Contrasting tectonic styles in the Neogene orogenic belts of Indonesia

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Abstract: The recent compilation of a new tectonic map of Indonesia as part of the Geotectonic Map Project of East Asia has prompted a reassessment of the contrasted tectonic styles represented by currently developing orogenic belts. These orogenic styles provide a range of models illustrating the diversity and complexity of tectonic processes which may provide the key to the interpretation of other orogenic belts elsewhere in the world. The following distinctive types of orogenies have been recognized within Indonesia. 1. Sunda Orogeny in Java and Nusa Tenggara: involving subduction of oceanic crust with normal convergence, producing an orogenic belt of Andean type with trench, accretionary complex, forearc basin and Quaternary magmatic arc with active volcanoes built on the margin of the Sundaland continent. 2. Barisan Orogeny in Sumatra: with strongly oblique convergence and major strike slip transcurrent fault movement within the magmatic arc, along which a segment of continental crust is being displaced northwards along the western margin of Sundaland. 3. Talaud Orogeny in the northern Molucca Sea: convergence of the Sangihe and Halmahera oceanic magmatic arcs as the Molucca Sea Plate subsides beneath them. 4. Sulawesi Orogeny in eastern Sulawesi: collision of microcontinental blocks with subduction systems along the eastern margin of Sundaland. 5. Banda Orogeny in the southern Banda Arc between Sumba and Tanimbar: collision of the northern margin of the Australian continent with the subduction system along the southern segment of the Banda Arc. 6. Melanesian Orogeny in Irian Jaya and Papua New Guinea: a more advanced stage in the collision of the northern margin of the Australian continent with a magmatic arc on the Philippine Sea plate, commencing in the early Miocene with a partial reversal of polarity and the subduction of the Caroline plate beneath the collision zone.

The present phase of orogenic activity in most of these occurrences commenced in mid-Miocene times and orogenic processes are still in progress.

Since the commencement of the first five year National Development Plan of Indonesia (Pelita I) in 1970 the geology of the whole country has been systematically and intensively investigated both by government institutions and by the private sector. These investigations have included the systematic geological mapping of the Indonesia archipelago, initially by the Geological Survey of Indonesia and later by the Geological Research and Development Centre (GRDC), partly in collaboration with the United States Geological Survey (USGS), the British Geological Survey (BGS), the Australian Bureau of Mineral Resources (BMR) (now the Australian Geological Survey Organisation: AGSO) and the Japanese International Cooperation Agency (JICA). At the same time geological and geophysical research has been continually in progress in many parts of Indonesia in collaboration with geoscientists from the University of London, UK; University of California, Santa Cruz, USA; Institute of Geophysics, Hawaii, USA; INSU, France; the Snellius Programme, Netherlands; and JICA, Japan. Geological and geophysical investigations have also been carried out by the Indonesian government institutions and the private sector, including both domestic and foreign companies, in the exploration for energy and mineral resources.

The result of these investigations has been an immense increase in the knowledge and understanding of the geological and tectonic development of the archipelago. The present paper is a review of this current understanding of the tectonic development of the Indonesian archipelago through Neogene times to the present day. The review arose out of the responsibilities of one author (TOS) in the compilation of the new Geotectonic Map of Indonesia as a member of the Working Group on the Geotectonic Map of East Asia organized by the Commission for the Geological Map of the World (CGMW) and the Committee for Coordination of Joint Prospecting for Mineral Resources in Asian

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Offshore Areas (CCOP) as part of the NW Quadrant Circum-Pacific Map Project.

Tectonic setting of Indonesia

The present physiographic and tectonic configuration of Indonesia is considered to have developed since late Neogene times due to the interaction of three of the Earth's major lithospheric plates: the NNW-moving (*c.* 10 cm a^{-1}) Philippine Sea plate; the NNE-moving (*c.* 8 cm a^{-1}) Indo-Australian plate and the stationary, or slowly SE-moving (*c.* 0.4 cm a^{-1}) Eurasian plate (Minster & Jordan 1978). The Indonesian archipelago therefore represents an immensely complicated triple junction, involving a complex pattern of small marginal ocean basins and microcontinental blocks bounded by subduction zones, extensional margins and major transcurrent faults. On the basis of geological and geophysical characteristics five regions of crust of different origins can be distinguished in the Indonesian region (Fig. 1). (1) Southeastern promontory of the Eurasian plate forming the Sundaland continental craton in Sumatra, West Java and Western Kalimantan; (2) Philippine Sea oceanic plate in the northeast; (3) Australian continental craton extending into the Indonesian region in Irian Jaya and the Arafura and Sahul Platforms; (4) Indian oceanic plate in the southwest; (5) a transition zone, marking the zone of current plate interaction with active seismicity and volcanism extending through western Sumatra, eastern Java and the Banda arcs to northern Irian Jaya and through Sulawesi and the Moluccas to Mindanao in the Philippines in the central part of the region. In this zone subduction is still active, with the development of thrust, transcurrent and extensional faults. This region is also characterized by allochthonous continental microplates with Tertiary and Mesozoic sediments overlying Palaeozoic basement, juxtaposed against Cretaceous and Tertiary terranes to form collision complexes.

Tectonic development of Indonesia

Pre-Neogene tectonics

Western Indonesia. A concentric accretionary model for the tectonic evolution of western Indonesia, with the addition of successive orogenic belts to a continental core in Sumatra and Kalimantan from the Palaeozoic through the Mesozoic and Tertiary to the present day, was proposed by Katili (1973) and Gage & Wing (1980). Basaltic to andesitic volcanic rocks and granites dated at 276–298 Ma, and volcaniclastic

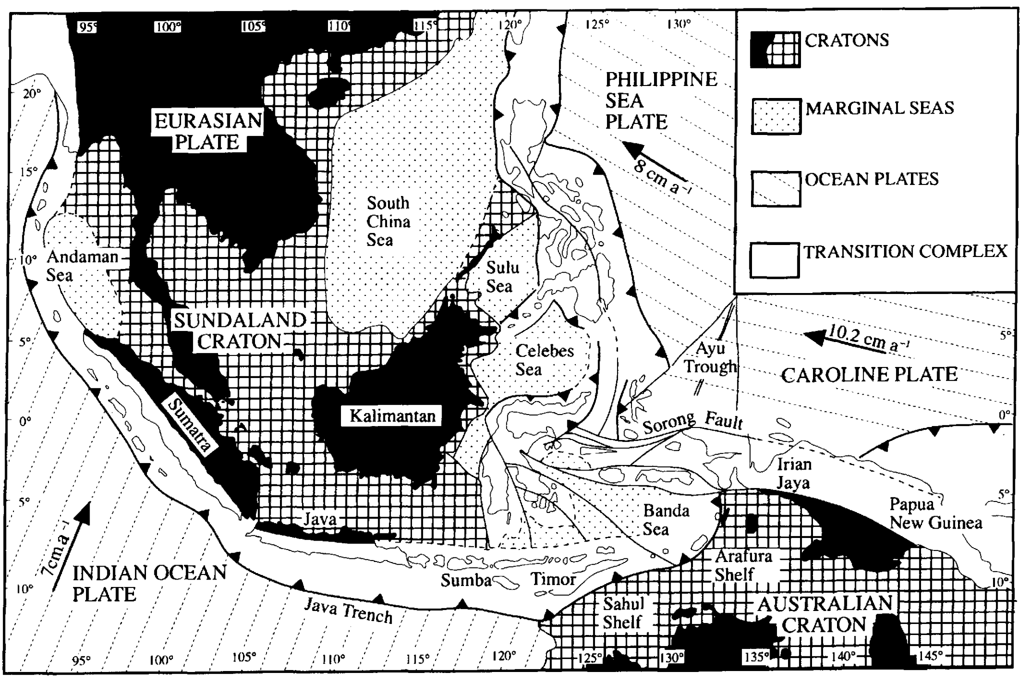


Fig. 1. The structure of the Indonesian archipelago and its tectonic setting in SE Asia.

