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Australia and the Melanesian arcs: a review of tectonic settings

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Until about 1950, the southwest Pacific region was thought by many to be the foundered eastern half of Greater Australia, 'Tasmantis'. The Outer Melanesian arcs defined the northern part of the Tasmantis boundary to the Pacific Ocean basin. Others considered the Inner Melanesian arcs to be the expanded rim of the Australian craton, the outwardly propagated expression of the Tasman Geosyncline. With the surge of exploration after World War II, new data showed that the outer islands could not be matched with island-arc models such as the Sunda Arc, and that New Caledonia, of the inner arcs, seemed increasingly to have Tasman Geosyncline affinities. By 1968, the land and sea data had produced a cluttered and confused picture, ripe for the application of new global tectonic models. After 1968, the Tasman Sea was shown to be a product of Late Cretaceous seafloor spreading and New Caledonia was accepted as part of the expanded rim of eastern Gondwana. The sea floor between the inner and outer chains was relatively young and the product of complex seafloor spreading. Over recent years, the southwest Pacific has in many respects been a showcase of plate tectonic theory. The region is intensely mobile. The obliquely convergent northern Indo-Australian/Pacific plate boundary carries great crustal blocks as allochthons to join others in eastern Indonesia. These crustal blocks also undergo vertical and rotational movement. The outer island chains do not fit the conventional models of an island arc — they are hybrid entities made up of the byproducts of subduction and of exotic terranes; as arcs, they continually change composition, form and configuration, even as they are being built. These outer chains are components of what is here called an 'accommodation boundary'.

Introduction

The Inner and Outer Melanesian arcs were terms proposed first by Carey (1938), and then by Glaessner (1950), for the sub-parallel arc-type strings of islands which border Australia in the southwest Pacific. The Outer Melanesian arcs included northern coastal New Guinea, Bismarck Archipelago, Solomon Islands, New Hebrides and Fiji (Fig. 1). The Inner Melanesian arcs included parts of eastern New Guinea, Rennell–Bellona, and New Caledonia–Norfolk Island. These arc terms have endured and so this paper reviews the broader aspects of geology, geophysics and tectonics of the Melanesian arcs from the days before plate tectonics theory, essentially the 1950s and 1960s, to the present.

Umbgrove wrote his classic *Pulse of the Earth* in 1947 and the Sunda Arc became an island arc model, supplemented by the Japanese Archipelago. By an extension of thought, the outer island chains in the southwest Pacific were also supposed to be island arcs, but with peculiar features, such as the difficulty of putting them into a geosynclinal context. The inner islands, closer to Australia, did not fit any arc model, but it was recognised that these islands lay on one or another of several submarine ridges that seemed stepped-out from the east coast of Australia and connected in some way to the continent. Rifting of bits of continent to give slabs such as New Caledonia was hypothesised. All this was embodied in the concept of a foundered Tasmantis (e.g. Bryan 1944; Fairbridge 1953 — with historical reviews), with a northern and eastern boundary roughly corresponding to the 'Andesite Line'. For those few who espoused continental drift, Tasmantis was eastern Gondwana. The more adventurous geological synthesisers, in the immediate post-World War II period, considered that southern Papua, eastern New Guinea and New Caledonia were the most recent expressions of the continuing, eastern development of the Tasman Geosyncline. Geosynclines were thought to migrate outwards from the core-shield somewhat as a propagating wave-form. All parties would have found much to agree with in the reconstructions shown in Figures 2A (pre-plate tectonics) and 2B (post-plate tectonics), especially Figure 2A. The Tasman Sea was an enigma. A connection with New Zealand was conjectured.

The outer chain of islands — Solomons to Fiji — contains part of the Indo-Australian/Pacific plate boundary, a part here termed the Melanesian Boundary; these islands also make up Fairbridge's Melanesian Border Plateau or Borderlands (Fairbridge 1961). Carey, the major spokesman for the drift or mobilist camp, included them in the Tethyan Shear System (Carey 1958, 1963).

But generally speaking, the post-World War II period up to 1968 was a time of 'fixist' dominance; 'drifters' or 'mobilists' were regarded at best as amiable eccentrics, albeit talented ones, for whom the laws of physics had only passing significance. All this, despite the evidence of differential

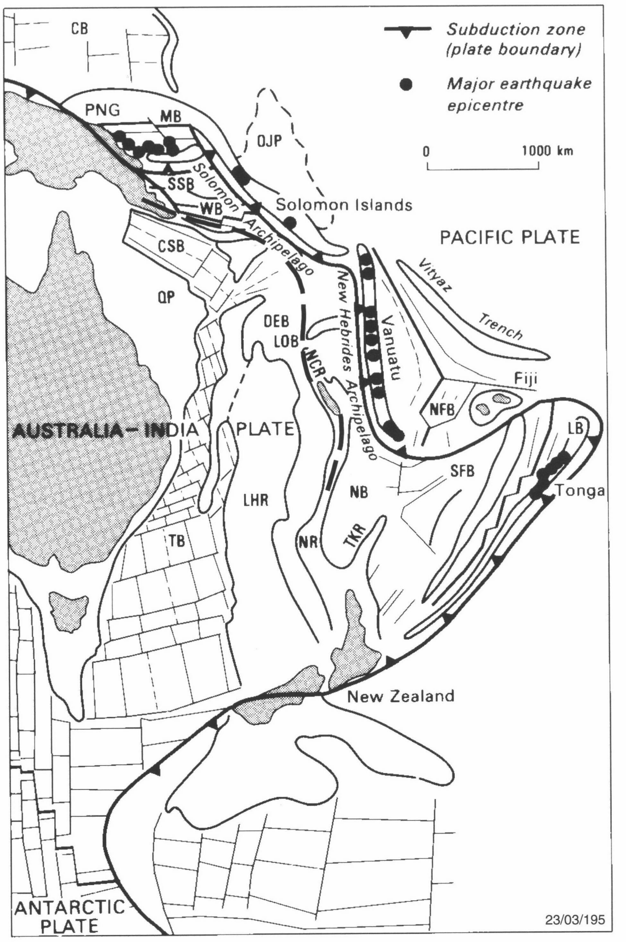

Figure 1. Main physiographic features, locations, and regional tectonic features of the SW Pacific. The Outer Melanesian arcs are defined by the northern line of epicentres New Guinea to Fiji; the Inner Melanesian arcs by the heavy dashed line (after Falvey et al. 1991).

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strike-slip movement of several hundred kilometres along the Alpine Fault (there was also the matter of the Great Glen fault on the other side of the world). Horizontal movement of great crustal blocks was perhaps acceptable if it had taken place on land. In this regard, Umbgrove's *Pulse of the Earth* was an electrifying stimulus. Although not espousing continental drift, Umbgrove argued convincingly that the Earth was an extremely vigorous entity and that this vigour is shown in its grand architecture. The southwest Pacific offers prime support to his argument.

This is a review, essentially of tectonic setting and history, and necessarily of limited length. I have not been able to give even a summary of the geology of each and all of the many geographic entities involved. As well, literature on the southwest Pacific is voluminous (for an extensive coverage until 1983 see Jouannic & Thompson 1983). I have had to be selective in citing references. A general review of the geology, structure and tectonics of the southwest Pacific and its component territories is given by Kroenke (1984).

Following the intensive land and marine surveys of the 1950s and 1960s, the cascade of new information has highlighted particular aspects of plate tectonics theory. I have concentrated on these aspects — the notions of subduction flip, horizontal movement (translation) of great blocks, and migration of whole island chains.

