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The continent/island-arc collision in northern Papua New Guinea

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Recent geological mapping in the north coast ranges of Papua New Guinea has recognised a Paleogene island arc. This arc is believed to have faced southward, and formed at the northeastern boundary of the Indo-Australian plate. The arc collided with continental crust of the Indo-Australian plate to the south; collision is thought to have occurred first in the west in the Early Miocene and to have progressed eastwards. Crustal shortening on collision resulted in foreland-type folding and thrusting at the continental margin, emplacement of ophiolite allochthons from the arc-trench gap at the collision zone, and uplift and fracturing of the accreted arc. Post-collision plate adjustments are thought to include extensive transcurrent faulting about the former plate boundary, southward thrusting of part of the arc (Finisterre-Huon block), and extensive faulting in a complex linear zone extending from south of Manus Island through New Ireland and the Solomon Islands. Present-day interaction between the Indo-Australian and Pacific plates is spread over a wide zone in which at least two minor plates are involved.

Despite previous claims, plots of the most accurately located earthquake foci define a northward-dipping seismic zone beneath the Late Cainozoic volcanoes at the southern margin of the Bismarck Sea. We find no evidence to substantiate a reversal of arc polarity at any time after the Mid-Tertiary collision. Mid to Late Cainozoic magmatism in central Papua New Guinea appears to have been triggered by uplift inducing partial melting of mantle modified by Cretaceous subduction. The present-day northward-dipping seismic zone is believed to be a vestige of the Early Tertiary subduction zone; the hanging slab is now slowly sinking and equilibrating with the mantle. If northern New Guinea can be considered to be the type example of a continent/island-arc collision then reversal of arc polarity may not be a necessary consequence of such collisions.

Introduction

In a recent review of island arcs Coleman (1975a) lists three mechanisms for continent/island-arc collisions: retracking following polarity reversal of a marginal arc complex; rafting of a continent over a subduction zone which dips below an oceanic arc; and encroachment against a fringing arc by a continent over a subduction zone dipping below the continent. According to widely accepted plate tectonic theory a reversal of arc polarity should occur in the first two instances. To date there are few well documented examples of continent/island-arc collisions, probably because it is difficult to recognise facing criteria in former arc-trench systems.

Northern Papua New Guinea is widely cited as a probable example of a continent/island-arc collision. Several previous interpretations of the tectonic evolution of the New Guinea region suggest that a southward-facing Tertiary island-arc collided with the continent to the south in the Mid-Tertiary, and that after collision the direction of subduction reversed to dip southwards beneath the continent and the accreted arc (e.g. Dewey & Bird, 1970; Johnson & Molnar, 1972; Karig, 1972; Hamilton, 1973; Dickinson, 1973). Until recently the geology of the north coast ranges of Papua New Guinea was known only from early reconnaissances. Systematic 1:250 000 scale regional mapping since 1970 of the Adelbert and Finisterre Ranges and the Huon Peninsula region by the Geological Survey of Papua New Guinea (Robinson and others, 1974; Jaques & Robinson, 1975; Robinson, 1976), and of the Bewani and Torricelli Mountains to the west, by BMR (Hutchison, 1975) coupled with isotopic and palaeontologic dating, and regional geophysical surveys (gravity, aeromagnetic, and seismic), now permit a re-examination of earlier interpretations. This paper presents a synthesis of the geology of the Adelbert-Finisterre-Huon region and adjacent northern Bismarck and Schrader Ranges in northeastern mainland Papua New Guinea, and outlines a plate tectonic model for the origin of the region invoking a Mid-Tertiary continent/island-arc collision. Present-day volcanism off the north coast of mainland Papua New Guinea is associated with a steeply northward-dipping (almost vertical) Benioff Zone, and the evidence suggests that, contrary to theoretical predictions and previous interpretations, a reversal of arc polarity has not occurred since collision. The significance of this for continent/island-arc collisions in general is discussed, and an alternative model to explain the Middle to Late Cainozoic magmatism in the Papua New Guinea Highlands and the Late Cainozoic volcanism at the southern margin of the Bismarck Sea is examined.

Regional framework

Essential elements of the regional geology of the newly independent country of Papua New Guinea have been outlined by Thompson & Fisher (1965), Bain (1973), and Dow (1976), and geologic maps at scales of 1:1 000 000 (BMR, 1972) and 1:2 500 000 (D'Addario and others, 1975) have been compiled from standard 1:250 000 scale geologic maps. For simplicity, this paper recognises only three major geotectonic provinces in Papua New Guinea (Fig. 1).

Southwest Papuan Platform

The Southwest Papuan Platform (Brown and others, 1975) consists of sialic crust—Palaeozoic metamorphic and granitic rocks—overlain by Mesozoic and Cainozoic shelf sediments (APC, 1961), and forms a stable basement extension of continental Australia. A northeastern extension of the basement platform underlies Mesozoic miogeosynclinal shale and Tertiary limestone of the Papuan Fold Belt (Bain, 1973)—a zone of detachment tectonics (Jenkins, 1974)—and forms the core of a basement high in the Papua New Guinea Highlands—the Kubor Anticline (Bain and others, 1975). In places the fold belt is blanketed by volcanic rocks from several large Quaternary stratovolcanoes. The

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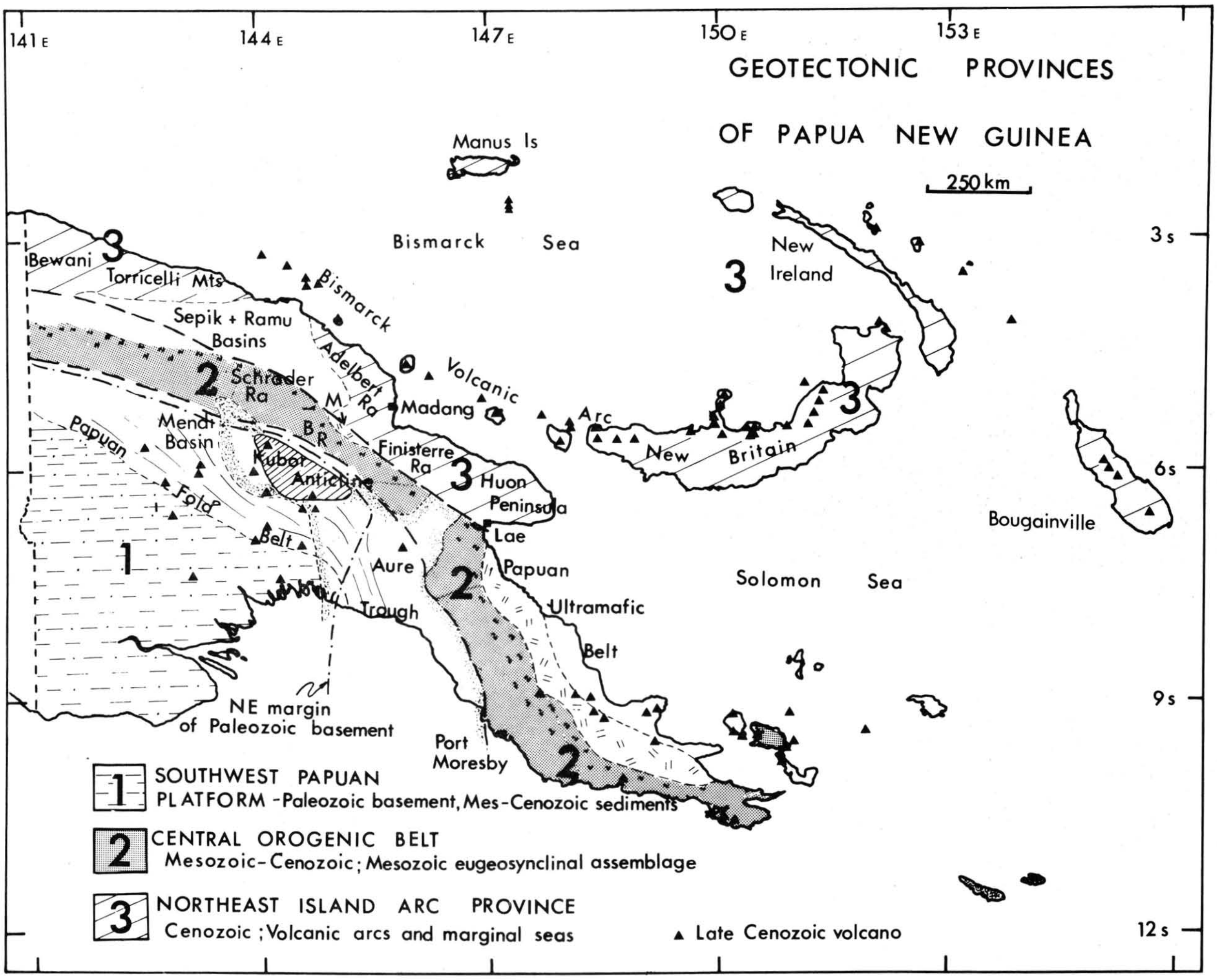

Figure 1. **Major geotectonic provinces of Papua New Guinea; adapted after Bain (1973). Marum ophiolite complex; BR = Bismarck Range.**

platform is isostatically stable, and has a crustal thickness of 30-35 km (St John, 1970; Jenkins, 1974).

