the lake passed through stages where lake levels oscillated, at times seasonally, conditions were saline and groundwater processes became the dominant control of sedimentation. Landforms present include lake floor terraces, formed as basin-in-basin topography developed in response to fluctuating lake levels, and lunettes of sand, gypseous clay and gypsum, associated with different salinity phases of the hydrologic evolution, gypsum dunes are located on the floor of the inner basin. Lake sediments vary from calcareous terrigenous sediments of the fresh water phases to
gypsum evaporites. Thin beds of algal mat carbonate sediments are common in the brackish and saline oscillating lake level phases. There is no evidence of more soluble evaporites preserved in the sequence. Dolomitization of carbonates occurs in sediments of the inner basin, particularly around the margins of that basin.

Near the end of the hydrologic cycle, when lake level oscillations were large and ground waters had not yet dropped to their present level many metres below the surface, crystallization of gypsum and more soluble salts occurred at the capillary fringe of the water table, within the sediment matrix of seasonally exposed mud flats. Lacustrine sediments, disrupted by this process, and salt and gypsum crystals, were deflated from the lake floor and deposited in lee shore lunettes or removed from the basin as dust. Since the lakes dried and sedimentation ceased pedogenesis has flushed out the soluble salts and modified the upper portions of all sedimentary units producing the landscapes we see today. In this fossil landscape the geomorphic elements were all formed by processes which are today inactive. Conditions in the past have been both much wetter and much drier than those of today. Even the extremes of today's climate are insufficient to reactivate any of those processes which formed the Mallee landscape.

The conclusions which follow from this study may be summarized as set out below.

1. The environments identified at Prungle and the Willandra system do not occur in the region, or in fact in Australia today. This reflects the profound effects of the glacial/interglacial fluctuation of global climate on low latitude and low altitude environments.
2. More specifically a range of sedimentary environments are identified which depend on strong seasonal oscillations (gypsum/clay laminites and groundwater controlled deflation of disrupted sediments and salts). These environments are virtually absent from the continent today, and their occurrence during the Pleistocene supports Bowler's (1975,) contention of enhanced climatic seasonality at that time.

3. The array of sediment types and mineralogy, including calcareous terrigenous material, algal mats, subaqueous gypsum, displacive groundwater gypsum, dolomites and celestite are almost identical to those characteristic of coastal sabkha sequences. Despite the lack of nodular anhydrite, this thinly bedded cyclic sequence would almost certainly be identified as coastal sabkha when observed in limited core or outcrop in an ancient sequence. The common occurrence in Australia of brines with seawater-like chemistry (Bowler 1986a, Macumber 1983) points to the difficulty of relying on unusual evaporative mineralogy to differentiate marine and non-marine environments. There is a distinct bias in the literature of lacustrine evaporites towards lakes in younger and geologically active regions, such as rift valleys and basin and range provinces, which are characterized by unusual brine chemistry and evaporite assemblages.

4. Many of the contentious issues in the study of evaporite basins relate to the interpretation of depositional environments, particularly the debate concerning deep water versus shallow water origins of such sediments. Hardie (1984) has suggested that detailed petrographic studies are a necessary prerequisite both for elucidating sedimentary environments and in understanding the complexity of brine chemical evolution. This detailed petrographic study of the Prungle Lakes sequence, by examining micro-laminated sediments at the level of individual evaporative events in
a context of known basin parameters, source area, climatic setting and chronologic framework provides a valuable analogue for interpreting ancient sequences. This aspect is the subject of a further paper by this author (Magee, in prep.).
LATE QUATERNARY LACUSTRINE, GROUNDWATER,  
AEOLIAN AND PEDOGENIC GYPSUM  
IN THE PRUNGLE LAKES, SOUTH-EASTERN AUSTRALIA

A. INTRODUCTION:

Ancient evaporite deposits have long been of more than academic interest to geologists as a source of salts particularly halite and potash. More recently lacustrine evaporites, especially in alkaline and hyper-arid regions, have become important sources of rarer salts and trace elements (eg Searles Lake, United States, Smith, 1979; and Qaidam Basin, China, Chen, K and Bowler, 1986). Salt deposits and associated deformation structures have long been known to form structural traps for oil and gas and more recently the potential of evaporites as source rocks for hydrocarbons has been recognized (Warren, 1986).

Evaporite basins, though widely distributed in time and space, do not seem to be well represented in modern environments, at least at the larger end of the scale. This paucity of modern analogues has led to difficulties in interpreting the depositional environments of the ancient saline giants. Since the recognition, very early in the study of evaporites, that relative salt abundances in natural sequences do not match the ratios predicted from experimental evaporation of sea water, models have been proposed which encompass partial evaporation, water body replenishment and even the loss of concentrated brines. The barred-basin model of Scruton (1953) and
Schmalz (1969) has been the most popularly accepted theory and has been extended and modified by various authors to encompass particulars of certain evaporite deposits (e.g., Brongersma-Sanders, 1971; Margaritz, 1987).

Most barred-basin models assume a deep basin because depositional rates are usually well in excess of acceptable rates of subsidence. The nature of the model with replenishment and/or reflux over a shallow sill implies that a deep basin must mean deep water. Deep Sea Drilling Project cores in the Mediterranean have established the great depth and areal extent of Miocene Messinian evaporites in that basin (Ryan et al., 1973; Nesteroff, 1973). Many petrographic studies have suggested a shallow water origin for evaporite sequences within the Messinian (Hardie and Eugster, 1971). These observations have led to the proposal of a deep basin/shallow water model for the Messinian evaporites (Hsu, 1973), and the suggestion that such a model might be applicable to many of the ancient saline giants (Hsu, 1972).

The deep water/shallow water debate has not been resolved, even for the Messinian sequence. In the ancient saline giants, shallow water deposition would not be accepted by those sedimentologists who point to thin parallel lamination, particularly anhydrite/calcite couplets assumed to be formed by seasonal variation, which are traceable over tens and even hundreds of kilometres, as clear evidence of deep water deposition (Richter-Bernburg, 1964; Anderson and Kirkland, 1966). The presence in such laminae of equant blocky anhydrite which appears petrographically to be primary is difficult to explain in light of the almost universal occurrence of gypsum in modern depositional environments.

In attempts to resolve some of these problems many studies have looked at modern evaporitic environments particularly coastal sabkhas and lacustrine evaporites. The discovery of a distinctive array of evaporites, including
apparently primary anhydrite, in sabkha settings, particularly in the Trucial Coast region in the Persian Gulf (Shearman, 1963, 1966; Kinsman, 1966; Butler et al., 1965) has led to the popularity of the sabkha evaporite model (Kendall, 1978; Lucia, 1972). Clearly some ancient evaporite sequences do conform to the sabkha model (Shearman, 1966). However there is a danger in the assumption of a sabkha origin merely because some or even all of the individual elements of that model are present in a sequence. Most anhydrite fabrics, including enterolithic bedding, are due to volume changes caused by diagenetic growth within a sediment matrix or to dehydration/rehydration processes which can occur sub-aqueously as well as sub-aerially (Davies and Nassichuk, 1975; Dean et al, 1975) and be syndepositional or late diagenetic (Shearman, 1985). These processes can occur in combination and be multi-cyclic and the fabrics produced tend to be process specific rather than indicative of a particular environment. As has been demonstrated by Bowler and Teller (1986) from Lake Tyrrell, Australia, and from the Prungle Lakes (Magee, in prep.) thin cyclic sequences with lenticular gypsum, algal mats and dolomites can occur in a shallow lacustrine setting. With the exception of enterolithic anhydrite these sequences are virtually identical to sabkha cycles and might easily be misidentified if found in limited outcrop as an ancient sequence.

Many recent studies of lacustrine evaporites have concentrated on chemical evolution of the evaporating brines (Hardie and Eugster, 1970; Eugster, 1980). Many such studies have highlighted lakes in active tectonic settings (e.g. the Basin and Range province lakes, North America and the African Rift Valley lakes) where unusual mineralogies represent end members of brine evolution pathways. Hardie (1984) has pointed out the value of integrating detailed petrographic analysis with studies which concentrate on chemistry and mineralogy. This integration will not only enable a more thorough
interpretation of the chemical and mineralogical evolution of evaporation systems, as suggested by Hardie, it will make such studies more useful analogues for ancient evaporite sequences where petrography is often the major tool of sedimentary analysis. Hardie et al. (1985) have emphasized the value of thin section studies in examining criteria for distinguishing between primary and secondary features in evaporites.

This study is an attempt to provide a detailed petrographic study of a subrecent lacustrine evaporite sequence. Occurring as it does in a stable geologic context many critical environmental parameters, such as water and sediment sources, lake area and depth, chronology of sedimentation and climatic pattern can be defined with some confidence. A more detailed description of the setting, stratigraphy, depositional history and palaeohydrology of the Prungle Lakes sequence is provided elsewhere (Magee, in prep).

The nature of the Palaeozoic source rocks in the hills rimming the basin, the recent marine influence in the Murray Basin and the relatively close source of marine aerosols all tend to promote a sea water like chemical nature of the brines, although debate exists in Australia about the relative importance of these salt sources. This brine chemistry results in petrographic observations which are applicable to marine evaporites. There is a clear danger in assuming a marine or marginal marine origin on purely mineralogical or chemical grounds and conversely in using unusual mineralogy as a criteria for recognizing lacustrine sediments.
1. REGIONAL SETTING:

The Prungle Lakes are part of the Willandra system of dry lakes in semi-arid southwestern New South Wales in southeastern Australia. The Willandra Lakes were fed by the Willandra Billabong Creek, a distributary of the Lachlan River which drains the relatively well watered southeastern highlands. The lakes are located within the Mallee region, an east-west dunefield now stabilized by shrubby *Eucalyptus* vegetation.

The Mallee region is part of the Murray Basin, a major Tertiary and Quaternary sedimentary basin in southeastern Australia (Fig 1a). Sedimentation in this shallow tectonic basin was initially continental but since the Eocene, marine conditions have dominated in the west. Quaternary continental sediments form a thin but almost continuous cover with both the physiography and sediment type reflecting the marine and non-marine division of the underlying Tertiary. In the east, fluvial sedimentation has continued and in the west the Pliocene regressive littoral sands have been reworked by aeolian action to form the Mallee dunefield.

There is a strong climatic gradient across the Murray Basin from the southeastern highlands to the Willandra Lakes in the semi-arid zone. An increase in temperature and evaporation is accompanied by a decrease in amount and reliability of rainfall. Mean annual rainfall is about 250 mm and is evenly distributed throughout the year. Mean annual evaporation is approximately 1600 mm, with a maximum in the summer, and exceeds rainfall in all months. Summers are hot with maxima commonly above 35° C and winters are cool with maxima around 15° C and mild frosts common at night. Winds in the region are controlled by the migrating high and low
FIGURE 1a. Regional geomorphic map of the Murray Basin in southeastern Australia, showing the two main physiographic components, the Mallee and the Riverine Plain. The inset shows the location of Figure 1b. Modified after Bowler (1971); Bowler and Magee (1978); Magee (in prep).

FIGURE 1b. Geomorphic map of the Willandra Lakes, southwestern New South Wales, showing lakes, lunettes river course and dune fields. The Prungle Lakes are located at the downstream end of the system. The inset shows the location of Figure 2. Modified after Bowler (1971); Bowler and Magee, 1978; Magee (in prep).
pressure cells, swinging from north westerly to south westerly or southerly with the passage of a cold front. Bowler (1975) has argued that climatic conditions during the Pleistocene may have been similar to those of today in summer but cooler in winter, probably with an increase in wind strength. Thus seasonality and evaporation may have been enhanced relative to the present.

The Willandra Lakes form a complex overflow system of large and small lakes as the Willandra Creek follows a southerly course through the Mallee dunefield (Fig. 1b). These lakes have been sites of intermittent deposition synchronous with formation of the aeolian dunefield (Bowler and Magee, 1978), and are characterized by lee-side crescentic dunes (lunettes of Hills, 1940) formed from material derived from the lake basin. During the Quaternary, deposition in the lakes, lunettes and dunefield has been cyclic in response to the world wide glacial-interglacial climatic fluctuations (Bowler, 1978). From stratigraphic, sedimentologic and pedologic evidence, Bowler (1971, 1980, 1986a & b) has developed a cyclic lacustrine depositional model, characterized by a hydrologic oscillation from dry, to lake-full, to saline and back to dry lake conditions. Bowler and Magee (1978) report the possible presence of three such cycles in the Willandra Lakes. The origin of the lake basins is uncertain, with Bowler and Magee (1978) suggesting formation by drainage disruption behind subdued strandline ridges in the regressive Pliocene sands.

2. PRUNGLE LAKES STRATIGRAPHY:

The Prungle basins, with a maximum surface area of about 90 km², are less than 10% of the total Willandra system. The lakes are at the southern downstream end of the overflow system, isolated from the majority of larger
FIGURE 2. Geomorphic map of the Prungle Lake South basin showing the topographic units described in the text and the location of trench profiles in a transect across the basin. The extent of lacustrine gypsum evaporites on the inner basin floor has been mapped from colour aerial photographs with ground control provided by the transect trenches.
basins. The Prungle Lakes consist of a north and south basin joined by a short channel (Fig. 2). In common with other lakes in the Willandra system (Bowler, 1971), the basins are sub-elliptical with relatively smooth shorelines and flat floors. The western shoreline is cliffed and the eastern lee-side shoreline is characterized by a regular transverse crescentic dune or lunette. The nature of the sediments deflated to the lunette depend on the hydrologic regime in the basin.

Being at the downstream end of the Willandra system the Prungle Lakes have, at times of hydrologic stress, inherited high salinities from evaporative concentration and from inflow of saline groundwaters. Fluctuating lake levels have produced a complex array of concentric shorelines, lake floor terraces and lunettes. This complex geomorphology and the high gypsum content of the inner basin reflects the oscillating water level and the saline nature of conditions as the Willandra system began to dry. Gypsum rich material has been reworked by deflation to form an irregular network of transverse dunes and lunettes.

A section through the Prungle South basin shows the geomorphic relationship between the dunefield, terrace, lake floor and lunettes (Fig. 3). The sediments associated with those geomorphic units include freshwater lake sediments, gypsum evaporites, groundwater gypsum, and lunettes rich in quartz sand, pelletal clay or gypsum. Between the inner western cliff and the easternmost gypsum lunette is a distinctive array of genetically related sedimentary units which were termed the Prungle Beds by Magee (in prep). The gypsum rich sediments which are the focus of this study are part of the Prungle Beds sequence.
FIGURE 3. Cross section across the Prungle Lake south basin showing the relationship between topography, geomorphic units and subsurface sediments.
Sediments on the upper lake floor terrace are the oldest lacustrine sediments in the basin exposed at the surface. A trench to 190 cm (Trench 12, Fig. 3) shows terrigenous freshwater deposits consisting of clay and silty clay with brown iron mottling, biotubules, pedogenic vertical clay structure and a well developed secondary carbonate horizon. Freshwater unionid mussel shells are preserved within the carbonate horizon. Magee (in prep) has suggested that these sediments are equivalent to the Lower Mungo Lacustral phase of Bowler (1980) and that the contraction of the lake marked by the formation of the inner cliff represents the first signs of drying in the system dated by Bowler (1986b) to about 36,000 BP.

