

Tectonic Evolution of Sundaland: A Phanerozoic Synthesis

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“You behold a range of exhausted volcanoes.”
—Benjamin Disraeli, 3 April, 1872

Abstract: The palaeo-tectonic evolution of the Sundaland region is interpreted in terms of the plate tectonic model, with special reference to igneous events.

In Lower Palaeozoic time, the Malay Peninsula lay along the subducting contact between an easterly oceanic and a westerly Precambrian continental plate, with the trench occupying the eastern foothills of the Main Range. A volcanic arc extended along the western margin of the Main Range. Miogeoclinal shelf sedimentation occupied the back-arc region between the volcanic arc and the Precambrian landmass, while eugeosynclinal sedimentation occupied the trench region east of the Main Range. The Malayan plate became detached from its Precambrian foreland in the mid Palaeozoic and drifted eastwards ahead of the ocean spreading of a new marginal basin.

From Late Carboniferous onwards, Sundaland played the role of a small continental plate, with active eastwards oceanic subduction underneath it from a trench located along the axis of Sumatra, and westwards subduction from a trench located in the South China Sea. Volcanic and plutonic arcs of Late Carboniferous, Permian and Triassic in the Malay Peninsula, Sumatra and West Borneo can be related to these opposite-facing arc-trench systems. Igneous arcs in the Malay Peninsula are commonly broad, often with no clear time separation—attributed to the median position of the Peninsula between the two subduction systems, and the shallow dips of the Benioff Zones.

The trenches moved progressively away from the Malay Peninsula as Sundaland grew by sedimentary accretion on its eastern and western sides. By Late Cretaceous, the western Sumatran and the eastern South China Sea arc-trench systems formed one convoluted arc wrapped around the southern end of Sundaland. The arc-trench system has straightened in the Late Cenozoic, and now occupies the southern coast of Java and western coast of Sumatra.

Shallow dips of the Benioff Zones and interaction between their eastern and western subduction components caused uplift of the East Coast and Main Range zones of the Malay Peninsula, resulting in a restriction of the Mesozoic sedimentary trough to the central axis of the Peninsula, and eventually its transformation from shallow marine to a continental environment. The deeper parts of this trough were metamorphosed in amphibolite facies and later uplifted as gneiss domes.

The sequence of granite emplacement in the Peninsula evolved progressively from dioritic in the Late Carboniferous to highly differentiated granite in the Late Cretaceous, in keeping with the progressive transformation of the Peninsula from mainly oceanic in the Palaeozoic to predominantly sialic and continental in the Late Mesozoic.

Uplift and cratonization of the Peninsula and the surrounding Sundaland region caused important deep-seated wrench and block faulting in the Late Mesozoic and Cenozoic, which has controlled the patterns of sedimentation, the Late Cretaceous high-level granite emplacement, and the highly alkaline Cenozoic basalt flows.

INTRODUCTION

The distribution of igneous rocks in an orogenic system is not random. They usually occur in belts parallel to the regional tectonic trends. In the younger orogenic systems of the Circum-Pacific, igneous belts of volcanic and plutonic rocks related to island arc systems, occur with definite geometric relations to the trenches,

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which reflect subduction patterns of oceanic material beneath the continental crust. Kuno (1966) has shown that the geochemistry of such igneous rocks changes systematically with their positions in relation to their proximity to the trench.

Progressing backwards in time from the present through the Phanerozoic, it becomes increasingly difficult to unravel the relationships between the igneous rocks and their sedimentary envelopes, and to relate these to any scheme of plate tectonics based on the distribution of the present arc-trench systems. This article is an attempt to reconstruct such relationships for the past history of the Malay Peninsula and the immediate region around the South China Sea. The plate tectonic model of Dickinson (1971) is closely followed. The reconstruction is severely handicapped by a lack of published information on the geology underlying the South China Sea. Oil exploration companies have unfortunately been generally unwilling to release the data from their drilling programmes; and this has hampered a regional synthesis.

The deductions of the positions of the structural elements throughout the Phanerozoic of the region will rely therefore predominantly upon the known positions of the igneous arcs; for these are rather well exposed on the landmass. The positions of the trenches are less well defined, and often are not exposed because of the cover of younger sedimentary formations. Their positions will be deduced indirectly from the polarity of the igneous arcs when there is an absence of outcrops of an ophiolitic suite to indicate the actual trench position.

LOWER PALAEOZOIC

The earliest record of the Malayan Geosyncline is of Upper Cambrian age, beginning with the Machinchang Formation of the Langkawi islands (Jones, 1973). A Lower Palaeozoic rock succession is well established both west of the Main Range and along its eastern foothills. The age of these rocks extends mainly over the Ordovician and Silurian to Lower Devonian. The outline picture of the palaeogeography of the Malay Peninsula during the Lower Palaeozoic is reasonably clear and allows a surprisingly good fit to any present day-based tectonic model (Fig. 1).

The trench can be accurately located along the eastern foothills of the present Main Range, indicated by a schist belt of Lower Palaeozoic age with numerous ophiolitic bodies of serpentinite and metabasite (Jones, 1973). Sedimentation in Langkawi, Perlis, and Kedah, beginning with the Upper Cambrian Machinchang Formation, clearly indicates a stable shelf, and rocks in this region have remained in the epizone since their time of deposition (Hutchison, 1970). The cross-bedding of the Machinchang sandstones indicates derivation from a landmass not far to the west and north (Jones, 1973).