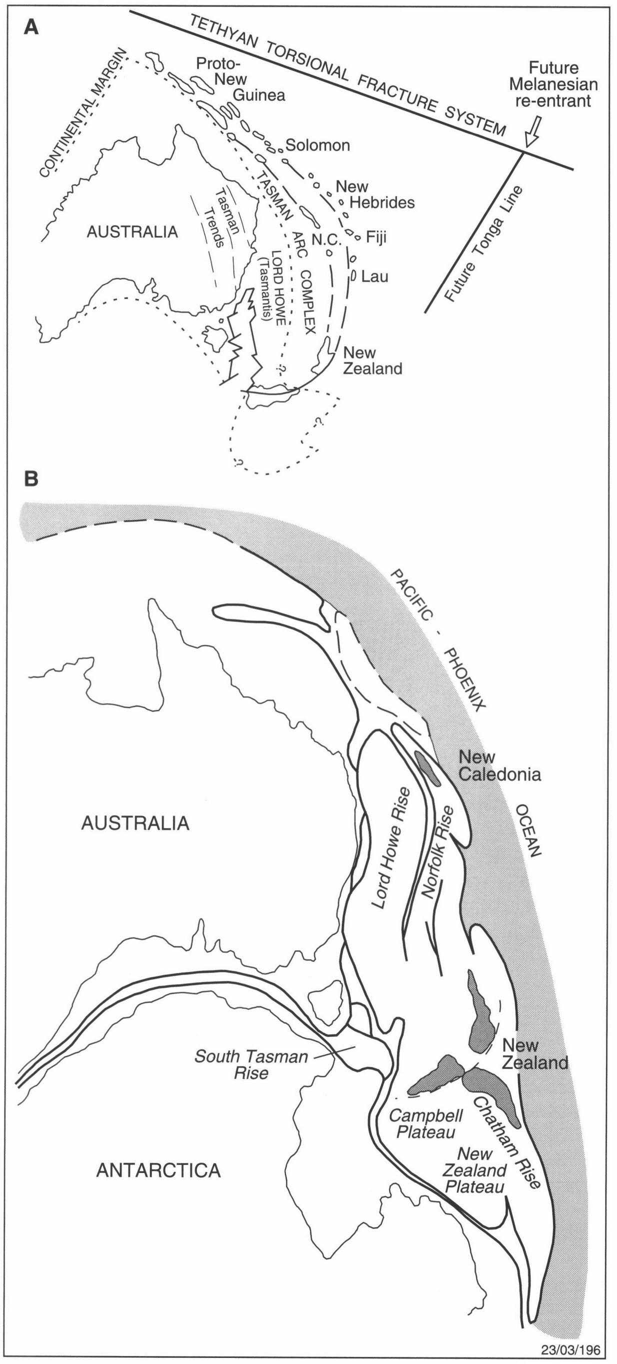

Figure 2A. A pre-plate tectonics attempt (Coleman 1967) to reconcile the land and other elements of the southwest Pacific as they were thought to have been in the earliest Tertiary. The diagram is highly speculative.

Figure 2B. A reconstruction for the Early Cretaceous, mildly speculative, and reflecting the plate tectonics view (after Griffiths 1975).

Before plate tectonics

By the end of the 1950s, land areas of both Inner and Outer Melanesian arcs had been mapped at least to reconnaissance level. Most of this new data was obtained by land surveys of the boot and hammer variety, assisted by wartime aerial photographs. In most areas, there were no maps for these early surveys, not even rough topographic ones. The geologist had to produce his own maps and include in them not only geology but all manner of useful topographic and demographic information.

Land geology

Outer Melanesia. By about 1960, the broader aspects of Solomon Islands geology (Fig. 3) did not match up closely to the Sunda arc. There was no clear distinction between 'inner' and 'outer' arcs (as there was in the East Indies: Umbgrove 1947). The profile was unlike that of the Sunda Arc — the volcanic front was too close to the trench (New Georgia Group) although some volcanoes were too far to the rear (on Choiseul). Forearc rocks were present on Choiseul, but not on Guadalcanal, an island which gave way almost precipitously to the trench. Although seismically active, the spread of hypocentres beneath the chain was diffuse and did not define a zone. The symmetry presented by the Sunda Arc was altogether lacking.

Similarly, in the New Hebrides Arc (a large part of it occupied by Vanuatu), although there was a neatly-defined Wadati-Benioff zone (with easterly dip opposed to that of the Tonga Arc), a well-placed volcanic front or axis, and the arc profile had symmetry, the symmetry was reversed. Later, this reversal was to be explained, of course, by applying the notion of polarity reversal or subduction 'flip'.

Fiji had the longest history of geological exploration, but its geology as known in the mid-1960s was confusing and, again, did not agree with the Sunda model. In particular, there were anomalous contrasts in the sequences of adjacent areas on Viti Levu, which could not be explained in terms of facies or structural controls. The pattern of lineaments was highly evocative of rotation — indeed, the Fiji platform, including the Lau Group to the southeast, was reminiscent of a spiral nebula. Sunda Arc terminology could not be applied to the Fiji platform.

At the other end of the arc system, the Bismarck Archipelago, there were also misfits. New Ireland was clearly an extension of the Solomon arc system. New Britain did not match up closely to the Solomons or to adjacent New Guinea (and still does not). There was no explanation for its volcanic front, the Quaternary Bismarck volcanic arc, which extends to the northwest as far as the Schouten Islands offshore of north coastal New Guinea. The Torricelli–Bewani block, essentially a Neogene arc sequence on northwest coastal Papua New Guinea, was thought even then to be an arc in collision with New Guinea proper, but no mechanism was proposed.

Inner Melanesia. The Louisiade Archipelago (off the tail of New Guinea), had been the target for gold prospectors for

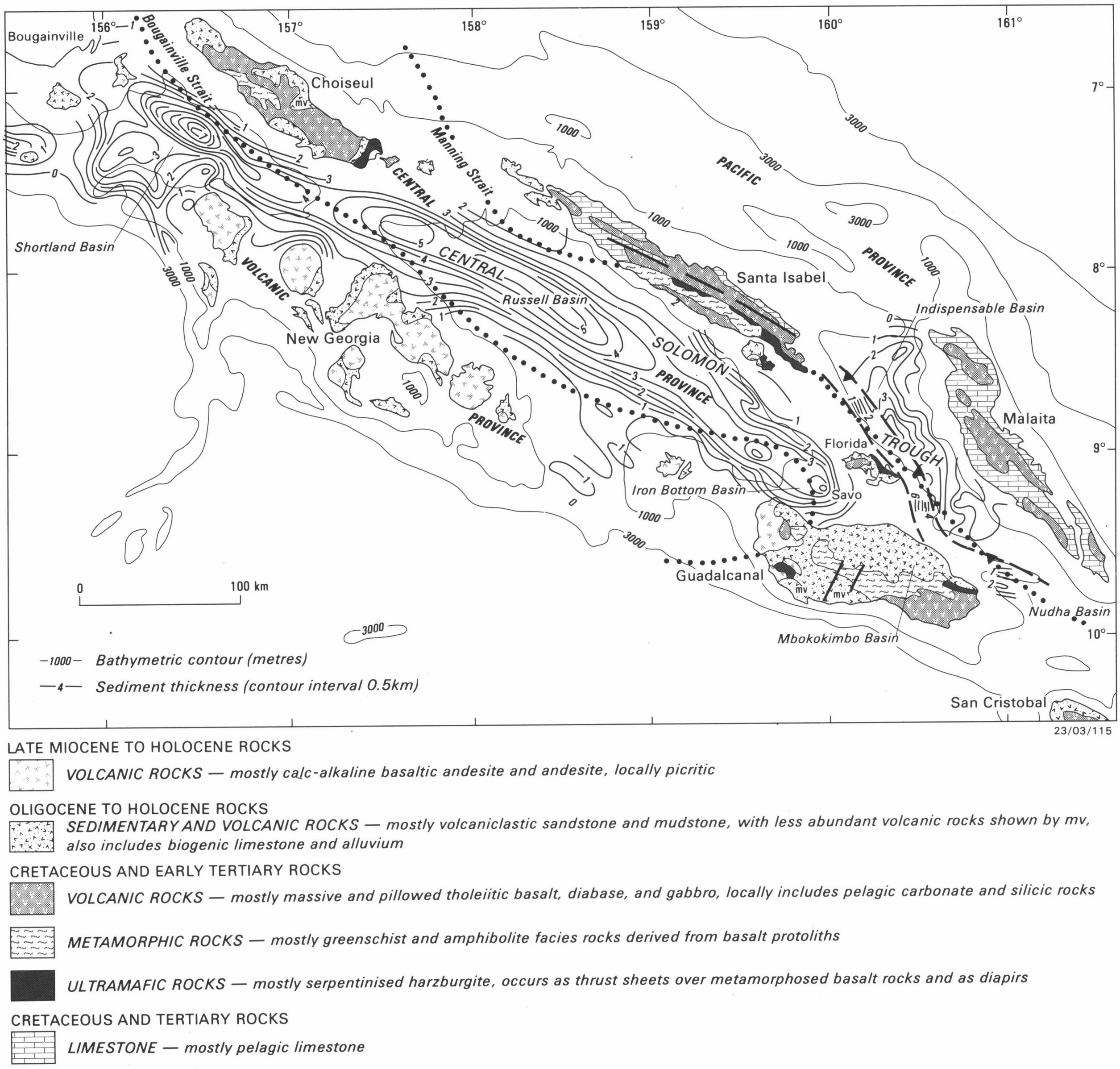

Figure 3. Simplified geology of the Solomon Islands and Solomon Trough sediment thickness (from Falvey et al. 1991).

many years and before 1900 gold was mined at Woodlark, Misima and Sudest, but knowledge of the geology was sketchy (until World War II most of the gold taken in New Guinea was placer). The main conclusion was that the eastern archipelago tied in with the geology of southern Papua New Guinea, but had volcanics and intrusions not easily explained. To the east the large, recently-raised and well-preserved atolls, Rennell and Bellona, crown much larger edifices, part of a large submarine plateau immediately east of the still larger Louisiade Plateau. The nature of these plateaus was unknown.