Inside the inner cliff is the younger Prungle Beds sequence much less affected by pedogenesis. The sequence consists of calcareous laminated sands and muds which deposited in littoral, nearshore and occasionally deep water environments (Trench 11, Fig. 3). Ostracod shells and algal mat carbonates occur throughout the sequence, particularly in the nearshore zones. Towards the centre of the basin these sediments are interbedded with thin beds of laminated gypsum evaporites (Trench 10, Figs. 3, 4a). The deposition of the Prungle Beds sequence has been correlated by Magee (in prep) with the major zone of oscillating lake levels which occurred as the Willandra system dried and has been dated by Bowler (1980, 1986b) to the period 25,000-16,000 BP. At the end of this phase lake levels oscillated seasonally, exposing mud flats, and gypsum grew within the matrix of the sediments of the inner basin due to evaporation at the capillary fringe of the groundwater. Disruption of the sediment by this gypsum growth and associated soluble salt efflorescence has enabled deflation of sand sized clay aggregates and gypsum crystals to form transverse dunes and lunettes (Trench 6, Figs. 3, 9, 10a). Magee (in Prep) correlated the major period of this deflationary phase
with the Zanci clay deflation phase of Bowler (1980, 1986b) which he dated to the period 17,500-16,000 BP.

East of the gypsum lunette is the Main Lunette of the Prungle system, consisting of sands deflated from the lake shore during high water level phases. The inner flanks of the main lunette are blanketed by gypseous pelletal clays derived from deflation of the lake basin.

A. GYPSUM: MINERALOGY AND CRYSTAL HABIT

The calcium sulfates consist of three mineral species: anhydrite (CaSO$_4$), gypsum (CaSO$_4$.2H$_2$O) and bassanite (CaSO$_4$.1/2H$_2$O). A form of soluble anhydrite, known from laboratory studies, has not been found to occur naturally (Kinsman, 1974). The structure of gypsum is monoclinic but there is some disagreement in the literature concerning the basic unit cell and the orientation of crystallographic axes. However, there is general agreement in the naming of the major forms: pinacoids {010}, prisms {011} and pyramids {111} and their orientation relative to the c-axis. Gypsum possesses a perfect cleavage parallel to 010. Environmentally induced variations in the mineralogy and crystal habit of the calcium sulfates have been extensively investigated, principally because of the importance of gypsum crystal forms to the plaster board industry and in management of salt evaporation ponds. Information from such studies can enable the analysis of calcium sulfate mineralogy and crystal habit to shed light on the nature of sedimentary environments.

Many chemical compounds growing from solution vary in mineral species and crystal habit depending on the solubility relationship of the various
mineral species, the thermodynamics or kinetics of nucleation and growth, and the environmental conditions existing at the time of growth (Brice, 1967). Environmental conditions known to be important in controlling the nature of calcium sulfate crystal growth include degree of supersaturation, temperature, pH, growth medium, growth rate, growth period and presence of additive ions, complexes or organic molecules. These environmental conditions can exert strong control over solubility and the kinetics of nucleation and growth (Cody, 1979; Cody & Hull, 1980). Precipitation from solution can be by primary nucleation (spontaneous crystallization) or by secondary nucleation, about seed crystals of the same or another substance, which may later dissolve. Transmutation of species may occur by rearrangement of the lattice, as in subaerial dehydration and rehydration processes, or by a solution-precipitation mechanism, usually in an aqueous medium (Cody & Hull 1980). Rates of crystallization are primarily limited by the availability of nutrient ions. According to Cody (1979), reactions at or near the crystal faces are most important and ions may attach onto the crystal less than optimally when nutrients are abundant. When the rate of nutrient supply is low, the ions may have sufficient time to order themselves at optimal locations. Natural conditions often result in a gradation between these two extremes. For gypsum, which is characterized by rapid nucleation and growth due to rapid crystal surface processes (Kinsman, 1974; Cody, 1979), the slow supply of nutrients, controlled by bulk diffusion rates, is the dominant factor determining crystal form.

Additives can affect both nucleation and growth of crystals by increasing solubility, by slowing diffusion to crystal faces and by adsorption onto faces. Selective effects of additives can affect the mineral species precipitated, the number and size of crystals, the growth rate and the crystal habit. Additives adsorbed onto faces may combine with ions on the face and prevent growth.
Once saturation of the face with an impurity occurs there will be little noticeable effect from a further increase in additive concentration. Where the crystal face is growing by lateral migration of a growth step, even small quantities of additives can saturate the area of actively growing step faces and be effective in inhibiting growth (Cody & Hull, 1980). Migration of the growth step may be halted by impurities adsorbed onto the face if they are sufficiently well bound to resist being pushed aside or ahead of the step (Smith & Alexander, 1970)

Many organic additives are known to delay gypsum nucleation and reduce the size of gypsum crystals (Smith & Alexander, 1970). Some organics slow gypsum growth rates once nucleation is achieved (Smith & Alexander, 1970), but others do not (Barcelona & Atwood, 1978). Smith and Alexander (1970) suggested that the production of numerous small gypsum crystals by organic additive adsorption is the result of an increase in the number of effective nuclei. Larger nuclei are affected by adsorption more readily, slowing their growth and maintaining supersaturation thus allowing the smaller nuclei to continue to grow until an equilibrium size is approached. The nuclei continue to grow separately because the additive prevents coagulation and subsequent recrystallization of combined small nuclei.

1. CALCIUM SULFATE MINERAL SPECIES:

Calcium sulfate mineral species are not controlled by simple relationships of solubility, temperature and supersaturation. The solubility of the calcium sulfate minerals has been studied experimentally (Madgin & Swales, 1956; Hardie, 1967; Kinsman, 1974) and it has been shown that in pure water anhydrite is more soluble than gypsum up to 42°C where the solubilities
The addition of NaCl to the system increases the solubility of both phases by a factor of about 3.5. NaCl also lowers the temperature where the solubilities cross (occurring at about 25°C for a brine of 22% NaCl). Thus it could be expected that anhydrite should form as a primary precipitate in evaporite environments, and indeed most ancient calcium sulfate evaporites consist of anhydrite, often in a form which many petrographic studies interpret as primary (Brown, 1931; Dunham, 1948). However, experiments on growing calcium sulfates from supersaturation produce only gypsum at temperatures which are geologically feasible. Even at temperatures as high as 80°C gypsum was still the major phase, accompanied by minor bassanite (Cody, 1976).

In modern evaporitic systems anhydrite occurs rarely and in a restricted range of environments, most notably the coastal Sabkhas of the Persian Gulf (Shearman, 1966; Kinsman, 1966; Kendall, 1978) where there is considerable debate about whether the anhydrite has a gypsum precursor. Butler (1969) showed conclusive evidence of pseudomorphing of gypsum by anhydrite in certain areas and later studies have confirmed that anhydrite in sediments of marine origin is probably a diagenetic replacement of earlier gypsum (Kinsman, 1974). West et al (1985) described primary gypsum nodules from Egyptian sabkhas as "strikingly similar in morphology, displacive features and purity" to the Persian Gulf anhydrite nodules. However Kinsman (1974) suggests that the non-marine supratidal unit, which is the richest in anhydrite, has never contained gypsum and thus assumes the anhydrite to be primary. Cody (1976), finding that anhydrite did not precipitate even at 80°C and 200‰ salinity, suggested that as temperatures greater than 80°C could not be expected to occur in natural environments, then extremely high salinities might be the controlling factor. He suggested that the zone of evaporative capillary groundwater rise within muds in extremely arid
climates, as in the Persian Gulf Trucial Coast area, might be an environment where such high salinities could develop. However, at Prungle and at other sites where gypsum has been known to grow from groundwater capillary rise in arid and semi-arid situations (Caldwell, 1976; Arakel, 1980; Bowler & Teller, 1986), anhydrite is absent suggesting that salinity is not the major controlling factor.

Certainly in the majority of modern situations, whether in primary subaqueous precipitation, or in groundwater controlled and pedogenic precipitation, the calcium sulfate mineral is almost universally gypsum. Clearly there is a kinetic threshold in the crystallization process which inhibits nucleation and crystallization of anhydrite even well within its field of stability. Cody (1976) and Kinsman (1974) have suggested that the kinetic barrier consists of the high activation energy required for the dehydration of calcium ions before the anhydrous critical nucleus can form.

Cody and Hull (1980), in perhaps the first successful laboratory growth of anhydrite at temperature and salinity levels likely to be found in the geological environment, added considerably to our understanding of this system. Organic additives, particularly high molecular weight compounds, have long been known to inhibit crystallization of many substances and be very active in the calcium sulfate system (Barcelona & Atwood, 1978; Smith & Alexander, 1970). Cody and Hull (1980) did not find any substance which promotes the precipitation of anhydrite, within its stability field, by overcoming the kinetic barrier to nucleation. They did find, however, a number of high molecular weight organic compounds which selectively inhibited gypsum and bassanite crystallization while allowing nucleation of anhydrite. When growth occurred within a solid medium, closely spaced nucleation produced numerous small well-formed rectangular laths
aggregated into micro-nodular masses, similar to sabkha anhydrite occurrences. Growth from mixing of solutions produced small blocky equant crystals similar to those of many ancient laminated anhydrites assumed to be primary. Whilst the organic additives Cody and Hull used are not found in nature they pointed to a number of analogous compounds which do occur naturally. The common occurrence of ancient, putatively primary anhydrites interlaminated with sapropelic material (Dean et al, 1975; Taylor, 1980) might be significant.

Under normal circumstances, as salinity increases and the solubility of anhydrite is exceeded, the kinetic barrier prevents nucleation and growth of anhydrite crystals. Further salinity increase produces supersaturation with respect to anhydrite, but because of the similarity of the gypsum and anhydrite solubility fields, the solubility of gypsum is exceeded before a high level of anhydrite supersaturation can occur. Gypsum can nucleate and grow quickly, preventing normal concentrating mechanisms from generating a high degree of anhydrite supersaturation. Only in unusual circumstances, where gypsum and bassanite are selectively inhibited, will anhydrite supersaturation become sufficiently high for crystal nucleation and growth to occur. This may be further promoted by high temperatures, high evaporation rates, release of calcium ions by dolomitization or release of sulfate ions by oxidation of hydrogen sulfide. However, in most natural evaporation environments gypsum is the primary calcium sulfate phase.

2. ENVIRONMENTAL CONTROLS OF GYPSUM CRYSTAL HABIT:

There are two commonly occurring gypsum habits at Prungle: firstly, prismatic crystals, elongated parallel to the c-axis, dominated by the forms
{010} and {011}; and secondly, pyramidal crystals which are flattened in the c-axis direction, dominated by the {111} form. In the pyramidal crystals the {111} form is often disrupted by forms {\overline{1}02} (Cody, 1976) or {\overline{1}03} (Masson, 1955) causing the formation of characteristic curved faces and disc or lens shaped crystals.

Gypsum forms a number of quite different crystal habits which are controlled by the environment of crystallization, particularly by the additives in solution. There are eight factors which have been found by experiment or observation to influence the morphology of gypsum (Table 1). The three most common habit faces exhibited by gypsum lie in the (111), (110) and (010) planes. The (111) face is populated by calcium ions and the (110) and (010) faces by both calcium and sulfate ions (Barcelona & Atwood, 1978). Because of these differences in ionic arrangement, additives are selectively attracted to particular faces, thus inhibiting growth of one face relative to the others.

The preferred growth habit of gypsum when growing from a pure supersaturated aqueous solution is acicular prismatic. This is probably a result of hydrolisation of water molecules and the tendency for adsorption of H\(^+\) on the (110) faces and (OH\(^-\)) on the (010) faces (Edinger, 1973). This inhibits growth on those faces promoting extreme elongation parallel to the c-axis. Such prismatic crystals grow at the brine surface, the water sediment interface and within clean sterile solid media (Cody & Shanks, 1974; Cody, 1976).

The presence of other ions such as Na\(^+\) (Edinger, 1973), and more importantly, organic matter (Cody, 1979), causes complexing on the (111) faces, thus inhibiting growth on that face and promoting growth of
pyramidal crystals flattened in the c-axis direction. The muds of natural evaporative environments contain enough of these additives to promote pyramidal forms and occurrences of gypsum growing from evaporation of capillary rise of groundwater within muds are almost universally of the disc or lens shaped pyramidal type (Masson, 1955; Shearman, 1966; Bowler & Teller, 1986). This agrees with growth experiments in organic rich solid media by Cody (1976, 1979). Cody and Cody, (1988) have recently confirmed this relationship and suggested that higher temperatures favour the curved (103) faces and lenticular habit.

Subaqueous prismatic shapes and organic adsorption-controlled, lenticular pyramidal shapes are the dominant gypsum crystal forms occurring in natural environments. However, a number of other factors can override, enhance or modify these controls. Only with prolonged slow growth in neutral or alkaline conditions will adsorption of organic additives produce lenticular pyramidal crystals. Where growth is rapid, stubby prismatic crystals are produced despite the presence of organics (Cody, 1979). Growth experiments (Cody, 1976) and observations of natural crystals (Masson, 1955) suggest that these initial stubby prismatic corrodents and are replaced by lenticular crystals. Low temperatures can slow this process of replacement (Cody, 1976; Cody and Cody, 1988). Low pH can counteract the adsorption effect of organic matter and this, combined with the presence of H+ ions adsorbed on the (110) faces can promote growth of prismatic crystals even within solid media rich in additive ions and organics (Cody, 1979; Teller et al, 1982). The degree of supersaturation and NaCl content can enhance or modify the primary controlling factors, producing modifications of the two commonly occurring crystal forms. Where organic matter is absent (or extremely scarce) the various combinations of other usually less prominent
controlling factors can produce a variety of crystal habits, as at Lake Amadeus, central Australia (Chen, X.Y., pers. comm.)

As organic content increases (100) penetration twinning develops, secondary complex nucleation occurs near the twin interfaces and, at high organic concentration, rosettes develop (Cody and Cody, 1988). These rosettes are better formed and larger at higher temperatures (Cody and Cody, 1988). Slow growth rates produce fewer and larger crystals and as growth is displacive rather than inclusive, inclusions are rarer than where growth is rapid (Kastner, 1970; Edinger, 1973). Low pH can promote twins (Edinger, 1973).

Thus it may be possible to associate the two common gypsum morphologies found at Prungle with particular environments: prismatic crystals resulting from sub-aqueous deposition and pyramidal (particularly discoidal) crystals formed by displacive growth within sediments, as a result of groundwater evaporation or pedogenesis. However, it must always be remembered that reworking of gypsum crystals can occur, and the environment of final deposition may not always be the same as the environment of growth.