Central Orogenic Belt

The central orogenic belt, or New Guinea Mobile Belt Dow and others, 1972; (Bain, 1973; Bain and others, 1975; Dow, 1976), lies to the north and east of the Southwest Papuan Platform, and extends from the Owen Stanley Ranges of the Papuan Peninsula through the Papua New Guinea Highlands (Fig. 1). This province, of Mesozoic-Cainozoic age, consists mainly of a thick sequence of Mesozoic to early Tertiary geosynclinal sediments and volcanics which have been strongly folded, faulted, and metamorphosed on the outer northern and eastern margin. Ophiolite allochthons form a discontinuous belt along the outer margin, the largest of which, the Papuan Ultramafic Belt, is believed to be a 10-16 km-thick thrust sheet of oceanic crust and mantle emplaced in Eocene-Oligocene times (Davies, 1971). A smaller ophiolite body, the Marum ophiolite complex, some 90 km long, lies on the northern side of the Bismarck Range centred at about 145°E, and is thrust over low-grade metasedimentary rocks of Cretaceous to Eocene age, which form part of a large structural belt affected by foreland-type folding and thrusting with superimposed intense strike-slip faulting. Farther south, approaching the Kubor Anticline, the Late Mesozoic sedimentary succession is continuous (Bain and others, 1975); to the southwest the succession passes into the Mesozoic shelf strata of the South West Papuan Platform.

A number of major Mid to Late Cainozoic, mostly mid-Miocene (Page, 1976), intermediate plutons intrude over the entire length of the central orogenic belt, and some of these have associated gold and copper mineralisation. The Aure Trough and the Mendi Basin are Tertiary geosynclinal basins, which lap over the deformed Mesozoic-Early Tertiary strata from the Southwest Papuan Platform. Late Cainozoic volcanism both in the Highlands and in southeast Papua has constructed large stratocones; some of these have recently been active (Johnson and others, 1973). Crustal thickness beneath the central orogenic belt are comparable to those of the Platform—i.e., 30-35 km (St John, 1970).

Northern Island Arc Province

This province includes the islands of the Bismarck Archipelago, the Bismarck and Solomon Seas, and the north coast ranges. The region is defined by a high level of seismicity and is characterised by active tectonism and volcanism in the Bismarck volcanic arc (Johnson and others, 1971, 1973) at the southern margin of the Bismarck Sea, and in the Bougainville-Solomon Islands chain. The province is made up almost entirely of Cainozoic rocks. The larger islands of the Bismarck Archipelago (i.e., New Britain. New Ireland) and the north coast ranges, consist predominantly of Tertiary volcanic and sedimentary rocks, and are believed to have originated as Tertiary island arcs (Thompson & Fisher, 1965; Bain, 1973; Dow, 1976; D'Addario and others, 1976). The Bewani and Torricelli

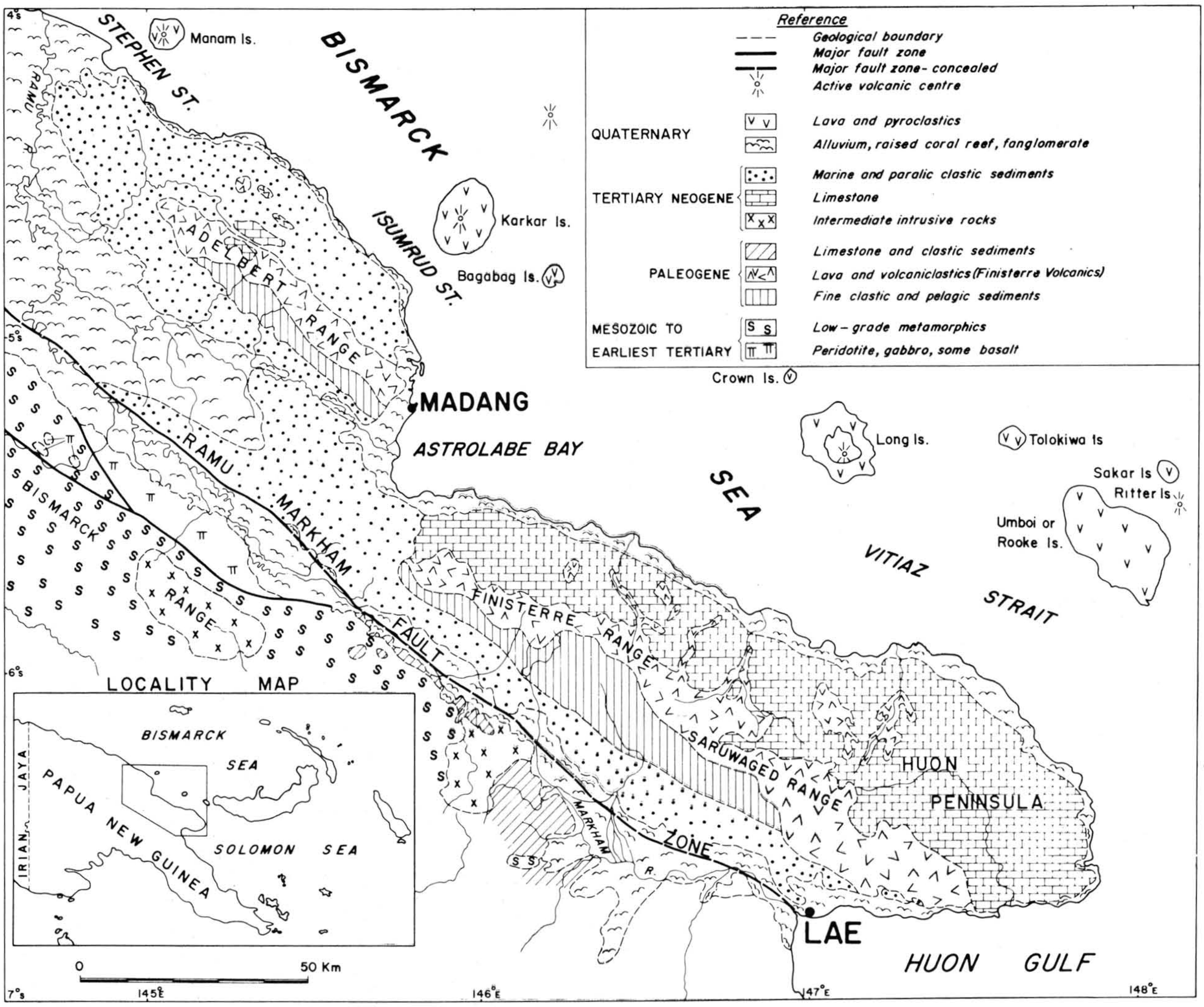

Figure 2. Simplified geology of the Adelbert-Finisterre Range-Huon Peninsula region, northern Papua New Guinea. Geology adapted after BMR (1972), Robinson and others (1974), and Jaques & Robinson (1975), Robinson (1976).

Mountains to the west also include Cretaceous volcanic rocks; strike-slip faulting is intense (Hutchison, 1975). The Bismarck Sea is considered to be an active Tertiary marginal basin, with sea floor spreading taking place in the east-west seismic zone that crosses the basin (Connelly 1974, 1976). The crust thins rapidly northward from continental-type thicknesses (30-35 km) beneath the north coast ranges (Brooks, 1969; St John, 1970) and New Britain (Finlayson & Cull, 1973) to about 18-20 km under the Bismarck Sea (Connelly, 1976).

Geology of collision area

The region discussed (Fig. 2) involves the north coast ranges (Adelbert, Finisterre Ranges, Huon Peninsula) of the northeast island arc province, and the Bismarck and Schrader Ranges of the central orogenic belt to the south. The simplified geology is shown in Figure 2, and Table 1.

The two provinces are separated by the elongate, alluviated, graben-like Ramu-Markham Valley (Figs. 2, 3) which coincides with a major fault system, the Ramu-Markham Fault Zone. This fault zone is believed to extend some 300 km in a northwest-southeasterly direction. The nature of faulting along the zone has not been determined precisely, but considerable horizontal as well as vertical movements seem likely. Faulting, in particular strike-slip faulting, is not confined to the Ramu-Markham Fault Zone,

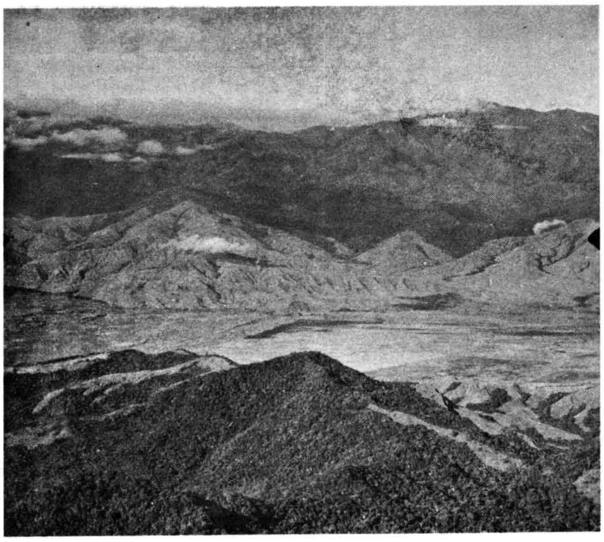

Figure 3. Photograph taken looking south toward the alluviated Ramu-Markham valley. The valley extends some 350 km, and is from about 5-25 km wide. The valley floor is of less than 500 m elevation, and contrasts with the mountains both north and south. The valley coincides with the Ramu-Markham Fault Zone, which is believed to be a major fault with considerable transcurrent displacement.

but is common both in the north coast ranges and in the Bismarck and Schrader Ranges. The predominant trend in all cases is northwest.