sediments associated with limestones containing a Permian fauna in northern and central Sumatra, have been interpreted as representing a magmatic arc with associated forearc or backarc regions (Katili 1973; Silitonga & Kastowo 1975; Rosidi & Santoso 1976; Cameron *et al.* 1980; Simandjuntak *et al.* 1981). A similar assemblage of rocks was described from West Kalimantan (Gage & Wing 1980; Pieters & Supriatna 1990; GRDC 1992), from Sarawak (Tate 1991) and from the Main Range of peninsular Malaysia (Hutchison 1973; Gage & Wing 1980). Pupilli (1973) and Gage & Wing (1980) suggested that these Permian magmatic arc systems were related to an Asia-ward subduction system in Sumatra and an Indian Ocean-ward subduction system in Kalimantan. A similar opposed double subduction system is proposed by Hutchison (1973) and Pupilli (1973) for the Triassic, with the Malaysian–Indonesian Tin Belt representing the magmatic belt related to subduction from the Asian directed subduction system, while the opposing system is represented by the Serian Volcanics in Sarawak.

Cretaceous accretion complexes related to the Asian-ward subduction system can be traced through the melange wedges of this age in North and West Sumatra and Bengkulu, in Ciletuh and Karangsambung in Java, the Meratus Mountains of SE Kalimantan and in Bantimala and Wasapondo in South and central Sulawesi (Asikin 1974; Simandjuntak 1980; Sukamto 1986; Wajzer *et al.* 1991; GRDC 1995). Cretaceous magmatic arcs related to this system are represented by granites, basaltic–andesitic volcanics and volcaniclastics at Gumai and Garba Mountains in South Sumatra, the Meratus Mountains of SE Kalimantan and in SW Sulawesi (Musper 1937; Katili 1973; de Coster 1974; Sukamto 1975; Sikumbang & Heryanto 1986; GRDC 1992). These rocks together with associated sediments may represent forearc, trench slope, volcanic arc and backarc assemblages. The opposing Indian Ocean-ward directed system is represented by volcanic rocks and associated granites in the Anambas, Tambelan and Natuna islands in the South China Sea (Katili 1973; Pupilli 1973), the Schwaner Mountains of West Kalimantan and the Kuching–Sibu zone in Sarawak (Haile 1972).

Palaeogene subduction systems can be traced by melanges through the outer arc islands of Nias, Pagai and Sipora, offshore Sumatra and in S. Java (Katili 1973; Karig *et al.* 1978; Hamilton 1979) and by volcanics and intrusives, the 'Older Andesites' of van Bemmelen (1949) associated with volcaniclastic, volcanic and hemipelagic sediments in Sumatra, Java and W Sulawesi (Katili 1973; de Coster 1974; Djuri & Sudjatmiko 1975; Sukamto 1975; Koesoemadinata *et al.* 1978; Cameron *et al.* 1980; Sukamto & Simandjuntak 1983), extending into N. Kalimantan, Sabah and Sarawak (Hutchison 1988; Pieters & Supriatna 1990; Tongkul 1991). Palaeogene volcaniclastic, siliciclastic and carbonate sediments on the eastern flanks of the Barisan Mountains in Sumatra and in S. Java, SE Kalimantan and South Sulawesi, followed by shallow marine to terrestrial deposits with economic coals and hydrocarbon source rocks, may represent interarc and backarc sequences related to the Palaeogene subduction systems of western Indonesia (de Coster 1974; Koesoemadinata *et al.* 1978; Cameron *et al.* 1980; GRDC 1995).

Eastern Indonesia. In the Neogene a number of microcontinents, e.g. Buton, Banggai–Sula, collided with subduction systems along the eastern margin of Sundaland to form the present tectonic framework of eastern Indonesia. The pre-Neogene history of eastern Indonesia relates therefore to the origin and earlier history of these microcontinents before these collisions took place. All the microcontinents are considered originally to have formed part of the northern margin of the Australian continent and to have separated during Mesozoic or Palaeogene time. The history of break up and the subsequent development of these microcontinents is represented by sedimentary sequences on the northern margin of Australia, in northern Irian Jaya, the Arafura and Sahul platforms and within the microcontinents themselves (Dow 1977; Pieters *et al.* 1983; Pigram & Panggabean 1984; Simandjuntak 1986; Dow *et al.* 1988; Garrard *et al.* 1988).

Thermal doming, volcanism, rifting and subsidence to form sedimentary basins commenced during the Palaeozoic on the northern margin of the Australian continent, which at that time formed part of Gondwanaland (Veevers 1984), and intensified during the Permian and Triassic (cf. Bird & Cook 1991 from Timor). The exact timing of separation of the microcontinents from Australia is still very much in dispute. Pigram & Panggabean (1984), based on the model of breakup sequences proposed by Falvey & Mutter (1981), suggested that the separation of microcontinents from central Papua New Guinea occurred in the early Jurassic between 141° and 145°E longitude. Rifting with the deposition of red beds in Irian Jaya and Papua New Guinea was followed by the deposition of a passive margin sequence which continued into the early Tertiary.

It was earlier suggested that the microcontinents were detached from Irian Jaya in the mid-Tertiary and displaced westwards by movements along the Sorong Fault and/or its subsidiary traces (Visser & Hermes 1962; Krause 1965; Katili 1971; Gribi 1973; Hamilton 1979; Silver & Smith 1983).

However, the Jurassic passive margin sequence preserved in the microcontinents is overlain para-unconformably by Upper Cretaceous pelagic calcilutites; the Early to mid-Cretaceous was a period of non-deposition in the microcontinental blocks (Pigram *et al.* 1985; Simandjuntak 1986; Garrard *et al.* 1988). This depositional hiatus, followed by the abrupt deepening of the margins of the microcontinents in the Late Cretaceous, has been used to argue that the microcontinents were already detached and displaced from the northern margin of Australia by this time (Simandjuntak 1986, 1994; Réhault *et al.* 1991).

Neogene orogenies in Indonesia

The present physiography of the Indonesian archipelago can be attributed directly to Neogene orogenic events. These events included plate convergence with subduction beneath the margins of Sundaland to produce a Cordilleran type of orogeny, a unique arc–arc collision in the Moluccas, collision of arcs and microcontinents and major continental blocks with the construction of mountain belts, transpression and transtension along major transcurrent belts, the construction of foreland fold and thrust belts, back-arc thrusting and reversal of subduction polarity. Examples of all of these types of orogenic event can be found among the islands of the Indonesian archipelago. These events will be described in terms of their contribution to the development of five orogenic types in Indonesia (Fig. 2).

Sunda orogeny

The Late Neogene Sunda orogeny affected the segment of the Indonesian arc between West Java and the islands of Nusa Tenggara as far east as Flores (Fig. 3). In this segment of the arc convergence between the Indian Ocean and SE Asian plates is normal to the subduction trace in the Java Trench with a rate of *c.* 7 cm a^{-1}. The subduction system comprises an accretionary complex composed of offscraped Indian Ocean floor materials in the Java forearc ridge, a forearc basin developed on extended continental crust and containing late Palaeogene to Recent sediments. The volcanic arc which forms the backbone of Java and forms the islands to the east is constructed on continental crust in West Java, on Mesozoic accretionary complexes in Central and East Java and on oceanic crust in Sumbawa and Flores. To the north of the arc in Java and in the Java Sea Tertiary backarc basins have developed on continental crust in the Sunda Shelf and on oceanic crust north of Bali and Flores. The basins on the Sunda Shelf formed in the late Palaeogene as rift basins in a terrestrial environment and subsided in the Neogene to be transgressed and covered by marine sediments.