C. GYPSUM SEDIMENTS OF THE PRUNGLE LAKES:

There are many ways of classifying sediments employing genetic or descriptive criteria or a combination of both, and gypsum sediments are no exception. Two studies of Holocene gypsum depositional environments in Australia have resulted in quite different classification systems for gypsum-rich sediments. Warren (1982) chose to use a simple three-part descriptive system based on particle size and using terms already in use in the literature.
In this system he used the terms *gypsite* for silt sized, *gypsarenite* for sand sized and *selenite* for larger than sand sized. Caldwell (1976) in a detailed study of a wide variety of gypsum depositing environments, found that existing classification systems could not cope with the complexity of sediment types he observed. He erected a complex hierarchical system with the higher order divisions genetically based and the lower orders descriptively based. His four main categories were *precipitates* (chemical precipitate from solution), *clastites* (physically reworked evaporite precursor), *diagenites* (diagenetic modification by precipitation, solution, dehydration or bioturbation) and *metamorphites* (overprint by metamorphic processes). He subdivided the precipitates into *prismatic* (formed subaqueously on a substrate) and *hemi-pyramidal* (formed within a host sediment). All of these genetic types are subdivided according to observed variations in texture, fabric and structure. This results in a complex but useful classificatory system which would undoubtedly be applicable to most, if not all, gypsum sediments and has been used by Arakel (1980) and Bowler and Teller (1986) but is only recently published in a modified form (Logan, 1987)

The classifications of Warren (1982) and Caldwell (1976) are in conflict over the use of the term gypsite. Warren's use of the term is in accordance with the most common definitions in the literature which refer to powdery fine grained gypsum rich material. Caldwell on the other hand uses gypsite as a term for any rock or sediment rich in gypsum, as has been suggested by Visser (1980). Because of this conflict the term gypsite will not be used in describing the Prungle sequence.

At Prungle, gypsum has precipitated, or continues to precipitate, due to supersaturation arising from three processes: evaporation of lake waters;
evaporation of groundwater chiefly by capillary draw; and by evaporation of meteoric soil water which has leached primary gypsum. Gypsum has also been reworked after precipitation by both water and wind and been redeposited as clastic gypsum. Rather than base the description on a pre-existing classification system the gypsum-rich sequence at Prungle will be presented under headings based on a time/evolutionary sequence reflecting the depositional history of the lake system. Looking in turn at lacustrine sub-aqueous deposits, early diagenetic precipitation from groundwater (displacive within sediments), aeolian reworking to form a gypsarenite dune and subsequent pedogenic modification of that dune. These four processes have all involved significant phases of precipitation and/or modification of gypsum. Reference will be made to how the sediment types relate to the classifications of Warren (1982) and Caldwell (1976).

1. LACUSTRINE SUB-AQUEOUS GYPSUM:

The most important component of the lacustrine gypsum evaporites are a series of laminated gypsum/clay couplets (Figs. 4a, b, c). These are made up of discrete laminae of white sugary gypsum approximately 1mm thick separated by slightly thinner detrital clay layers. Individual laminae are wavy and tend to pinch out regularly, usually within one metre. However, combinations of thickness colour and structure can be correlated across interruptions to individual laminae but it is not known over what distance within the basin such correlations can be extended.

Characteristic sedimentary structures at this scale are pinch and swell, wavy laminae, and draping by clays. These are suggestive of deposition in shallow water, but sheltered from the effects of vigorous wave or current
FIGURE 4a. Photograph of trench profile 10 showing calcareous sandy terrigenous sediments at the base. Finely laminated gypsum/clay couplets show up clearly in the centre of the trench. Upper homogeneous material is modified by pedogenesis.

FIGURE 4b. Photograph showing gypsum/clay couplets in the centre of trench profile 10, in detail. Three major zones of laminites are visible with occasional thicker individual gypsum laminae.

FIGURE 4c. Photomicrograph of laminated gypsum/clay couplets, at 177-178 cm in trench profile 10. Both gypsum and detrital layers are variable in thickness and pinch out regularly.
action. Climbing ripples and cross lamination have not been observed. Despite the imperfections, the regular repetition of lithology and thickness is reminiscent of varves and it is difficult not to look on these couplets as the product of a seasonal cycle. In such a cycle spring thaw in the periglacial highlands would send a pulse of sediment-charged water into the lake which is at gypsum saturation. The silts and clays settle out, draping and blanketing the gypsum deposited during the previous year. Summer evaporation would then reconcentrate the brine allowing gypsum precipitation to re-commence.

In thin section the gypsum crystals deposited under this regime are prismatic forms which occur as a dense fabric of euhedral crystals lying with their long axes horizontal. Thus most crystals are cut at an angle to that axis giving an equant polygonal outline (Fig. 5a). Occasional grains lie in an orientation which shows the prismatic form. This suggests two possibilities: either the crystals have formed at the brine-air interface (or even within the brine) and settled to the lake bottom (Schreiber et al., 1982), or they have grown at the water-sediment interface. In the latter case the vertical orientation known from elsewhere (Schreiber, 1978; Warren, 1982) to be characteristic of growth when attached to the bottom has been disturbed by reworking, but the lack of sedimentary structures, such as graded beds and ripple cross-bedding, and the lack of damage to crystals suggest that reworking has been minimal. Unless reworking is evident, crystals are assumed to have been deposited by simple settling through the brine and will be referred to as "settled".

Reverse graded bedding is very common within gypsum laminae in the sequence (Fig. 5a). This suggests that supersaturation produces initial rapid nucleation and a mush of small crystals on the lake bed. Then, as
FIGURE 5a. Photomicrograph of a gypsum layer from the gypsum/clay laminites at 186 cm in trench profile 10. Gypsum crystals (g) are prismatic forms and are reverse graded. Patches of primary celestite (c) occur in the lower portion of the layer. Plane light.

FIGURE 5b. Photomicrograph of a gypsum layer from the gypsum/clay laminites at 178 cm in trench profile 10. Gypsum crystals (g) are prismatic forms and prolonged growth attached to the substrate has produced large bladed forms ("sedentary" gypsum of Bowler and Teller, 1986). Plane light.
equilibrium with further evaporation is reached, growth slows and fewer and larger crystals are produced as individual crystals of the early mush continue to grow upwards into the brine (Schreiber, 1978). Such enlargement probably takes place in situ at the sediment-water interface as shown by occasional layers where such growth has proceeded a step further producing large bladed crystals with long axes oriented sub-vertically (Fig. 5b). Such crystals were termed "sedentary" gypsum by Bowler and Teller (1986) to differentiate them from reworked or clastic precursors, at Lake Tyrrell.

a. Oriented Clays:

The laminae interbedded with the gypsum are clearly detrital in origin. They consist of small amounts of fine sands or silts in a matrix of clay-sized particles. They are often graded and occasionally multiply graded (Fig. 6a). They rarely contain carbonate and are distinguished from laminae of most other environments by the well developed alignment of clay particles, giving a high degree of optical orientation. Figure 6b shows a clay lamination in the 45° position in maximum illumination, clearly indicating the degree of preferred orientation. Clays from elsewhere in the sequence are similar in composition but are non-oriented. These clays contain detrital silt grains and commonly have additional minor carbonate grains, but the extinction pattern is random.

The clays of both oriented and non-oriented types are mixtures of kaolinite and illite and show poor crystallinity. XRD analyses failed to show the presence of any authigenic magnesium rich clays (sepiolite or palygorskite) which are known to occur in saline lacustrine sequences elsewhere (Singer
FIGURE 6a. Photomicrograph of a portion of a thick multiply graded layer at 151 cm trench 10. View shows a graded sub-lamination with quartz fine sand (q) and silt at the base grading through silty clay to clay with an abrupt transition to the overlying fine quartz sand of the next graded sub-lamination. Crossed polarisers.

FIGURE 6b. Photomicrograph of a detrital layer in the gypsum/clay laminites, showing optically oriented clay, at 162 cm trench profile 10. The detrital layer is oriented at 45° to show the oriented clay (oc) in maximum illumination. Prismatic gypsum (g) occurs below the detrital layer (lower right). Quartz fine sand and silt are evident at the base of the detrital layer. Crossed polarisers.

FIGURE 6c. SEM view of non-oriented clay. Crystallinity is poor and clays are mixtures of kaolinite and illite.

FIGURE 6d. SEM view of oriented clay. Crystallinity is poor and clays are mixtures of kaolinite and illite. Fabric appears to be similar to non-oriented clay and no preferred orientation is apparent.
and Galan, 1984). All the available evidence points to a detrital origin for the clay fraction.

The mechanisms resulting in strong orientation of clays are not fully understood. Preliminary SEM analyses of oriented and non-oriented clays do not shed light on the problem. The oriented clays tend to have larger and more discrete particles, but no preferred orientation is obvious (Figs. 6c, d). The preferred orientation is not simply a function of compaction and de-watering at such shallow burial depths as evidenced by the existence of oriented and non-oriented clays in close vertical proximity. Additionally, Meade (1964) suggests a relatively poor correlation between the amount of compaction (depth of burial) and the degree of preferred orientation, even where depths are comparatively large.

Charged clay particle layers tend to repulse each other and to attract cations. In addition, the attraction of cations exerts an osmosis-like pressure forcing water between the clay particles (Meade, 1964). These two forces must be overcome for compaction and de-watering to occur. At extremely close particle distances (5 - 10 Å) van der Waals attractive forces become dominant resulting in a net attraction. High electrolyte concentration suppresses layer charge repulsion and lowers the osmotic pressure holding water between particles. Thus the repulsive force distances might be suppressed to within the range of net attraction (Meade, 1964). This would promote flocculation of particles in suspension and early de-watering and compaction of sediments.

It would be expected that as an inflow carrying a suspended clay load enters a lake filled with a brine precipitating gypsum, that flocculation would be immediate and dramatic. It seems generally accepted that flocculation
orients the clay grains in criss-crossing arrangements and a high degree of parallel orientation would not be expected. Sonnenfeld (1984) suggests that criss-crossing ("house of cards") structure in flocculated clays and consequent high porosity can be preserved if sealed by an evaporite layer. However this does not occur at Prungle. He further suggests that dewatering might be achieved by hygroscopic absorption of fresher waters trapped in clays by by more saline brines. This could result in syneresis shrinkage cracks. Detrital laminae at Prungle often show shrinkage cracks (Fig 6a) which are clearly not due to pene-contemporaneous subaerial exposure as they do not open down from the upper surface and are never filled with gypsum crystals of the overlying evaporite layer. It is not clear if these cracks are syneresis shrinkage cracks or due to shrinkage after subaerial exposure of the whole sequence after the lake dried.

In reviewing the effects of forces operating on clay particles, Meade (1964) suggested that flocculated aggregates at lower salinity are in a true edge - to - face arrangement ("house of cards" of Sonnenfeld, 1984). However, this tends towards face - to - face flocculation at higher salinities, because of the lowering of repulsive forces in an electrolyte. Higher pH, by reducing the negative charge at the particle layer edges, also lowers the tendency for edge to face flocculation. Meade suggested that at the onset of compaction, the partial or incipient preferred orientation in face - to - face flocs favours the production of preferred orientation. He also suggests that larger grain size (often reflecting kaolinite and/or illite mineralogy) also favours the development of preferred orientation due to physical processes. Although these factors might indeed encourage the development of preferred orientation, it seems unlikely that they would be strong enough to exert a controlling influence.
In describing oriented clays from a similar sequence at Lake Tyrrell Bowler and Teller (1986) have suggested that the explanation lies in the exclusion of sediment churning benthos by high salinities. This contention is supported by analyses of laminations found in a proglacial lake and from a deep water reservoir. In both of these cases anoxic bottom waters, maintained by thermal stratification, exclude benthic organisms. Thin sections from these sites show clay laminations to be as strongly oriented as those from the Prungle Lakes or from Lake Tyrrell.

At this time there is no alternative explanation of this phenomenon, and it has two important implications for sedimentological studies. Firstly, moderate compaction and de-watering processes can realign platy sediment particles parallel to bedding even if they have a strong original criss-crossing orientation due to flocculation. Secondly, many sediments must be severely disturbed by benthic micro-organisms, as oriented clays would otherwise occur much more commonly than they apparently do. There are few references to orientation of clays in the literature and it is not known if this reflects the rarity of clay orientation or a lack of observation. The detailed mechanisms of orientation at the individual particle level are not yet understood.

The influx of floods bearing a heavy sediment load into a brine filled lake should, under normal circumstances, lead to immediate flocculation. The sands and flocculated clays should settle quickly, forming a wedge thinning away from the point of entry. Thin even laminae (some including fine sand) would not be expected to spread over the whole of a large lake basin. Furthermore, inflow reaches Prungle South via Prungle North, which should act as an effective sediment trap. Similar difficulties have been
encountered in attempts to explain the occurrence of thin detrital clay laminae in thick halite evaporite sequences (Sonnenfeld & Hudec, 1985a).

A possible explanation lies in the density difference between the flood inflow and the lake brine. Sediment-charged waters in rivers normally have a suspended load of less than 10 g/l (Richards, 1982). Whilst this is considerably denser than sediment-free fresh water, it is much less dense than a brine supersaturated with respect to gypsum at perhaps 150-200 g/l dissolved load. Just as sediment-charged river waters are known to flow over sea water in the absence of vigorous wave-induced mixing, the inflow to the lake might have quite quickly spread across the brine bodies and between basins before mixing and flocculation could occur. Indeed a considerable amount of fine detrital material may even have been carried right through the system. Hite (1968) postulated such a process to explain constant thickness of widespread clastics in an evaporite sequence, but in a deep water setting. Sonnenfeld and Hudec (1985b) report widespread movement of clay suspensions at the density interface and slow flocculation and settling through the brine. Sonnenfeld and Hudec (1985a) point out that if inflow into an evaporite-precipitating brine freshens the whole water body, then dissolution and corrosion of existing evaporites would take place. No evidence of re-solution of this type has been observed in the Prungle sequence.

b. Celestite:

Celestite (SrSO$_4$) is a relatively abundant primary accessory mineral in the Prungle Beds gypsum-clay laminites. Celestite occurs throughout the laminitite sequence, most commonly as discrete patches within the prismatic gypsum laminae (Fig. 5a). Occasionally thicker bands which clearly drape
FIGURE 7a. Photomicrograph, at high magnification, of a celestite (c) patch from within a gypsum lamination at 184 cm in trench profile 10. The radial arrangement of acicular crystals in spherical aggregations is apparent. Plane light.

Figure 7b. SEM view of fan-like arrangements of acicular celestite crystals illustrating the delicate nature of the crystals.
the gypsum crystals occur as a primary precipitate. Examination under high magnification light microscopy indicates that they occur as fan like bundles of acicular crystals a few microns in length which are occasionally arranged radially in a circular (or perhaps spherical ) pattern (Fig. 7a). SEM analysis confirms this structure (Fig. 7b). These delicate fan like structures could not survive intensive reworking. Bulk strontium analyses of laminite samples including detrital layers occasionally reach nearly 1% by weight. Javor (1985) describes primary precipitation of celestite crystals of similar size and crystal form, but in bilobate bundles, from within the brine of salt crystallization ponds at Baja California, Mexico and Chula Vista, California, USA. Javor ascribes the peculiar crystal morphology to slow growth due to slight supersaturation and the effects of dissolved organic constituents in the brine.