To the southeast, separated by a complex break, the d'Entrecasteaux–New Caledonia platform carries New Caledonia. For New Caledonia, some few geological reports go back to the last century, but over the inner arcs as a whole, not much solid geological groundwork had been done before 1950. The four prime elements in the geology of New Caledonia had been mapped by the mid-1960s (Fig. 4). These are: over the southeastern half of the island, the great thrust sheets of ultramafics responsible for the presence of mineable nickel; the extensive outpourings of basalt along, and inland from, the northwestern coast; the widespread and thick succession of late Cretaceous and Palaeogene marginal/basinal sediments (metamorphosed in the northeast); and lastly, over the central part, and often shown through windows in the younger sediments, there are older paralic sediments, especially Permian, Triassic and Jurassic, large areas of which had been regionally metamorphosed (Brothers & Lillie 1988, Paris 1981).

Structurally, faulting is intense and many faults show wrench features. The dominant fault systems tended to be parallel to the island axis. The older sediments are orogenic, typically wackes, the younger sediments are typical of marginal paralic basins; the Late Cretaceous in particular was deposited over widespread coastal marginal marine areas and includes extensive minor coal deposits. The Tertiary is a mixed succession and in places includes juxtaposed bathyal sediments, shallow-water platform sediments and occasional reefal deposits. The Miocene carbonates are shallow water reefal in origin.

The absence in the stratigraphic column of Early Cretaceous and Oligocene components, and the uplifting of the vast ultramafic sheets, supported the idea of profound vertical movements not only of individual faults blocks but also of the New Caledonian platform itself. In the late 1950s and in the 1960s, Bureau de Recherches Geologiques et Minieres, Noumea, and ORSTOM pioneered neotectonic and geomorphological studies, results of which anticipated the requirements

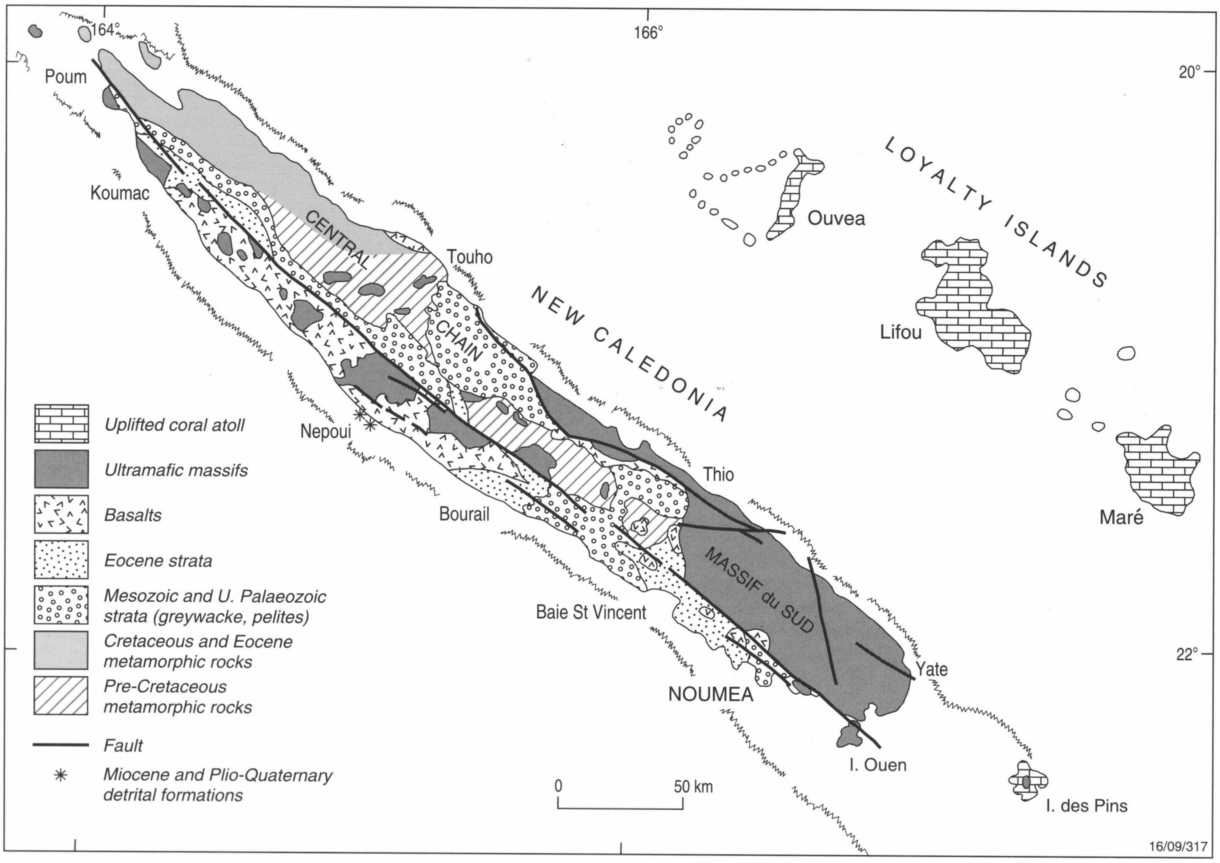

Figure 4. Basic geology of New Caledonia (from Brothers & Lillie 1988).

of plate tectonic theory. For example, the new data showed strong tilting of the New Caledonia platform, and its elevation, poised on what we now recognise as the lithospheric bulge just outboard of the South New Hebrides Trench.

In summary, the geology of New Caledonia was sufficiently well known by the mid-1960s to justify the belief that New Caledonia was the eastern limit to Australia (and, of course, new and old knowledge of the flora and fauna, supported this same message). But the 'why' and the 'how' of the New Caledonia platform remained unknown.

Marine geology

The 1950s and 1960s saw an enormous increase in the knowledge of oceans generally, including the southwest Pacific area. The stimulus arose from the need of military forces with missile-launching submarines to have detailed information about the ocean basins. This knowledge was to include not only detailed bathymetry but also the physics of the ocean floors and crust, especially gravity and magnetics. Much of this knowledge was dramatically new; some of it has only recently been released (e.g. the truly detailed bathymetry of the ocean basins); some of it is still classified. Civilian instrumentalities provided much of this information: they included the Hawaii Institute of Geophysics, Lamont Geological Observatory, Scripps Institution of Oceanography and Russian Academy of Science (with RV *Vityaz*).

In the southwest Pacific region, a major contribution was the revelation of the presence, size and structure of large submarine plateaus and ridges, e.g. the Ontong Java Plateau (Kroenke 1972) and Lord Howe and Norfolk/New Caledonia Ridges (the last two had been roughly mapped previously). The sedimentary caps of these were dredged and cored. Seismic refraction work suggested thick crust of suspected continental origin.

Outer Melanesia. Within the island chains, the presence of basins was securely established, e.g. the Russell Basin in the Solomons (Fig. 3) and the Aoba and Ambrym intra-arc basins in the New Hebrides. However, several of these basins appeared to have three or four kilometres of sediment in them (a minimum figure as it turned out). The presence of these basins gives a severely broken profile. In the Solomon Islands (Fig. 5), vertical relief can be as much as six km over a distance of some 20 km — and more to the structural floors of the basins. The gravity gradients are enormous, as had been suggested earlier by a land gravity survey on northern Guadalcanal (Coleman & Day 1965). Similarly, the Bligh Basin offshore of Viti Levu, Fiji, was shown to be a complex containing several kilometres of sediment (details in Rodda 1994, Johnson 1994).

