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Magmatism in western Indonesia, the trapping of the Sumba Block and the gateways to the east of Sundaland

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Abstract—The western Sulawesi magmatic belt and the Sunda–Banda arc define the eastern and south-eastern margins of Sundaland, which is part of the relatively stable Eurasian plate. The eastern margin is bounded by the Makassar Strait which separates western Sulawesi from Kalimantan. The initial opening of the Makassar Strait took place in the late Cretaceous–Early Tertiary leading to the opening of the Pacific–Indian Ocean gateway during Neogene time. Recent studies indicate similarities in the late Cretaceous–Paleogene stratigraphic sequence and calc-alkali magmatism between Sumba, south Sulawesi and south-east Kalimantan, suggesting a Sundaland origin for all of these areas. The southward migration of Sumba to the present frontal arc position of the Sunda–Banda arc has occurred since Late Cretaceous–Paleocene time. © 1998 Elsevier Science Ltd. All rights reserved

Introduction

This paper comprises the results of studies of the Tertiary magmatic evolution of Java, Kalimantan, western Sulawesi and Sumba based on the K–Ar dating of volcanic rocks. The distribution of the volcanic units and their magmatic affinities are the results of the interaction of the Indo-Australian Plate with Sundaland, representing the Eurasian Plate, in the west and the Banda Arc to the east. The tectonic reconstructions of western Indonesia presented in this paper are based on the finding that peaks of calc-alkali volcanic activity occurred at 62 Ma (Paleocene), 55–50 Ma (Early Eocene), 20–18 Ma (Early Miocene), 10–7 Ma (Late Miocene) and 4 Ma (Pliocene).

Sunda–Banda magmatic arc

Sumatra lies on the western edge of Sundaland (Fig. 1), a southern extension of the Eurasian Continental Plate, which was constructed through collision and suturing of discrete microcontinents in the late pre-Tertiary (Pulunggono and Cameron 1984; Suparka 1995). Volcanic rocks outcropping along the length of Sumatra have been extruded intermittently since Late Permian time (Katili 1970, 1973; Hutchison 1975).

A north–south spreading regime, established in the Indian Ocean during the Late Cretaceous, resulted in a system of oblique subduction beneath Sumatra which was contemporaneous with an inferred clockwise rotation of Sundaland (Tapponnier *et al.* 1982). Pre-Tertiary magmatic rocks are represented by Permian basalt lavas outcropping within the Barisan Mountains from Aceh to Lampung (McCourt *et al.* 1996, their Fig. 2) and the Permian to Cretaceous granitoids of Aceh, Sibolga, west Sumatra and Lampung. Jurassic–Cretaceous volcanics of basaltic to andesitic composition are also distributed along the arc.

This magmatic arc extends from north Sumatra eastwards through Java and can be traced as far as the western part of Banda Arc; only Neogene–Quaternary volcanics occur in the islands to the east. The western regions of this arc, from Sumatra to west Java and part of central Java, have been interpreted by many workers as an arc resting on continental type crust. Evidence of Paleocene to Early Eocene magmatism is documented by the calc-alkali volcanics of Sitaban island, Natal, Padang (granitoid intrusions), the Kikim tuff of south Sumatra and Lampung (Aspden *et al.* 1982; Wajzer *et al.* 1991; Katili 1973; Andi Mangga *et al.* 1988; Gafoer *et al.* 1992). Paleocene–Eocene to Early Oligocene subduction is evident from sporadic occurrences of subduction-related andesites, indicating a limited active volcanic arc at that time. The Sumatran fore-arc basins are extensional in origin (Daly *et al.* 1987), unlike the back-arc basins of north Sumatra, which have the geometry of large-scale pull-apart basins generated by dextral strike–slip displacement in a major strike–slip fault zone (Uyeda and Kanamori 1979). Structural inversion of the fore-arc basins in Sumatra and Java took place during the Oligocene, while the convergence rate remained constant (Karig *et al.* 1979).

The Oligo–Miocene paleogeography of Sumatra was dominated by a landmass in the south and a chain of intermittently active volcanic islands in the north. The Oligocene– Early Miocene volcanics make up the "Old Andesite" Formation of west Sumatra (Van Bemmelen

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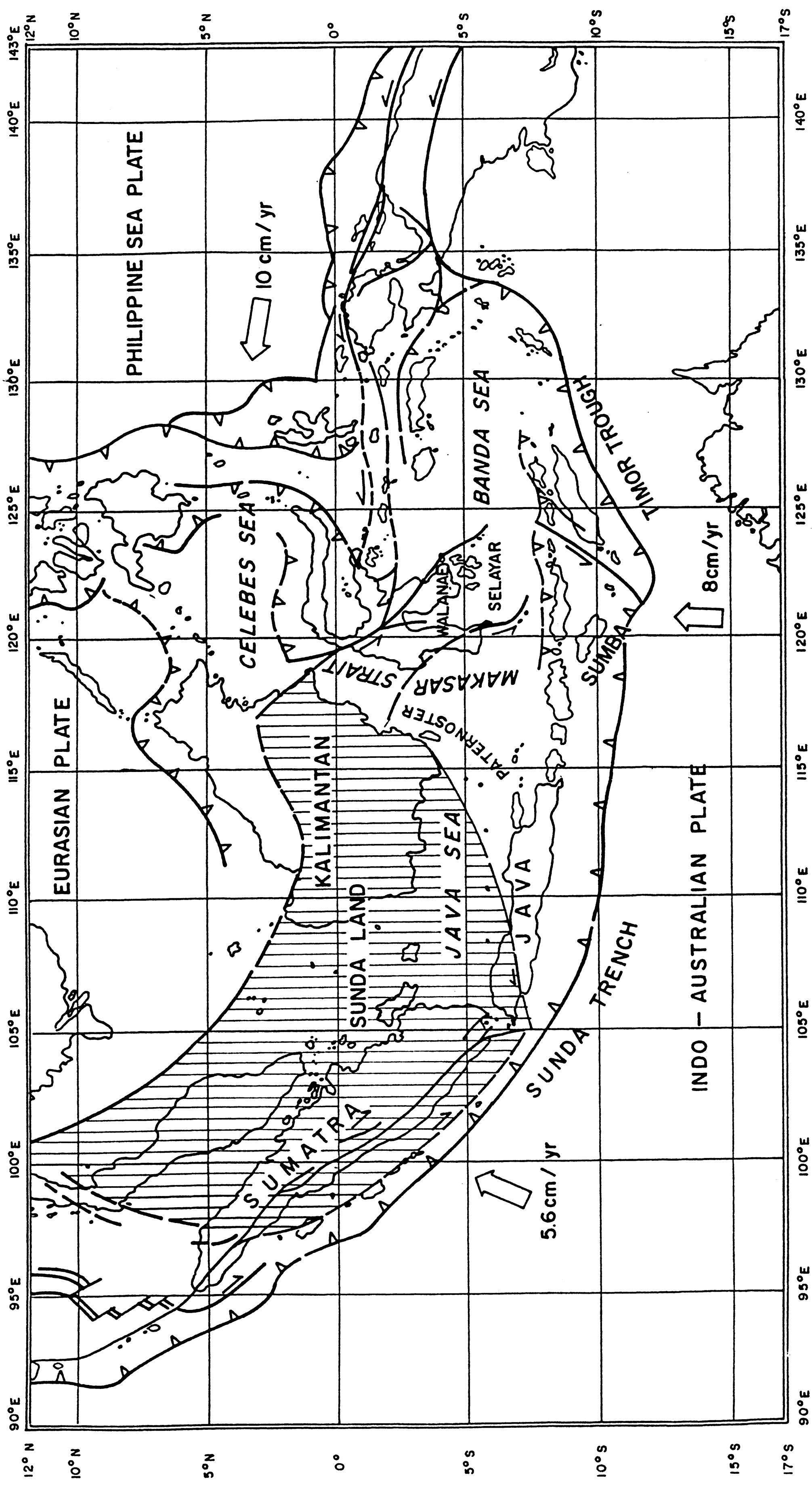