In the Late Neogene this system was affected by compression associated with the Sunda orogeny.

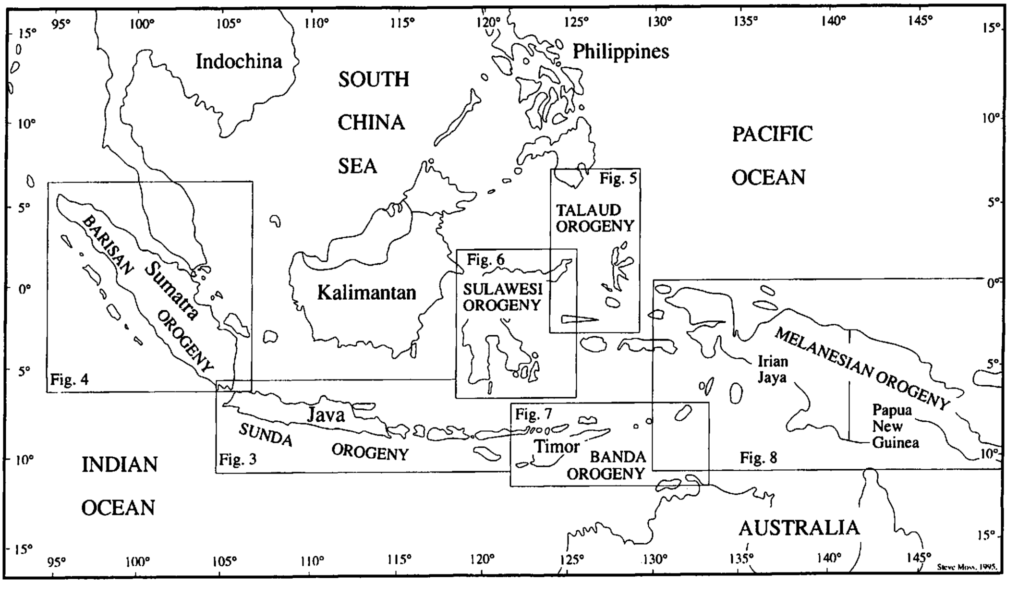


Fig. 2. Location of Neogene orogenies in Indonesia. Detailed figs to illustrate the structure of these orogenies are specified.

In N. Java Mio-Pliocene turbidites are deformed into tight, locally isoclinal folds, readily observed in the field and on aerial photographs, while in S. Java–Nusa Tenggara older volcanic sequences are folded, faulted and uplifted to form mountains more than 3500 m above sea level. This phase of folding is associated in time with the intrusion of acid plutons, the uplift of the volcanic arc, the development of a major thrust system in which the volcanic arc is overthrust towards the Java Sea to the north, and the subsidence of the backarc basins, with the deposition of fine siliciclastic sediments, marls and carbonates of Plio-Pleistocene age.

In N. Java the trace of a major backthrust, the Barabis–Kendeng Thrust (Simandjuntak 1992) can be traced from the Sunda Strait eastwards across Java and through the Bali Basin into the Flores Thrust, north of Flores (Prasetyo 1988). The thrust may continue eastwards as the Wetar Thrust to the north of Timor. The Barabis–Kendeng Thrust has been imaged in seismic reflection profiles in the northern part of West Java (Supryanto & Ibrahim 1993) and offshore north of Flores (Hamilton 1979; Prasetyo 1988), whilst the Bouguer gravity anomaly pattern in the northern part of East Java indicates the location of the Kendeng Thrust. In Central Java the thrust is cut and disrupted by the Cimandari and Citandui Faults which have wrench components of movement (Dardji *et al.* 1994). Earthquakes recorded at Majalengka, Brebes (West Java) and Pekalongan (Central Java) show that segments of the backarc thrusts are currently active (Kertapati *et al.* 1972).

The causes of the Late Neogene Sunda orogeny, with a change from an extensional to a compressional regime across the subduction system, are not clear. Compression may develop when smooth subduction of the downgoing oceanic plate is interrupted by topographic irregularities on the sea floor. This explanation could apply in the East Java–Bali segment of the subduction system where the Roo Rise is beginning to enter the subduction trench (Fig. 3), but does not explain compression elsewhere in the arc. It may be that the compression is localized along the northern margin of the volcanic arc due to magmatic intrusion and the consequent uplift of the arc.

Barisan orogeny

The Late Neogene Barisan orogeny affected the segment of the Indonesian arc occupied by the island of Sumatra (Fig. 4). Convergence in this segment of the arc between the Indian Ocean and Southeast Asian plates at a rate of *c.* 7 cm a^{-1}, is currently markedly oblique (50–65°). The subduction system includes an accretionary complex, exposed in the offshore islands such as Nias (Moore & Karig 1980), and a forearc basin. The volcanic arc is constructed on continental crust and

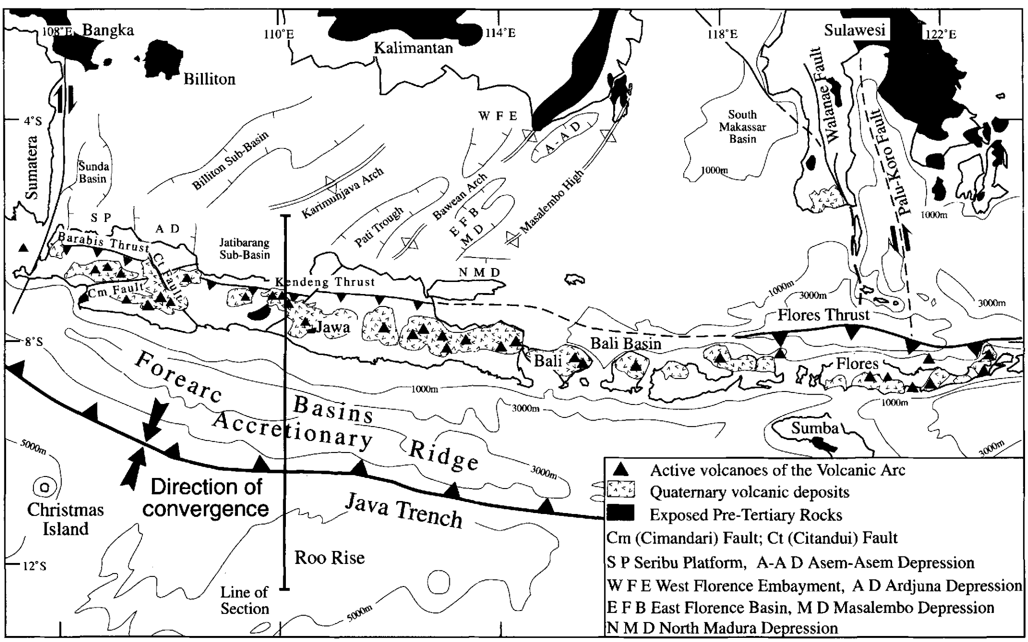


Fig. 3. Sunda orogeny in Java and Nusa Tenggara. Line of section illustrated in Fig. 9 is indicated.

the volcanoes sit on an uplifted pre-Tertiary basement terrane which forms the Barisan Mountains running the whole length of Sumatra. Both the basement and the volcanic arc are dissected by the Barisan dextral transcurrent fault system. Extensive Tertiary backarc basins lie to the northeast, behind the arc.

Sumatra forms part of the Sundaland continental craton. In the Palaeogene the region was affected by extension and subsidence, resulting in the formation of rift basins. Some of these basins, such as the coal-bearing Ombilin Basin of West Sumatra, lie within the Barisan Fault System and have been interpreted as pull-apart basins formed by transtensional movements along the fault (Koesoemadinata *et al.* 1978; Koning & Aulia 1985; Wang *et al.* 1989; Situmorang *et al.* 1991). Continuation of movements along the fault led to the opening of the Andaman Sea (Curray *et al.* 1979; Harding 1983).