The severely broken profile of Figure 5 characterises all of the Outer Melanesian arcs. The blocky nature of the crust was revealed by refraction seismic studies (e.g.Wiebenga 1973). Extensive heatflow measurements showed that dilational areas of sea floor, such as the North Fiji Basin, had consistently high flow values. These areas we know today as intra-arc and backarc basins and marginal seas. Older seas had relatively lower values. Mapping of anomalous magnetic lineation patterns was still exploratory.

Inner Melanesia. In the 1950s and 1960s, Inner Melanesian submarine plateaus such as Louisiade and Rennell were discovered and the main ridges delineated. Both New Caledonia and Lord Howe Ridges are broken transversely by defined lines, presumably fracture zones, with offsets suggesting relative horizontal movement. These ridges carry roughly the same amount of sediment, estimated at about 600 m of pelagic oozes. Limited refraction and gravity studies strongly suggested that they were submarine continental crust (Officer 1955). The mystery was, and still is, what kept them down, and how they had achieved isostatic balance so rapidly (even today, a common notion is that high basification of the lower crust has occurred, a kind of 'Beloussovian' oceanisation).

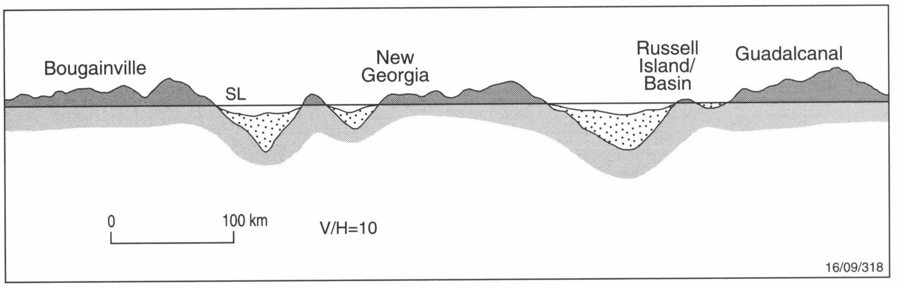

Figure 5. Solomon Islands, longitudinal profile, northwest–southeast. Overall relief is as much as 9 km over 70 km. The deepest basin has 4.5 km of sediment below a water column of more than 2 km. B — Bougainville, SL — sea level, NG — New Georgia, R — Russell Is/Basin, G — Guadalcanal.

New Caledonia was now mapped to at least reconnaissance level, as part of the further delineation of nickel deposits. A synopsis of the geology is contained in Brothers & Lillie (1988), and in the expansive synthesis of Paris (1981). Petroleum prospectivity is summarised by Vially & Mascle (1994). The place of the Louisiade Archipelago as part of the Papuan Orogen (approximates to New Guinea Mobile Belt, e.g. figure 3.3 of Kroenke 1984), marginal to the Australian craton, was confirmed; the large volcanic content arose because of contributions from the Woodlark spreading ridge.

The Tasman Sea is an entity to itself, a classic Careyan sphenochasm. In brief, new bathymetric data showed that the northeastern boundary was not the Lord Howe Ridge, but an ancillary ridge, the Dampier Ridge. The thickness of the pelagic carbonates suggested a relatively young age, guessed to be about Cretaceous. A north–south-trending twin row of seamounts and guyots (Lord Howe is one) was located. The steepness of the continental shelf (sometimes as steep as 20 degrees), the narrowness of the shelf, and the general lack of sediments along the southeastern Australian margin all suggested faulted margins. A pattern of magnetic anomaly lineations was delineated (and later interpreted by Ringis 1972 and Shaw 1978).

Post-plate tectonics

With the advent and widespread acceptance of plate tectonic theory in 1968, the southwest Pacific took on a flawed but recognisable unity (e.g. Packham 1973). The distinction between Inner and Outer Melanesian islands will no longer be stressed in this account; they will be treated as parts of a recognisable whole.

Land geology

In the 1970s and after, new data from land surveys in both Outer and Inner Melanesia, refined existing knowledge rather than adding greatly to it. Gold and copper exploration dominated land activities, and was inspired by the lucky discovery of several epithermal and porphyry copper deposits, e.g. Panguna on Bougainville (Panguna had in fact been recognised as a prospect in the early 50s, but the recognition of its vast promise had to wait — production began in 1972; Lum et al. 1991). By the late 1970s, most islands had been covered by broad-scale geochemical surveys — not very productively as it turned out.

Additional and more detailed land surveys, using satellite-derived imagery, emphasised the prevalence of faults. Some very large faults showed up in satellite imagery, but the ground evidence was scanty or failed to show the true dimensions of these faults. In contrast, as mentioned later, a better appreciation of the size of faults and their intensity was obtained from marine seismic reflection profiles (next section).

Major advances, however, were made in the 1970s in the knowledge of the refined geochemistry of the igneous rocks. Geochemical zonation in lava types shown in the Sunda (and other) volcanic arcs was not demonstrated to the same degree in the outer islands, a partial explanation for this being polarity reversal and the sometimes indiscriminate methods of sampling. The new work emphasised the complex geochemistry of rocks found in the outer islands, e.g. New Georgia onshore (Ramsay et al. 1984) and offshore (Johnson et al. 1987) in the Solomons, and New Hebrides volcanic belt (Crawford et al. 1988). The Solomon Islands, Vanuatu and Fiji furnished material for monographs such as Stanton's *Ore elements in arc lavas* (1994).

Marine work

The dominant activity by far was an increased tempo in marine surveys. Some of this was done by petroleum companies in, for example, the Solomons, Vanuatu and Fiji, but most continued to be done by government and academic institutions. Under the auspices of the Circum-Pacific Council (CPCMER) and the Australia-New Zealand-United States Tripartite Agreement, several major agencies carried out surveys in the Southwest Pacific. The agencies included the Bureau of Mineral Resources, Canberra (now AGSO), New Zealand Department of Scientific and Industrial Research, Hawaii Institute of Geophysics (University of Hawaii) and Scripps Institution of Oceanography (University of California), South Pacific Applied Geoscience Commission (SOPAC) and US Geological Survey. ORSTOM was very active. Additional work was done by German, Japanese and Russian agencies.

Apart from the data of obvious use in the search for petroleum, reflection profiles defined the boundaries of the intra-arc basins and confirmed the presence of enormous thicknesses of volcaniclastics in these basins (thicknesses suggested previously by refraction surveys). Sediment thicknesses in the Russell Basin, central Solomon Islands, had been thought to be overestimated, but were now shown to be considerably underestimated. The source areas for the tremendous volumes of this sediment — epiclastic, not all subaerial — is still a puzzle. Surprisingly, the close spacing of reflection seismic profiles confirmed the fault-ridden nature of the arc terrains, especially in the orogenically active outer islands. The elaborate 'flower structures' and riffle-pattern of large strike-slip faults are readily seen in seismic profiles all along the island chains (Figures 6 & 7). These are of great significance in determining the tectonics of the chain as part of the Indo-Australian/Pacific plates boundary (Ryan & Coleman 1992). Seafloor mapping and seismological analysis showed that convergence was oblique and sinistral (Abers & McCaffrey 1988; Auzende et al. 1994; Cooper & Taylor 1984).