Adelbert-Finisterre-Huon region

The extremely rugged, mountainous (up to 4100 m) Adelbert and Finisterre Ranges trend northwestward, and comprise Cainozoic sedimentary and volcanic rocks exposed in a series of northwest-trending fault blocks which dip northeastward. Faults bounding the tilted blocks are predominantly high-angle normal faults downthrown to the south (Figs. 4, 5). The fault blocks are cut by numerous strike-slip faults, and, on the northern slopes of the Finisterre Range-Huon Peninsula, by normal faults (Fig. 5); all faults trend northwestward. Superimposed on these is a series of composite fractures, whose areal distribution suggests that most may have formed initially as shears but took on a tensional character during uplift. Aeromagnetic surveys (Continental Oil Co. Aust., 1969) have defined a number of northeasterly trending basement faults normal to the dominant structural trend. The Adelbert and Finisterre Ranges are offset along such a trend, suggesting dextral transcurrent faulting along a line trending southwest from Madang. A pronounced northeast-southwest submarine excarpment lying off Madang in Astrolabe Bay may be the offshore extension of this inferred fault. The age of the offset is not known, but probably pre-dates the late Neogene as there is no evidence of meridional faulting in the latest Neogene strata south of Madang; nor are the volcanoes of the Bismarck volcanic arc offset.

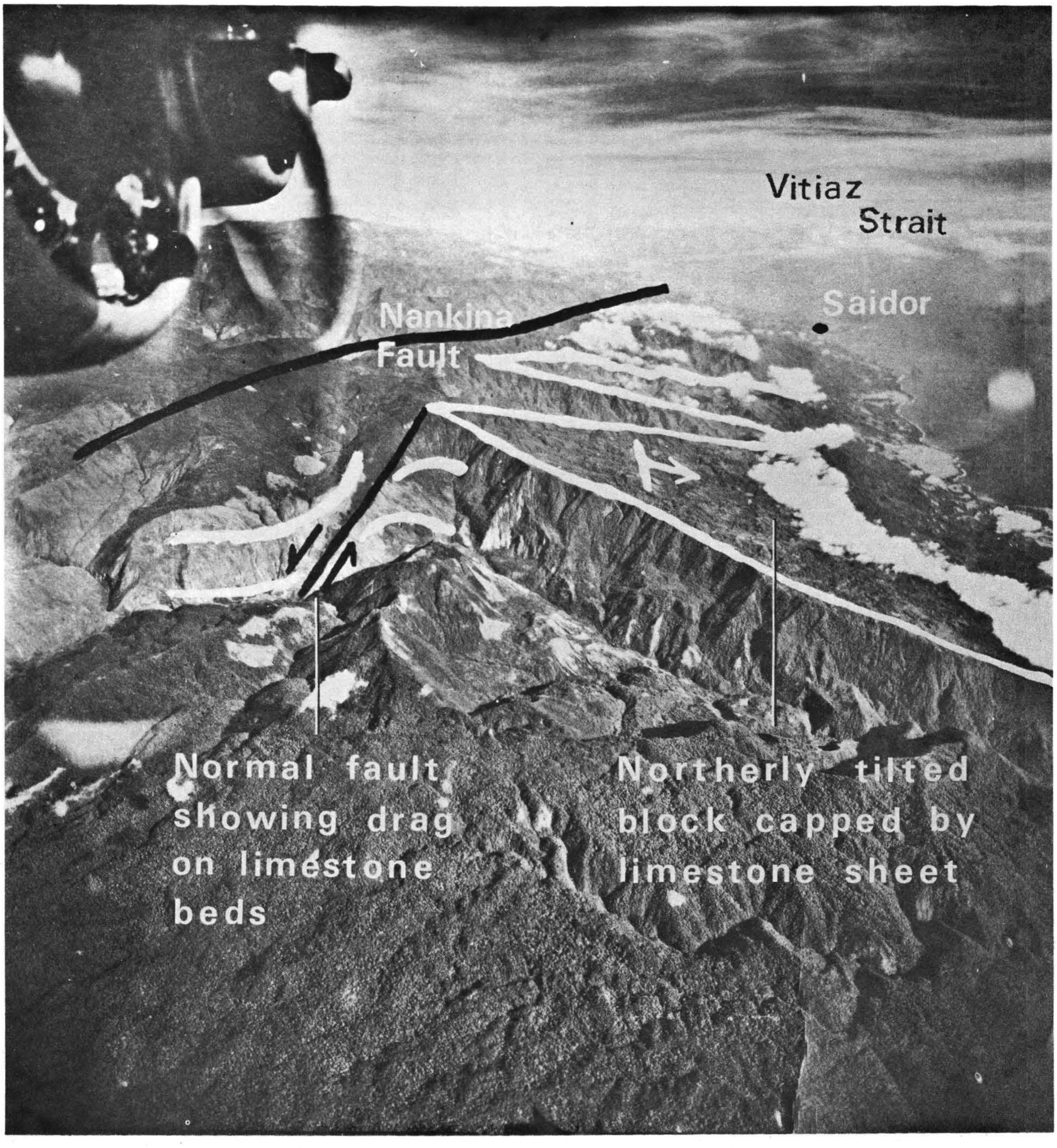

Figure 4. **Oblique aerial photograph showing northeastward-tilted block of Miocene limestone. Note downthrown block to south with drag folding of limestone. Photograph taken looking west along the central Finisterre Range (about 145° 40′ E) from 8000 m. Limestone sheet is about 1 km thick.**

The oldest rocks exposed in the Adelbert-Finisterre-Huon region, with the possible exception of some bodies of tectonised peridotite (see later), are highly sheared Eocene hemipelagic and pelagic sediments, dominantly cherty argillite, which are exposed on the southern flanks of the Adelbert and Finisterre Ranges. The argillite is overlain by dominantly Oligocene (late Eocene to early Miocene) basalt, and low silica-andesite lava and volcaniclastic rocks (Finisterre Volcanics), which form the central peaks of the ranges. The Finisterre Volcanics are unconformably overlain by thick sequences of Neogene (Miocene-Pliocene) limestone and clastic sediments. The limestone forms a prominent northward-dipping sheet on the northern slopes of the Finisterre Range and Huon Peninsula (Figs. 4, 5); only discontinuous remnants occur in the Adelbert Range. Raised Quaternary coral reefs fringe much of the north coast, particularly the Huon Peninsula where a spectacular flight of reef occurs (Chappell, 1974; Robinson, 1976). The Neogene clastic sediments form thick wedges flanking the Eocene argillite and Oligocene volcanics from which they are derived (with extensive reworking) in the Adelbert and western and southern Finisterre Range (Fig. 2). Greatest thicknesses occur in an elongate, northwest-trending structural basin (Ramu Basin) south and southwest of the Adelbert Range, where they are mostly covered by Pleistocene sediments and Quaternary alluvium. At the

Figure 5. **Oblique aerial photograph of northeastward-dipping Miocene-Pliocene limestone sheet in the Huon Peninsula, showing northward-tilted fault blocks downthrown to the south. Note the drag flexure with tension fractures of the limestone by the large normal fault at the front (north) of the sheet. Raised Quaternary coral terraces, up to 600 m high, north of the fault have been described by Chapell (1974); elements of a Holocene fracture set are evident. Note also the large bottlenecked valleys at the front of the limestone sheet cut by consequent rivers and streams. Photograph taken looking east along Huon Peninsula at about 147° 30′ E, from 8000 m.**

northern margin of the Ramu Basin the clastic sequence rests unconformably on Eocene argillite. Further south aeromagnetic and gravity patterns (St John, 1970) suggest a floor of dense, basic rocks. Results of a more recent gravity survey (Milsom, 1975), and the occurrence of Jurassic gabbro-peridotite basement unconformably overlain by Neogene (early-middle Miocene and younger) sediments at a depth of 2000 m in Keram No. 1 wildcat well (Harrison, 1974) drilled in the Ramu Basin southwest of the Adelbert Range (at 4° 26′ S, 144° 09′ E), have been interpreted as indicating a floor of oceanic crust in the southern part of the basin (Jaques & Robinson, 1975).

Ophiolite belt

The Marum ophiolite complex lies immediately south of the alluvium-covered Ramu Basin, and is bounded by major faults to the north and south. The complex consists of two major thrust sheets: a radiolarite-pillow basalt-spilite (with some diabase) allochthon lies to the south of and beneath a larger sheet of peridotite, pyroxenite, and layered norite-gabbro. At the base of the larger sheet harzburgite, with some dunite, is overlain by a thick sequence of cumulus peridotite, pyroxenite and layered norite, gabbro and anorthositic gabbro.