Fig. 1. Tectonic features of Indonesia.

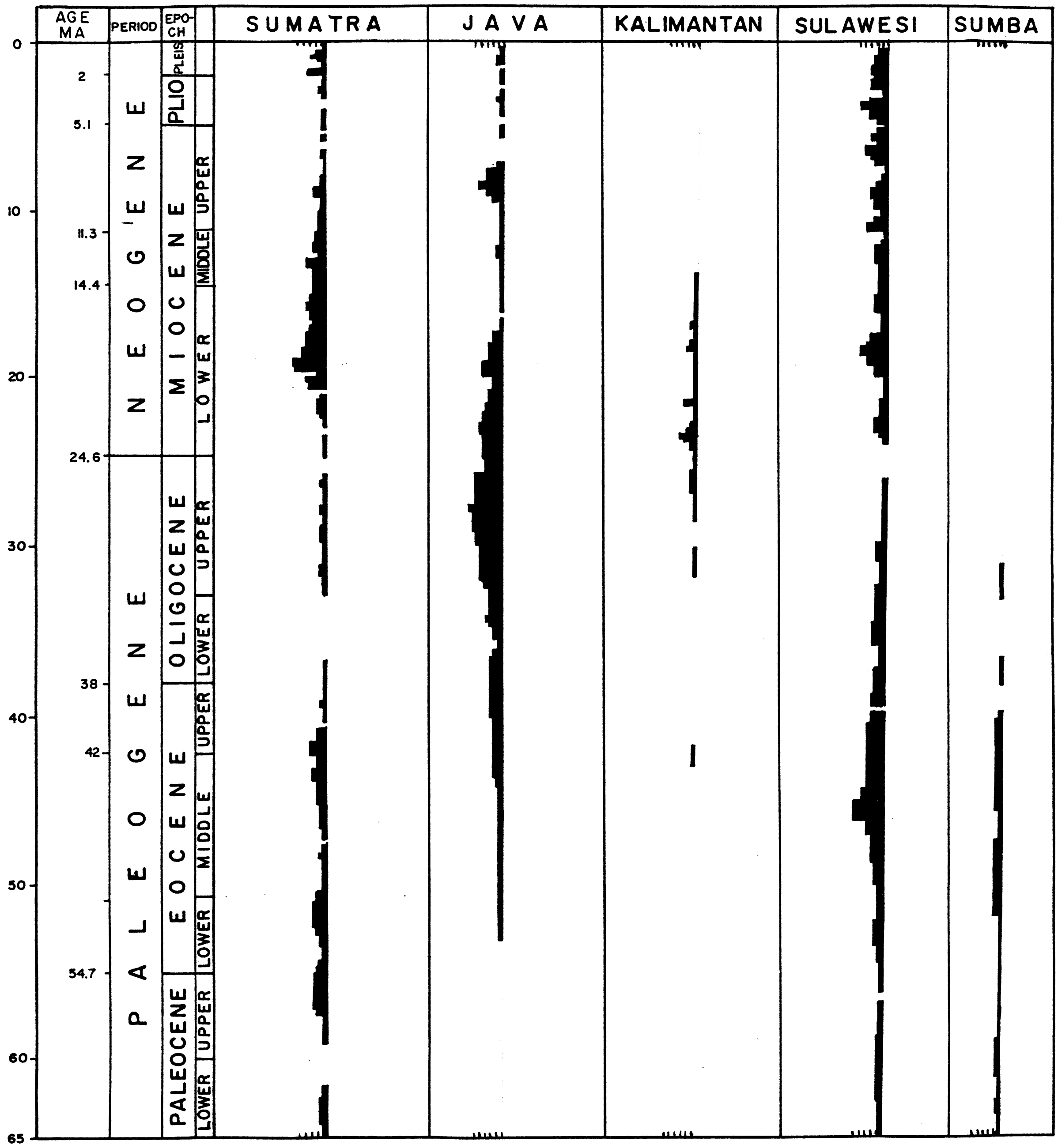


Fig. 2. Histograms of K–Ar and fission-track-dated Tertiary magmatic rocks in Indonesia.