Commencement of the Barisan orogeny was marked by the uplift of the Barisan Mountains and arc volcanism, signalled by the influx of volcaniclastic sediments and regressive sequences in the Sumatran back-arc basin in the mid-Miocene. Uplift was accompanied by intrusions in the volcanic arc and transpressive movements along the Barisan Fault System. Fault movement resulted in the imbrication, duplexing and stacking of crustal slices to form a large-scale positive flower

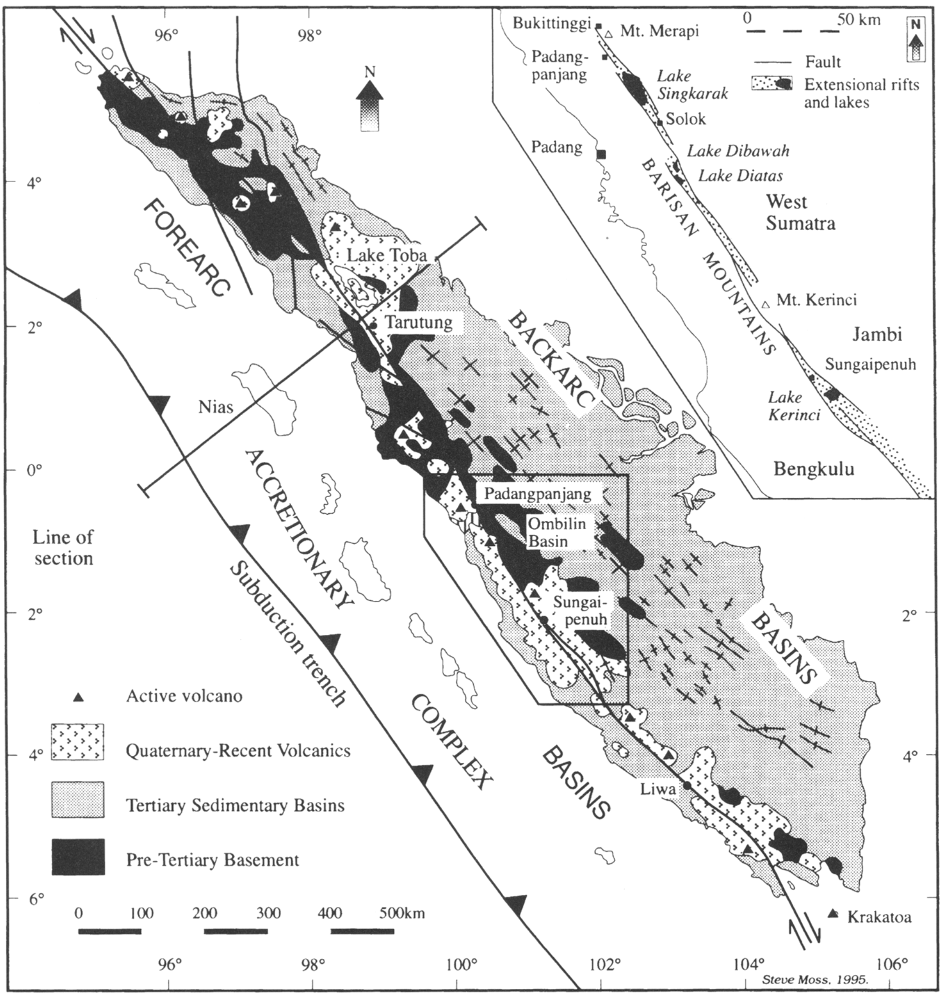


Fig. 4. Barisan orogeny in Sumatra. Crossed lines in the back-arc basins indicate fold axial traces. Inset map shows extensional features in the section of the Barisan Fault between Bukittinggi and Lake Kerinci (location indicated on main map). Line of section illustrated in Fig. 9 is indicated.

structure, leading to the erosion of the cover and exposure of the basement rocks which now rise to nearly 4000 m above sea level. Uplift of the Barisan Mountains was accompanied by subsidence of the forearc and back-arc basins.

Plio-Pleistocene transpressive movements along the Barisan Fault System are considered to have induced fold structures in the sediments of the back-arc basins on axes which trend at an angle of 20° to the main fault (de Coster 1974; Hamilton 1979). The folds are commonly associated with small-scale wrench faults and may be related to large-scale wrench faults in the underlying basement (Tiltman 1990). Pleistocene movements along the fault system have, at least locally been transtensional with the opening of pull-apart basins, often holding lakes, such as Laut Tawar, Toba, Singkarak, Diatas, Dibawah, Kerinci (Fig. 4, inset), Ranau or a Recent sedimentary fill as in the Semangko Valley.

Recent earthquakes resulting in the cessation of sulphuric hot springs and the disappearance of ponds at Tarutung (North Sumatra), and at Padang Panjang in Central Sumatra, indicate dextral transpressional reactivation along the northern segment of the Barisan Fault System. In Lampung Province, S. Sumatra NW–SE extensional cracks formed during an earthquake near Liwa in early 1994, indicating sinistral transtensional movement along this segment of the fault.

The Neogene Barisan orogeny is attributed to variations in the rate of subduction of the Indian Ocean plate and the response of SE Asia to the continuing collision of India with the southern margin of Asia and the adjustment of crustal blocks by movements along major transcurrent faults (Tapponnier *et al.* 1982). The obliquity of subduction is considered to be responsible for the development of the Barisan Fault and the detachment of the Sumatran forearc to form a 'sliver plate', which is partially coupled to the northward movement of the Indian Ocean plate (Fitch 1972; Curray 1989; McCaffrey 1991). Movements along the Barisan Fault are considered to be responsible for the uplift of the Barisan Mountains and the transtensional and transpressional effects seen along the fault trace. Results of break-out analysis of sediments from boreholes in the Sumatran backarc basins show that the effects of oblique subduction are also being transmitted across the Barisan Fault into the backarc (Mount & Suppe 1992).

Talaud orogeny

The Neogene Talaud orogeny of the N. Moluccas provides the only example of an active arc–arc collision in the world. The Molucca Sea is bounded to the west by the Sangihe volcanic arc and to the east by the Halmahera Arc (Fig. 5). Seismicity shows that the Sangihe Arc is underlain by a west-dipping Benioff zone extending to a depth of 700 km, while an east-dipping Benioff zone underlies the Halmahera arc to a depth of 200 km (Silver & Moore 1978; Hamilton 1979; Sukamto *et al.* 1981). The shallow Molucca Sea between the two arcs is considered to be underlain by the collided accretionary complexes of the two opposing arcs uplifted to form the central Talaud–Mayu Ridge, the underlying Molucca Sea plate having subsided back into the mantle between them. Hamilton (1979), on the basis of seismic reflection profiles, suggested that the volcanic aprons from the forearcs of the Sangihe and Halmahera arcs had been thrust backwards across their corresponding arcs as the result of the collision. Recent Seabeam and seismic reflection data from the northern part of the Molucca Sea indicate that the floor of the sea consists entirely of the Sangihe forearc which has been thrust eastwards over the Halmahera forearc (Rangin *et al.* 1996). To the south the collision complex is truncated by a major strand of the Sorong Fault System. The Sangihe subduction system may swing round to the west and continue as the Batui Thrust in the East Arm of Sulawesi. Frequent earthquakes show that all these structures are currently active (McCaffrey *et al.* 1983; Simandjuntak 1989; Kertapati *et al.* 1972).