Pelagic sediments, including radiolarites of probable Eocene age, overlie and are intercalated with pillow basalts of the other major thrust sheet, and pass upwards into a sequence of argillite, radiolarite, tuffaceous argillite and graywacke, and tuff. The upper part of this sequence is intruded by pyroxene and hornblende-phyric basalt and basaltic andesite of island-arc affinities.

Windows exposed in several river sections show an imbricate zone of low-grade metamorphic rocks at the base of the harzburgite, with thrust surfaces dipping northeastward at a shallow angle. The dip of the thrusts and the northeastward-dip of igneous layering in many of the cumulate rocks suggests emplacement from the northeast as a series of shallow-dipping thrusts. In addition, the northeasterly displacement of the regional gravity high associated with the ophiolite complex toward the Ramu valley suggests thickening of dense basic rocks beneath the Ramu valley (Milsom, 1975), consistent with this interpretation.

Emplacement of the ophiolite complex clearly postdates the (?)Early Eocene as it is thrust over low-grade metamorphosed sediments of Late Cretaceous to Eocene age. An upper limit of middle Miocene is suggested by the unconformable relationship between the gabbro-peridotite basement (interpreted as oceanic crust) and Neogene strata in the Keram well. Farther west in the south Sepik region there is stratigraphic evidence that ophiolite bodies occupying a similar tectonic and stratigraphic setting were emplaced in post-Eocene and pre-middle Miocene times (Dow and others, 1972).

Small faulted bodies of peridotite (commonly serpentinite), pyroxenite, and gabbro (dismembered ophiolites) occur as klippen on, and thrust slices in, low-grade metamorphic rocks farther west (144° E) in the Schrader Range. Small bodies of harzburgite, dunite, and serpentinite of unknown age have also been recorded from the Huon Peninsula (Robinson, 1976) where they crop out amongst the Finisterre Volcanics; relationships are uncertain.

Metamorphic belt

The metamorphic rocks of the northern Bismarck Ranges, and Schrader Range immediately west, are mostly low-grade metamorphosed pelites. Quartz-veined slate, phyllite, and graphite and mica schist crop out east of the ophiolite belt, and grade laterally into, and in many cases are faulted against, fossiliferous flysch, mostly dark coloured shale and siltstone, but with some sandstone, conglomerate and limestone of late Cretaceous to Eocene age (Bain, 1967; Dow & Dekker, 1964; Jaques & Robinson, 1975; Dow and others, 1972; A. L. Jaques and C. J. Pigram, unpublished data). The metapelites contain abundant quartzo-feldspathic and metamorphic detritus (e.g., quartzite, quartz-mica schist) derived from pre-Mesozoic granitic and metamorphic rocks (i.e., the continental basement) and reworked basement-derived sediments. In addition many contain abundant volcanic detritus, some of which is tuffaceous, indicating contemporaneous volcanism (Thompson, 1967; Harrison, 1969; Dow, 1976). The flysch sequence is interpreted as continental slope and continental rise deposits formed at the margin of the continental mass (platform) to the south.

The degree of deformation and grade of metamorphism, mostly lower greenschist, decrease to the south toward the platform. At least two, and in places three (C. J. Pigram, pers. comm., 1976), phases of deformation are apparent (McMillan & Malone, 1960; Robinson and others, 1974). Early formed folds are commonly overturned to the southwest and asymmetric (many are isoclinal), and cleavage is commonly parallel to bedding; fold axes trend northwest. Second-generation folds are of a smaller scale and more open.

Thrusting occurs over a wide zone at the northern margin of the orogenic belt. Allochthonous strata, bounded in places by curvilinear thrusts dipping northeastward, pass southwestwards towards the Kubor area into thick successions of autochthonous coherent strata of uniform age and lithology. Farther south the autochthonous strata pass into a thick continuous Mesozoic succession at the margin of the platform.

Stratigraphic and structural relations indicate a post-mid Eocene and pre-mid Miocene metamorphic event; this age is consistent with that obtained from stratigraphic relations and isotopic dating for metamorphism of similar rocks farther west in the south Sepik area (see later). There is also some stratigraphic evidence in the Bismarck Range to suggest an earlier (Cretaceous?) metamorphic event McMillan & Malone, 1960; (Robinson and others, 1974; C. J. Pigram, pers. comm., 1976).

Interpretation

The close stratigraphic and structural similarities between the Adelbert-Finisterre-Huon region, and New Britain and the other islands of the Outer Melanesian Arc provide compelling evidence that the north coast ranges originated as a Tertiary island arc, and have since become attached to the continental mass to the south (Thompson & Fisher, 1965; Robinson, 1973; Bain, 1973; Dow, 1976). South of the island arc (Adelbert-Finisterre-Huon arc) the ophiolite belt and outer margin of the central orogenic belt, with the zone of metamorphism and foreland-type thrusting, mark the zone of collision. Figure 6 shows the morphologic and structural relations of these tectonic elements.

Adelbert-Finisterre-Huon Arc

The Adelbert-Finisterre-Huon arc comprises pre-volcanic, volcanic, and post-volcanic assemblages.

Pre-volcanic argillite. The Eocene argillite is believed to have been deposited on the sea floor, and to grade laterally southwards into the Late Cretaceous-Eocene metapelites (Robinson and others, 1974); similar pelagic-hemipelagic sediments overlie the metabasalts of the

Marum ophiolite complex. Sediments low in the argillite sequence are derived from continental basement and predate volcanism in the arc. Argillites higher in the sequence are tuffaceous, and grade into the volcanic and volcaniclastic rocks of the Finisterre Volcanics; the upper part of the argillite is synvolcanic.

Volcanic arc. The abundant, diverse volcaniclastic rocks of the Finisterre Volcanics are lithologically similar to coeval volcanic sequences on New Britain and the other Tertiary island arcs of outer Melanesia. The absence of continent-derived material from the thick volcaniclastic-volcanic pile, and occurrence of pillow lava and radiolarian chert and argillite at the base of the formation, imply that the volcanic arc was oceanic. Lateral transitions from lava to lava breccia to volcanic paraconglomerate to conglomerate to turbidite have been observed in places, and this, together with the abundance of epiclastic rocks, indicates development of extensive clastic aprons about a chain of emergent and near-emergent volcanic centres.

Volcanism in the arc ceased in the Early Miocene, although inter-tonguing relationships between basalt flows and Miocene limestone in the Huon Peninsula (Robinson, 1976) suggest that volcanism may have continued slightly longer in that area. The early Miocene cessation of volcanism coincides with the timing of metamorphism in the outer portion of the orogenic belt, the emplacement of ophiolites and correspondingly the continent/island arc collision (see later).

Post-volcanic-arc assemblages. The contrasting post-volcanic depositional regimes of the western and eastern part of the arc indicate that tectonic events were not synchronous along the arc. In the west the volcanics and argillite were uplifted immediately after cessation of volcanism, and yielded the thick clastic wedge. This uplift coincided with the timing of the orogenesis south of the arc, and we interpret uplift of the western part of the arc to be the direct result of collision of that segment of the arc with the continental mass. Uplift, we suggest, may be the isostatic reaction to underthrusting, or attempted underthrusting of sialic material.

Limestone was deposited in the eastern part of the arc in the northern Finisterre Range-Huon Peninsula region, which was not uplifted until the Pliocene. Uplift since then has been rapid: some 3000 m of uplift has occurred since the late Pliocene. The raised Quaternary coral-reef terraces of northeast Huon Peninsula indicate rapid present-day uplift (Chappell, 1974). We interpret the younger uplift of the eastern part of the Adelbert-Finisterre-Huon arc as indicating a slightly younger collision of that segment of the arc.

Collision zone

Blueschist terrains and ophiolite belts are widely held to mark former convergent plate boundaries. Although ophiolites are conspicuous, melanges containing high-pressure mineral assemblages have not been reported from the Bismarck Range (rare pumpellyite has been found in some metabasites). The outer margin of the central orogenic belt is generally regarded as the zone of interaction between opposing crustal plates (e.g., Thompson & Fisher, 1965; Bain, 1973; Dow, 1976). The foreland-type of folding and thrusting, the nature of the metasediments—i.e., continental slope and rise type, and the lateral transition from deformed allochthonous to undeformed autochthonous successions toward the continental platform in the southwest, provide compelling evidence that the outer margin of the central orogenic belt marks the site of a collision