1949), which can be traced eastwards into the southern part of Java (Fig. 1), but is not exposed in Bali, further east. Magmatic activity continued until the Middle Miocene, producing basalt andesite and dacite of calc-alkali, potassic calc-alkali to shoshonitic affinities, which is distributed primarily to the west of the Sumatra Fault Zone (Karig *et al.* 1979; Cameron *et al.* 1980; Rock and Shah 1982; Wajzer *et al.* 1991). Volcanic activity of andesitic to dacitic composition continued until Recent time, followed by largely Quaternary rhyolitic tuffs of Toba and Ranau (Jeffery 1977; Page *et al.* 1979; Rock *et al.* 1983). A major marine transgression began in the Late Oligocene, reaching its culmination in the Mid-Miocene. During the Late Miocene (10 Ma), the northward movement of India caused continued strike–slip movements along the Sumatra Fault System and structural inversion of the back-arc pull-apart basins of Sumatra (Karig *et al.* 1979). According to Karig *et al.* (1979), the uplift of the Barisan Mountains began in the Late Mid-Miocene. Uplift is believed to have been associated with renewed magma supply, related to the increase in subduction rate from 3–4 cm/year to 5–7 cm/year; the peak of uplift probably occurred at the Mio-Pliocene boundary and has continued intermittently until the present day. However, Pulunggono and Cameron (1984) state that the maximum arc volcanicity and transgression in the back-arc region occurred at the Early–Middle Miocene boundary, which was a period of maximum crustal extension.

In Java (Fig. 2) the Tertiary magmatic belt consists of subduction-related calc-alkali volcanics which represent products of two distinct periods of magmatic activity: Late Eocene–Early Miocene (Old Andesite Formation) and Late Miocene–Late Pliocene (Bellon *et al.* 1989; Soeria-Atmadja *et al.* 1990; Soeria-

Atmadja *et al.* 1994). A northward shift of the magmatic belt underlying the present locus of Quaternary volcanic cones has taken place since Eocene/Oligocene time (Soeria-Atmadja *et al.* 1994). Sukarna *et al.* (1993) distinguished two phases of Paleogene calc-alkali magmatism in the westernmost part of west Java (Bayah); the earlier event (Late Eocene–Early Oligocene) represents magmatism in the frontal arc and the later event (Oligocene–Pliocene) took place in the central part of the arc. These volcanic rocks constitute the Old Andesite Formation. Arpandi and Patmosukismo (1975) report subsurface samples of Paleogene volcanic rocks in the northern part of west Java. An earlier reported break in magmatism between 18 and 12 Ma is questionable as more recent K–Ar results have filled this gap (Fig. 2).

Recent studies on the Tertiary magmatic evolution of Bali indicate that Early Neogene sediments are limited to the southern coastal area, where there are also exposures of intercalated undersaturated alkali basalt pillow lavas. The state of alteration of the volcanic rocks precludes K–Ar dating. However, studies on the faunal assemblage of the associated sediments give an age of N_{18}–N_{19} in Blow's zonation (Pringgoprawiro, personal communication). Younger Neogene sediments and associated potassic calc-alkali lavas (mostly andesitic) are exposed along the north coast of Bali and are separated from the previously described sediments to the south by the products of the active volcanoes of G. Agung and G. Batur.

In Lombok, Sumbawa and Flores in the eastern part of the Sunda Arc the oldest exposed rocks are of Miocene age, suggesting that subduction and volcanism at the eastern end of the arc commenced later than in Java and Sumatra (Foden and Varne 1981). The oldest rocks in the southern part of Lombok include Early Miocene andesitic and dacitic flows and breccias associated with volcanic sediments; they are overlain by late Miocene limestone. Unlike Quaternary calc-alkali products of Rinjani on Lombok, Quaternary volcanic rocks from Sumbawa consist of potassic calc-alkali, alkali-potassic and ultra-potassic rock types (Sangenges, Soromundi and Sangeang Api). The leucitic lavas of Sumbawa are very similar to those found in continental rifts; these potassic rock cannot be related to their depth above the Benioff zone; their generation has been attributed to extrusion along a transcurrent fracture (Foden and Varne 1981). According to Foden and Varne (1981), the offset in the linear volcanic zone between Sangeang Api and Flores marks the trace of a major transcurrent fault between Sumbawa and Flores; this discontinuity may be the result of displacement along a major strike–slip fault which extends into south Sulawesi (Katili 1970; Hamilton 1979). In Sumbawa Tertiary volcanic rocks exposed in the south-west consist of andesitic lava flows and volcanic sediments with minor limestones. Associated with these rocks are intrusive rocks including diorite, tonalite and andesite porphyry. Landsat imagery of south-west Sumbawa shows prominent WNW (parallel to arc trend) and NE lineaments (normal to arc trend) associated with Tertiary subduction (Meldrum *et al.* 1994).

Western Sulawesi–east Mindanao magmatic belt

Recent studies on the Tertiary and Quaternary magmatic evolution of western Sulawesi by many authors have provided new information on its tectonic evolution. The tectonic implications, as deduced from chemical signatures of the Tertiary magmatic rock suites, point to a number of separate regions in which the volcanic rocks have distinct tectonic settings. The new tectonic scenario departs considerably from the interpretation of Sulawesi by previous workers as a typical volcanic island arc.

The oldest magmatic activity in the western Sulawesi magmatic belt (Fig. 2) led to the formation of back-arc basalts and gabbros of possibly Late Jurassic age (Priadi *et al.* 1994). They are believed to represent fragments of back-arc basin basaltic crust which was formed during extension and break-up of blocks of Gondwana origin in Mesozoic time (Polve *et al.* 1997; Priadi *et al.* 1994). The thrusting of these rocks together with the eastern Sulawesi ophiolites onto the western Sulawesi Arc took place in the Early Miocene (Yuwono *et al.* 1988). Evidence of early Tertiary subduction-related magmatism, prior to the Eocene, is found in south Sulawesi (Ujungpandang area), represented by 60 Ma old calc-alkali volcanics (Yuwono *et al.* 1988); similar Paleocene subduction-related calc-alkali magmatism has also been documented elsewhere around the southern margin of Sundaland (central Java, Suparka and Soeria-Atmadja 1991; south-east Kalimantan, Pryomarsono 1985 and Sumba, Abdullah 1994).

Subduction-related magmatism continued between 40 and 15 Ma generating typical island-arc tholeiitic and calc-alkali volcanics in the northern arm; however, such magmatism is very scarce in south and central Sulawesi. The limited occurrences of these volcanics have been explained by Polve *et al.* (1997) and Priadi *et al.* (1994) as the result of intensive tectonic erosion which led to the consumption of a large part of the magmatic arc and westward retreat of the belt in central and south Sulawesi.