Although most surveys had the assessment of petroleum potential as their primary aim, many surveys had other targets as well. Major efforts were made to map and evaluate manganese nodules (e.g. Skornyakova 1979). Lately, frequent targets have been seafloor hydrothermal systems and associated polymetallic sulphides at spreading centres (as in the North Fiji Basin — Ishibashi et al. 1994; Auzende et al. 1995; Stachelberg & Rad 1990). The Japanese South Pacific seafloor atlas (South Pacific Seafloor Atlas 1995) is a major contribution and covers all sea-bed metals. Methods to obviate the effects of alteration on marine samples of igneous rocks, and the increasing use of refractory components for analysis, constituted a considerable achievement (see Mahoney 1987). Until this time, distribution diagrams based on analyses of marine igneous rocks, using susceptible elements (e.g. FMA diagrams), were of dubious

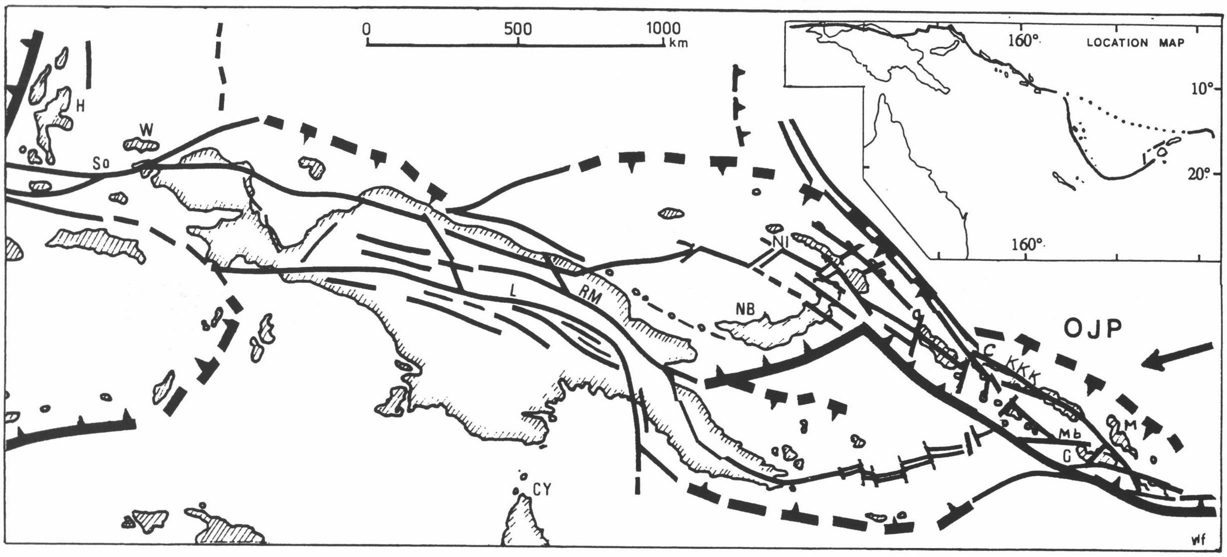

Figure 6. Melanesia and the Melanesian Boundary, an oblique convergence. The three largest fault systems are the Sorong-Ramu (So — RM), Sula — Lagaip (L) and Kia-Kaipito-Korigole (KKK). Both old and new subduction zones tend to transform into faults. OJP is the Ontong Java Plateau. H — Halmaheras; So — Sorong fault; W — Wageo Island; T — Timor; L — Lagaip fault system; RM — Ramu-Markham fault system; CY — Cape York; NB — New Britain; NI — New Ireland; G — Guadalcanal; C — Choiseul; Mb — Mborokua lineament; M — Malaita. Heavy arrow is the convergence vector, Indo-Australian/Pacific plates.

validity. Other work, especially that inspired by SOPAC, looked at the marine-derived geological and pollutant hazards most likely to affect island nations.

As a major side benefit of this varied work, the new data and the wide spectrum of scientists involved led to several programs of deep sea drilling, including the DSDP/ODP Leg 21, sites 203–210 — Tasman-Coral Seas; Leg 30, sites 285–289 — Ontong Java Plateau; Leg 90, sites 587–594 — Tasman Sea; ODP Leg 130, 803–807 — Ontong Java Plateau; Leg 134, 827–833 — Vanuatu; Leg 135, and 834–841 — Lau Basin/Tonga Ridge. The results of these programs included the proving of relative youth for the basins, with basal sediment no older than mid-Cretaceous. The large basins such as the Tasman Sea and New Caledonia Basin had typical open ocean sequences of pelagic oozes, with low terrigenous content and chert layers, no older than late Cretaceous. The ridges such as Lord Howe Ridge had deep-sea sediments no older than latest Cretaceous with thicknesses of 500–700 m. The drill holes within the chains, e.g. the Aoba Basin in Vanuatu (New Hebrides arc), or on the flanks, revealed typically volcaniclastic sequences, including distal turbidites, interspersed with carbonate oozes. These sequences are records of the high tectonism in these chains throughout the Neogene Tertiary. The younger sequences showed very high rates of sedimentation. As with the Solomon Islands basins, the provenance of these sediments is a problem. Oceanic basalts were drilled on the Ontong Java Plateau, and additional refraction results confirmed the great crustal thickness. At present, the plateau is thought to be the result of outpourings of lava from a very slow spreading ridge (Hussong et al. 1979). The overlying pelagic oozes were no older than mid-Cretaceous.

The recording of seafloor marine magnetic anomaly patterns led to striking results. The recognition and interpretation of the magnetic anomaly pattern over the Tasman Sea led almost at once to its recognition as an asymmetric seafloor spreading creation, predominantly of Late Cretaceous age (Ringis 1972); the revised version of Shaw (1978) is still accepted today. Within the Tasman Sea, the Dampier Ridge was a demonstration of spreading ridge jump (Shaw 1978; and see McDougall et al. 1994). The plate motions that led to Tasman seafloor spreading also caused the rifting that led to the separation of Lord Howe and Norfolk ridges (Symonds & Colwell 1992) and the creation of the New Caledonia Basin (Uruski & Wood 1991). Unlike the Tasman Sea, however, the New Caledonia Basin floor shows no formal pattern of magnetic anomalies and so a normal pattern of seafloor spreading seems unlikely. Rifting may have been followed by stretching of continental crust, its thinning and extension (Etheridge et al. 1989), but the mechanism for this is not proven. The twin row of seamounts was due to the passage of the plate over a hot-spot (McDougall & Duncan 1988), seamount ages being from 24 to 6.4 Ma with progressive younging southward of about 7 cm a year.

The North Fiji Basin is complex and the seafloor spreading pattern not easily identified (Hamburger & Isacks 1988, von Stackelberg & von Rad 1990, Auzende et al. 1995). A diffuse pattern of multiple spreading centres was proposed by Hamburger & Isacks (1988); Tanahashi et al. (1991) followed a more conventional model. The North and South Norfolk Basins formed in the early Oligocene.

The Coral Sea was shown to be the result of complex rifting of the continental crust of northeastern Australia (Mutter & Karner 1978). It may have been an offshoot of spreading in the Tasman Sea, but spreading began along a roughly east–west median ridge, the accommodating boundary to the west being a transform along the edge of the Australian craton (Falvey & Taylor 1974, Taylor & Falvey 1977). The southern margin lay along the submarine Queensland Plateau. The northern one lay along the southern edge of the 'tail' of New Guinea (marked by a volcanic sequence).

All of this work had many side benefits. A cruise aimed at mapping of nodules would be accompanied by the running of reflection seismic profiles, and very often, magnetic anomaly profiles. Coring would produce sub-seafloor sediment samples. Swath mapping, to obtain side-scan imagery, is of special use in checking hydrothermal systems and has added enormous detail to bathymetry. Techniques continued to improve — petroleum companies had greatly refined methods of multichannel seismic reflection surveying and the processing of data. The many-faceted nature of this marine work in the southwest Pacific is detailed in Crook et al. (1991).

The data from this surge of varied activity appeared in scientific journals, proceedings of SOPAC- and ORSTOM-inspired workshops (e.g. Anonymous 1977), and also in a set of monographs published by the Circum-Pacific Council for Energy & Mineral Resources. This latter series covered the