Celestite is less soluble than gypsum in pure water, but it rarely reaches supersaturation and forms as a discrete phase because strontium is preferentially absorbed by living organisms. In particular it is incorporated into the soft tissue of invertebrates, assimilated by algae and most importantly, included in solid solution in biogenic carbonates, particularly aragonite (Vlasov,1966). Strontium is known to be present in low abundance in virtually all river waters. If biota and carbonate production are suppressed by high salinities, evaporation might produce supersaturation of celestite, despite the initial low abundance of Sr$^{2+}$ and the increase in solubility of celestite in the presence of NaCl. An additional factor favouring supersaturation due to evaporation is the extremely poor substitution of Sr$^{2+}$ for Ca$^{2+}$ in the gypsum crystal lattice. Butler (1973) intensively studied the strontium-calcium-sulfate system and suggested that in the presence of NaCl celestite is slightly more soluble than gypsum. This agrees very well with the occurrence of celestite at Prungle, where it appears
after the onset of gypsum precipitation, often in the zone of reverse graded bedding where the initial rapid crystallization of gypsum has given way to slower growth of fewer crystals.

3. EARLY DIAGENETIC - GROUNDWATER GYPSUM:

This gypsum type has developed as a result of evaporative concentration of groundwater at the capillary fringe after the lake dried, but before the water table dropped to its present level, many metres below the lake floor. Most of this gypsum growth has occurred within sediments overlying the gypsum-clay laminites, often at textural breaks, and has caused considerable disruption of the matrix of those sediments. Crystal growth has occurred within the matrix of the sediment and the forms are universally pyramidal, presumably under the control of organic matter in the host muds. These gypsum deposits are equivalent to the hemipyramidal gypsite of Caldwell (1976) and many of the fabric and structural varieties he differentiated are present in the Prungle sequence.

Crystal habits are dominated by the hemipyramid (111) and tend to form subhedral, discoidal crystals, commonly with disruption of the hemipyramid by (102) and (103) to form curved faces, giving a characteristic lens shape in thin section (Fig. 8a). The discoidal shape is more common in larger crystals. Crystals vary in size from less than 1 mm up to 4 cm, with crystals around the 1mm and 1 cm sizes being most common. Growth is always displacive, the lack of inclusions of host sediment, indicating slow growth under constant conditions. Crystal orientations are variable with random, vertical (or sub-vertical) and horizontal (or sub-horizontal) types occurring.
Similar gypsum occurrences have been reported from coastal sabkha or lagoon settings in Laguna Madre, Texas (Masson, 1955); Trucial Coast, Persian Gulf (Shearman, 1966); Western Australia (Caldwell, 1976; Arakel, 1980); and from a lacustrine setting at Lake Tyrrell, Australia (Teller et al, 1983; Bowler & Teller, 1986). In all of these cases the gypsum crystals were hemipyramidal forms and, in light of the review of the factors controlling gypsum crystal habits presented earlier, the form is believed to be due to the adsorption of additive ions and more particularly organic matter during slow growth under neutral to alkaline conditions. The production of this crystal form by sediment confining pressure acting in concert with controls on crystallization due to lattice geometry, as suggested by Caldwell (1976), is not supported by experimental or field observations. This process might control the orientation of crystals however, with a random orientation where pressures are isotropic and preferred orientation where pressures are anisotropic (Caldwell, 1976). Shearman (1966) reports a common vertical orientation of discoidal crystals.

Early diagenetic gypsum growth is clearly controlled by groundwater (Teller et al, 1983; Bowler & Teller, 1986) and is a near surface phenomenon associated with evaporation at the capillary fringe. Bowler (1973, 1983) has described in detail the disruptive effects of salt crystallization from saline groundwaters within sediments near the surface of seasonally exposed lake floors. Growth of lenticular gypsum and efflorescence of more soluble salts (e.g. halite and thenardite) breaks up the dry lake mud and forms pelletal aggregates which can be reworked, with the lenticular gypsum, by subsequent water or wind action. This process has clearly been of great importance at Prungle (Magee, in prep.). Whilst the more soluble salts have been removed through leaching by meteoric water, there is a common
FIGURE 8a. Photomicrograph showing pyramidal displacive gypsum crystals (g) grown from evaporation at the capillary fringe of the water table at 118 cm in trench profile 10. The crystals clearly show the curved faces and lens or disc-shaped outline characteristic of this form of gypsum. Plane light.

FIGURE 8b. Photomicrograph of gypsum crystals showing iron oxides located along cleavage plains, at 162 cm in trench profile 10. Iron oxides are due to oxidation of iron sulfides which were produced by the action of desulfatizing bacteria along cleavage plains. Plain light.
association of pyramidal groundwater gypsum with disrupted clays. Where these are still in situ the gypsum crystals and clay aggregates are poorly sorted and the clay aggregates retain their original ragged outline. Where transport has occurred the gypsum crystals and clay pellets are better sorted, oriented and rounded.

Of the crystal fabrics recognized by Caldwell (1976) the most commonly occurring at Prungle is isolate, whereby crystals are not in contact and float freely in the host sediment. Occasionally an intergrown fabric is developed, where growing crystal faces have begun to interfere. All of the crystallization structures differentiated by Caldwell have been recognized in the Prungle sequence: massive where crystals are distributed equally in three dimensions; layered where crystals form layers creating a bedded (cm scale) or laminated (mm scale) deposit; directed where crystals follow bedding or jointing features of the host sediment; tubular directed where crystals follow burrow structures; and clotted where crystals form isolated aggregates. The occurrence of pyramidal gypsum at Prungle will be described under headings derived from these structural groupings.

a. Massive groundwater gypsum

This type occurs in moderately thick beds (20-30 cm) of non-oriented clay or sandy clay (Fig. 4a). Hemipyramidal gypsum tends to be isolate and non-oriented, although there is sometimes a tendency towards sub-vertical orientation. There is a wide variety of crystal sizes (<1 mm-4 cm) and often a reverse size grading within beds. Crystals are often corroded, with points commonly missing, occasionally twinned and rarely show overgrowths. The matrix is usually severely disrupted, forming irregular, ragged clay aggregates. These units are interpreted as representing in situ growth of
displacive gypsum by relatively prolonged slow growth under constant conditions, in a uniform sandy clay or clay host sediment.

b. Directed groundwater gypsum:

This type occurs in fine sand and silt partings (1-3 mm thick) between clay laminae and beds (3-15 mm thick), in the lower portions of upwards-fining sequences which grade to a deep water non-oriented clay with ostracod shells (Magee, in prep). The hemipyramidal gypsum is isolate and commonly oriented sub-vertically. Crystals tend to be uniform in size at about 1 mm and may be corroded. They are interpreted as in situ growth of displacive gypsum in short lived dry-lake phases during cyclic oscillations of lake level (Magee, in prep.). Growth of crystals along coarser partings might be due to greater permeability in these zones with the preferred orientation reflecting the anisotropic nature of the displaced host sediment and its confining pressure (Caldwell, 1976).

c. Tubular directed groundwater gypsum:

This type occurs in variably oriented zones, cutting across bedding and is occasionally clearly associated with bio-tubules. The gypsum crystals are isolate to intergrown, with variable orientation and size. Corrosion and overgrowth can be common. They are interpreted as representing periodic in situ growth of displacive gypsum in zones controlled by sedimentary structures, especially where such structures act as preferentially permeable zones.
d. Clotted groundwater (or pedogenic?) gypsum:

This type occurs as discrete aggregates apparently independent of host sediment bedforms or structures. The crystals are intergrown and randomly oriented. They are variable in size, tending to be larger in the larger aggregates and sometimes grade in size within an aggregate from larger in the centre to smaller on the outside. No corrosion of crystals has been observed in these aggregates. It is not yet clear whether these aggregates are groundwater or meteoric water (pedogenic) controlled early diagenetic features. The lack of corrosion, evident in all other groundwater gypsum types, and the similarity with soil nodules or glaebules (Brewer, 1976) suggest that they are pedogenic and may still be growing. The downward decrease in size of these nodules, in profiles where they are common, is consistent with a pedogenic origin. Their location is presumably determined by preferential nucleation or permeability variations, but the detailed mechanism has not been determined.

e. Layered clastic groundwater gypsum:

There are two distinct types of gypsum occurring at Prungle which fall into this category. Firstly, small (<0.5 mm) pyramidal crystals form thin matrix-free laminae (~1 mm thick), with crystals well sorted and lying horizontally. These laminae occur very rarely in the gypsum/clay laminite sequence, and are probably formed from crystals eroded from displacive growth positions within clay laminae.

Secondly, beds (1-3 cm thick) of larger (up to 1-2 mm) hemipyramidal crystals are found at the base of the lake-level oscillation cycles with which the directed groundwater gypsite is associated. These beds often overlie the
ostracod rich non-oriented deepwater clays at the top of each cycle. The contact is sharp and erosional. Vertical shrinkage cracks extend downwards into the clay from the sharp break. The gypsum crystals are tightly packed and oriented sub-horizontally. They are often associated with pelletal clay aggregates which show evidence of rounding and sorting. Corrosion and overgrowths occur. These units are interpreted as representing redeposition of hemipyramidal gypsum grown in the underlying clay following a drop in water level. The gypsum was then eroded and transported by water as the lake rose again. Many of these gypsum crystals show small concentrations of iron oxides along cleavage planes (Fig. 8b). These are produced by oxidation of iron sulfides which result from the activity of sulfate reducing bacteria. Gypsum cleavage planes containing frambules, with a distinct metallic lustre and believed to be iron sulfides, are known from Lake Frome, South Australia (Bowler and Magee, in prep). The cleavage planes allow the sulfate reducing bacteria to reach faces parallel to (010) which contain sulfate ions and calcium ions, whereas the pyramidal faces which dominate these habits contain only calcium ions.

4. AEOLIAN GYPSUM:

The precipitation of groundwater pyramidal gypsum and associated efflorescence of soluble salts within the sediment matrix, disrupt the sediment and allow significant deflation and reworking of clay aggregates and gypsum crystals to take place. During periods when lake levels were oscillating at Prungle (Magee, in prep.), such deflation from seasonally exposed mudflats provided sufficient sand-sized material for construction of a number of irregular gypsarenite dunes on the lake floor and a lee-side transverse dune (or lunette) on the eastern margin of the inner basin.
FIGURE 9. Log of trench profile 6 (see Figs. 2 & 3 for location), located on the gypsum lunette on the eastern (lee-side) margin of the inner lake basin. Below 225 cm are terrigenous sediments deposited during the higher fresher-water phases of the Prungle Beds sequence, partially disrupted by the growth of pyramidal displacive gypsum. Between 225 and 125 cm are plane bedded and cross bedded clay pellet rich gypsarenite layers. Above 125 cm is powdery pedogenic gypsum developed from the gypsarenite. A thin gypcrete horizon occurs at the surface. Relative abundance of sand, silt and clay (finer than 2 μ), carbonate mineralogy and abundance (weight %) and gypsum abundance (weight %) are shown.
Dunes on the lake floor probably accumulated on slight topographic highs on the basin floor, probably above the level critical for interaction with the capillary fringe (Bowler, 1983). As deflation continued from the hollows and further accumulation occurred on the dunes, the original slight irregularities were greatly enhanced, leading to the irregular topography seen today on the inner lake floor. Intermittent higher lake levels, perhaps accentuated in effect as the area of the inner basin was reduced by dune construction, would have trimmed and smoothed the dune shape by wave action, possibly with reworking of aeolian components. Evidence of this process has been reported from Holocene levels in lake cores at Lake Tyrrell (Bowler & Teller, 1986).

Considerable quantities of gypsum and clay were also deflated beyond the gypsarenite lunette to blanket the earlier lunettes to the east (Magee, in prep.). An unknown quantity of sub sand-sized gypsum, clay and soluble salt must have been lost from the lake basin as dust. Bowler (1983, 1986b) has demonstrated the regional extent and profound effect on the landscape, of this saline groundwater controlled deflationary event, which occurred between 18,000 and 16,000 BP over much of southern Australia.

The dunes and the lunettes consist of a clay pellet rich gypsarenite which overlies terrigenous clays and sandy clays. In the profile examined in detail for this study (Figs. 9, 10a), primary aeolian sedimentary structures are preserved from 125 cm to the base of the gypseous sediments at 225 cm. In the upper portion of the profile bedding has been destroyed by pedogenesis, and a thin gypcrete crust has developed at the surface. The nature of the aeolian gypsarenite will be discussed in this section and the pedogenic modification of that sediment in the next section.
FIGURE 10a. Photograph of plane and cross bedded portion of the clay pellet rich gypsarenite between 225 and 125 cm, and the overlying pedogenic unit, in trench profile 6.

FIGURE 10b. Photomicrograph of laminated gypsarenite at 187 cm in trench profile 6. The lower laminae consists of a bimodal population of coarse sand sized gypsum (g) and medium sand sized gypsum and clay pellets (cp). The upper layer contains fine to medium sand sized gypsum crystals and clay pellets with a much higher clay pellet/gypsum ratio. Gypsum crystals are pyramidal discoidal forms and show evidence of corrosion and abrasion (especially in larger crystals). Clay pellets are non-oriented calcareous clay and are well sorted in this layer. Plane light.

FIGURE 10c. Photomicrograph of a large pyramidal discoidal gypsum crystal at 47 cm in trench profile 6. The crystal shows well developed pyramidal overgrowths in optical continuity with the corroded detrital core which can be seen clearly outlined by a zone of included impurities. Plane light.

FIGURE 10d. Photomicrograph of a large detrital prismatic gypsum crystal, with overgrowths, at 123.5 cm in trench profile 6. The crystal shows a number of small and large discoidal pyramidal overgrowths which are in optical continuity with the abraded detrital prismatic core, clearly outlined by a zone of included impurities. Crossed polarisers.
The lowest 30 cm of the gypsarenite sequence (195-225 cm, Fig. 9) is horizontally laminated, as in typical lunette sequences. This atypical aeolian lamination is attributed by Bowler (1973, 1983) to the hygroscopic nature of the efflorescent salts associated with the clay pellets, which stabilize the laminae when moisture becomes available. Above this (125-195 cm, Fig. 9) is a sequence of beds up to 10 cm thick which show large scale aeolian cross-bedding. An increasing proportion of gypsum crystals relative to clay pellets results in sands which are more free running and counteracts the cohesive effects of hygroscopic salts allowing the production of more typical aeolian cross bedding. Planar truncation of beds occurs frequently, producing a number of wedge shaped sets. Individual laminae within the the truncated beds are parallel and of uniform thickness. In thin section the lamination is seen to be due to a combination of variation in clay pellet content and variation in the mean grain size of adjacent individually well sorted laminae. The lamination is emphasized by a conspicuous orientation of gypsum crystals with their long axes oriented parallel to bedding (Fig. 10b).