The island arc segment includes most of the east–west trending northern arm from Toli-Toli to Sangihe and eastern Mindanao and is characterized by basaltic andesites to rhyolites of tholeiitic and calc-alkaline affinities. This magmatic belt continues westwards, following the neck of Sulawesi to Palu, changing in its geodynamic setting to that of an arc constructed on a continental margin composed of pelitic schists and post-collision potassic calc-alkali granitoids. Tertiary back-arc volcanics, extending over most of western Sulawesi, except the south arm, are related to a major Eocene magmatic event which ranges in age from 50 to 40 Ma (Priadi *et al.* 1994; Polve *et al.* 1997).

It has been confirmed from K–Ar ages of volcanic rocks from central Sulawesi that a time gap in magmatism between 23 and 15 Ma corresponds to the period of collision of Sulawesi with the Banggai–Sula microcontinent in the Middle–Late Miocene (Hamilton 1979; Rangin *et al.* 1990; Smith and Silver 1991; Polve *et al.* 1997). It seems that collision has resulted in subduction reversal at the North Sulawesi Trench, clockwise rotation of the northern arm and changes in the nature of magmatism.

In the northern arm subduction-related magmatism (arc tholeiite and calc-alkali rocks) was continuous and the K–Ar ages of the volcanics show eastward migration with time. According to Surmont *et al.* (1994) this phenomenon was related to the 20° clockwise rotation of the northern arm at 4 Ma. In central Sulawesi (Palu and Toli-Toli) magmatic activity between 9.0 and 0.6 Ma was characterized by potassic calc-alkali acid magmatism with evidence of crustal contamination, presumably due to thickening of the continental crust as the result of collision and melting of high-grade metamorphic rocks (Priadi *et al.* 1994; Polve *et al.* 1997), which gave rise to the potassic calc-alkali magmatism. The rocks include the Barupu Tuff of Toraja, granitoid intrusions of Palu-Koro and Dondo Bay (north arm) and the felsic volcanics of Pani (Kavalieris *et al.* 1992). In south Sulawesi Neogene magmatism took place in a within-plate extensional regime, resulting into the formation of ultrapotassic rocks (shoshonites–ultrapotassic basanites) the time span of which is relatively short (13–0.7 Ma) in south Sulawesi (Ujungpandang area) and even shorter in the Toraja area (13–11 Ma; Priadi 1993). These rocks are also attributed to the effects of continental collision (Bergman *et al.* 1996).

From the distribution and characteristics of hydrothermal mineralization, which is closely related to Neogene magmatism, it is very likely that the western Sulawesi magmatic–porphyry belt continues northwards to Mindanao and southwards to Sumbawa (Soeria-Atmadja *et al.* 1995), as represented on tectonic reconstructions of the early Tertiary Sunda Arc (Rangin *et al.* 1990). According to Kavalieris *et al.* (1992), the porphyry Cu–Au mineralization and the tectonic environment in the north arm of Sulawesi is comparable with those of Luzon in the Philippine Arc.

Kalimantan: the eastern Sunda plate margin

Kalimantan (Borneo) is part of the Sundaland Plate which is separated from the magmatic belt of western Sulawesi arc by the Makassar Strait. The main tectonostratigraphic elements consist of: (1) Mesozoic–Paleozoic sediments and volcanics, with granitoid intrusions of Cretaceous age; (2) subduction complexes, consisting of strongly folded and faulted shelf sediments, turbidites and melange of Cretaceous–Eocene age; (3) a smaller subduction complex of similar age in the south-east corner of the island; and (4) gently folded post-orogenic Cenozoic continental and shallow marine sediments with volcanic intercalations (Van Leeuwen *et al.* 1990; Simmons and Browne 1990). In Sabah and Sarawak, rocks of Cretaceous to Early Tertiary age show evidence of Eocene deformation during southward subduction of the China Sea Plate beneath Kalimantan, succeeded by calc-alkali magmatism (Simmons and Browne 1990), while in the south-eastern part of the island Eocene time was marked by basin formation (Van de Weerd *et al.* 1987) and continental rifting (Situmorang 1982).

The origin of Makassar Strait has been the subject of much discussion. Differing views on the opening mechanism of Makassar Strait include, among others: a Tertiary intracontinental rift basin, followed by oceanic spreading or a foreland basin, bounded on both sides by converging Neogene thrust belts (Bergman *et al.* 1996). According to Sopaheluwakan (1995) the evolution of the Makassar Strait dates back to late Paleozoic–Early Mesozoic and was related to a long-standing westward subduction of Tethyan lithosphere, which, during the Cretaceous, resulted in the uprise of buoyant metasomatized mantle, causing continental stretching and opening of the strait in the Early Tertiary. According to Nishimura *et al.* (1981) opening started in the northern part of the strait from 3 Ma and has continued to the present. However, subsidence curve data obtained from this region indicates that rifting commenced in Early–Middle Eocene time (Situmorang 1982).

Results of work by previous investigators (Lefevre *et al.* 1982; Williams and Heryanto 1986; Pieters and Sanyoto 1987; Williams and Harahap 1987) indicate widespread Paleogene calc-alkali magmatism in Kalimantan during Late Oligocene–Early Miocene times. Age dating of a number of intrusive rocks (basaltic and andesitic compositions) gave K–Ar ages of between 24.0 and 14.4 Ma (Van de Weerd *et al.* 1987). Williams and Harahap (1987) recorded K–Ar age ranges of 30.4–23.0 Ma for the volcanic rocks in the Melawi Basin, while younger volcanics in the Ketunggau Basin range in age between 17.9 and 16.4 Ma. They conclude that magmatic activity commenced in the southern region in Late Oligocene to Early Miocene and extended progressively northwards in the Late Miocene. Epithermal gold mineralization is thought to be related to the Early Miocene magmatism, giving rise to NNW–SSE trending mineralized structures in the regions of Kelian and Mount Muro (Van Leeuwen *et al.* 1990; Simmons and Browne 1990). Epithermal gold occurrences plot along a narrow north-east–south-west trending zone between the Paleogene and Neogene sedimentary belts of central Kalimantan. Similar Neogene magmatic events are described from Sarawak by Kirk (1968) who reported K–Ar ages of 16 ± 4 and 19 ± 3 Ma from the volcanics. Williams and Harahap (1987) suggest deep crustal re-melting and intrusion in a passive post-subduction environment for the origin of these volcanics. The youngest phase of magmatism occurred in the Plio-Pleistocene, represented by the widespread occurrence of plateau basalts in central Kalimantan.