Sulawesi orogeny

Sulawesi is made up of three structural units: pre-Cretaceous accretionary material in the west upon which later developed a Neogene volcanic arc; Central Sulawesi and part of the SE Arm are composed of metamorphic rocks; the E. Arm and the remainder of the SE Arm are made up of a major ophiolite complex. The metamorphic rocks in Central Sulawesi and in the SE Arm include materials of both continental and oceanic derivation. These rocks are locally affected by high pressure metamorphism forming blueschists, developed in an east dipping Paleogene mid-oceanic subduction zone. Subduction resulted in the obduction of the East Sulawesi Ophiolite westwards across the metamorphic belt, accompanied by the extrusion of ophiolitic melange (Parkinson 1991).

Neogene orogeny in Sulawesi was initiated by the collision of the two microcontinental blocks of Buton–Tukangbesi and Banggai–Sula with the eastern part of the island (Fig. 6). These two microcontinental blocks, having separated from the northern continental margin of Australia, possibly from the region of central New Guinea as has been

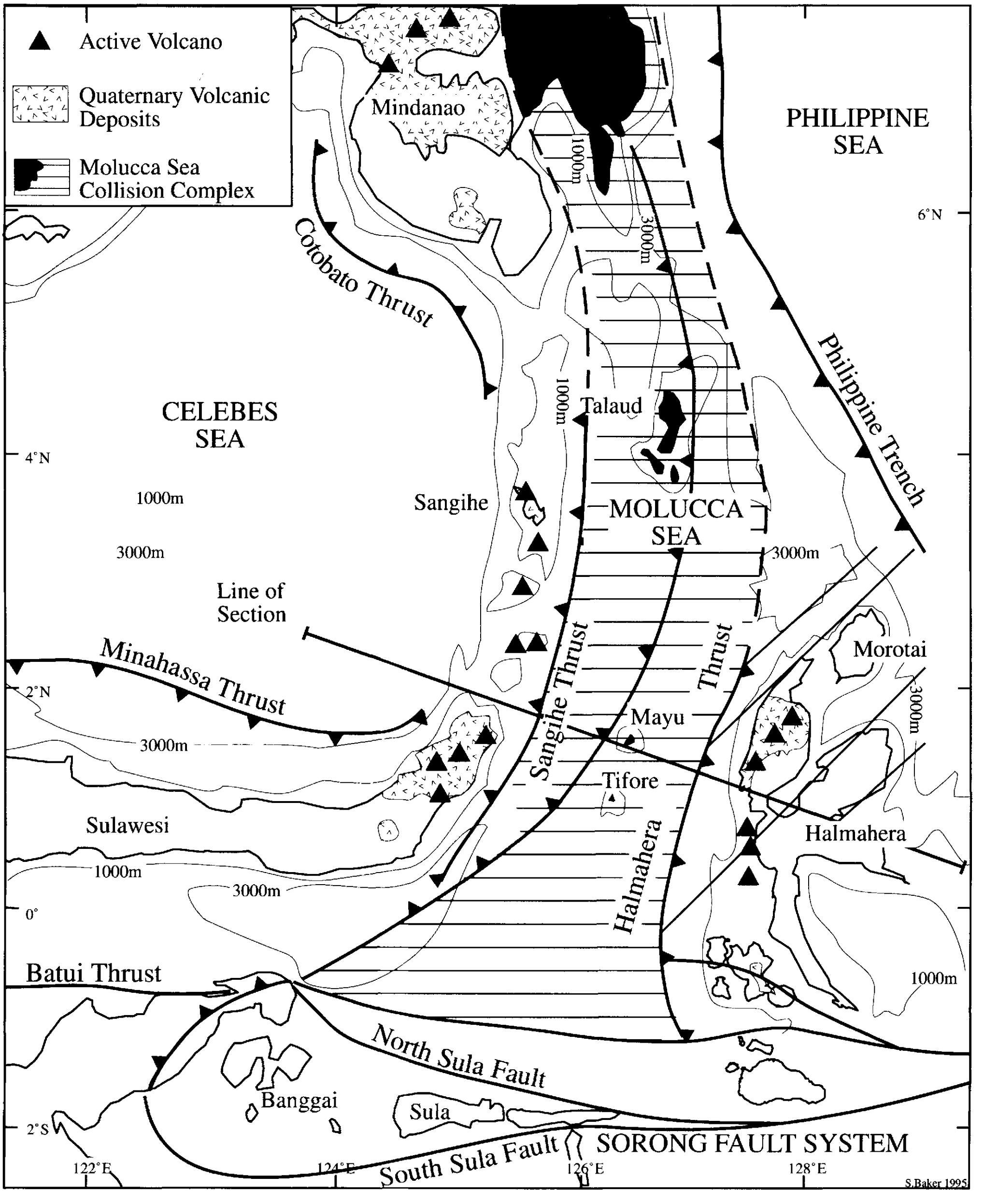


Fig. 5. Talaud orogeny in the North Moluccas. Line of section illustrated in Fig. 9 is indicated.

previously discussed, were carried westwards along the Sorong transcurrent fault zone by movements of the Philippine Sea plate (Ali & Hall 1995) and collided with the eastern margin of the ophiolite complex. The collision caused the obduction of the ophiolite onto the microcontinental blocks and the shortening and thickening of the ophiolite by imbrication. The leading edges of the Buton–Tukangbesi and Banggai–Sula microcontinents were thrust beneath the ophiolite, uplifting the tightly folded, faulted and imbricated ophiolite and its pelagic cover to heights of more than 3000 m above sea-level (Smith 1983; Simandjuntak 1986; Garrard *et al.* 1988; Fortuin *et al.* 1990; Davidson