The gypsum crystals vary in size from fine to very coarse sand (0.1-2 mm), but are most commonly in the fine to medium sand range (0.1-1 mm), and well sorted within individual laminae. There is often a sharp contact between adjacent laminae. Almost all crystals are hemipyramidal discoidal forms, although some of the smallest crystals (0.1-0.15 mm) appear equant in thin section and might be prismatic forms. Many crystals are significantly corroded by dissolution, occasionally fractured and rarely rounded (Fig. 10b). Occasional crystals have a poorly preserved discontinuous coating of calcareous clay inherited from their displacive growth within lacustrine clay sediment and only partially removed by erosion during transport.
The dominant clay pellet type consists of aggregations of silt to fine sand-sized quartz and minor muscovite with red-brown iron/manganese soil nodules in a matrix of non-oriented, slightly calcareous clay (Fig. 10b). This fabric is typical of the deeper water lacustrine clay sediments from the Lake Prungle sequence (Magee, in prep.), and clearly has been derived by disruption and subsequent deflation of these sediments. These pellets vary from coarse silt to coarse sand sized (0.05-2 mm).

More rarely occurring are larger, denser, well-rounded, highly calcareous, brown clay aggregates, which are thought to be derived from disrupted calcareous algal mat sediments known to have been common during the oscillating lake level stages (Magee, in prep.). Occurring even more rarely are much larger (up to 5 mm) reworked sediment lithoclasts which show microlamination and which might be either micro laminated lacustrine sediment or reworked mud curls.

Clay pellet occurrences vary from well rounded and sorted laminae to poorly sorted laminae with ragged clay pellets. They are not generally as rounded, sorted or uniform in composition as those reported by Bowler from upstream in the Willandra system (Bowler, 1971, 1973), perhaps reflecting a shorter distance of transport and consequent reduction in abrasion. Occasionally pellets in the profile are compressed or degraded by disaggregation and coalescence. Above about 170 cm some pedogenic modification is apparent (plasma separations, Brewer, 1976), though bedding is still clearly evident.
4. PEDOGENIC GYPSUM:

Above about 125 cm in the gypsum lunette profile (Fig. 9), bedding becomes indistinct and then disappears as a result of pedogenic processes of leaching, translocation and precipitation by meteoric water. In thin section some evidence of lamination is still observable up to 72 cm, but above this level all traces of primary sedimentary structures disappear. This disruption of sedimentary fabric is due to modification of primary grains (both gypsum and clay pellets) and to the precipitation of secondary gypsum and minor secondary carbonate.

a. Primary gypsum modification:

Primary detrital gypsum crystals, often originally corroded broken or rounded, act as sites of deposition of secondary gypsum precipitated from downward leaching meteoric water. Overgrowths are of the hemipyramidal form, in crystallographic continuity with the original detrital grain and clearly show lenticular shapes with curved faces and sharp terminations (Fig. 10c). Rare large prismatic detrital crystals show a series of multiple lenticular terminations growing off the prismatic faces (Fig. 10d). In most cases zones of included impurities clearly indicate the outline of the original detrital core. Twins occur frequently.

Above about 120 cm the sub-horizontal orientation of the detrital hemipyramidal discoidal crystals, with their plane of flattening parallel to bedding, disappears as the bedding becomes disturbed. The gypsum orientation becomes random. Occasional traces of laminae with a preferred gypsum orientation still occur as high as 70 cm. Between 70 cm and about 30
cm the gypsum crystal orientation becomes distinctly sub-vertical. The reason for this change in orientation is not clear. Caldwell (1976) has suggested that anisotropic sediment confining pressure can affect lattice arrangement-based controls on differential growth and therefore favour one orientation over another. However, he was discussing nucleation and growth within that confining pressure, whereas these crystals are essentially detrital grains with an overgrowth which have become reoriented. One possibility is that the grains have become reoriented due to lateral pressure produced by growth of small (0.05-0.1 mm) secondary gypsum which begins to form large patches with intergrown fabric in these horizons. However, in the upper 20 cm, where secondary gypsum growth is at a maximum, the larger primary grains are in a more random orientation. It might be that extremely dense intergrown secondary gypsum induces pressures which are more isotropic and do not favour any particular orientation. Alternatively, overgrowths might be favoured on crystals lying sub-vertically, thus leading to growth of those crystals and dissolution and removal of crystals in other orientations. No evidence of this selective dissolution has been observed.

b. Clay pellet modification:

By comparison with the detrital gypsum crystals the clay pellets remain relatively unaltered (Fig. 11a). Where original laminae were apparently rich in clay pellets, perhaps with more of the unstable ragged variety, some coalescing and pellet breakdown is apparent. This process has been documented in detail from studies of pedogenesis on clay pellet-rich lunettes upstream in the Willandra system (Dare-Edwards, 1982). Even as high as 20-40 cm in the profile, relatively undisturbed primary clay pellets are preserved. Only in the very surface layers, which are heavily cemented by secondary gypsum, are pellets completely broken down to form a
FIGURE 11a. Photomicrograph of detrital pyramidal gypsum crystals (g), at 47 cm in trench profile 6. Zones of inclusions clearly outline the detrital crystal cores. Low magnesium calcite (c) is replacing gypsum preferentially along cleavage plains. Clay pellets (cp) are relatively unaltered. Plane light.

secondary pedogenic clay fabric. This lack of pellet breakdown is difficult to explain in light of Dare-Edwards' (1982) work on lunette soils of the same age.

c. Secondary gypsum growth:

In addition to detrital grain overgrowths, secondary gypsum nucleates and grows in two distinct forms within the sediment matrix. Firstly, very small (0.01 mm) pyramidal crystals occur as densely intergrown aggregates. This form occurs as small isolated patches to at least 180 cm in the profile. These gradually increase in size and abundance up the profile until they are common at a level of 70 cm. Above this level larger more continuous patches appear and many voids are lined with intergrown secondary gypsum of this type. The second type occurs above about 50 cm taking the form of larger (0.05-0.1 mm) discrete discoidal crystals with a sub-vertical orientation which occur randomly throughout the sediment matrix. These discrete crystals are sufficiently common to form an interconnecting fabric in patches above about 20 cm, at which levels the smaller intergrown variety also forms large patches (Fig. 11b). Above these levels the different forms of secondary gypsum form an interconnecting and intergrown mass which increases in density towards the surface. The gypcrete consists of a massive intergrown felted mass of secondary gypsum.

d. Secondary carbonate growth:

Secondary carbonate only appears in the higher portions of the profile and is closely connected with gypsum grains. At about 60 cm very small (3-20 m) isolated equant rhombs of carbonate occur in association with gypsum crystals. Above 40 cm, carbonate crystals with the same morphology occur
most commonly associated with the larger gypsum crystals. Carbonate occurs adhering to the gypsum crystals or replacing the gypsum, with preferential location along cleavage planes (Fig 11a). Near the surface gypsum replacement along cleavage planes becomes particularly well developed, with some crystals almost entirely replaced. In the near-surface horizons, and in the gypcrete, secondary carbonate is scattered throughout the massive secondary gypsum fabric (Fig. 11b). The carbonate is low magnesium calcite (Mg_{2.5}).

There are a number of unusual features in the occurrence of secondary carbonate in this profile. Usually secondary carbonate horizons are developed at depth within a profile as meteoric water leaches primary sedimentary carbonate or calcareous aeolian dust down the profile. In this case however, the most abundant secondary carbonate occurs at the surface and the amount decreases rapidly down the profile. In addition, the original gypsarenite dune sediments are almost devoid of carbonate. The only primary carbonates observed in thin section were silt sized crystals within the internal matrix of clay pellets and the very rare carbonate rich aggregates of presumed algal mat origin. These sources could easily account for the traces of carbonate detected in bulk chemical analyses of the sediment (typically less than 1% CO_3 by weight). In most cases clay pellets have not broken down physically and this source of carbonate has not been available for solution and translocation by meteoric waters. The close association of secondary carbonate with gypsum crystals, especially the penetration and replacement along cleavage planes, is also unusual.

Some of these unusual features might be explained by the effects of rainfall on a gypsum-rich substrate. As has been well documented, rain dissolves minute quantities of CO_2 from the atmosphere to form dilute carbonic acid.
Soil CO$_2$ generated by plant root respiration and decay of organic matter boosts the activity of carbonic acid as it passes through the soil profile (Jennings, 1984). This dilute acid should readily attack and dissolve gypsum, releasing an abundance of calcium and sulfate ions. Calcium should combine with carbonate ions from dissociated carbonic acid and calcite precipitation could be expected as a result of simple ion mixing or from evaporation induced supersaturation. Preferential attack of the gypsum crystals might be located along the cleavage planes thus leading to gypsum replacement by calcite along those planes as well as adhering directly to the crystals. Even in these semi-arid soils there may be sufficient soil CO$_2$ for this process to occur. Additional CaCO$_3$ is probably supplied as aeolian dust.

D. DISCUSSION:

1. DEPOSITIONAL MODEL FOR PRUNGLE BEDS GYPSUM DEPOSITS

A detailed five phase model for the Late Quaternary hydrologic evolution and depositional sequence of the Prungle Lakes is presented elsewhere (Magee, in prep). This model is expanded from the generalized lunette-lake model of Bowler (1980, 1986a & b), to include the greater complexity of saline sediments in the Prungle Beds sequence. The model is outlined briefly here, with emphasis on the saline Phases C and D (Fig. 12). For a full description and illustration the reader is referred to Magee (in prep).

During Phase A the lake is high and fresh and terrigenous sediments, often calcareous, are deposited in the lake basin and on the lunette. Phase B is marked by the first reductions in lake level, which may cut inner basins and depressions into the lake floor as the lake contracts. Conditions are still
FIGURE 12. Saline, oscillating lake phases of the depositional model for the Prungle Lakes sequence. A detailed explanation is presented in the text. Modified after Magee (in prep, a).
generally fresh and sediments are terrigenous and calcareous, with occasional exposure of mudflats and development of algal mats.

Phase C is marked by low lake levels and oscillating brackish and saline conditions. As lake levels drop further the lakes become restricted to smaller inner depressions which may have been initiated in Phase B. The lakes are fed by discharge from saline groundwaters and periodic (probably seasonal) inflow of floodwaters. Oscillations are more regular than in Phase B as the low lake volumes now respond to each seasonal inflow, with attendant changes in depositional conditions. Thin detrital clay laminae are deposited as couplets with gypsum, precipitated subaqueously as evaporation raises the salinity. These couplets form rhythmic varve-like deposits. Seasonal exposure of mud flats, coupled with high saline water tables, allows the crystallization of displacive discoidal gypsum and the efflorescence of salts (particularly sodium sulfates and chlorides) which break up the lake muds allowing deflation of clays as sand sized pelletal aggregates to the lunette (Bowler, 1973; 1983). As evaporation from the capillary fringe proceeds, the precipitation of gypsum progressively raises the Mg/Ca ratio of the groundwaters. Such high Mg/Ca ratio groundwaters in contact with carbonate sediments provides ideal circumstances for dolomitization to occur.

Phase D is marked by oscillation between low and dry lake conditions and the lake is fed mainly by discharge from saline ground waters with overflow rare or absent. Irregular seasonal floods still reach the basin but deposition is controlled by groundwater processes. Much of the inner lake floor is exposed seasonally and salt efflorescence from the capillary fringe breaks up the sediment allowing considerable quantities of clay pellets and gypsum to be deflated to the small rises on the basin floor between the final inner
basins, where they accumulate as small irregular lunettes. The dominance of sand-sized, discoidal crystal forms in these gypsum lunettes suggests that groundwater efflorescence features similar to those known to occur in Lake Amadeus ("gypsum ground" of Chen X.Y. and Bowler, 1986), may have existed on the floor of the lake during during this phase. Subsequent deflation and pedogenesis have removed all evidence of these features. Occasional flooding would temporarily raise lake levels in the inner basins, transforming the irregular gypsum lunettes into islands which would be locally trimmed by erosion. Where the gypsum content of aeolian deposits is high, slip faces with high angle bedding can form as the sand sized gypsum crystals are much less cohesive than clay pellets.

Phase E is characterized by dry lakes and regionally lowered water tables. Deposition ceases, meteoric water gradually flushes soluble salts through the sediments and a soil develops over both the lunette and the lake floor.

In this depositional model phases A-E clearly form an evolutionary sequence which the Late Quaternary depositional history follows from an initial high level fresh water phase, through lower more saline phases and eventually reverting to an inactive dry phase. Whilst the long term trend is from A to E, minor perturbations in the hydrological evolution can cause the lake basin to oscillate between phases. In particular, the small volume of lake water in the oscillating lake phases B, C and D, in relation to inflows and evaporation, implies a delicate hydrological balance in those phases. Additional factors complicating the sedimentary record of these hydrologic oscillations are erosion and redeposition during lake transgressions and regressions and the disruption and removal of material by deflation during groundwater controlled phases. The quantity of sediment contained in the lunettes indicates the considerable volumes which have been removed
from the basin. Thus individual sequences will not contain a complete record and exact correlation between sequences within the basin will not be possible.

2. COMPARISON WITH CALCIUM SULFATE DEPOSITS FROM OTHER SITES

As the gypsum sediments of the Prungle Lakes have originated by a number of mechanisms namely sub-aqueous lacustrine precipitation, growth from groundwater, aeolian reworking and pedogenic remobilization, they can be compared with sediments from a variety of settings, both modern and ancient.

a. Sub-aqueous lacustrine precipitates:

Sub-aqueous precipitation of gypsum has has been described from a number of environments including lacustrine at Lake Tyrrell, Australia (Bowler and Teller, 1986); marginal marine from a number of coastal lagoons in Western Australia (Caldwell, 1976; Arakel, 1980; Logan, 1987); and from the marine Miocene (Messinian) of the Mediterranean (Hardie and Eugster; 1971; Ogniben, 1955; Richter-Bernburg, 1973; Nesteroff, 1973). Schreiber (1978) has provided a review of sub-aqueous precipitation of gypsum.

Except where rapid clastic input to deep waters by turbidity flows occurs (Schlager and Bolz, 1977; Ricci-Lucchi, 1973), preservation of subaqueously deposited gypsum can only occur in relatively shallow water where oxygenated conditions inhibit the activity of desulphatizing bacteria (Schreiber et al, 1982). The type of gypsum sediment produced is dependent on the depth with relation to wave base and the variability of
environmental conditions. Evaporite basins tend to be outside the humid equatorial regions, in more temperate zones where evaporation is concentrated in the summer and input of fresh water, detrital material and biologic activity is concentrated in the cooler, more humid season. This results very commonly in rhythmic lamination of evaporite sequences, which may be due to annual variations in seasons or due to spasmodic individual events of shorter or longer recurrence. Many subaqueous evaporite deposits are characterized by well developed primary fine lamination which Warren (1985) relates to periodic, though not necessarily seasonal, changes in brine chemistry.

The relationship between environmental conditions and sub-aqueous gypsum depositional style are presented diagrammatically (Fig. 13) and will be discussed in detail below. The location in this environmental continuum of the Prungle Lakes and other sequences described in the literature, is indicated.