Detachment and southward displacement of Sumba

Sumba is located between the Sunda subduction system in the west and the Australia–Banda Arc collision system in the east (Fig. 1). The island anomalously occupies a position in the fore-arc, south of the present Sunda–Banda volcanic arc, between the deep sea fore-arc basins of Lombok and Savu. Its position is unique in that it is a foreign continental fragment which does not fit into the arc system. The island is characterized by very weak tectonic deformation, the presence of Late Cretaceous–Oligocene calc-alkali volcanics and the lack of Neogene magmatism (Abdullah 1994).

Abdullah, in his detailed work in Sumba, recognizes three periods of magmatic activity: Late Cretaceous, end Cretaceous–Paleocene and Paleogene. The results of K–Ar dating on a number of volcanic rocks are in good accordance with their stratigraphic position and faunal assemblages obtained from associated sediments.

Late Cretaceous calc-alkali magmatic activity (85–78 Ma) is represented by the granodiorite pluton of Masu in the south-east corner of Sumba. This magmatic activity was accompanied by the deposition of marine turbidities during Late Cretaceous–Paleocene time. According to Abdullah (1994) the products of magmatism are outcrops of basalt on the south coast (71–65 Ma) and the Tanadaro diorite intrusion (65–56 Ma). Eocene–Early Oligocene time (42–31 Ma) was marked by deposition of volcanic and neritic sediments, during which calc-alkali magmatic activity accompanied sedimentation in west Sumba, suggesting a westward shift of magmatism with time. The Neogene was a period of widespread transgression, with the deposition of volcanic turbidites similar to the neighbouring Lombok and Savu forearc basins. By that time Sumba had reached its position within the forearc basin of the Sunda–Banda arc system.

The present structure of Sumba is the result of weak tectonic deformation. Evidence of intensive folding or collision are lacking in rocks of Late Cretaceous to Neogene age. Except for a minor compressive episode in the Late Paleogene, Sumba has been constantly subjected to an extensional tectonic regime (Abdullah 1994). From the results of previous oceanographic survey and paleomagnetic surveys (Hamilton 1979; Wensink 1994), Sumba has been interpreted as a separated fragment of the Eurasian Plate underthrust by the Indo-Australia Plate. Abdullah (1994) noted similarities in the Paleogene sedimentary facies and magmatism on Sumba and Sulawesi and concluded that the island was originally part of a Paleogene volcanic arc which was situated near western Sulawesi from Late Cretaceous to Paleogene time. The southward movement of Sumba took place during pre-Neogene time and the island has occupied the position in the forearc basin since the Neogene (Fig. 3). Sopaheluwakan (1995) suggested that the uprise of buoyant metasomatized mantle in connection with the initial opening of Makassar Strait in the Early Tertiary was responsible for the separation of Sumba from the mainland of Sulawesi, as well as the islands of Doang and Salayar which now lie to the south of Sulawesi (Fig. 2). Translation of these continental fragments which took place along the N–S trending proto-Paternoster–Walanae–Salayar fault between the Late Cretaceous and the Early Miocene accompanied crustal rifting and the left lateral fault system facilitated the southward migration of Sumba and its anticlockwise rotation.

Concluding remarks

The onset of magmatism along the Sunda–Banda Arc took place at different times as indicated by the ages based on paleontological studies and radiometric dating of the volcanic units. According to Cameron *et al.* (1980) Sumatra was established as an island arc by Late Permian time. Subduction-related volcanics rocks of Mesozoic age are more widespread in distribution. According to Sutanto (personal communication 1995), the magmatism was predominantly of calc-alkali and potassic calc-alkali affinities, with minor occurrences of arc-tholeiites. The onset of magmatism in Java and the other islands to the east occurred in the Early Tertiary. The Tertiary and Quaternary mark the principal magmatic episodes along the arc, of which the products (calc-alkali and potassic calc-alkali) make up a large part of the rock stratigraphy. Sumatra and the western part of Java exhibit the features of an Andean continental margin, the volcanic products being underlain by continental crust. Quaternary volcanism in Sumatra is notably different from the other regions within the magmatic arc in the voluminous production of acidic tuffs and ignimbrites. Rock chemistry implies a crustal contribution to the composition of these rocks, indicated by very high Sr^{87}/Sr^{86} ratios. Scattered occurrences of Palaeocene calc-alkali volcanic rocks in south Sulawesi (K–Ar age 60 Ma; Yuwono *et al.* 1988), south-east Kalimantan (K–Ar age 59.1 Ma; Pryomarsono 1985) and central Java (Suparka and Soeria-Atmadja 1991) suggest that subduction-related magmatism occurred all along the Sundaland margin at that time.

Although western Sulawesi shares some features of island arcs, different magmatic provinces point to volcanism in different tectonic settings. The more typical island arc system, underlain by oceanic crust, includes the northern arm from Toli-Toli eastwards to Manado and the Sangihe arc. The Tertiary arc-tholeiites (40–15 Ma) and calc-alkali to potassic calc-alkali rocks (10 Ma to present) constitute volcanic arc associations, related to northward-dipping subduction. While subduction took place, collision of Sula between 23–15 Ma gave rise to important Neogene acidic magmatism of potassic calc-alkali affinity, which includes the granitoids along the neck of Sulawesi and in central Sulawesi and the high-K magmatism in south Sulawesi (Toraja to Ujungpandang). The former has been ascribed to crustal thickening and subsequent melting, whereas the latter was emplaced in a within-plate extensional regime.

The Makassar Strait, located along the eastern margin of Sundaland, is important in that it is one of the corridors connecting the western Pacific through the Sulawesi and Java seas to the Indian Ocean. Studies on clastic and carbonate sequences in south Sulawesi and south-east Kalimantan indicate that the Makassar Strait was quite deep during Neogene time, after the initial opening in the Early Tertiary (Hantoro and Suharyono 1995). Similarities in the Paleogene volcanics and the stratigraphic sequences of south Sulawesi and west Sumba suggest that these areas were linked by a north–south corridor prior to Neogene time. The driving force responsible for the opening of Makassar Strait was also responsible for the southward displacement of Sumba. The plate tectonic reconstructions of the region at different time intervals, shown in Fig. 3, are based on geochronologic evolution of magmatism and changes in the directions and rate of plate movements.