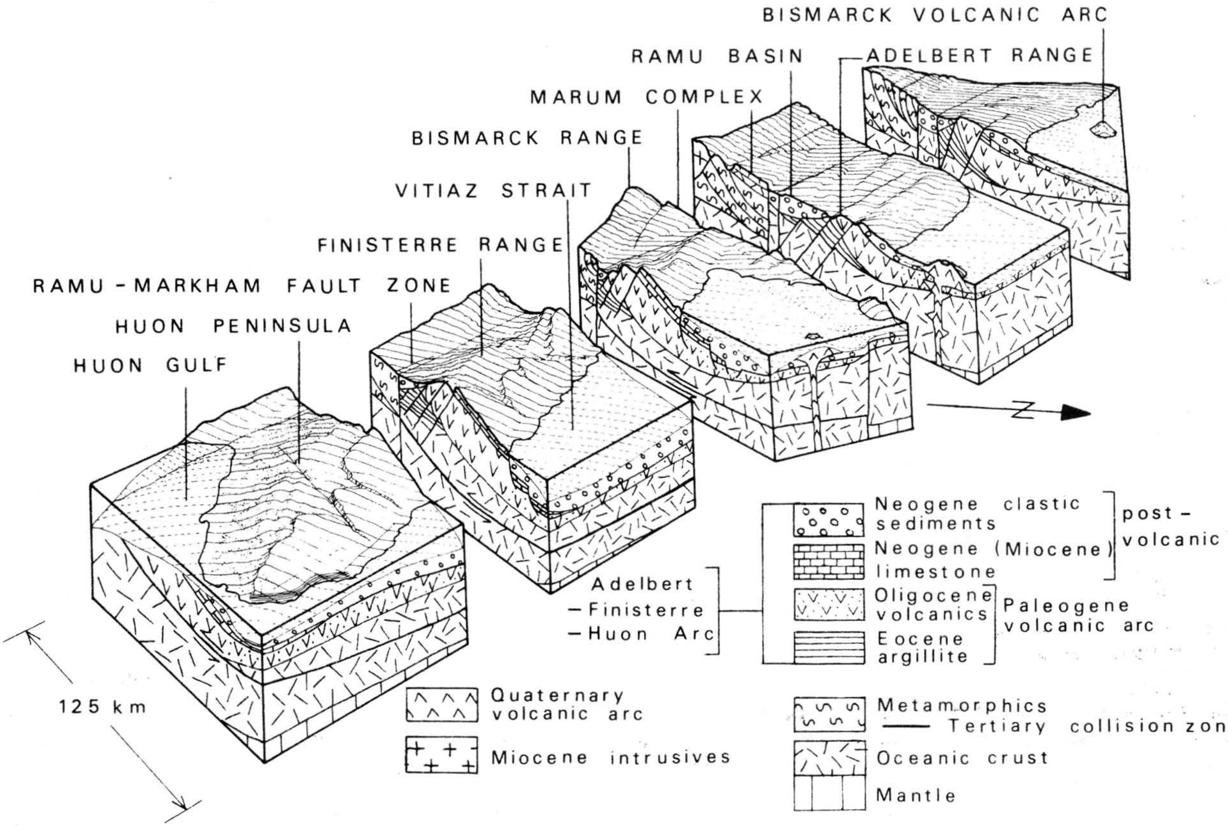

Figure 6. **Block diagram showing structure and petrotectonic assemblages of the Adelbert-Finisterre-Huon arc to the north, and the collision zone to the south. Vertical exaggeration is about 2.5 times.**
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between the continent and its welt of marginal sediments to the south, and the island arc to the north.

High-pressure metamorphic rocks associated with ophiolites have been mapped farther west in the south Sepik region (142-144° E), where lawsonite and glaucophane-bearing rocks, amphibolite, and, locally, eclogite, form a melange within low-grade metamorphic rocks similar to those of the Bismarck and Schrader Ranges (Ryburn, 1976; Dow and others, 1972). Isotopic dating (Page, 1976), and structural relations (Dow, 1972), indicate a late Oligocene-early Miocene age of metamorphism. Immediately north of the blueschist belt lies another metamorphic belt of similar age characterised by low to moderate pressure, and higher temperature mineral assemblages. Ryburn (1976) has interpreted the two belts as constituting a paired metamorphic belt associated with a northward-dipping Early Tertiary subduction zone.

The similar tectonic setting and close stratigraphic similarities between the south Sepik region and the Bismarck and Schrader Ranges lead us to infer that the former subduction zone associated with the Palaeogene Adelbert-Finisterre-Huon arc was choked by the wedge of sediments at the continental margin, resulting in collision between the continent and the island arc. Rocks of the trench melange, including metamorphic rocks with high-pressure mineral assemblages, may lie beneath the northern edge of the Bismarck and Schrader Ranges, the Ramu-Markham valley, and possibly beneath the ophiolite slabs forming the floor of the southern part of the Ramu Basin. The Marum ophiolite complex represents a segment of oceanic crust and mantle from the arc-trench gap region of the upper plate thrust over the choked subduction zone as a consequence of the collision.

Plate tectonic reconstruction

Late Mesozoic—Early Tertiary

Late Mesozoic-Early Tertiary plate configurations and tectonic events are not well understood at this stage, but several important events seem clear. Cretaceous (early Cretaceous?) andesites in the northern central orogenic belt probably formed in a volcanic arc at the northern margin of the continental crustal platform, most likely as a result of southwestward subduction beneath the continent, as suggested by Johnson and others (1977). Formation of oceanic crust of the ophiolite belt appears to be caused by a period of Late Mesozoic-Early Tertiary sea-floor spreading or marginal basin formation peripheral to the volcanic arc and the continent. Extensive deposition of fine clastic sediments (dominantly marine shale) occurred on an extensive continental shelf, slope and rise in the Late Cretaceous to Eocene. These continental margin sediments are thought to have graded into the deeper water, more distal Eocene argillites and cherty micrites. This sequence of events implies that the northern (northeastern) edge of the continent changed from a convergent type in the Early Cretaceous to a divergent or Atlantic-type in the Late Cretaceous-Eocene.

Separation of Australia and Antarctica about 50-55 m.y. ago (Weissel & Hayes, 1971) is thought to have initiated northward movement of the Australian continent, and resulted in rifting and opening of the Coral Sea (Mutter, 1975), eruption of voluminous Eocene tholeiitic submarine basalts in southeast Papua (Davies & Smith, 1971; Milsom & Smith, 1975), and emplacement of the Papuan Ultramafic Belt (Davies, 1971). Tectonic syntheses of these events are provided by Davies & Smith (1971), and Pieters (1974).

Oligocene (Fig. 7)

Farther north and east, removed from the continental margin, plate convergence resulted in the formation of an extended arc-trench system with a northward to northeastward-dipping subduction zone in which oceanic crust at the leading edge of the continent was consumed—i.e., a southward-facing island-arc. Subduction-related volcanism commencing in the late Eocene, and continuing throughout the Oligocene and early Miocene, produced a chain of volcanic centres with extensive clastic aprons. As volcanism waned, fringing reef developed about near-emergent centres in the early Miocene. Early formed trends in the western part of the Bismarck Sea marginal basin parallel the north coast ranges (Connelly, 1976), and are probably of Tertiary, possibly Oligocene (Tilbury, 1975) age. We speculate that basin formation began in the Early Tertiary by a form of back-arc spreading related to mantle upwelling above the northward-dipping Paleogene subduction zone.

Miocene

Continued plate convergence in the early Miocene brought the continent (with its wedge of sediments at the margin) to the subduction zone where the buoyancy of the continental crust arrested subduction, resulting in the collision of the western segment of the Adelbert-Finisterre-Huon arc with the continental margin; volcanism in the arc ceased. The stresses of continued plate convergence were taken up by crustal shortening, in particular by 1) deformation and thrusting at the continental margin; 2) thrusting of oceanic crust from the arc-trench gap over the subduction zone and continental margin; and 3) arching, fracturing, and uplift of the western part of the arc. Examination of fractures in the Huon Peninsula has defined a major set of early fractures which are interpreted as forming a first order conjugate shear system, whose northerly trending acute bisectrix may be interpreted as being the direction of primary stress resulting from the collision (Robinson, 1973). An additional response to continued plate interaction was the formation of numerous northwesterly trending transcurrent faults at and near the former plate boundary. The Ramu-Markham Fault Zone, for example, is believed to be a post-collision transcurrent fault approximating the former plate boundary. Adjustments elsewhere along the plate boundary may also have accommodated plate convergence.

Thick limestone sheets were deposited as broad tabular platform reefs on submarine stepped blocks in the eastern part of the arc, suggesting that collision had not yet occurred in that segment of the arc. This implies that collision involved rotational closure by subduction of sea-floor between the continent and arc, and that after collision in the west a section of sea-floor existed between the eastern end of the arc and the continent. The inferred configuration (Fig. 7) may have been similar to the present-day distribution of the Solomon Sea between New Britain and mainland Papua New Guinea. Southward thrusting of the Finisterre-Huon block, probably along shallow-dipping thrusts as proposed by St John (1970), and Milsom (1975), on the basis of the regional gravity pattern, took place in the Late Miocene or Pliocene.