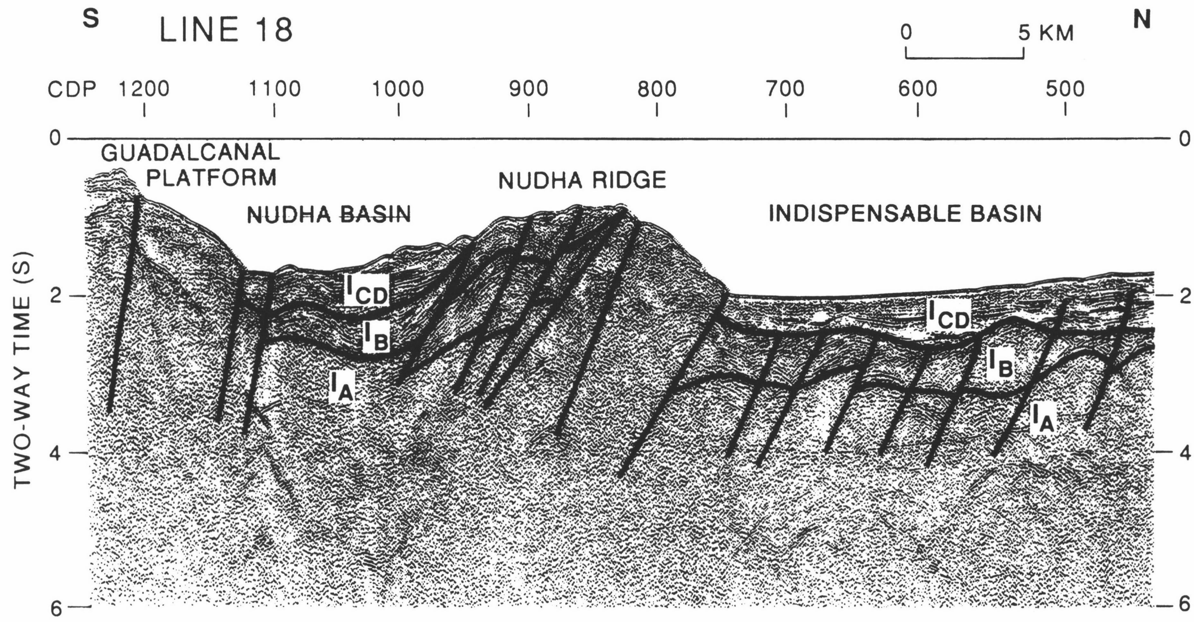

Figure 7. Seismic reflection profile of the easterly extension of the KKK fault complex, off the northeastern coast of Guadalcanal, Solomon Islands (from Vedder & Bruns 1989). The succession is made up mainly of volcaniclastic sediments — Oligo-Miocene (1_A), Late Miocene and Early Pliocene (1_B) and Pliocene/Quaternary (1_{CD}).

Outer Melanesian arcs, and although aimed primarily at petroleum search, contained generally thorough and extensive information (e.g. Taylor & Exon 1987 — Woodlark Basin, Papua New Guinea; Greene et al. 1988 — Vanuatu; Vedder & Bruns 1989 — Solomon Is). The deep sea drilling results were published as part of the DSDP/ODP program.

By about 1980, it was generally accepted that the Inner Melanesian arc system, and hence the old eastern Gondwana rim, had expanded to roughly its present position by the Early Tertiary (see next paragraph). The expansion can easily be followed over the southern part, where the Tasman Sea and the New Caledonia Basin are its measure. The northern part was not so clear, and still is not — the Solomon Sea and d'Entrecasteaux twin ridge complex are two puzzling features.

In 1978, the Outer Melanesian arc system was shown to be a linear set of islands well outside the expanded Inner Melanesian arc. Progressive reconstructions are in Cullen (1970), Packham (1973), Crook & Belbin (1978), Weissel et al. (1977), Falvey (1978), Kroenke (1984 Ch 8), and Walley (1992). The Outer arcs system is shown as building over a southwesterly-dipping subduction zone. The effect of polarity reversal, subduction 'flipping', was demonstrated for both the New Hebrides Arc and the Solomon Islands (Karig & Mammeryx 1972, Cooper & Taylor 1985). For the New Hebrides, subduction reversal resulted in the clockwise rotation about the Santa Cruz platform of the major part of the 'old', pre-7 Ma arc (a few elements were left near the old, Vityaz, trench), accompanied by falling away of slab lithosphere (Moberly 1972) and the seafloor spreading creation of the North Fiji Basin. The prime cause for this activity was the impinging of the great Ontong Java Plateau along the Outer Melanesian arcs while it moved west as part of the Pacific plate (the relative direction of motion of this plate had changed at about 41 Ma — reflected in the Emperor Seamounts/Hawaii 'Bend'). The new subduction direction explains the reverse symmetry of the New Hebrides Arc and the presence of a cluster of very deep earthquakes in the northeast — a deep, remnant expression of the old, abandoned, southwest-dipping slab. The linear Outer chain was now broken and the large sea (?marginal sea) between Inner and Outer chains partly replaced by the North Fiji Basin (see Figure 8 for a model of tectonic evolution).

Just this last paragraph shows the power of plate tectonics theory to coordinate, to bring together and explain, sets of apparently unrelated and contrary 'facts'. In this context, compare again Figure 2A with Figure 2B.

But the Solomons–New Hebrides–Fiji chain still has its peculiar features. It does not conform to arc models such as those of Karig (1974) and Coleman (1978). An alternative suggestion was that this chain had arisen as a linear structure (along a leaky transform?) comparable to that of the Line Islands. The chain was then incorporated as part of the Melanesian Boundary and took on the function and attributes of a young arc in the late Miocene (Coleman 1976). This notion, although venturesome, is not so far removed from the intra-oceanic creation of the same chain in the Yan & Kroenke reconstructions (1993) discussed below.

The Melanesian Outer arcs had been thought to be the expression of a shear zone for many years (Tethyan Shear System of Carey 1958, 1963). With plate tectonic theory, this shearing could be explained in terms of the differing directions of convergence of the Indo-Australian and Pacific plates, that is, the convergence was an oblique one. The Melanesian Boundary, the length of Indo-Australian/Pacific plate boundary along which the islands lie, is a linear mosaic of fault blocks (Fig. 6). The oblique convergence between Pacific and Indo-Australian plates results in intense strike-slip activity between blocks of the mosaic. This activity takes two primary forms (Fig. 9).

In the first, individual blocks can be rotated about vertical and horizontal axes and they can be shifted vertically by large amounts at rapid rates; this last phenomenon is primarily the result of 'ramping' by one block over another (Coleman 1991, Ryan & Coleman 1992). Many examples of anomalous juxtapositions of differing geology can be thus explained, e.g. the presence of bathyal carbonate oozes against shallow-water high energy wackes (Coleman et al. 1988).

In the second form, overall activity is focused along a 'master' fault system, so that the blocks on the outer side of the master fault tend to be carried with the outer plate (the 'translation' of blocks). With continuing oblique convergence the boundary takes on the function of a 'conveyor belt' so that terranes are carried along the boundary as allochthonous 'exotics'. These oblique composite convergences have been termed 'composite transform convergences' (Ryan & Coleman 1992), for they are composite and motion between the opposing plates is accommodated by subduction and by transform faults; but a better and simpler name would be 'accommodation boundaries', for that is what they are (Coleman 1995). Accommodation boundaries are common around the Pacific plate. For example, Alaska is well known as a composite of exotic terranes which were carried north as part of a great accommodation boundary which includes the San Andreas fault complex as a master.

An indirect consequence of the oblique convergence of the Indo-Australian and Pacific plates is shown in the development of the Bismarck Sea and the Woodlark Basin. In the Bismarck Sea, a broken median ridge proved to be a static spreading ridge. In the Woodlark Basin, spreading began about mid-Pliocene and the spreading system has itself been subducting beneath the central Solomons (a contributory cause of the anomalous geochemistry of the New Georgia volcanoes). Both these features can be regarded as ancillary structures accompanying the westward drive of the Pacific plate past the north-moving Indo-Australian plate. The study of the Woodlark system showed that the westward movement of the Solomon block (relative to Indo-Australian plate) has been at a fast rate; at about 3.5 Ma, New Ireland was positioned several hundred kilometres east of its present position (Weissel et al. 1982). Seismological evidence from New Guinea demonstrated strike-slip movement and thrusting (Abers & McCaffrey 1988). Rotation of individual blocks was suspected and then confirmed by palaeomagnetic studies of target blocks (see below).

Mobility

The southwest Pacific is an essay in the motion of great crustal blocks. Mobility is expressed in rotation of blocks about vertical and horizontal axes and by their translational or horizontal movement.

Major rotations

The southwest Pacific shows rotations of large blocks about both vertical and horizontal axes, similar to those from other areas, such as the Aleutians and western North America (Geist et al. 1988, Scholl et al. 1988).

The study of palaeomagnetic declination of ancient samples has a long history (see Green & Pitt 1957). On the basis of such study, the rotation of terranes was put forward long before the acceptance of plate tectonic theory. No mechanism was provided. In the southwest Pacific, evidence of block rotations has supported the conclusions based on other studies.