At 62 Ma, the Indo-Australian Plate moved northwards at a rate of 15–20 cm/year and was subducted beneath the Eurasian Plate (Sunda microcontinent), resulting in the formation of the calc-alkaline magmatic arc of Sumatra, the western part of Java, Sumba and west Sulawesi [Fig. 3(A)]. Between 55 and 50 Ma (Early Eocene), the Eurasian plate was subject to an extensional regime. Rifting, which commenced in the Paleocene evolved into spreading, caused the separation of Kalimantan and western Sulawesi [Fig. 3(B)]. Opening continued until the late Eocene (45–40 Ma), at which time the rate of Indo-Australian plate motion decreased to 11 cm/year, becoming 6 cm/year in the Oligocene (32–30 Ma). The decrease in the rate of plate convergence promoted roll-back phenomena (Dewey 1980) in the overriding plate (Sundaland), which was responsible for the southward shift of the magmatic arc [Fig. 3(C and D)]. Anticlockwise rotation of Kalimantan [Fig. 3(E)] has generated compression in the South China Sea, leading to southward

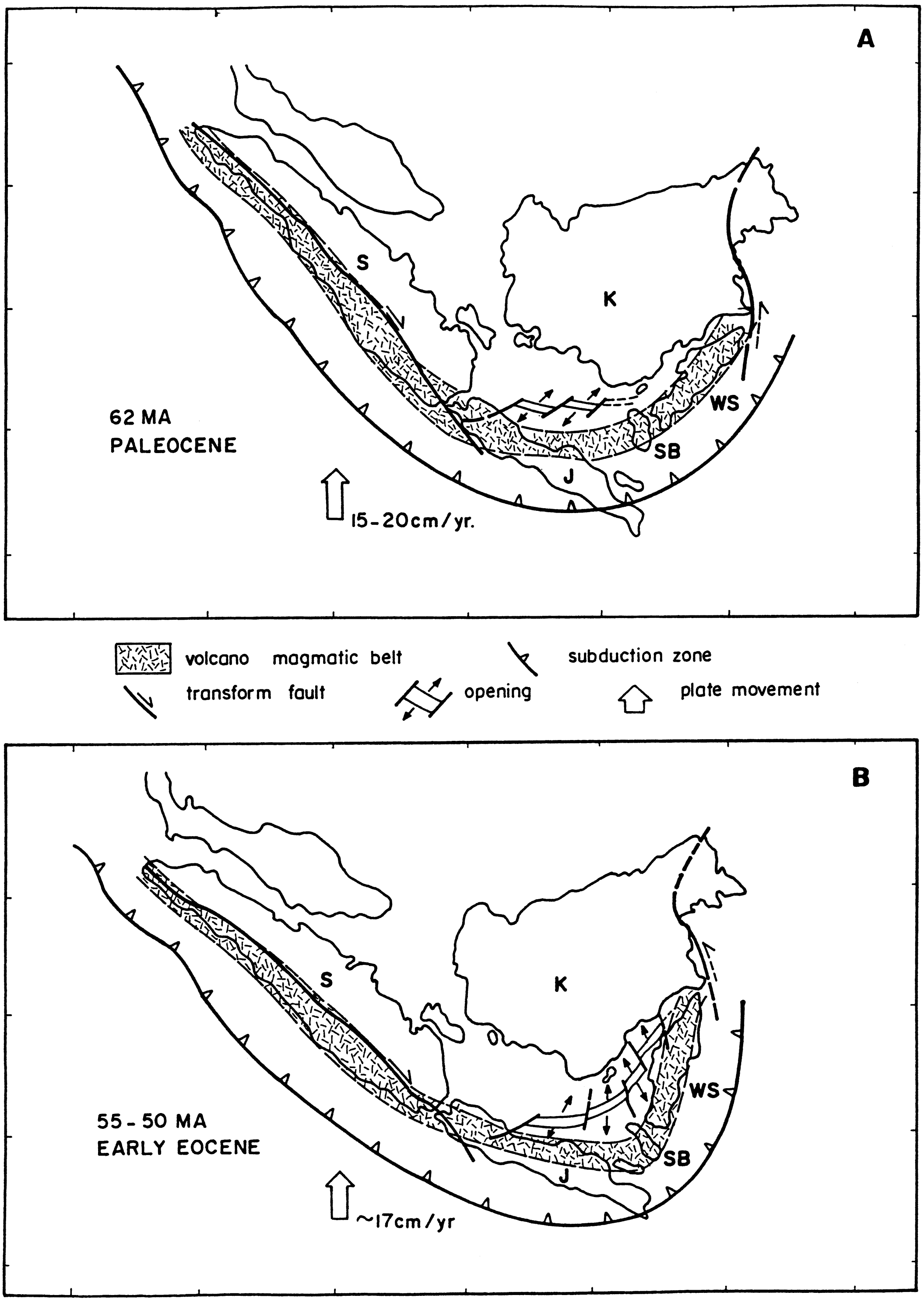
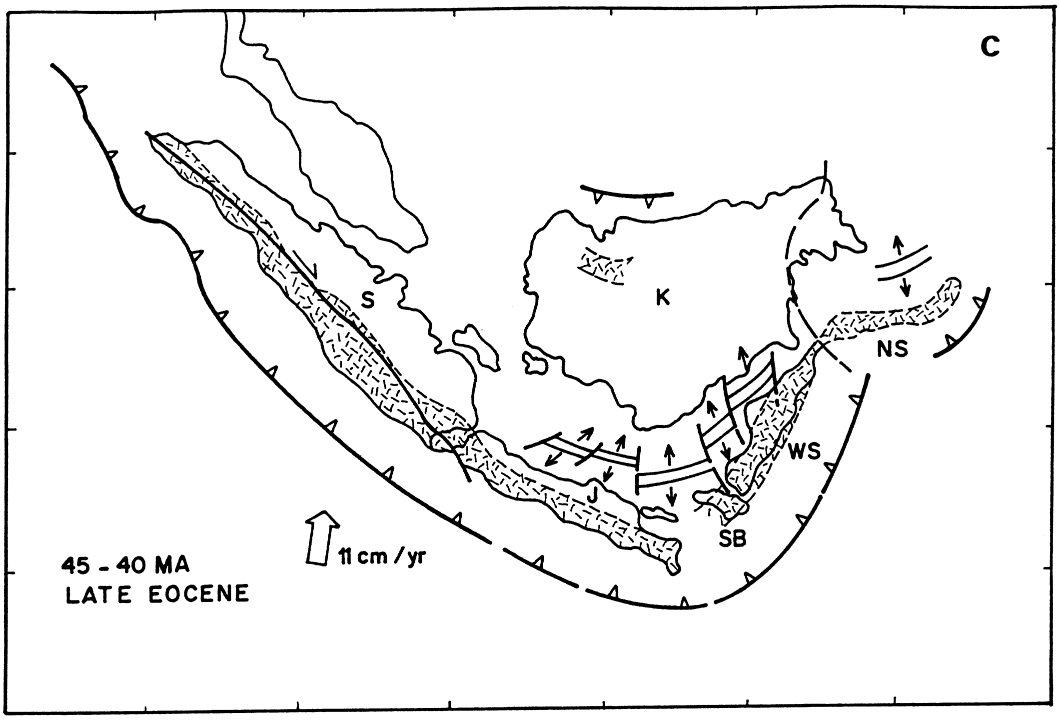