The collision, and cessation of volcanism in the arc in the Early Miocene, coincides with a short-lived but widespread period of calc-alkalic to alkalic plutonism and volcanism along the axis of New Guinea in the Middle Miocene (Page & McDougall, 1970; Page, 1976). Many of these rocks are a similar composition to island-arc rocks, suggesting that underthrust hydrated lithosphere was important in their

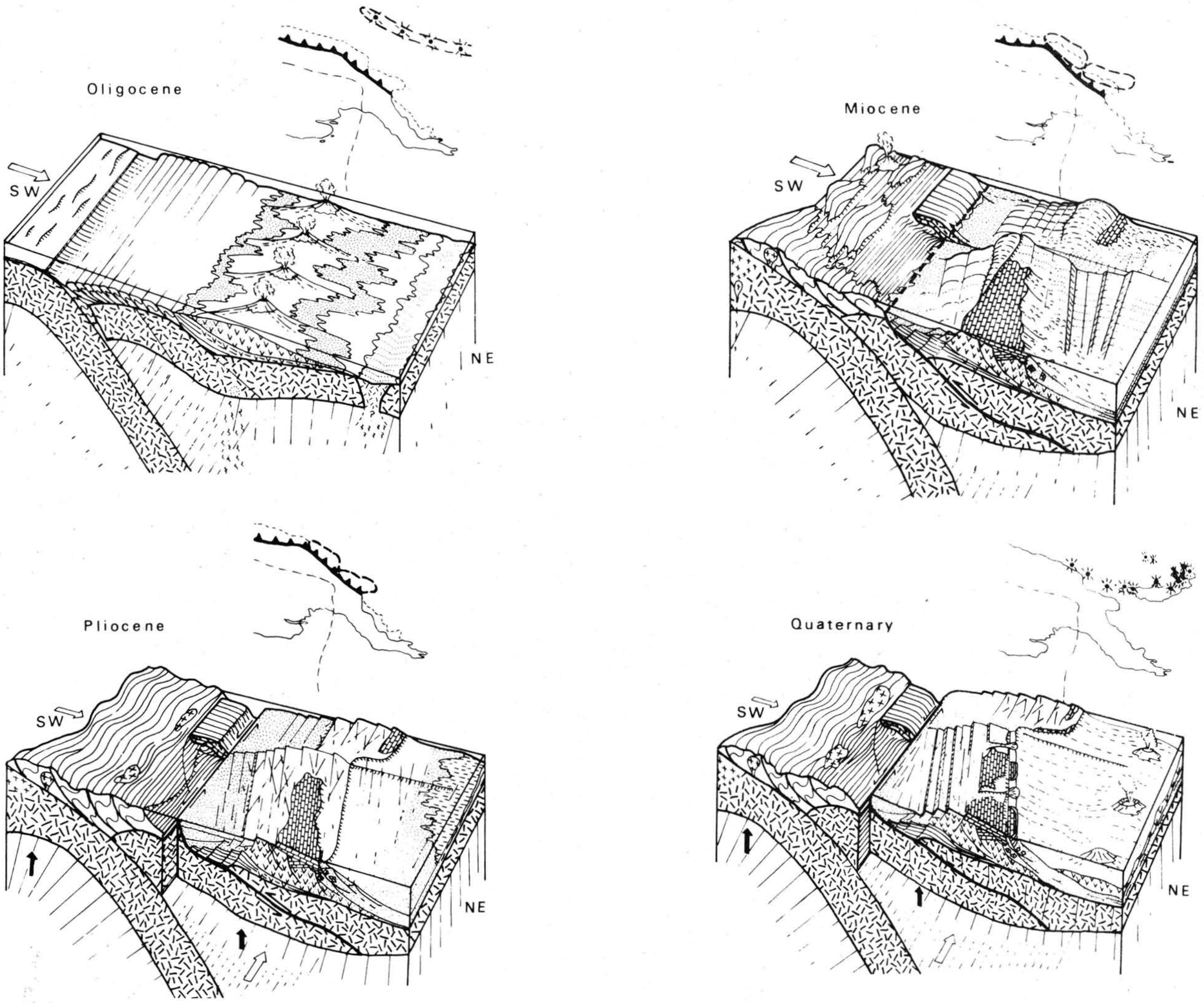

Figure 7. **Block diagrams illustrating conceptual Tertiary evolution of the Adelbert-Finisterre-Huon region as an island arc, followed by collision with the continental margin in the early Miocene. Vertical exaggeration is about 2.5 times. Crustal thickness (see text) is based largely on estimates by St John (1970), and is about 35 km beneath the central orogenic belt and the north coast ranges, and 18-20 km beneath the Bismarck Sea.**

TABLE 1. SUMMARY OF STRATIGRAPHY OF ADELBERT-FINISTERRE-HUON REGION

Unit	*Lithology*	*Remarks*
Neogene clastic sediments	Calcareous, lithic sandstone, siltstone, mudstone; some limestone and conglomerate. Lignite common.	Uncomformable on Eocene argillite, Finisterre Volcanics. Dated by planktonic foraminifera as Mid-Miocene to Latest Pliocene-Pleistocene. Extensive in Adelbert Range. Greatest thickness in Ramu Basin where 4-5000m deposited in elongate troughs between tectonically active basement ridges. Regressive and transgressive sequences, onlapping and foresetting of beds, diachronous beds, deltaic deposits. Marine and paralic sediments.
Neogene limestone	Massive algal-foraminiferal biomicrite and biocalcirudite; well-bedded calcarenite, calcilutite and calcareous mudstone.	Unconformable on argillite and Finisterre Volcanics. Dated as Early-Middle Miocene to Late Pliocene. Form northerly-dipping 1000m-thick resistant sheets in northern flank of Finisterre Range-Huon Peninsula. Only discontinuous sheet remnants in Adelbert Range. Miocene algal-foraminiferal biomicrite represents reef complexes formed as broad tabular platforms on submarine faulted step blocks (Robinson, 1973, 1976). Coarse biocalcirudites (reef talus deposits) surround platform reef complexes, pass into bedded biomicrite, calcarenite and calcilutite.
Oligocene (late Eocene-early Miocene) volcanics (Finisterre Volcanics)	Basalt and basaltic andesite lava breccia, lava, and volcaniclastic rocks, including tuffaceous lithic greywacke, tuff, peperite and peperitic breccia, palagonitic breccia, pillow lava, agglomerate, volcanic conglomerate. Argillite at base, limestone lenses at top.	Gradational contact with underlying Eocene argillite. About 4500m thick. K-Ar dates 34-22 m.y. (Jaques, 1976). Limestone lenses at top of Early Miocene age. Mostly dip steeply north. Strongly indurated; minor zeolite facies metamorphism. Pillow lava at base. Lava subordinate to variety of volcaniclastic rocks—autoclastic, pyroclastic and epiclastic rocks. Lavas of high-K calc-alkalic and shoshonitic affinities.
Eocene argillite	Indurated, strongly jointed, veined cherty argillite, chert, siltstone, tuffaceous lithic greywacke, cherty micrite.	Base not exposed. Dated as Mid to Late Eocene in part. Gradational contact with overlying Finisterre Volcanics. Strongly indurated, veined, sheared. Mostly dips northwards. Unknown thickness. Extensive zeolite facies metamorphism. Sediments lower in sequence derived from continent crust—quartzo-feldspathic detritus common. Upper part of sequence contains abundant volcanic detritus.

derivation from the upper mantle. Although some underthrusting may have taken place at the northern edge of the continent at or immediately after collision in the early Miocene, there is no geological evidence to indicate that an extensive southwestward-dipping subduction zone existed at that time, either north or south of the Adelbert-Finisterre-Huon arc. The present-day northward-dipping seismic zone beneath Vitiaz Strait defined by earthquake foci (see later; Figs. 8, 9) is believed to be a vestige of the northward-dipping Palaeogene arc-trench system (Johnson, 1976, 1977; Johnson & Jaques, 1977). In the absence of geological evidence to support a southwestward-dipping subduction zone in the Mid-Miocene, Johnson and others, (1977) invoke prior (Cretaceous) enrichment and modification of the base of the lithosphere, and generation of island-arc type primary magmas by partial melting on uplift.

Pliocene

Clastic sedimentation on the southern flanks of the arc extended progressively eastwards during the Miocene-Pliocene; limestone deposition continued in the north and east. Uplift of the Huon Peninsula in the Pliocene coincides with the eruption of valley-fill basalts in that area, and the emplacement of scattered diabase dikes and gabbro-diorite stocks and porphyries along the length of the arc. Subduction-related volcanism in the Bismarck volcanic arc to the north also probably commenced about this time. We suggest that the resurgence of volcanism may be the result of subduction of the remaining intervening lithosphere between the Huon Peninsula and the central orogenic belt in the Markham valley region; this completed the final stages of the continent/island-arc collision. Uplift resulted in crestal arching and fracturing, and formation of a complex fracture system with many early-formed shears changing to tensional fractures. Isostatic reaction to underthrusting of sialic material, and probably southward thrusting of the Finisterre-Huon block in the Miocene-Pliocene, may have been the cause of uplift. This thrusting might explain the presence of the small peridotite bodies of the Huon Peninsula, and perhaps, the regional gravity high over that region (St John, 1970). West-northwestward-trending sinistral shears found throughout the north coast ranges are interpreted as indicating widespread transcurrent motion throughout the collision zone caused by northwestward movement of the Pacific plate (and subplates) relative to the continent.