In a markedly seasonal regime, especially where the basin is small and/or shallow, the water body and the depositional conditions respond more quickly, and to a greater degree, to changes in external conditions of inflow or evaporation. This fluctuation results in stronger contrasts in seasonal laminae and abrupt changes in depositional style. As the evaporation season proceeds a high degree of supersaturation occurs quickly, resulting in nucleation of numerous small prismatic gypsum crystals at the air/brine interface (Schreiber et al, 1982). These crystals would settle to the basin floor and continue to build up until supersaturation was reduced and an equilibrium reached with evaporation. These "settled" deposits are common in the Prungle sequence and have also been reported by many others (Ogniben, 1955; Hardie and Eugster, 1971; Schreiber and Kinsman,
### Figure 13

Diagrammatic presentation of the relationship between different types of sub-aqueous gypsum precipitation and depositional environments. The positions in this series of the Prungle deposits and a number of sequences described in the literature are indicated.
1975; Caldwell, 1976; Arakel, 1980; Bowler and Teller, 1986). Where such basins are sufficiently shallow, waves and currents may rework the primary precipitates forming subaqueous clastic gypsum deposits. Although there is rarely evidence of this process at Prungle, Hardie and Eugster (1971), Arakel (1980) and Caldwell, (1976) report the common occurrence of such deposits which show abrasion, rounding, sorting, ripple cross laminations and graded laminae. At the end of the evaporating season the influx of fresh water and detrital material causes gypsum precipitation to cease. Schreiber and Kinsman (1975) report dissolution and corrosion of gypsum by freshening, but this has not been observed at Prungle. Deposition of the detrital layer seals the gypsum layer and the cycle recommences as evaporation reconcentrates the brine.

In a less seasonal regime, especially where basin is large and/or deep, the water body has more inertial resistance to environmentally-induced changes. Conditions may remain relatively constant close to gypsum saturation for a long period of time. Prolonged slow growth results in large prismatic crystals, generally twinned, which grow upward, into the brine, from the bottom, as in the selenites of the Solfifera Series, Sicily (Hardie and Eugster, 1971) and Marion Lake, South Australia (Warren, 1982). Fresh water and detrital input may temporarily halt crystal growth but when gypsum saturation recurs, crystal growth continues in crystallographic continuity with the established crystals. Detrital material (generally carbonate pelletoids) is incorporated poikolitically in a zig-zag pattern following the re-entrants of the large gypsum twins (Warren,1982, 1985; Hardie and Eugster, 1971). Schreiber and Kinsman (1975) suggest that the detrital layers must be at least 100 μ thick to inhibit further crystal growth. Hardie and Eugster (1971) report many beds of selenite at a scale of tens of...
centimetres to metres in thickness. They describe extreme gypsum crystal elongation, of up to 6 m.

Between these extremes of subaqueous gypsum deposition there are a number of gradations. Schreiber and Kinsman (1975), Arakel (1980), Caldwell (1976), and Warren (1982) all report thin (mm scale) laminations of vertically oriented, generally twined gypsum which represents growth upward into the brine from the substrate during a single evaporation season. These layers are sealed from further growth by deposition of a relatively thick detrital layer. Such gypsum layers are rare at Prungle but the "sedentary" Gypsum of Bowler and Teller (1986) which represents continued growth up into the brine after crystals have settled, occurs commonly at Prungle. The reversed grading described from the Solfifera Series thinly laminated sequences ("balatino") by Hardie and Eugster (1971) and Ogniben (1955) may be due to growth of sedentary gypsum. Hardie and Eugster rejected Ogniben's explanation whereby initial fine gypsum crystallization is followed by larger anhydrite crystals as temperature increases with eventual hydration of the anhydrite. However, they could not satisfactorily explain the reverse graded laminae with their shallow water clastic model for the balatino laminites. Schreiber (1978) suggested a mechanism similar to the "sedentary" gypsum model for these deposits, with emphasis on a slightly later, perhaps early diagenetic, timing of the continued growth of crystals.

The Prungle deposits appear to lie closer to the more variable end of this continuum, with conditions generally too variable for prolonged growth attached to the substrate. However, the lake rarely shallowed sufficiently to enable clastic reworking of precipitates to take place.
One notable difference between the Prungle subaqueous gypsum deposits and those reported from marine and marginal marine settings is the nature of the detrital laminae. In all deposits with a marine influence the detrital laminae are wholly or mostly carbonate. At Prungle the detrital laminae in the gypsum sequences are non-calcareous, consisting of silts and clays, usually graded, with a strongly developed orientation of particles parallel to bedding. Bowler and Teller (1986) report similar non-calcareous, oriented clay detrital laminae at Lake Tyrrell. Lower salinity sediments, above and below the gypsum laminites, are calcareous at both Prungle and Lake Tyrrell. The exclusion of biota by higher salinities is thought to be the reason for the lack of carbonate. It is not clear why the freshening which must be associated with the influx of detrital material, is not associated with a brief bloom of biological activity and carbonate production, as clearly occurs in most sequences in the literature (e.g. Arakel, 1980, Warren, 1982; Hardie and Eugster, 1971)

b. Early diagenetic groundwater gypsum:

Early diagenetic groundwater gypsum similar to that described from Prungle is known from many marginal marine (peri-tidal) settings (Shearman, 1966; Masson, 1955; Arakel, 1980; Caldwell, 1976) and lucustrine playas (Bowler and Teller, 1986). In Australia in both marginal marine settings (Caldwell, 1976; Arakel, 1980) and lucustrine playas (Bowler and Teller, 1986) the gypsum types are identical, with pyramidal (usually discoidal) gypsum growing displacively within the sediment matrix. Variations of fabric and structure are controlled by variations in the permeability and porosity of the sediment host. A wide variety of crystal sizes and sedimentary fabric and structure have been described by Caldwell (1976) and similar features occur at Prungle.
The best documented early diagenetic groundwater gypsum occurrences are from coastal sabkha environments, particularly the Trucial Coast, Persian Gulf (Shearman, 1966; Kinsman, 1966). Pyramidal displacive gypsum occurs scattered or as a mush of small (<1mm-1 cm) lenticular crystals in the intertidal zone algal mats and underlying sediment. In the supratidal zone large (up to 20 cm) pyramidal discoidal gypsum occur.

Early diagenetic anhydrite also grows from groundwater in the supratidal zone of these sabkhas as nodules which may coalesce to form enterolithic beds up to 45 cm in thickness. Whilst much of the anhydrite is clearly secondary after gypsum, debate about the apparent primary origin of some of the nodules has occurred (Kinsman, 1974). At Prungle, as for all other Australian settings so far reported, anhydrite does not occur and bassanite is a minor component. Environmental conditions such as temperature, aridity or salinity are more extreme in the Trucial Coast than in marginal marine or southern inland sites in Australia. It is not known if these harsher conditions, or the presence of an unidentified (perhaps organic) additive is controlling the occurrence of anhydrite in the Trucial coast sabkhas. An early diagenetic replacement of anhydrite in the supratidal zone forms distinctive small (few mm) non-pyramidal tabular gypsum crystals, commonly twined, which are flattened in the a-c plane.

c. Aeolian gypsarenite:

Aeolian reworking of sand-sized displacive pyramidal gypsum has been reported from a wide range of settings in Australia. Bowler (1973, 1983) has detailed the processes of sediment disruption by salt crystallization and subsequent deflation of sand-sized pyramidal gypsum crystals and pelletal
sediment aggregates. He has described clay pellet rich lunettes rich in gypsum crystals from the Chibnalwood Lakes of the Willandra System (Bowler, 1973,1983) and from Lake Tyrrell (Bowler and Teller, 1986). Bowler (1976) has also described gypsum-rich lunette material, with clay pellets, from islands in Lake Frome, South Australia which are apparently similar to those described here from Prungle. Aeolian gypsarenites of similar composition are also described from coastal salinas (Caldwell, 1976; Arakel, 1980; Warren, 1982) although detailed petrographic descriptions are not available to enable comparison with the Prungle material. Warren (1983) ascribes the lens-shape of the crystals to the partial dissolution of prismatic precursors by seasonal exposure to fresher water conditions.

Aeolian gypsarenites are known to occur in many parts of the world (Watson, 1983), but detailed petrographic descriptions which would enable comparison with the Prungle gypsarenites, are not known to the author.

d. Pedogenic gypsum:

Pedogenic modification of aeolian gypsarenite has been reported from Australia by Warren (1982) and from sites elsewhere by Watson (1983). In all cases gypsarenite is overlain a powdery gypsum unit commonly capped by a gypcrete crust, as is the case at Prungle. Whilst detailed petrographic descriptions of the products of this process are not provided, both Warren and Watson report the replacement of lens-shaped gypsum crystals (along cleavage planes) by low-Mg calcite. As at Prungle these replacements occur in the higher portions of the profile near the gypcrete crust.

Gypsarenite dunes occur in the Murray Basin associated with groundwater discharge basins or "boinkas" (Macumber, 1980). Sand-sized pyramidal
gypsum units are overlain by a fine powdery gypsum known in Australia as "kopi" and interpreted by Jack (1921) as pedogenic. Kopi is characteristically very pure in gypsum and extremely fine grained, consisting of silt-sized acicular crystals. The crystals of gyspite illustrated by Warren (1982) might be of a similar type, but they have not been found to occur in the Prungle pedogenic gypsum units. The quantity of clay pellets, and consequent reduction in gypsum purity is the only known difference between gypsarenite units of Prungle and those underlying kopi deposits. The details of this discrepancy and the detailed petrography and origin of kopi is currently the subject of further study by the author.

3. GYPSUM PETROFACIES AND PALAEOENVIRONMENTS:

As is evident from the review of controls on crystallization of the calcium sulphates presented earlier, environmental parameters determine the mineralogy and crystal habits which occur. These theoretical and observational data have been used in this paper, in conjunction with petrographic, mineralogical, textural and chemical analyses, to elucidate depositional environments. The resultant correlation of depositional environments with gypsum petrofacies and associated compositional, fabric or structural features is presented in a tabular manner in Figure 14.

In subaqueous lacustrine deposits primary precipitates are always prismatic, non-calcareous and associated with graded oriented detrital laminae. They are planar laminated and clay draped. Gypsum crystals can be oriented with long axes vertical or horizontal, and with reverse grading of gypsum laminae in the "sedentary" form. Delicate spherically arranged bundles of acicular fans of celestite occur as an accessory component.
<table>
<thead>
<tr>
<th>ENVIRONMENT</th>
<th>GYPSUM MORPHOLOGY</th>
<th>GYPSUM LONG AXIS ORIENTATION</th>
<th>CARBONATE</th>
<th>CLAY</th>
<th>SEDIMENTARY STRUCTURES</th>
<th>ACCESSORY COMPONENTS</th>
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<td></td>
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<td></td>
<td></td>
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<td>Prismatic</td>
<td>Horizontal (Most appear equant)</td>
<td>Non calcareous</td>
<td>Oriented (Often graded)</td>
<td>Planar laminae Clay draping</td>
<td>Celestite</td>
</tr>
<tr>
<td>BRINE SEDIMENT INTERFACE</td>
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<td>Vertical</td>
<td>Non calcareous</td>
<td>Oriented (Often graded)</td>
<td>Planar laminae Clay draping</td>
<td>Celestite</td>
</tr>
<tr>
<td>SEDIMENTARY</td>
<td>Prismatic</td>
<td>Horizontal and Vertical (Large bladed forms)</td>
<td>Non calcareous</td>
<td>Oriented (Often graded)</td>
<td>Planar laminae Reverse grading Clay draping</td>
<td>Celestite</td>
</tr>
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<td>LACUSTRINE</td>
<td>Reworked primary precipitate</td>
<td>Prismatic (Most appear equant)</td>
<td>Non calcareous</td>
<td>Oriented (Often graded)</td>
<td>Ripple cross laminae Graded bedding Sorting, abrasion Clay draping</td>
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<td>Pyramidal</td>
<td>Horizontal</td>
<td>Non calcareous</td>
<td>Oriented (Often graded)</td>
<td>Ripple cross laminae Graded bedding Sorting, abrasion Clay draping</td>
<td></td>
</tr>
<tr>
<td>Mixed primary and displacive</td>
<td>Prismatic and Pyramidal</td>
<td>Horizontal</td>
<td>Non calcareous</td>
<td>Oriented (Often graded)</td>
<td>Ripple cross laminae Graded bedding Sorting, abrasion Clay draping</td>
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<td>Sub-vertical and Random (Biogenic or dental) (May be dolomitic)</td>
<td>Non oriented</td>
<td>Displacive growth</td>
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</tr>
<tr>
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<td>Random and Intergrown (Biogenic or dental) (May be dolomitic)</td>
<td>Non oriented</td>
<td>Displacive growth</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OVERGROWTH ON PRIMARY PRECIPITATE</td>
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<td>Horizontal and Vertical (Large bladed forms)</td>
<td>Non calcareous</td>
<td>Oriented (Often graded)</td>
<td>Displacive growth Reverse grading Pressure solution Clay layers deformed</td>
<td></td>
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<td>AEOIAN</td>
<td>Lunate gypsumite clay pelet rich in ferroan calcite</td>
<td>Pyramidal</td>
<td>Horizontal</td>
<td>Reworked primary lacustrine (Non oriented)</td>
<td>Pelletal (Non oriented)</td>
<td>Aeolian cross laminae Sorting, abrasion, corrosion</td>
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<tr>
<td>ROSITITES</td>
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<td>Random and Intergrown</td>
<td>Secondary (Segregations, isolated crystals, replacing gypsum)</td>
<td>Pelletal (Non oriented)</td>
<td>Pedogenically altered</td>
<td>Displacive growth Discrete patches Void fillings Interlocking mass</td>
</tr>
<tr>
<td>OVERGROWTH ON DENTAL ORIGINS</td>
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<td>Sub-vertical and Random</td>
<td>Secondary (Zone around dental core, replacing gypsum)</td>
<td>Pelletal (Non oriented)</td>
<td>Pedogenically altered</td>
<td>Displacive growth Oriented overgrowth Inclusions outline Dental core</td>
</tr>
</tbody>
</table>

FIGURE 14. Gypsum petrofacies and depositional environments presented in a tabular form whereby depositional environment can be deduced from observations of gypsum fabric and associated components.
Clastic deposits are also non-calcareous and associated with draping by graded oriented clay but gypsum crystals can be prismatic or pyramidal and long-axes are always horizontal. Ripple cross laminae can occur and gypsum crystals can be graded, sorted and abraded. Celestite crystal aggregates, too fragile to survive reworking, are not preserved.

In early diagenetic groundwater gypsum, growth is always displacive, usually within non-oriented clay which may contain primary lacustrine carbonate. Crystals are always pyramidal and long axis orientation is variable. Early diagenetic overgrowth of prismatic primary precipitates is indicated by pressure solution boundaries and enlargement of upper crystals, which may be pyramidal, causing disruption or deformation of overlying clay layers.

Aeolian reworked gypsum crystals are sorted, abraded and corroded pyramidal forms with long axes horizontal or parallel to aeolian cross lamination. They are associated with reworked pelletal aggregates of non-oriented clay and occasional reworked primary lacustrine carbonate.