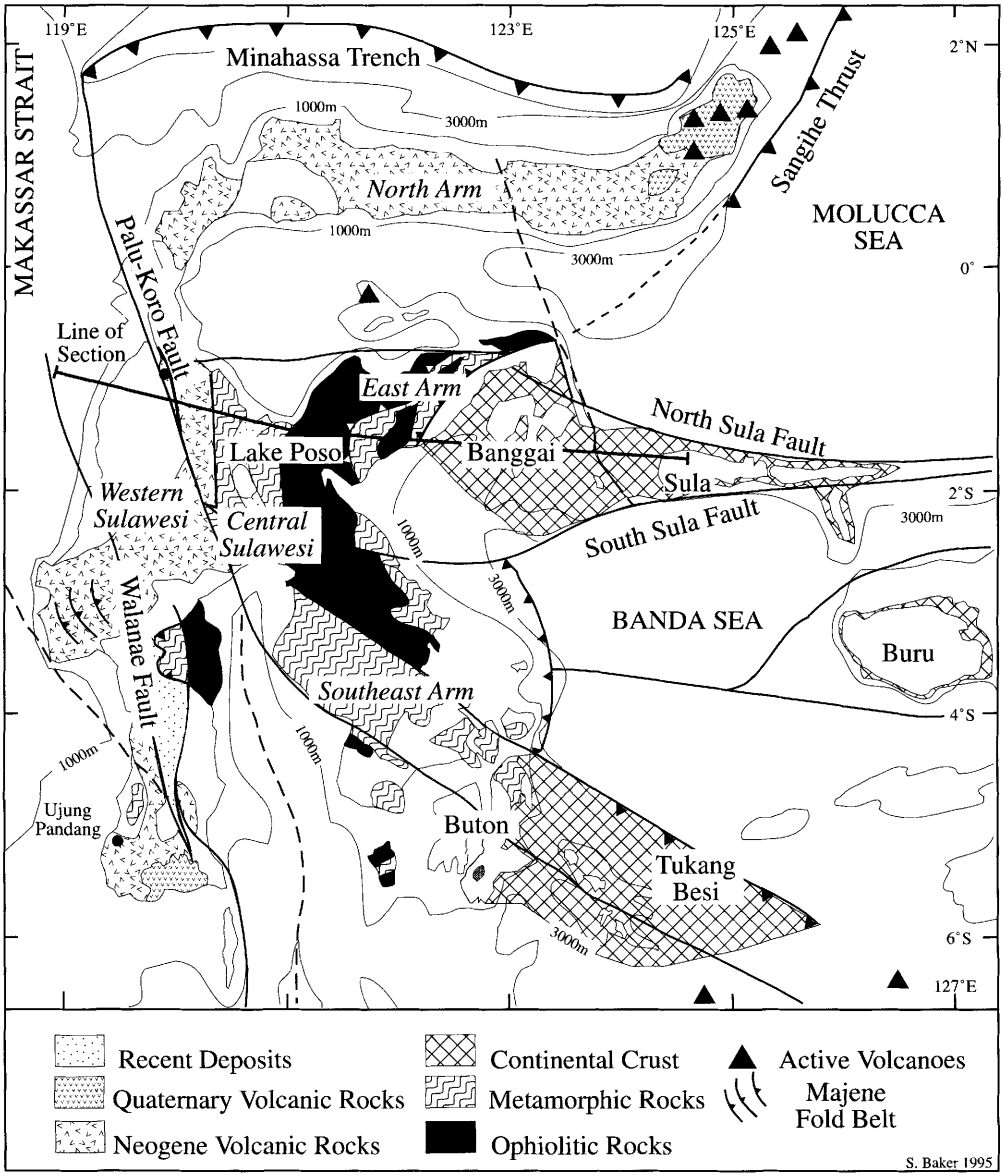


Fig. 6. Sulawesi orogeny. Line of section illustrated in Fig. 9 is indicated.

1991). Also as a result of the collision the metamorphic belt of Central Sulawesi was thrust westwards over West Sulawesi and uplifted to form mountain ranges of nearly 3000 m. Overthrusting resulted in the formation of a foreland fold and thrust belt in Tertiary sediments, the Majene Fold Belt, which continues to develop westwards to the present day, affecting Recent sediments in the Makassar Strait (Coffield *et al.* 1993; Bergman *et al.* 1996).

Associated with the collision, or following shortly after, was the development of the NNW–SSE trending Palu–Koro sinistral transcurrent fault, along which eastern Sulawesi has been displaced northwards with respect to western Sulawesi. Simandjuntak (1993a) has discussed the effects of transtensional movements along this fault and related displacement of the island of Sumba to its present anomalous position in the Banda forearc. More recent transtensional movements during the

Quaternary, continuing to the present time, are responsible for opening pull-apart basins, such as those of Lakes Poso, Matano and Towuti, as well as the Palu depression. Recent earthquakes along the Palu–Koro and related faults show that the system is currently active.

Banda orogeny

The Neogene Banda orogeny is due to a continent–arc collision where the northern margin of the Australian continent, moving NNE at *c.* 7 cm a^{-1} is colliding with the subduction system along the southern side of the Banda Arcs (Fig. 7). The deformation front, marking the southern limit of the collision complex, lies along the 2 km deep Timor trough. Seismic reflection profiling across the trough shows Australian passive margin sediments passing northwards down beneath the trough where, at the deformation front, the upper parts of the sequence have been uplifted on thrust surfaces to form fold ridges in an accretionary complex (Karig *et al.* 1987).

The structure of the collision zone is exposed in the island of Timor (Barber *et al.* 1977; Charlton *et al.* 1991; Harris 1991). The island is composed of sediments of Permian to Pliocene age, of Australian affinity which have been folded, thrust and imbricated. The Australian sediments have been thrust beneath an ophiolite slab with an underlying metamorphic sole, representing the trace of the Benioff zone prior to collision, but now uplifted to heights of more than 3000 m above sea-level in Timor (Sopaheluwakan 1990). Most of this uplift occurred in the Neogene, as Miocene, Pliocene and Pleistocene forearc sediments resting on the complex show a history of deposition shallowing upwards from bathyal facies through shallow water deposits to Pleistocene coral reefs (de Smet *et al.* 1990). These facies changes indicate two periods of rapid uplift, one 2 Ma and the other *c.* 100 000 years ago, representing different stages in the collision.

The collision between the Australian margin and the Banda Arc subduction system appears to have commenced in the region that is now East Timor, and the collision is at its most advanced stage in this segment of the arc. Here the forearc between

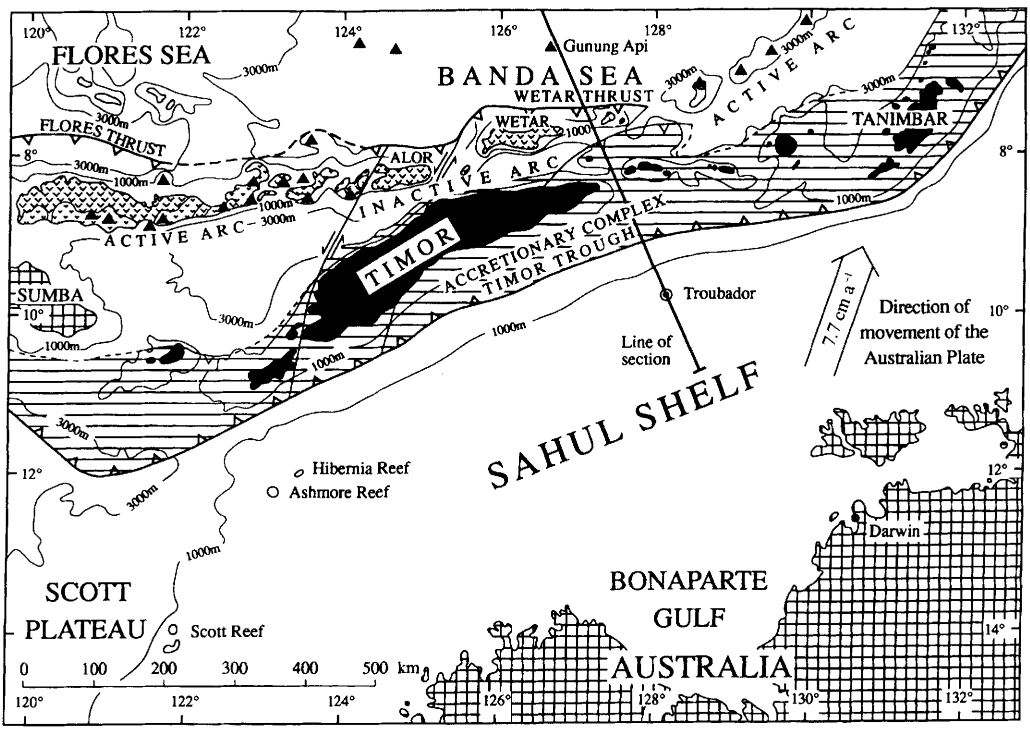


Fig. 7. Banda orogeny: the collision zone between the southern Banda Arcs and Australia near Timor, based on Hamilton (1979). Horizontal ruling, collision zone with islands in black; triangles, active volcanoes; small v, associated with Quaternary volcanics; larger v pattern, Neogene volcanics. Line of section illustrated in Fig. 9 is indicated.

the volcanic arc and the deformation front has been reduced to a width of less than 100 km, compared with over 400 km for the forearc east of Sumba where collision has commenced only recently.