Fig. 3(A, B).


C
S
K
NS
WS
J
SB
11 cm / yr
45 - 40 MA
LATE EOCENE

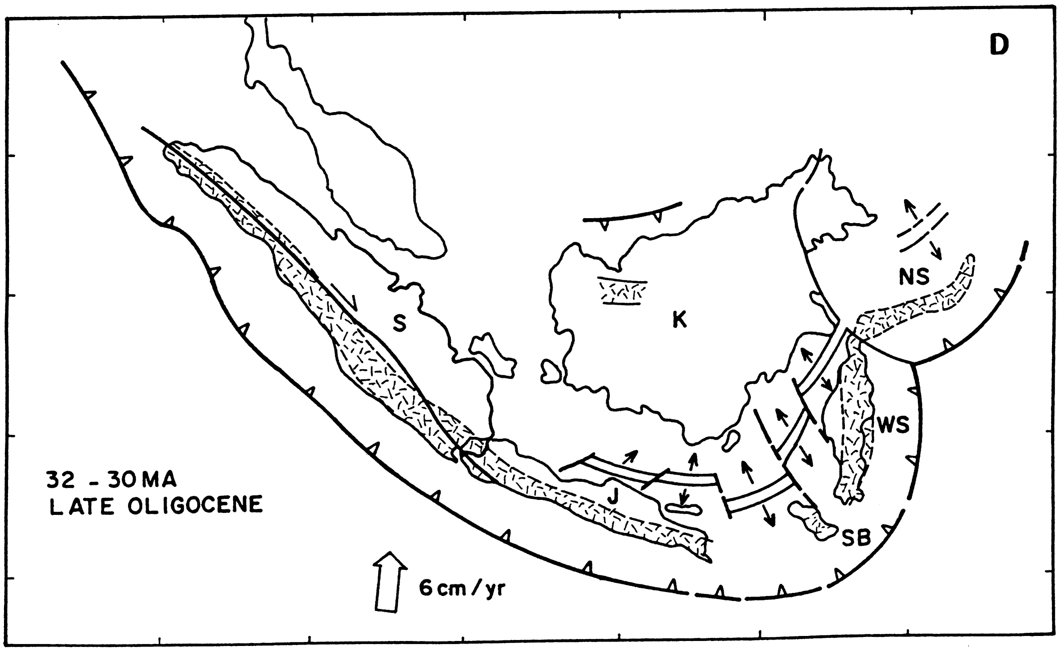
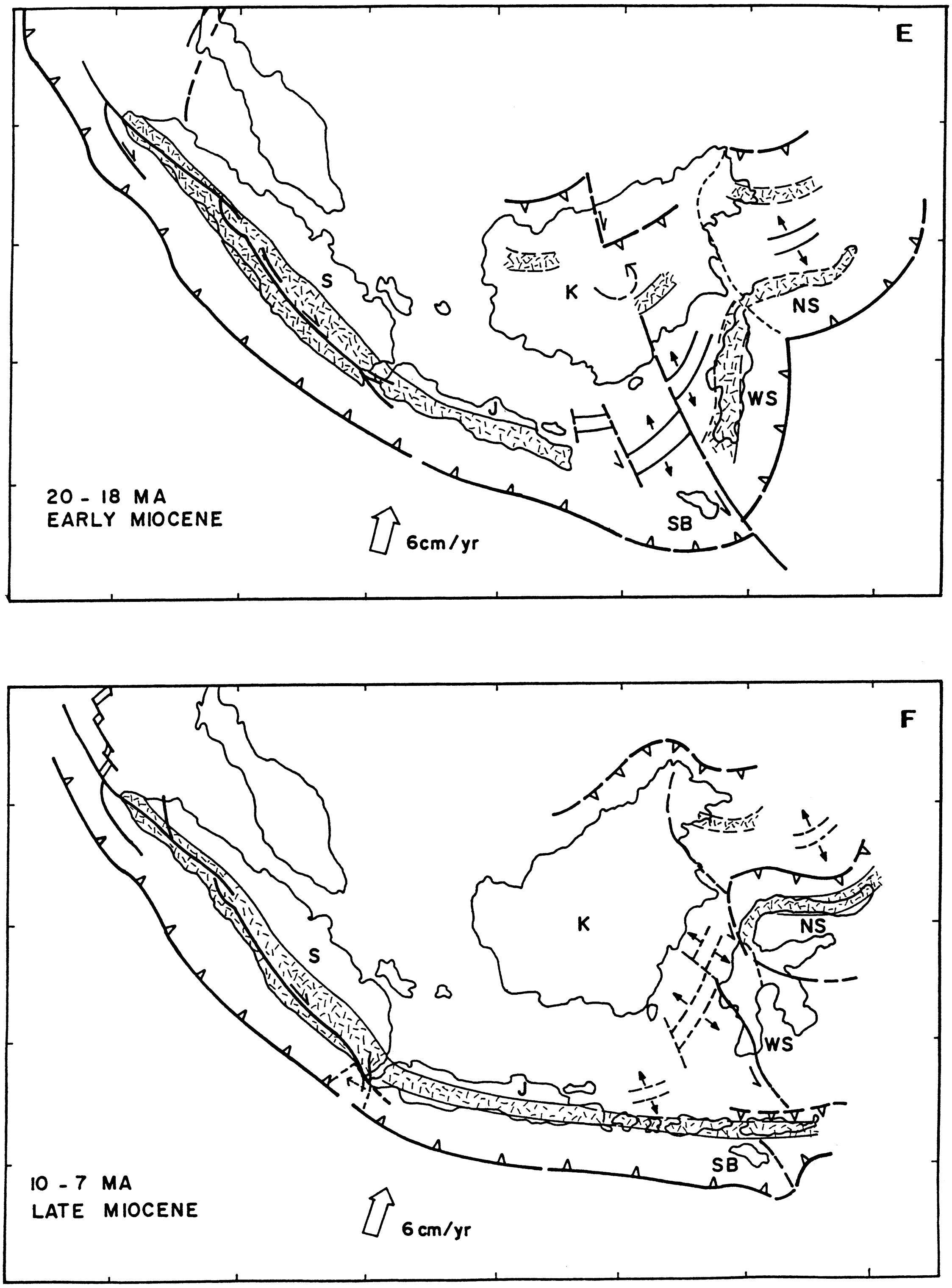