Pedogenic gypsum crystals are displacively grown, variably oriented pyramidal forms which occur as grain overgrowths, discrete patches, within voids or as an interlocking mass. They are associated with pelletal non-oriented clay, which can be pedogenically modified, and with secondary carbonate which can replace gypsum along cleavage planes.

All the examples of gypsum petrofacies types illustrated in Figure 14 have been observed in the Prungle sequence, although the sub-aqueous clastic types are rather poorly represented and the overgrowths on primary precipitates are rare. Comparison of these petrofacies types with modern
and ancient gypsum deposits from the literature suggest that they are applicable in a wide range of environments. Examples of sub-aqueous *in situ* growth at the brine sediment interface are clearly under-represented in the Prungle sequence, particularly the "selenite" forms recognized by Hardie and Eugster (1971) and Warren (1982).

**E. CONCLUSIONS:**

This detailed study of gypsum depositional environments at Prungle confirms the existence of strongly seasonal climatic conditions (Magee, in prep., Bowler, 1975). The environments identified at Prungle do not occur today, either in the region or elsewhere in the continent. This contrast reflects the profound influence of the glacial/interglacial fluctuation of global climate even on low latitude and low altitude environments (Bowler and Wasson, 1984). Under modern conditions the highest known floods do not reach even the northernmost of the Willandra lakes, and the mean discharge of the present Lachlan River could not maintain water in the system (Bowler, 1971). During the Pleistocene, in order to achieve the evaporation of each influx of freshwater and return the system to gypsum saturation, the summer evaporative conditions must have been at least similar to those of today. Summer temperatures were probably hot and wind systems enhanced (Bowler, 1975). Sedimentary environments identified with strong seasonal oscillations (gypsum/clay laminites and groundwater controlled deflation of disrupted sediments and salts) have been examined in detail.

Subaqueous gypsum deposition at Prungle is characterized by fine interlamination of clay and gypsum. As has been reported by Warren (1985) fine scale lamination in evaporites is due to periodic changes in brine chemistry.
At Prungle these changes are attributed to periodic, probably seasonal, inflows of sediment charged flood waters from the peri-glacial affected highlands to the east. The rarity at Prungle of examples of prolonged continued growth of gypsum crystals attached to the substrate (sedentary gypsum), and the complete absence of the enlarged selenite types characteristic of many subaqueous gypsum deposits elsewhere (Schreiber, 1974; Warren, 1982) is attributed to the strength and regularity of seasonality at Prungle.

The aeolian clay pellet rich gypsarenite deposits described here are also diagnostic of particular groundwater controlled, highly seasonal conditions. Seasonal exposure of mudflats, evaporative concentration and precipitation of salts at the capillary fringe of the water table and deflation of sand sized aggregates of disrupted lacustrine clays, are processes which were widespread in the Pleistocene of Australia but are virtually absent today. In Australian playas today it is only during extreme drought conditions, that these processes have even minor impact on the environment (Bowler, 1986). This contrasts markedly with the seasonal recurrence of such processes at Prungle and many other sites at the time of the glacial maximum.

Calcium sulphate evaporites occur extensively in ancient sedimentary sequences, most notably in the Miocene Messinian rocks of the Mediterranean and the Permian of Texas and Germany. Finely laminated evaporites occur commonly in these sequences and there has been considerable disagreement as to their environment of deposition. Detailed petrographic studies of recent sequences, such as Prungle, where independent environmental information is available, can resolve many of these difficulties. Depositional environments of the Prungle Beds sediments have been elucidated from detailed petrographic analyses, in
association with a review of theoretical, experimental and observational studies of the environmental controls of calcium sulphate mineralogy and crystal habit. This has resulted in a correlation of depositional environment with gypsum petrofacies and associated compositional, fabric or structural features. Where primary sedimentary mineralogy and fabric are preserved, all of the gypsum petrofacies types differentiated in Figure 14 can be distinguished by unique combinations of characteristic features of the gypsum or associated components.

Most descriptions of subaqueous gypsum deposition have come from marine or marginal marine settings in arid zones where the influx of detrital material is low. Under these conditions laminations marking interruptions to gypsum crystallization, which are due to periodic freshening, consist of carbonate peloidal material of biological origin (e.g. Warren, 1982). At Prungle, these interruptions are always marked by laminations dominated by detrital material which clearly imply the consistent input of significant quantities sediment charged waters. The subsequent identification of similar interlaminated gypsum and clay at Lake Tyrrell (Bowler and Teller, 1986), Lake Frome (Bowler and Magee, in prep) and Lake Eyre (Magee et al, in prep), strongly suggests that these deposits are characteristic of continental lacustrine environments of subaqueous gypsum deposition. Clearly the maintenance of evaporative conditions at gypsum saturation requires a delicate balance between evaporation and the regular input of freshwater and solutes. In a restricted or marginal marine setting, seawater inflow via constricted or periodic connection or via groundwater reflux can supply this freshening without the input of significant quantities of detrital materials. In a continental setting significant periodic inflows of fresh surface waters are required to maintain such a balance. When inflows become dominated by groundwater input, reflux of salts between the
evaporating brine and the underlying groundwater produces a net increase in groundwater salinity and evolution beyond the stage of gypsum deposition (Macumber, 1983; Bowler, 1986a). The detrital inter-laminations produced by these flood inflows might be used as a criterion diagnostic of such environments. Additional work on other examples, both modern and ancient, is necessary to establish this contention.

The abundance of groundwater controlled clay pellet rich gypsarenite at Prungle and the widespread occurrence of related features in the Late Quaternary of Australia suggests that similar conditions almost certainly existed in arid and evaporative environments of the past. The distinctive mineralogy, fabric, sedimentary structures and transverse dune morphology of these features should enable their recognition in ancient sequences.

The occurrence of early diagenetic gypsum grown within the sediment matrix from groundwater has been reported from many sites. Crystal morphologies are almost universally pyramidal and lenticular in response to the presence of organic matter. However, detailed petrographic descriptions of these deposits are extremely rare. Recent experimental evidence suggests that morphological features of crystals such as twinning, and rosette development are controlled by specific environmental parameters (Cody and Cody, 1988). The integration of detailed observations of crystal morphology, fabric and structure from groundwater gypsum deposits in geological settings with further developments in experimental crystal growth, might enable the extraction of detailed environmental information from such deposits.

In an ancient sequence, when observed in limited core or outcrop, this thinly bedded cyclic sequence would almost certainly be identified as a
coastal sabkha, despite the lack of nodular anhydrite (Magee, in prep.). The array of sediment types and mineralogy, including calcareous terrigenous material, algal mats, subaqueous gypsum, displacive groundwater gypsum, dolomites and celestite are almost identical to those characteristic of coastal sabkha sequences. Similarly, the common occurrence in Australia of brines with sea water-like chemistry points to the difficulty of relying on unusual evaporative mineralogy to differentiate marine and non-marine environments. There is a distinct bias in the literature of lacustrine evaporites towards lakes in younger and geologically active regions, such as rift valleys and basin and range provinces, which are characterized by unusual brine chemistry and evaporite assemblages.
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APPENDIX 1: Additional data from Trenches 6, 10 and 11.

WATER LEVEL CURVES:

The water level curves for Trenches 10 and 11 are drawn from detailed facies analysis of the sections and recognition of the phases A-E in the depositional model. Algal mat zones are plotted on the diagram as they are an important indicator of exposed mud flats and low lake levels. These curves were not included in the papers for publication because they have not been firmly dated. They are plotted against lithology rather than a time scale. Additionally, it has not been possible, without absolute dating or intermediate sections, to correlate accurately between the two sequences. There are clear similarities in the lower portions but as the lake entered the saline oscillating phase the two sites would have responded differently and detailed correlation becomes difficult.

CHEMICAL ANALYSES:

Chemical analyses from the three trenches studied in detail are presented in tables. These include carbonate and sulphate analyses, plotted with logs already, and additional analyses.

SIZE ANALYSIS STATISTICAL PARAMETERS:

A number of standard particle size statistical parameters (Folk, 1968) are presented in a table and plotted graphically with lithology. This was only done for Trench 11 because of the problems encountered in textural analyses of gypsum rich samples in Trenches 6 and 10 (see Appendix 3).
CHEMICAL ANALYSES: Trench 6

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<th>Mg</th>
<th>Sr</th>
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All analyses as weight % of air dried sample.

tr = trace present
CHEMICAL ANALYSES: Trench 10

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CHEMICAL ANALYSES: Trench 11

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All analyses as weight % of air dried sample.

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TRENCH 11: Statistical grain size parameters

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Depth: Mid point of sample.

Mz: Graphic mean (Ø16 + Ø 50 + Ø 84 /3)

σG: Graphic standard deviation (Ø84 – Ø16/2)

σI: Inclusive graphic standard deviation (Ø84 – Ø16) + (Ø 95 – Ø5)

SkI: Inclusive graphic skewness Ø16 + Ø84 –2Ø50 + Ø5 + Ø95 – 2Ø50

KG: Graphic kurtosis Ø95 –Ø5

\[
2.44(Ø75 – Ø25)
\]
APPENDIX 2: Field logs of Trenches 1-13

The lithology and brief field description are presented for each of the trenches excavated at Prungle. Although detailed descriptions were not made in the field, all major units have been differentiated and their character briefly described. Initially colour charts were used to record colours but after rain occurred as the sections were being described, the colour varied to such an extent they were not considered to be reliable. Descriptions of colour included in the field logs are therefore of a subjective nature, useful only for the broadest comparisons. These descriptions have been used with the detailed work on Trenches 6, 10 and 11 to draw the stratigraphic cross section across the lake, but in general no detailed analyses have been performed on sections 1-5, 7-9 and 12-13.
TRENCH I: LITHOLOGICAL PROFILE

- Structureless, yellow-orange sand
  - many root channels

- White secondary carbonate segregations
  - becoming smaller and less common as depth increases

- Fine to medium sand with some clay matrix
  - Occasional small shell fragments
  - Light brownish grey

- White secondary gypsum segregations
  - small and widely spaced
  - becoming less common as depth increases

- Light grey, fine to medium sand with clay matrix
  - Reddish grains common

- Indistinct planar bedding
  - Medium to coarse sand with small shell fragments

Legend:
- Coarse sand
- Medium to fine sand
- Secondary carbonate
- Secondary gypsum
- Fine, earthy
TRENCH 2: LITHOLOGICAL PROFILE

Greenish grey sandy clay, open fabric
rare small white segregations

Clay rich with weakly developed vertical illuvial clay structure
much denser and more cemented than overlying material
Poorly developed secondary carbonates as fine white rhizomorphs

Medium sandy clay with some coarse sand grains
Numerous root channels

Secondary gypsum as common small white segregations
Secondary gypsum segregations become larger and more scattered

Fine sandy clay

Scattered large secondary gypsum segregations

Very fine sandy clay

- Medium and fine sand
- Non-laminated sandy clay
- Non-laminated clay
- Secondary gypsum (sand sized crystals or larger)
- Vertical structure
- Root channels
TRENCH 3: LITHOLOGICAL PROFILE

Clayey sand with many rootlets

Clay rich moderately well developed vertical soil structure
Blocky prismatic structure (blocks= 10 x 5 cm)
Weakly developed secondary carbonate on clay skin surfaces of blocks
and along rootlets

Well sorted, fine quartz sand
Most grains with a greenish clay coating
No lamination

Greenish grey un laminated clay with common fine sand grains
Some small secondary carbonate segregations
Occasional dark segregations (Mn rich?)

Well sorted fine sand (sub-rounded), occasional reddish grains
Traces of lamination

Sandy clay similar to overlying unit but with more clay
Lenses of clean rounded medium sand
Thin bed of clay with Manganese segregations on clay skins
Sandy clay with root channels and large (1 - 3 cm) segregations of secondary gypsum
White medium to coarse sand, with discontinuous gravel at top of bed

Segregations of secondary gypsum

Poorly laminated clayey sand with occasional thin (1 - 2 cm) clay rich beds

Greenish sandy clay and yellow brown clayey sand
TRENCH 4: LITHOLOGICAL PROFILE

Clayey sand
Clay rich with weakly developed vertical structure

Clayey sand

Very sharp contact (erosional?)
Massive white secondary gypsum

Small thread-like gypsum segregations
Sandy clay
Small secondary gypsum segregations

Clayey fine sand with biotubules (up to 5 mm) filled with brown sandy clay
Small secondary gypsum segregations

Fine sands with reddish grains
Very small gypsum segregations

Sands, many reddish grains
Very small gypsum segregations

Greenish sandy clay with small secondary gypsum segregations

Sandy clay

Sandy clay with many dark manganese segregations

Massive greenish clay with: yellow iron mottling, black manganese segregations, and large (up to 3 cm) crystals of secondary gypsum occurring in segregations up to 10–20 cm long.

Plastic green clay with iron, manganese and gypsum segregations

Coarse sand
Medium and fine sand
Non-laminated sandy clay
Laminated sandy clay
Non-laminated clay
Laminated clay
Secondary carbonate
Secondary gypsum
Secondary gypsum (sand sized crystals or larger)
Non-laminated clay
Sandy clay
Laminated clay
Non-laminated sandy clay
Small thread-like gypsum segregations
Sandy clay
Small secondary gypsum segregations
Clayey fine sand with biotubules (up to 5 mm) filled with brown sandy clay
Small secondary gypsum segregations
Fine sands with reddish grains
Very small gypsum segregations
Sands, many reddish grains
Very small gypsum segregations
Greenish sandy clay with small secondary gypsum segregations
Sandy clay
Sandy clay with many dark manganese segregations
Massive greenish clay with: yellow iron mottling, black manganese segregations, and large (up to 3 cm) crystals of secondary gypsum occurring in segregations up to 10–20 cm long.
Plastic green clay with iron, manganese and gypsum segregations
TRENCH 5: LITHOLOGICAL PROFILE

Sandy clay

Poorly developed vertical structure, more clayey
Many burrows

Sandy clay, isolated small segregations of secondary gypsum

Secondary gypsum
Burrows without gypsum
Massive hard pan of secondary gypsum White segregations on all vertical and horizontal crack or bedding planes
Blocky vertical structure
Massive blue-green clay

Texturally graded disrupted iron rich clay filling desiccation cracks at top of underlying clay
Massive blue clay with zones rich in iron mottles

Dense plastic clay, well structured, conchoidal fracture of blocks, waxy appearance. Small iron and manganese mottles and segregations
Some indications of lamination

Sharp break
Sandy clay with yellow iron mottling

Sand with numerous dark grains (manganese? charcoal?)