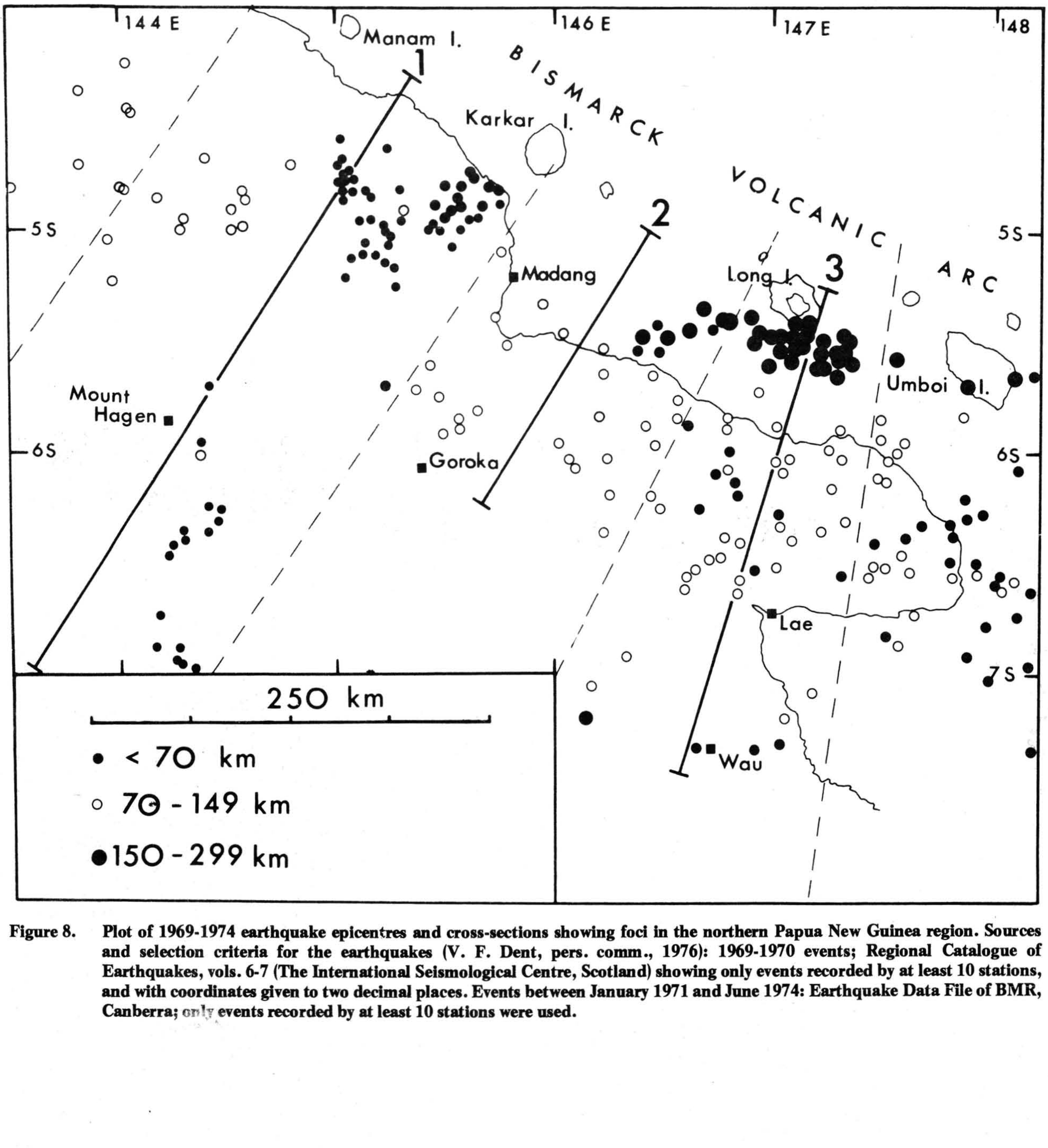

Figure 8. Plot of 1969-1974 earthquake epicentres and cross-sections showing foci in the northern Papua New Guinea region. Sources and selection criteria for the earthquakes (V. F. Dent, pers. comm., 1976): 1969-1970 events; Regional Catalogue of Earthquakes, vols. 6-7 (The International Seismological Centre, Scotland) showing only events recorded by at least 10 stations, and with coordinates given to two decimal places. Events between January 1971 and June 1974: Earthquake Data File of BMR, Canberra; only events recorded by at least 10 stations were used.

Quaternary

Uplift continued in the north coast ranges; extensive deposition of alluvium occurred in the Ramu and Markham valleys, and sedimentation in the Ramu Basin became terrestial after the Pleistocene. Holocene uplift exposed the flight of coral terraces on the northeastern Huon Peninsula.

Extensive Quaternary (partly Late Pliocene) volcanism occurred in the central highlands of Papua New Guinea. Although the volcanic rocks are chemically comparable to subduction-related island-arc and continental margin-type lavas the volcanoes are, with one exception, underlain by continental crust some 30-35 km thick (Mackenzie, 1976). Seismicity plots (Johnson and others, 1971; Figs. 8, 9) show that except for one volcano there are no underlying intermediate-to-deep focus earthquakes which can be attributed to a currently active Benioff zone. Johnson and others (1977) suggest that the volcanism is the result, not of contemporaneous subduction, but of partial melting of a source at the base of the lithosphere which had been modified by the introduction of fluids from a slab dipping beneath the continental margin in the Late Mesozoic. Diapirism and partial melting may have been initiated by periods of uplift following the mid-Tertiary collision. Evidence for the Cretaceous mantle modification are the Cretaceous andesites, and the recent recognition (D. E. Mackenzie, pers. comm., 1977) of a Cretaceous "psuedoisochron" (Brooks and others, 1976) in relatively unfractionated rocks from several Highlands volcanoes.

Present-day regime

The present-day plate boundary configuration in the region is complex. The distribution of earthquake epicentres suggests that at least two minor plates lie trapped between the larger Pacific and Indo-Australian plates (Johnson & Molnar, 1972; Curtis, 1973a, b; Krause, 1973). The chain of late Cainozoic volcanoes at the southern margin of the Bismarck Sea—the Bismarck volcanic arc (Johnson and others, 1971, 1973)—includes a number of active centres; eruptions on Manam, Karkar, and Long Islands occurred in 1973-75 (Cooke and others, 1976). Volcanism at the eastern end of the arc (north of New Britain) can be related to the northward subduction of the Solomon Sea beneath New Britain (Johnson, 1976).

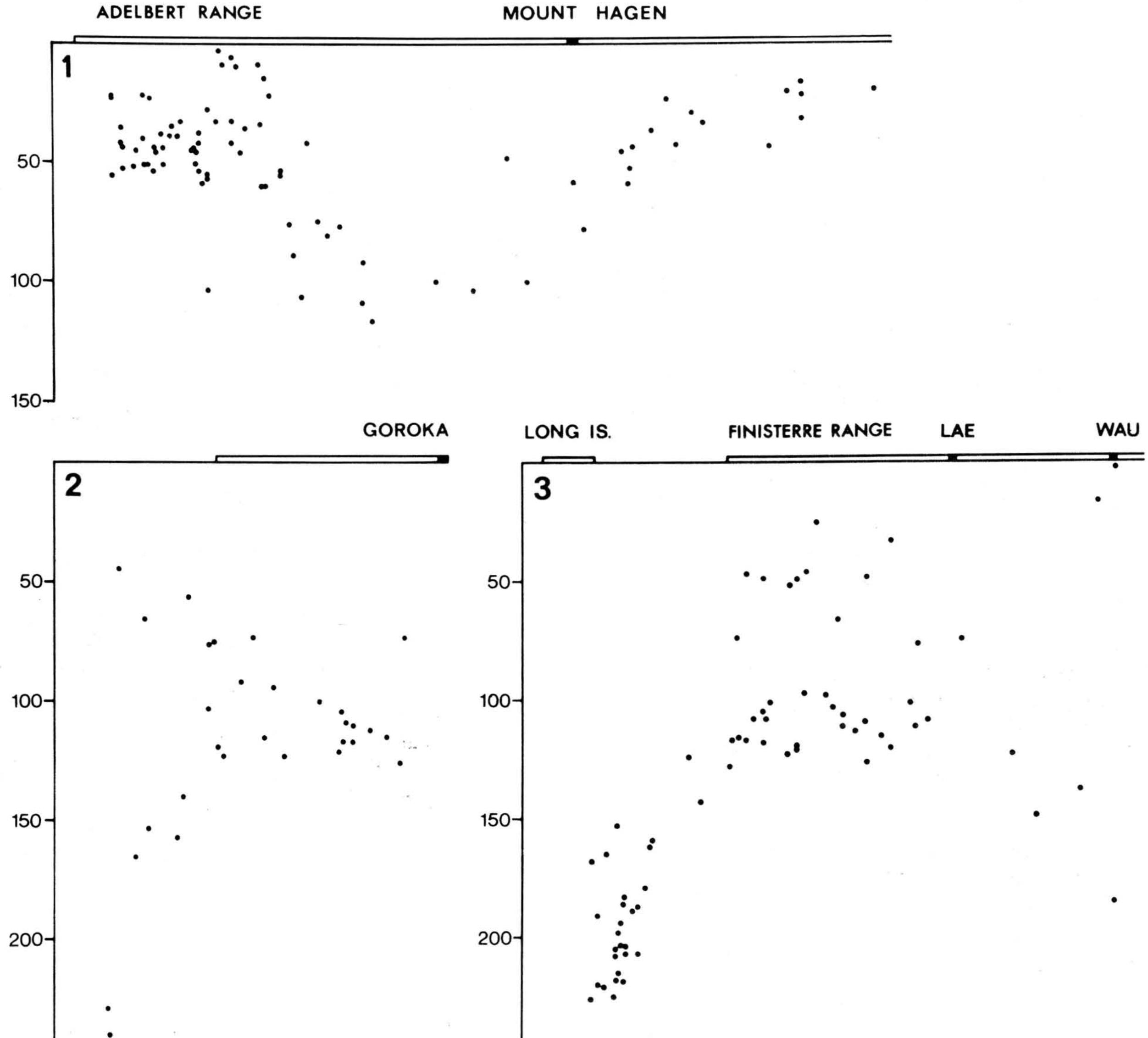

Figure 9. Cross-sections of earthquakes plotted against depth (km). Data from Johnson 1977.