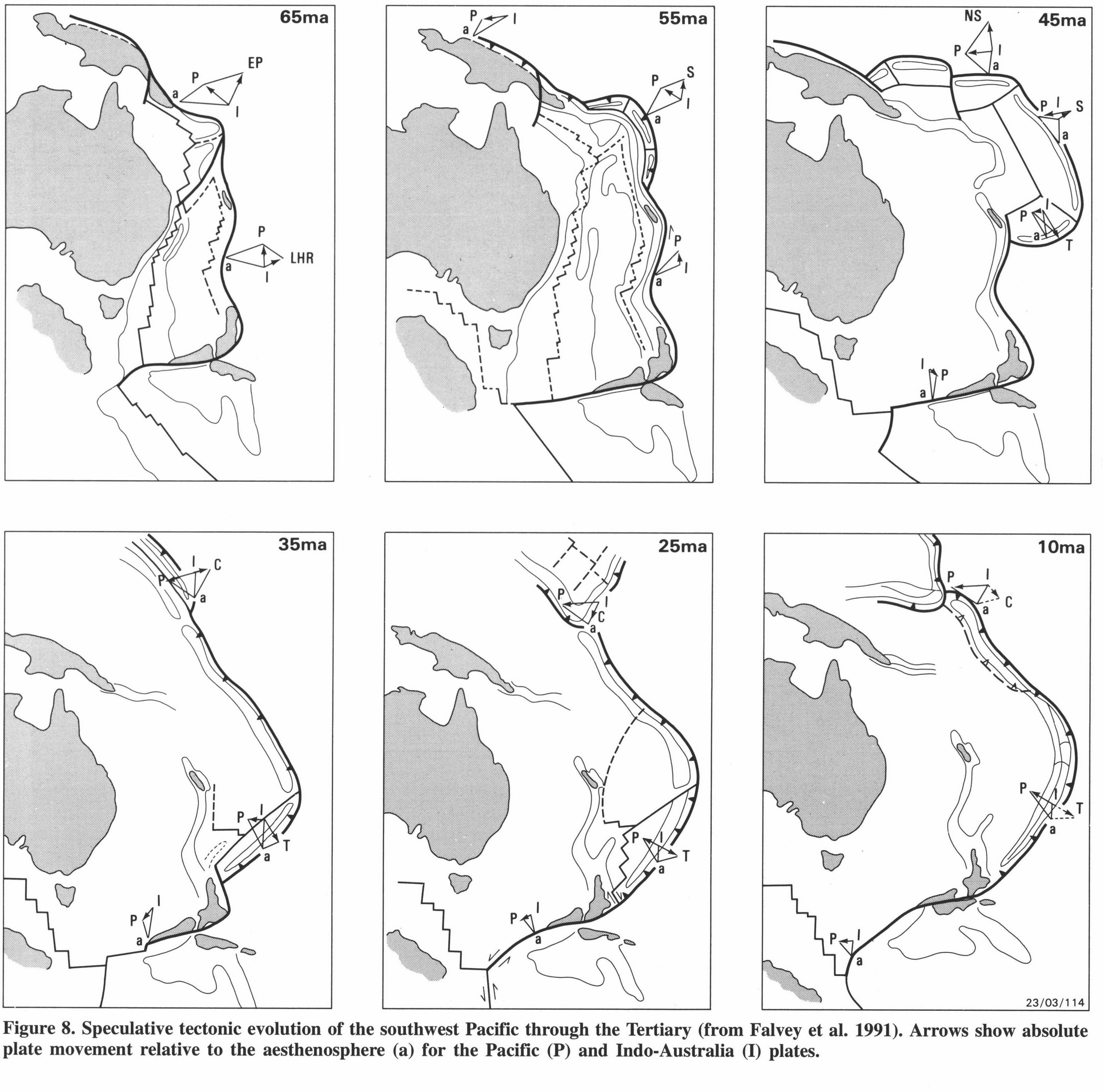

Figure 8. Speculative tectonic evolution of the southwest Pacific through the Tertiary (from Falvey et al. 1991). Arrows show absolute plate movement relative to the aesthenosphere (a) for the Pacific (P) and Indo-Australia (I) plates.

The Fiji results (James & Falvey 1978) suggested anticlockwise rotation of Viti Levu of some 21 degrees since the early Pliocene. Malahoff et al. (1982) supported rotation of Viti Levu: earlier suspicions were thus confirmed. Results from northern Papua New Guinea (Falvey & Pritchard 1984) suggested the westward passage of New Ireland (as part of the Solomon Islands) past New Britain in the late Tertiary (see also Weissel et al. 1982). As well, basins in the Solomon Islands and Vanuatu are of the summit and pull-apart type that have resulted, at least in part, from block rotation, as with those in the Aleutians (Geist et al. 1988).

Movements horizontal and vertical

By the late 1980s, these diverse and various studies in the southwest Pacific had provided, in its essentials, the picture we have today (Figs 1 and 8; and see Kroenke 1984 and Smith 1990). More recent studies have emphasised the speed of horizontal and vertical movements of crustal slabs within the southwest Pacific.

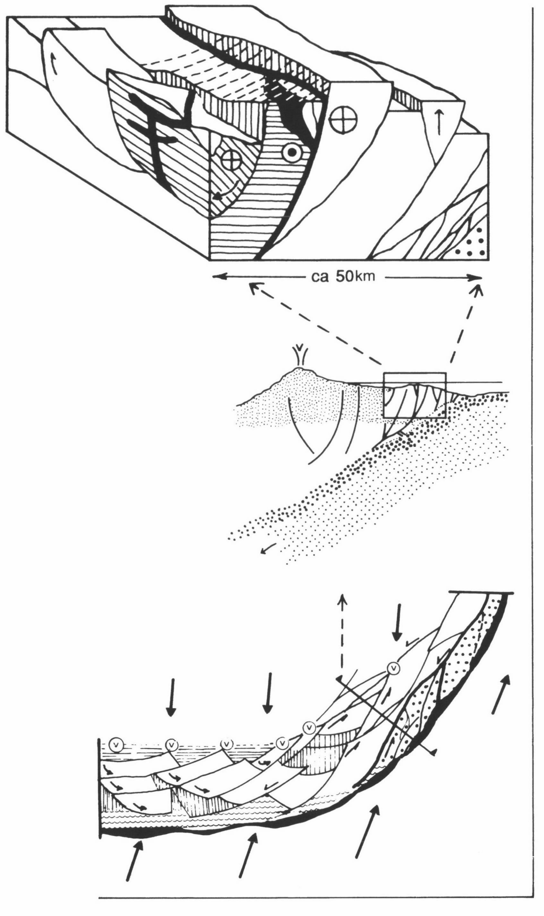

Figure 9. Cartoon of convergence with arc build-up and increasingly oblique angle of attack (Coleman 1991). The trench is in sinuous black. Bottom: plan view shows rotation, shearing of blocks with increased strike-slip fracturing as obliquity increases. Horizontal lines suggest summit or inner forearc basins, vertical lines basins of the pull-apart type, wavy lines near the trench are elements of the accretionary prism. The heavy line suggests the current master fault system. Individual blocks may be carried along the transform complex outboard of the master fault e.g. dotted blocks. Heavy bar is the approximate line of the section above: this is a profile of the arc with deep strike-slip fracturing — a part is enlarged as the block diagram. These profiles stress the undulations in the fracture surfaces both in plan and in profile. Relative motion on these surfaces produces vertical and horizontal movement of blocks and also rotation and tilting. Transtensional and transpressional situations arise along fractures and provide 'plumbing' for diapiric convective hydrothermal systems with caps enriched in metals. These caps can be concealed by debris from a ramped block (centre), tilted to give a misleading outcrop pattern (left) or even removed from the root stock.

Rates of vertical movement can be very high, amounting to a centimetre or more per year. Examples include the uplifted terraces of the Huon Peninsula, New Guinea (Chappell 1974a, b); and uplift of bathyal oozes in graben, north central Guadalcanal (Coleman et al. 1988).

On a large scale, the long-standing intensity of horizontal or translational movements in the southwest Pacific was illustrated by Pigram & Davies (1987). In this pioneer paper, they showed that a large part of northern New Guinea consisted of 'exotic' terranes transferred from southern and eastern locations. These results were amplified and supplemented by Struckmeyer et al. (1993). Coleman (1991) and Ryan & Coleman (1992) proposed a mechanism for shifts of this kind (outlined above) and suggested that eastern Indonesia is the future site of a 'New Alaska', a conglomeration of exotic terranes.