Sand with yellow iron mottles

Legend:
- Coarse sand
- Medium and fine sand
- Non-laminated sandy clay
- Laminated sandy clay
- Non-laminated clay
- Laminated clay
- Secondary carbonate
- Secondary gypsum (sand sized crystals or larger)
- Root channels
- Vertical structure
TRENCH 6: LITHOLOGICAL PROFILE

Gypcrete crust, irregular lamination, small white segregations of gypsum

White powdery gypsum, non-laminated
occasional sand sized gypsum

Large scale cross stratification (units up to 10 cm thick)
Long wedge shaped units with internal planar bedding
erosional upper surfaces of cross stratification units
Sand sized gypsum, discoidal crystals parallel to bedding
Rounded clay pellets, generally smaller than gypsum

Horizontally laminated sand sized gypsum and clay pellets

Horizontally laminated medium to coarse sand sized discoidal gypsum parallel to bedding, clay pellets

Sandy clay with isolated gypsum segregations and small rare manganese segregations
Irregular horizon of intergrown coarse secondary gypsum
Sandy clay with isolated gypsum segregations and small rare manganese segregations
Fine well sorted and rounded quartz sand with small secondary gypsum
Sandy clay with isolated gypsum segregations and small rare manganese segregations
Fine well sorted and rounded quartz sand with small secondary gypsum
Clay with small (1 mm) manganese segregations, isolated small gypsum segregations
Coarse (up to 2 cm) intergrown secondary gypsum
Clay with small gypsum segregations

Medium and fine sand
Gypsarenite with clay pellets
Secondary gypsum (sand sized or larger)
Non-laminated sandy clay
Powdery pedogenic gypsum
Gypcrete
Non-laminated clay
TRENCH 7: LITHOLOGICAL PROFILE

Unlaminated whitish gypsarenite, small (1 mm) milky white segregations of gypsum
Some larger (2 mm) gypsum crystals
Some clay coated grains or clay pellets

Planar bedded gypsarenite, bedding poorly developed
Seed gypsum crystals commonly larger than 1 mm, clay pellets and very fine sand
or silt sized red grains (wustenqarz?)
Some laminae of finer grain size

Greenish clay disaggregated by displacive growth of secondary gypsum (1-3 cm)
Clay aggregates are blocky with conchoidal fracture
Chlorine well sorted fine to medium quartz sand with some large gypsum crystals
grown through from the unit above

Dark greenish grey blocky conchoidally cracked clay with brown iron/manganese
mottles, weak vertical structure, small (4-5 cm) segregations of secondary

gypsum cutting across bedding

Large irregular cross-cutting segregations (up to 30 cm) containing large
gypsum crystals (average 0.5-1 cm, up to 4 cm)

Greenish sandy clay

Gypsum segregations become smaller with depth

Unlaminated sandy clay numerous iron/manganese mottles,
some small burrows with clay concentration at boundary

Gypsum segregations small (1 mm)

Unlaminated sandy clay

Fine sand with clay matrix
Laminated clay
Fine well sorted and rounded sand
Clayey fine sand

Coarse sand
Laminated sandy clay
Gypsarenite with clay pellets
Root channels

Medium and fine sand
Non-laminated sandy clay
Non-laminated clay
Laminated clay
Powdery pedogenic gypsum
Secondary gypsum (sand
sired crystals or larger)
Vertical structure
TRENCH B: LITHOLOGICAL PROFILE

Uniform grey brown sandy clay

Grey brown sandy clay with rare small granules of green clay

Grey brown sandy clay with small granules of green clay

Grey brown sandy clay containing common green granules of reworked clay
Disrupted dark blue green granular clay
Beds of finely interlaminated gypsum and clay
Thinner interbeds of disrupted dark grey green granular clay
Dark green grey disrupted clay granules (1 cm) Darker iron/manganese mottles on crack surfaces
Thin fine sand layer
Hard greenish sandy clay, small rare Gypsum segregations

Unlaminated greenish clayey sand, with large red orange iron mottles
Iron mottles become smaller and rarer with increasing depth
Gypsum segregations become larger and more common with increasing depth
Crystals within segregations become larger and grade from large to small from the centre of individual segregations

Greenish sandy clay with small yellowish iron mottles

Green clay with small yellow iron mottles

Legend:
- Coarse sand
- Medium and fine sand
- Non-laminated sandy clay
- Laminated sandy clay
- Non-laminated clay
- Laminated clay
- Secondary carbonate
- Secondary gypsum
- Fine, earthy
- Secondary gypsum (sand sized crystals or larger)
- Laminated prismatic gypsum and clay
- Root channels
- Vertical structure
TRENCH 9: LITHOLOGICAL PROFILE

Grey clay with weak vertical structure and poorly developed "crab holes" at the surface

Light grey sandy clay

Sharp erosional boundary cutting across lower bedded units
Inter laminated orange and white gypsum and clay
Massive intergrown large (up to 3-4 cm) gypsum
Finely interlaminated white gypsum and clay
Massive intergrown gypsum crystals (1-2 cm), irregular upper and lower boundaries
Inter laminated gypsum and clay with thin interbedded layers of coarse (1 cm) gypsum

Dark grey green disrupted granular clay
Grey green sandy clay with small gypsum segregations
Secondary gypsum crystals, generally less than 1 cm
Brown sands with many small gypsum segregations

Inter bedded brown and green clayey sands

Inter bedded brown green and white sandy clay

White clean well rounded and sorted fine sand
Inter bedded with green sandy clay
TRENCH 10: LITHOLOGICAL PROFILE

Uniform grey brown sandy clay, with root channels and weakly developed vertical structure, Small isolated secondary gypsum segregations

Disrupted green grey clay with many coarse secondary gypsum crystals
Green grey sandy clay with secondary gypsum
Thin white fine grained gypsum layer
Green grey clay and sandy clay with secondary gypsum
Thin white carbonate layer
Green grey clay and sandy clay

Interlaminated white and orange gypsum and grey clay

Blue grey clays with isolated secondary gypsum, vertical structure
Green grey clays, with cracks from upper surface filled with orange mottled sands
Interbedded clay and sand with white carbonate layers

Thin bed of gypsum clay laminites
Clay with thin white carbonate layers
Fine wavy laminated white and orange gypsum and clay laminites
Clay with large gypsum crystals (up to 3-4 cm)

Fine wavy laminated white and orange gypsum and clay laminites
Interlaminated clay, sand and sandy clay
Secondary gypsum (< 1 cm)
Thin white carbonate layer
Orange mottled sands

Laminated sands with small orange mottles

Grey brown sands
Sands with many coarse grains
Clayey sands
Thin white carbonate layer
Inclined laminae of sands and coarse sands truncated at upper surface
Thin white carbonate layer
Green clayey sands

Sand medium and fine
Laminated Clay
Laminated Sandy clay
Non-laminated clay
Laminated prismatic gypsum
Displacive gypsum, sand sized
Non-laminated sandy clay
Algal carbonate
Soil horizon
Carbonate
Large displacive gypsum
Root casts
TRENCH 11: LITHOLOGICAL PROFILE

Depth Cm 0

Reddish brown sand

Hard carbonate cemented sand
Light red brown sand, traces of lamination
Hard carbonate cemented sand
Brown sands with reworked white carbonate aggregates
Green clay
White carbonate aggregates in a sandy matrix
Brown sands
White carbonate layers separated by laminated green clayey sand
Green laminated clayey sands, with thin white carbonate horizons
White carbonate layer
Green laminated clayey sands
White carbonate layer
Green laminated clayey sands
White carbonate layer
Fine sands, hard, mottled
Hard carbonate cemented sand
Laminated clayey sands with thin white carbonate layers
Laminated clayey sands
White carbonate layer
Green grey clay
Laminated sands and greenish clayey sands
Green grey clay layer
Laminated clayey sands
Green grey clay layer
Finely interlaminated clay, sand and clayey sand
Poorly laminated or non-laminated grey clayey sands
White carbonate layer laminated
White clean well sorted sands with strong red orange mottles, occasional hard iron concretion in the centre of mottles
Greenish clay and sandy clay with yellow mottles
Greenish white sands

Sand medium and fine
Laminated Clay
Laminated Sandy clay
Non-laminated clay
Non-laminated sandy clay
Algal carbonate
Soil horizon
Carbonate
TRENCH 12: LITHOLOGICAL PROFILE

Red brown sand

Unionid shells
Massive white secondary carbonate, many hard nodules in a soft earthy matrix
Some sandier burrows

Secondary carbonate less massive
Dense dark green brown clay with secondary carbonate concentrated along vertical cracks, many burrows, dark brown iron mottles

Light green brown sandy clay with minor secondary carbonate
Light brown iron mottles

Fine and medium sand
Non-laminated sandy clay
Non-laminated clay
Secondary carbonate
Grey sandy clay

Clay rich vertically structured with white segregations of secondary gypsum

Disrupted green grey granular clays
Finely interlaminated gypsum and clay
Sandy clay with secondary gypsum crystals
Finely interlaminated gypsum and clay
Coarse granules of disrupted green grey clay
disrupted green grey granular clay with many small (1-2 mm) gypsum crystals
Clean fine sand
Greenish clayey fine sands with dense secondary gypsum at base of bed

Segregations of secondary gypsum

Interbedded green and yellowish sandy clay and clayey sand

Clayey sand with yellow orange and orange red iron mottles
Gypsum segregations 1-2 cm

White fine to medium sands

Interbedded sand and clay poorly bedded

Interbedded green and pale green sandy clay and clayey sand

Strong yellow orange iron mottles
Small (<1 cm) secondary gypsum segregations (concentrated in finer layers)

Green clay with yellow iron mottles
1. FIELD METHODS:

a. Trenching:
Trenches were dug, using a tractor mounted backhoe, to a depth of 3 m, the maximum possible with the machine. Trenches were initially logged by observation of features, hand-lens examination and estimation of relative abundance of carbonate, gypsum, textural grades etc. Sample locations were then selected. After sampling the trenches were backfilled.

b. Sampling of Trenches 1-5, 7-9, 12 & 13:
All units identified during logging were sampled by selective siting of monolith tins and corresponding bag samples.

c. Sampling of Trenches 6, 10 & 11:
These trenches were chosen after field logging as the most complete sections representative of the sedimentary units recognized. Each trench was sampled completely by the use of overlapping monolith tins, except for the surface soil overlying the laminated lacustrine sequences in Trenches 10 and 11. Corresponding bag samples were also taken.

d. Surveying:
A cross section along the line of trenches was surveyed accurately using an AGA Geodimeter distance measuring instrument mounted on a WILD T2 theodolite. The relative level of each trench was plotted on the section as well as all topographic features. It was not possible to tie the transect into the Australian Height Datum because of the lack of nearby bench marks.
The transect was not closed but was found to agree well with a previous survey on a similar transect using an automatic level and staff.

2. LABORATORY METHODS:

   a. Air photograph interpretation:
   A detailed geomorphic map of the Prungle System was prepared using 1:30,000 scale colour and 1:68,000 black and white aerial photographs, viewed with a scanning stereoscope.

   b. Profile logging and sampling:
   Trenches 6, 10 and 11 which had been sampled fully in oriented monolith tins were logged in detail, using stereo-microscope observations and carbonate presence and relative abundance were estimated from effervescence in 10% HCl. All sedimentary units recognized in this logging were sub-sampled and bagged separately.

   c. Thin sections:
   After sampling the remaining material in the monolith tins was vacuum impregnated with polyester resin, slabbed on a diamond saw and thin sections made by oil lapping techniques. The thin sections were sited to sample all sedimentary units and where possible the boundaries between them. Thin section numbers for each profile were 24 for Trench 11, 23 for Trench 10 and 18 for Trench 6. Twenty four of the sections measured 40 x 60 mm, and the remainder 20 x 60 mm.

   d. Textural analyses:
   Samples from representative units throughout each profile (Trenches 6, 10, 11) were selected and split using a random sample splitter. In some cases
washing and centrifuging was necessary to remove small quantities of soluble salts. Sub samples were placed in 600 ml distilled water with dispersant (5 ml of 5% NaOH and 10 ml of 10% Na Tri-poly-phosphate) and dispersion achieved by ultra-sonic disaggregation and stirring with an electric paddle mixer. The sample was made up to volume in a settling tube and silt and clay size classes determined by the hydrometer method after settling in a constant temperature environment. The sand fraction was separated and size classes were determined by sieving with a mechanical sieve shaker. Standard statistical parameters were calculated by computer.

Problems in dispersion were encountered in samples rich in gypsum finer than sand sized, and in samples rich in clay pellets. Sand sized gypsum was only present in abundance in the aeolian gypsarenite sequence where it forms a major component of the primary grains and was therefore included in the analyses. Samples of the gypsum/clay laminites and the pedogenic portion of the gypsum dunes contained considerable amounts of silt sized gypsum and would not stay in suspension for more than 2-3 hours. These samples were treated with dilute HCl until all gypsum was removed and then washed, re-dispersed and analyzed. Duplicates of these samples, without gypsum removal, were analyzed using a HORIBA CAPA-300 Centrifugal Particle Analyzer in order to estimate the size range of the gypsum silts by comparison with the treated samples. However, the results were disappointingly inconsistent and not considered sufficiently reliable even for estimates of size classes to be made. The results did indicate that up to 40-50 % silt sized gypsum was present in some of the laminites and pedogenic samples. Clay pellet dispersion was achieved using a SONIFIER B-30 Cell Disruptor. Binocular microscope inspection of the sand and coarse silt fractions confirmed the success of this technique.
e. Chemical analyses:
Chemical analyses were performed by or under the guidance of Mr. J.R. Caldwell, Department of Biogeography and Geomorphology, ANU.

ORGANIC CARBON: By Schollenberger chromic acid wet oxidation.

CARBONATE ABUNDANCE: By volumetric calcimeter, measuring CO₂ evolution from reaction with HCl, under constant temperature conditions.

SULPHATE ABUNDANCE: By gravimetric analysis of BaSO₄ precipitated by the addition of BaCl to a 1N HCl digest.

STRONTIUM ABUNDANCE: By atomic absorption spectroscopy (l 4607 Å) of a 1N HCl digest.

CALCIUM ABUNDANCE: By Na₂EDTA titration of a 1N HCl digest.

MAGNESIUM ABUNDANCE: By Na₂EDTA titration of a 1N HCl digest.

IRON ABUNDANCE: By colourimetric (480 μ) measurement of KScN complex from 1N HCl digest (adjusted for pH and oxidised by H₂O₂).

f. Mineralogical analyses:
All mineralogical determinations were made by X-Ray diffraction analysis of samples on a flat plate prepared by evaporation of slurried powdered or dispersed samples.
CARBONATES: The relative abundance of Mg\(^{2+}\) in calcite and Ca\(^{2+}\) in dolomite were determined by the relative displacement of the 100 reflection peak. Exact peak position was calibrated by the addition of reagent grade CaF\(_2\) for calcite peaks, and NaCl for dolomite peaks and measurement relative to them. Where carbonate abundance was sufficiently high, the relative amounts of calcite and dolomite were determined by the ratio of the peak heights.

CLAYS: Samples were washed to remove soluble salts, then dispersed and the fraction less than 2 μ separated by sedimentation in a settling tube. Gypsum, carbonate and exchangeable cations were removed by acetic acid digest, organics by H\(_2\)O\(_2\), and Iron by oxalic acid. The resulting clay sample was slurried and duplicate samples were allowed to dry on stainless steel plates, producing a preferred orientation. One sample was then glycolated and the other dried at 600° C for 1 hour. Both samples were examined in the diffractometer and the results compared.

CELESTITE: When the presence of celestite was suspected from thin section analyses, a concentration from selected horizons was made by heavy liquid separation and the presence of celestite confirmed by X-ray diffraction.