Tectonic events in the western part of the arc are more complex; a submarine trench is lacking, and plots of earthquake foci show an absence of intermediate focus earthquakes west of Karkar Island (Fig. 8). East of Karkar Island, however, a well-defined seismic zone dips steeply northwards beneath Long Island to almost 250 km. Steep dip-slip underthrust mechanisms have been obtained for some of these events (Ripper, 1975). Other apparent inclined seismic zones are also evident in Figure 8. Both northward and southward-dipping 'zones' are apparent in Section 1, and in Section 2 a shallow southward-dipping 'zone' intersects the deeper northward-dipping one. The events defining these 'zones' are all less than 125 km deep (most are less than 100 km), and as the thickness of lithosphere beneath the southern part of the platform (Fig. 3) has been determined as about 125 km (Brooks, 1969), we believe that the earthquakes cannot be assumed to represent penetration of subducted lithosphere into the underlying asthenosphere. Some of the shallow events beneath the north coast ranges are associated with strike-slip faulting (Robinson and others, 1974; Everingham, 1976). Other earthquakes, particularly those south of the collision zone, may indicate overthrusting, possibly within lithosphere that may be thicker than normal. Focal mechanism solutions do not appear to clarify interpretations of the tectonic setting, as strike-slip, dip-slip overthrust, dip-slip and normal solutions have all been obtained (Ripper, 1975).

A few intermediate-depth earthquakes localised in the Highlands-Wau area give the impression of a south-southwest-dipping structure in Section 3. However, Dent (1976) examined the distribution of these events in detail by plotting them on several planes with different azimuths, and concluded that a localised seismic zone dips at about 30° towards 230-240°. Dent (1976) postulated that the earthquakes were related to rare intermediate-depth events that form a diffuse band extending south-southeastwards beneath the Papuan Ultramafic Belt into the western Solomon Sea area. Although the significance of these earthquakes remains obscure, Dent's interpretation is consistent with those of Curtis (1973), and Ripper (1975b), who considered that the events are part of a generally vague seismic zone dipping away from the Solomon Sea area. While it seems likely that the events are associated with underthrust lithosphere, there is no justification in assuming that these earthquakes beneath the orogenic belt are evidence for an extensive seismically active slab extending westwards beneath the stable platform and the Highlands volcanic province.

Lateral changes in chemistry and an increase in volcanic volumes along the western portion of the arc have been recognised by Johnson (1976, 1977), who relates the variation to an increase in the rate of plate convergence along a northward-dipping subduction zone away from a pole of rotation centred in northwest mainland Papua New Guinea. The Quaternary volcanism is believed to be related to reactivated subduction of the same, but now steepened, subduction slab responsible for the Palaeogene volcanism (Johnson, 1976, 1977; Johnson and others, 1977). It is suggested that reactivation of the slab occurred in the Late Pliocene—possibly by rotational closing of sea floor between the eastern portion of the Adelbert-Finisterre-Huon arc and the continental margin. The absence of deep-focus earthquakes beneath the Bismarck volcanic arc, and of intermediate focus events in the far western part of the arc, is attributed to thermal equilibration of subduction slab and surrounding mantle under slow rates of subduction (Johnson, 1976).

Additional responses to present-day plate convergence at this boundary are found in the Adelbert-Finisterre Range-Huon Peninsula. Focal mechanism solutions (Everingham, 1975), and the spatial distribution of epicentres associated with two clusters of shallow-focus earthquakes in the eastern Adelbert Range (Fig. 8), strongly suggest that the two clusters form a conjugate shear system related to north-northeast-south-southwest primary stress (Cooke and others, 1976). This supports earlier interpretations based on mapping sets of Quaternary fractures (Fig. 5), recognised as conjugate shear systems with a northeasterly trending acute bisectrix (Robinson, 1973, 1976), that the north coast ranges form a zone of compression imposed by interaction between the Indo-Australian and Pacific plates (and sub-plates). Strike-slip faulting is common both north and south of the Ramu-Markham Fault Zone, suggesting that part of the present-day convergence is achieved by transcurrent motion. The Ramu-Markham Fault Zone is believed to be a sinistral transcurrent fault, but unequivocal evidence of both past displacements and present-day movement is lacking. As pointed out by Coleman & Packham (1976), the geological data appear to be in conflict with the high rate of convergence of the Indo-Australian and Pacific plates, of the order of 14.5 cm per year along an azimuth of 78° (Le Pichon and others, 1973), estimated for the New Guinea region from sea-floor spreading data. Rather the broad belt of earthquake epicentres coinciding with zones of strong transcurrent faulting suggest that present-day plate interaction in the region is spread over a broad zone and that no single, finite plate boundary can be identified (Johnson, 1976).

Discussion and conclusions

Recent geological information from northeastern Papua New Guinea has enabled reconstruction of Tertiary tectonic events associated with the Mid-Tertiary collision between a southward-facing island arc to the north and the continental mass to the south. Our model is similar to that proposed by Dewey & Bird (1970), and more recently by Dewey (1976), for collision at Atlantic-type continental margins (Dewey, 1976, Fig. 4 D, E, F). However, unlike a number of previous interpretations and theoretical predictions we find no evidence to substantiate a reversal of the direction of subduction following the collision. Models invoking short-lived southward-dipping subduction in the Mid to Late Cainozoic to explain the magmatism in central Papua New Guinea find little support from the geology, although the possibility of some underthrusting at the northern continental margin is not discounted. Late Cainozoic volcanism in the Bismarck volcanic arc at the southern margin of the Bismarck Sea is related to a steeply inclined seismic zone which dips northwards beneath Vitiaz Strait (Johnson, 1976). This seismic zone is believed to be a vestige of the Early Tertiary northward-dipping subduction zone: the hanging slab is slowly sinking and equilibrating with the mantle under slow rates of subduction.

Johnson & Jaques (1977) point out that this interpretation has implications for continent/island-arc collisions in general, as northern New Guinea is widely accepted as a classic example of a region in which a reversal of arc polarity took place after collision. Johnson & Jaques (1977) argue that, not only is there no compelling evidence for a present-day southward-dipping subduction zone beneath mainland Papua New Guinea, but that such a zone is unlikely to form in the presence of an active marginal basin at the rear of an arc where heat flow is generally high. The limited data available for the Bismarck Sea (Halunen & Von Herzen, 1973; see also Karig, 1973, p. 360) suggest that heat flow may be high and typical of active marginal basins. High heat flow and thin lithosphere are the antithesis of conditions normally considered to be prerequisites for the initiation of subduction (Ringwood, 1975).

We believe the stresses of convergence of the Indo-Australian and Pacific plates after collision were taken up by 1) transcurrent movements at and about the former plate boundary; 2) crustal telescoping and shortening at the collision zone; 3) fracturing, faulting, and uplift of the accreted arc; and 4) large sinistral transcurrent movements along a complex linear zone through the Solomon Islands, New Ireland, and south of Manus Island. These responses may have generated the present-day tectonic regime in which a number of minor plates form a broad zone of interaction.

The striking structural and stratigraphic similarities between north coastal Papua New Guinea and the islands of the Outer Melanesian Arc have been pointed out previously (Robinson, 1973; see also Coleman, 1970; Coleman & Packham, 1976).

The majority of plate-tectonic reconstructions made to date regard the islands of the Outer Melanesian Arc as having formed as an extended, fractured island-arc system in response to Early Tertiary interaction between the Indo-Australian and Pacific plates. However, interpretations of the polarity of that arc differ: a southwestward-facing arc system has been inferred by some authors (Robinson, 1969, 1973; Curtis, 1973b; Mallick, 1973), whereas a Late Tertiary reversal of polarity from a previously northeasterly facing arc-trench system has been argued on geochemical (Mitchell & Warden, 1971; Gill & Gorton, 1973; Colley & Warden, 1974), and structural and stratigraphic grounds (Karig & Mammerickx, 1972; Falvey, 1975). However, much of the evidence (at least for the Solomon Islands) is not compelling, and the case for viewing the Outer Melanesian Arc as a northeastward-facing arc in the Palaegoene cannot be regarded as proven (Coleman, 1975b). The relationship of the Adelbert-Finisterre-Huon arc to the islands of the Outer Melanesian Arc therefore remains unresolved; the marked similarities suggest a contiguous Palaeogene arc system prior to the continent/island-arc collision in the Miocene. Breakup of the arc by transcurrent faulting associated with the collision, and interaction with thickened oceanic crust of the Ontong Java Plateau (Kroenke, 1972), may be responsible for many of the present apparently anomalous features in the region.

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