D
S
K
NS
WS
J
SB
6 cm / yr
32 - 30 MA
LATE OLIGOCENE

Fig. 3(C, D).


E
S
K
NS
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J
SB
20 - 18 MA
EARLY MIOCENE
6cm/yr
F
S
K
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WS
J
SB
10 - 7 MA
LATE MIOCENE
6 cm/yr

Fig. 3(E, F).

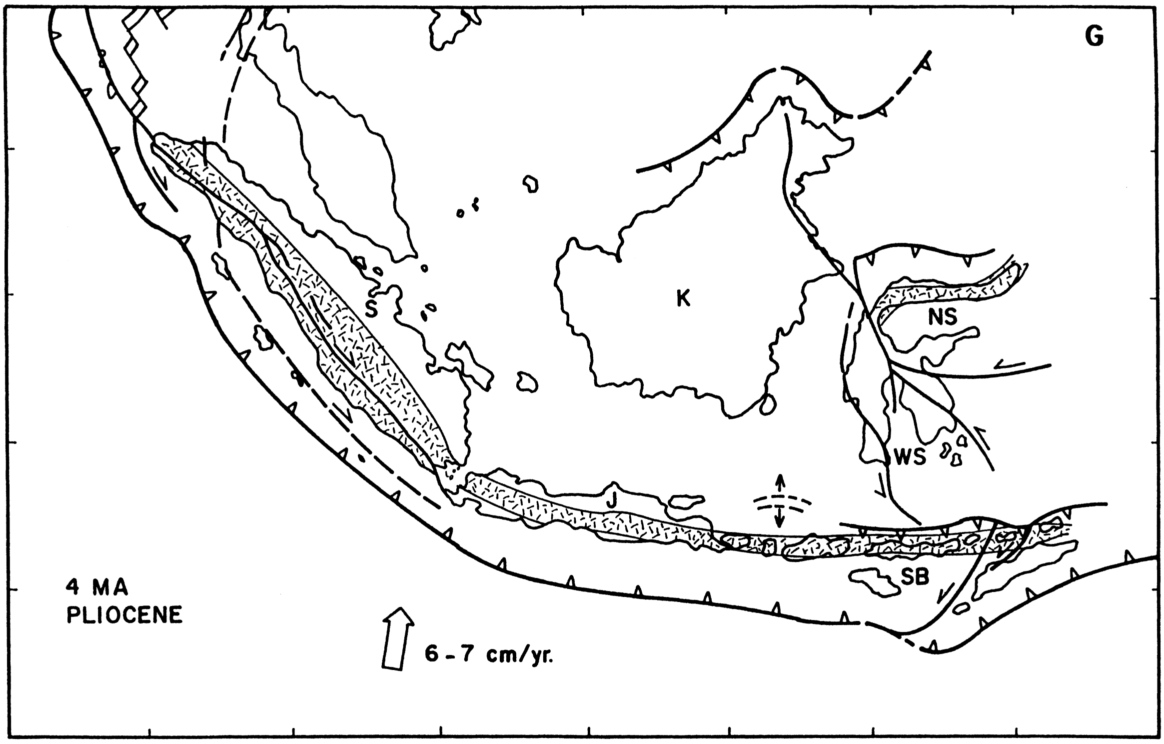

Fig. 3. Reconstructions of the paleogeography of Western Indonesia, based on the dating of magmatic rocks. A, 62 Ma (Paleocene); B, 55–50 Ma (Early Eocene); C, 45–40 Ma (Late Eocene); D, 32–30 Ma (Late Oligocene); E, 20–18 Ma (Early Miocene); F, 10–17 Ma (Late Miocene); G, 4 Ma (Pliocene); S = Sumatra; J = Java; K = Kalimantan; WS (western Sulawesi): NS = northern Sulawesi; SB = Sumba.

subduction and the development of the related magmatic arc of western Kalimantan [Fig. 3(C and D)], while east of Sulawesi the Pacific plate subducted southwards, with the consequent development of a Paleogene magmatic arc in the north arm of Sulawesi [Figs 2 and 3(C and D)].

In the Miocene, the rate of Indo-Australian Plate motion was constantly at 6 cm/year, while the intensity of spreading became stronger in the back-arc basin, displacing Sumba south-eastwards to become trapped between the magmatic arc and the Sunda Trench [Fig. 3(E)]. In Java the magmatic arc shifted northwards in the Late Miocene to form the Neogene Sunda–Banda Arc (Bali, Lombok, Sumbawa, Flores, Alor, Wetar). At that time Sumba was already trapped in the outer-arc basin [Fig. 3(F)] and was submerged, with the deposition of volcaniclastic turbidites and carbonates. At the end of Pliocene time the rate of Indo-Australian Plate motion increased to 6–7 cm/year, during which compression was active in the Eurasian Plate (Indonesian archipelago). During the last few million years, collision has taken place in eastern Indonesia between the island arc, including the continental fragment of Sumba and the Australian continental crust, resulting in the uplift of Sumba, Savu, Roti and Timor. Continued uplift is demonstrated by elevated Quaternary reef limestone terraces on these islands.

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