Mobility on an even larger scale is demonstrated by Yan & Kroenke (1993). They attempted a palaeogeography of the southwest Pacific going back 100 m.y., using intervals of 0.5 m.y., set in frames defined by today's latitudes and longitudes. This set of reconstructions is the most sophisticated available.

Among major block movements, Yan & Kroenke stipulate a growth-position of the Solomon–Fiji block far to the northeast of Australia in the mid-Eocene, and then show its movement south and west to its present position (Fig. 10). This is in contrast to the older view that the Solomon-Fiji block was part of an arc developed outboard of the Inner Melanesian arc and separated from the latter by a large marginal sea/backarc basin. These differing viewpoints have yet to be reconciled.

On a smaller scale, Yan & Kroenke show rotation eastward of the 'Eua Ridge' from a position south of New Caledonia to its present position as part of the Tonga platform, over the period 40–32 Ma (Fig. 10). The northern part of the Eua Ridge was then 'collected' by the southeastern end of the Solomon–Fiji as it moved westwards, at about 6 Ma (L. Kroenke, University of Hawaii, pers. comm. 1995). This sort of jump of a block across a boundary transform system can be readily explained (Fig. 9). The 'exotic' part is now the Yavuna Group, an anomaly in the general geology of Viti Levu. The Yavuna Group is an allochthon, a Paleogene exotic, with an odyssey that ranged eastwards from near New Caledonia to Tonga and then westward as part of the Fiji platform.

Movements such as these call for an elaborate system of transforms (there is ample evidence for the existence of such a system), together with accommodation boundaries, such as the Melanesian Boundary, that will shift large crustal blocks. Indeed, as discussed earlier, the Melanesian Boundary is studded with assorted crustal blocks. Rotated, raised or lowered, their dominant motion is lateral and to the west.

Such movement also implies not only that arcs may be composite but also that the form and configuration of arcs built along obliquely convergent boundaries is transitory and may change even as the arc is being built. In this sense, to speak of an 'early Miocene' Solomons arc is something of a misnomer.

Summary and conclusions

In the 1950s, the inner arc areas were considered to have been emplaced at the outer edge of mid-Mesozoic 'Australia' (the eastern rim of Gondwana — Fig. 2A). The outer arc areas developed later as bordering oceanic arcs. A genetic connection was implied between these so-called arcs and the Australian continent (Fig. 2A). But the data from the land areas and from the intensive marine studies that began in the 1950s and in the early 1960s did not altogether agree with contemporary models of island arcs.

The new marine data supported the global tectonic theories

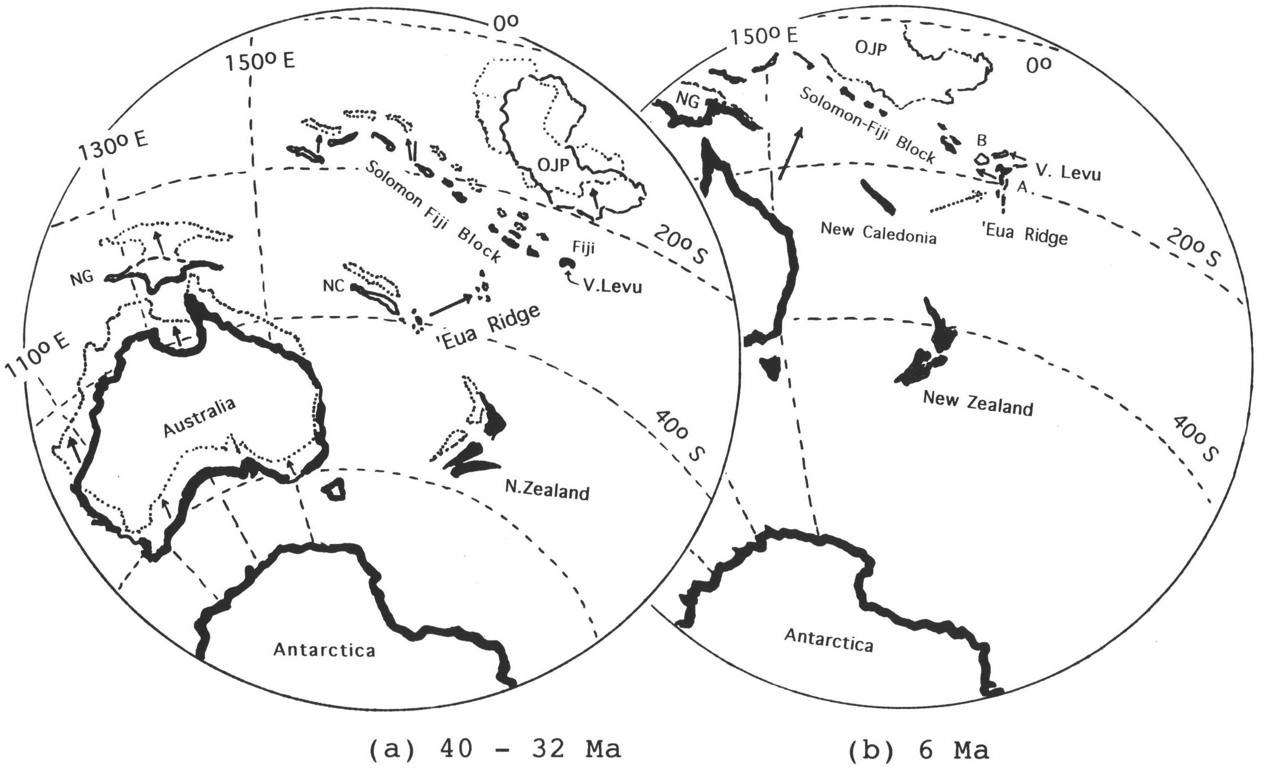

Figure 10. Reconstructions adapted from Yan & Kroenke 1993) — (a) and (b). Figure (a) 40–32 Ma: Now part of Tonga arc massif, the 'Eua Ridge lay south of New Caledonia on the eastern border of Gondwana, and moved eastwards (heavy arrow). Dotted outlines show the 32 Ma positions. In (b), at about 6 Ma, the northern portion of 'Eua Ridge moves westwards as the 'Yavuna Group', part of Viti Levu. 'A' is Viti Levu at 6 Ma, 'B' with open outline is its present position.

of the late 1960s, and in the early 1970s gave rise to new notions of arc behaviour, in particular the idea of arc piles building on the rim of the superposed plate. The geological and geophysical data stressed the mobility of the outer island chains and the pronounced vertical movement of individual crustal blocks. The difficulty of reconciling the early growth stages of the outer chains to conventional arc models was not resolved. Over the same period, new data from the inner arc areas confirmed that they were built up as Andean-type arcs along continental edges.

In the 1980s, the translational movement of discrete crustal blocks was recognised. Pioneer workers within AGSO recognised that much of northern New Guinea was composite, just as much of Alaska had been seen to be composite and made up of 'exotic' terranes. Further work has amplified these results, so we can predict that, in the geological future, eastern Indonesia will become a 'New Alaska' — barring a drastic change in plate geometry.

Most workers would now say that the Outer islands have stepped out and been separated from the inner arcs by dilational seas. But some evidence suggests that these outer islands may have developed independently and been brought to their present connection with old Australian forelands by interplate action. The Outer Melanesian islands mark a special kind of convergent plate boundary — an accommodation boundary. Along this type of convergence, marked by a zone of strike-slip faults and subduction zones, terranes are translated by activity along large-scale strike-slip faults to be mixed with newly formed crust, the by-products of subduction. In brief, the arc being built along such a boundary consists of subduction products plus introduced allochthons. Such hybrid entities include large parts of the Solomon–New Hebrides–Fiji chain. While building, these arc-hybrids continually change their composition, form and configuration.

The southwest Pacific has supplied major contributions in data to support such aspects of plate tectonics as polarity reversal, collision tectonics, the movement of arcs, the splitting of arcs, the broken nature of arc profiles, the importance of strike-slip components along oblique convergences, the transport of allochthonous terranes, the effects of the style of subduction and the digestion of spreading ridges on the genesis of arc rocks, crustal attenuation, the creation of submarine plateaus and the 'oceanisation' of cratonic slices. Researchers have found the southwest Pacific to be an appropriate testing ground for plate tectonic theory. The new data have refined plate tectonic principles; they have added, and will add, to its concepts.

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