Continued northward movement of the Australian continent has been accommodated by the uplift of the collision complex in Timor and lateral extension along conjugate faults (Charlton *et al.* 1991). Compression of the forearc has virtually eliminated the forearc basin which is only 40 km wide to the north of East Timor. Furthermore, shallow seismic activity is absent beneath East Timor suggesting that the downgoing plate and the collision complex have become locked in this segment of the arc. Volcanic activity in the islands of Alor and Wetar to the north of East Timor ceased about 3 Ma (Abbott & Chamalaun 1981) and the volcanic arc now rests on a southward-dipping thrust plane, the Wetar Thrust. The development of a small accretionary complex to the north of the thrust (Breen *et al.* 1989) suggests that the whole of the forearc and the volcanic arc are being carried northwards with the movement of Australia, and are overthrusting the Banda Sea floor to the north. These may be the first indications of reversal of the polarity of the subduction system, with the Banda Sea floor passing down southwards beneath the northern margin of Australia. Recent deep-seismic reflection profiles to depths of up to 100 km, a short distance to the east of East Timor, show reflections representing thrust surfaces dipping both northwards and southwards beneath the collision complex which has been uplifted as a wedge by the convergence of the Australian and the Banda Sea lithosphere (Snyder *et al.* 1996).

Melanesian orogeny

The Neogene Melanesian orogeny in Irian Jaya and Papua New Guinea is considered to be the result of oblique convergence of the Australian and Philippine Sea (and Caroline) plates (Dow & Sukamto 1984). In the late Palaeogene or very early Neogene, the northern promontory of the Australian Continent collided with an oceanic island arc constructed on the southern margin of the Philippine Sea plate (Hall *et al.* 1995). The remnants of this arc are now distributed through the northern part of New Guinea (Pigram & Davies 1987), disrupted by transcurrent fault movements to form discrete terranes (Fig. 8).

The Central Ranges of New Guinea are composed of a major ophiolite complex, here interpreted as the oceanic lithosphere which underlay the oceanic island arc, subsequently uplifted as the result of the collision with Australia. To the south of the ophiolite the Australian passive margin sediments are deformed by thin-skinned thrust tectonics into a foreland fold and thrust belt, with folding, imbrication and duplexing. At deeper levels seismicity indicates that the underlying Australian continental crust is also involved in the thrusting (Abers & McCaffrey 1988). The whole collision belt is being thrust southwards over the northern

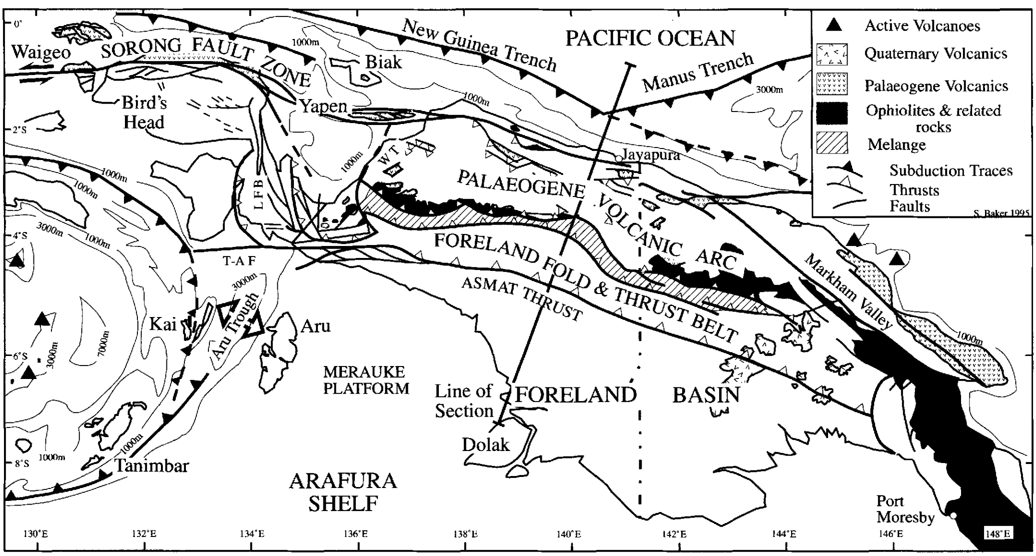


Fig. 8. Melanesian orogeny in New Guinea, based on Hamilton (1979), with modifications after BMR (1972) and Dow *et al.* (1986). LFB, Lengguru Fold Belt; T-AF, Tarera–Aiduna Fault; WT, Waipona Trough. Line of section illustrated in Fig. 9 is indicated.

margin of the Australian continent. The southern margin of the overthrust belt is marked by the Asmat Thrust (Fig. 8).

The progress of the Banda and Melanesian orogenies in eastern Indonesia has been controlled by irrregularities in the northern margin of the Australian continent (Charlton 1986). Collision commenced in New Guinea. Using the known rate of northward movement of the Australian continent, Simandjuntak (1993*b*) postulated that at the time of the original collision, the subduction zone to the north of New Guinea was continuous with the subduction zone to the south of the Banda Arcs. Continued northward movement of Australia since the collision has displaced the collision zone northwards. Simundjuntak (1993*b*) also suggested that the western margin of the New Guinea promontory is marked by the Waipona Fault which transects the Asmat Thrust. He speculated that the northward movement of New Guinea relative to the Banda Arcs is responsible for the northward curvature of the Banda Arcs near Tanimbar and for the curvature of the Lengguru Fold Belt of the Bird's Head of Irian Jaya. Transcurrent movement along this fault is transpressive near Tanimbar and transtensional in the Aru Trough

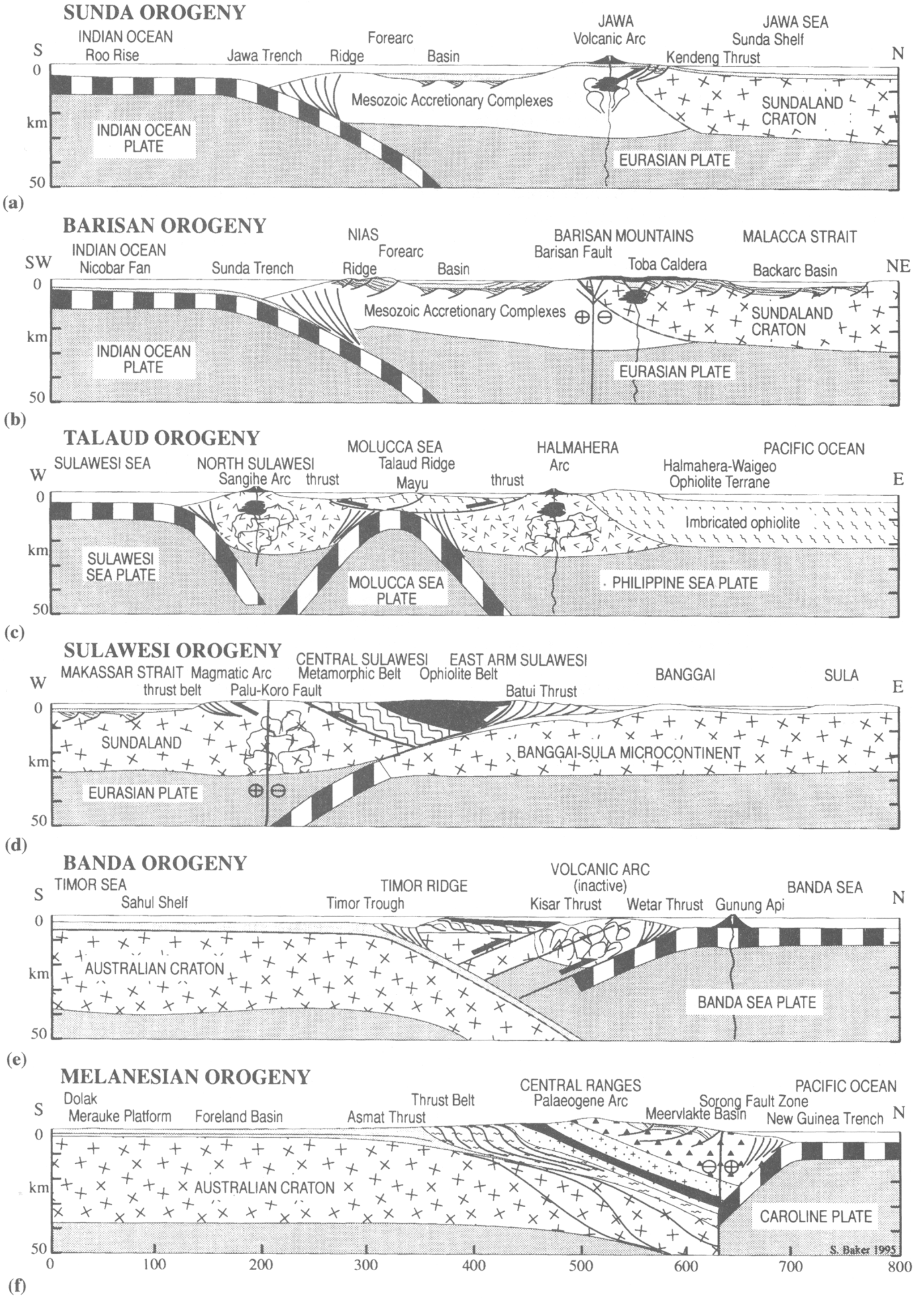
Following the collision, continued northward movement of Australia has thrust the Palaeogene arc, now attached to the northern margin of Australia, over the Caroline plate to the north in a much quoted example of polarity reversal (Dewey & Bird 1970; Johnson & Jaques 1980; Cooper & Taylor 1987). Recent geophysical studies in the Manokwari Trough immediately to the north of Irian Jaya, however, show that subduction is no longer in progress there (Milsom *et al.* 1992). Extensive outcrops of andesitic volcanic rocks of mid- to late Miocene age throughout northern New Guinea indicate that southward subduction of the Philippine Sea plate beneath Australia occurred at that time. Quaternary and Recent volcanism is largely restricted to Papua New Guinea, and the potassic nature of the volcanic rocks suggests that they are related to extension rather than to subduction (Dow 1977).

The northern part of New Guinea is transected by a major E–W strike-slip fault system, the New Guinea Megashear, which continues westwards into the Sorong Fault System of the Moluccas, already mentioned. Some of the records of shallow earthquake activity, especially concentrated in central Irian Jaya, may be related to continued movement on this fault system. Most records, however, show a thrust sense of movement related to compression in the Momberama Thrust Belt (Abers & McCaffrey 1988). These thrust movements may be the effects of transpression which may also be responsible for the uplift of the Central Ranges to a height of nearly 6000 m. Transtensional movements in other parts of the fault system may be responsible for the opening up of rifts such as the Markham Valley in Papua New Guinea (Hill & Gleadow 1989). Transcurrent fault movements in northern New Guinea are attributed to the continued westward movement of the Caroline/Philippine Sea plate at a rate of 12.5 cm a^{-1} relative to the Australian plate.

Conclusions

The whole range of plate tectonic and orogenic processes of subduction, accretion, construction of volcanic arcs, back-arc thrusting, strike-slip faulting, formation of sliver plates, arc-arc,

Fig. 9. Comparative interpretative cross-sections across the Neogene Orogenic Belts of Indonesia, all at the same scale. (**a**) Sunda orogeny. Convergence between Indian Ocean and Eurasian plates is normal to the subduction trench. The system consists of an accretionary complex, forearc basin, volcanic arc and backarc basin. Compression across the system has resulted in backarc thrusting. (**b**) Barisan orogeny. Oblique convergence of the Indian Ocean and Eurasian plates. The system is modified by the development of a 'sliver plate' where the forearc is driven northwards along the Barisan strike-slip fault by the movement of the Indian Ocean plate. (**c**) Talaud orogeny. The Molucca Sea plate is subsiding between the colliding Sangihe and Halmahera forearcs. The Sangihe forearc has been thrust over the Halmahera forearc to form the Talaud Ridge. Subduction of the Sulawesi Sea plate has commenced only recently. (**d**) Sulawesi orogeny. The Banggai–Sula microcontinent has collided with the ophiolite in the East Arm of Sulawesi. Repercussions of this collision include strike-slip movements along the Palu–Koro Fault and overthrusting in the Makassar Strait. (**e**) Banda orogeny. The Australian craton has been subducted beneath the accretionary and collision complex in the Timor Ridge. The ridge is composed of accreted Australian continental margin sediments and earlier collided microcontinents. Subduction has ceased in this section of the collision zone, but the collision complex is being driven over the volcanic arc, which is in turn being driven over the Banda Sea plate to the north, in the earliest stages of subduction reversal. (**f**) Melanesian orogeny. The Australian Craton has been subducted beneath a Palaeogene volcanic arc with the development of a foreland fold and thrust belt from its overlying sediments. Ophiolite and arc volcanics in the central Ranges represent the uplifted hanging wall of the subduction zone. The system has reversed its polarity with the subduction of the Caroline Sea plate but the system is truncated by movement along the Sorong strike-slip fault zone due to the westward movement of the Caroline Sea plate. Data are drawn from references quoted in the text of the paper.


SUNDA OROGENY
INDIAN OCEAN
Roo Rise
Jawa Trench
Forearc
Ridge
Basin
JAWA
Volcanic Arc
JAWA SEA
Sunda Shelf
Kendeng Thrust
S
N
0
km
50
Mesozoic Accretionary Complexes
SUNDALAND
CRATON
INDIAN OCEAN
PLATE
EURASIAN PLATE
(a)
BARISAN OROGENY
INDIAN OCEAN
Nicobar Fan
Sunda Trench
NIAS
Forearc
Ridge
Basin
BARISAN MOUNTAINS
Barisan Fault
Toba Caldera
MALACCA STRAIT
Backarc Basin
SW
NE
Mesozoic Accretionary Complexes
SUNDALAND
CRATON
INDIAN OCEAN
PLATE
EURASIAN PLATE
(b)
TALAUD OROGENY
SULAWESI SEA
NORTH SULAWESI
Sangihe Arc
thrust
MOLUCCA SEA
Talaud Ridge
Mayu
thrust
HALMAHERA
Arc
PACIFIC OCEAN
Halmahera-Waigeo
Ophiolite Terrane
W
E
Imbricated ophiolite
SULAWESI
SEA PLATE
MOLUCCA SEA
PLATE
PHILIPPINE SEA PLATE
(c)
SULAWESI OROGENY
MAKASSAR STRAIT
thrust belt
Magmatic Arc
Palu-Koro Fault
CENTRAL SULAWESI
Metamorphic Belt
EAST ARM SULAWESI
Ophiolite Belt
Batui Thrust
BANGGAI
SULA
SUNDALAND
BANGGAI-SULA MICROCONTINENT
EURASIAN PLATE
(d)
BANDA OROGENY
TIMOR SEA
Sahul Shelf
TIMOR RIDGE
Timor Trough
VOLCANIC ARC
(inactive)
Kisar Thrust
Wetar Thrust
Gunung Api
BANDA SEA
AUSTRALIAN CRATON
BANDA SEA PLATE
(e)
MELANESIAN OROGENY
Dolak
Merauke Platform
Foreland Basin
Asmat Thrust
Thrust Belt
CENTRAL RANGES
Palaeogene Arc
Sorong Fault Zone
Meervlakte Basin
PACIFIC OCEAN
New Guinea Trench
AUSTRALIAN CRATON
CAROLINE PLATE
S. Baker 1995
0
100
200
300
400
500
600
700
800
(f)

micro-continental–arc and continental–arc collision, foreland fold and thrust belt formation, obduction and the uplift of mountain belts may be found currently in progress in the Indonesian archipelago. Our present understanding of the structure of the Neogene–Recent orogenic belts of Indonesia is illustrated in a series of cross-sections in Fig. 9. These present-day examples of orogenic processes provide models for the interpretation of older orogenic belts such as the Alpine–Himalayan system, the Hercynides and the Caledonides.

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