Hence northwest Malaya may be designated a miogeocline (Dickinson, 1971) formed upon continental crust. The trench therefore can be deduced to indicate westwards subduction of an easterly oceanic plate under a westerly continental plate as shown in the diagrammatic cross-section of figure 1. The present day curvature of the outcrop of the trench may now be the reverse of what it was originally, for a westwards dip of a planar surface requires an eastwards outcrop convexity. In which case the present westwards convexity can be attributed to the numerous east-west strike-slip faults causing left-lateral displacement of the trench outcrop (see Gobbett, 1972; and Tjia *et al.*, 1973). However, as indicated by the complicated arcuate nature of many of the present day trenches and arcs, the Benioff Zone can rarely if ever be a

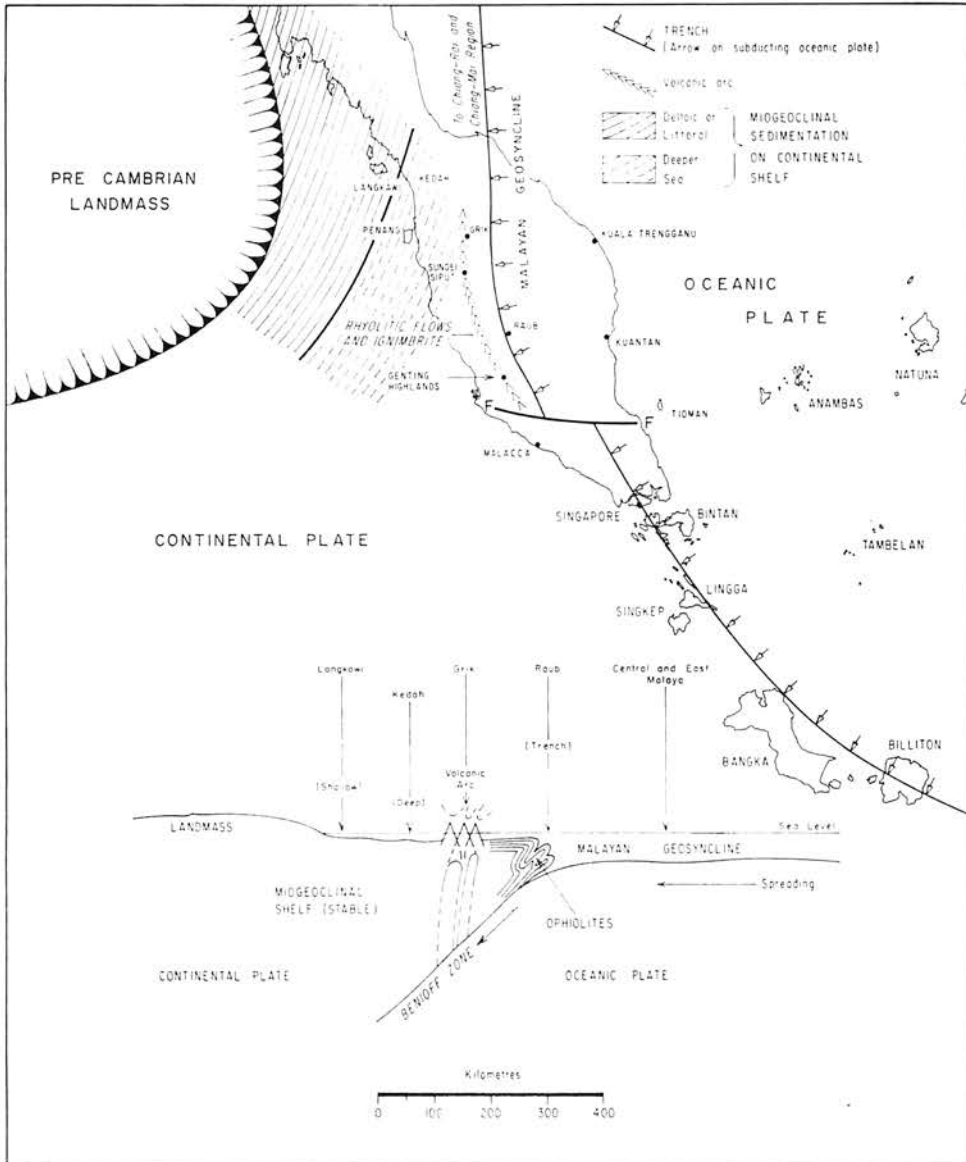


Fig. 1. Palaeo-tectonic scheme for the Lower Palaeozoic of the Malay Peninsular region. An easterly oceanic plate is subducting beneath a westerly continental plate. The diagrammatic cross section shows the relationship of the various tectonic features in terms of subduction along the inferred Benioff Zone.

simple planar surface, and commonly must possess curvature and even corrugations. Hence the convexity of the trench outcrop need not be a criterion for the direction of dip of the subduction.

The Lower Palaeozoic trench is assumed to have extended southwards into the Indonesian area, and it is tentatively suggested that the eucrite of south Johore and the gabbro of Singapore (Hutchison, 1973B) can be considered as part of the ophiolitic suite. It is possible also that the gabbroic rocks of Billiton (Aleva, 1960) can also belong to this suite. Accordingly the trench is shown in figure 1 extending southwards into the Indonesian region.

The northwards extension of the Lower Palaeozoic trench may well be represented by an ophiolitic suite in north Thailand, consisting of gabbro, pyroxenite, serpentinite, and metabasite, to the north of Chiang Rai and northeast of Uttaradit (Klompé, 1962). Baum *et al.* (1970) show this important ophiolitic belt extending north-south between Chiang Rai and Chiang Mai, and they consider it to be of Carboniferous age in agreement with Klompé (1961), who showed it on his maps as of Variscan (Late Devonian to Permian) age. It is reasonable to assume that this Thai ophiolite belt was initiated in Lower Palaeozoic time, and represents the northwards extension of the Malayan trench.

Figure 1 illustrates the deduced palaeogeography of the Lower Palaeozoic; and the volcanic arc, as can be predicted from present day tectonic models (Dickinson, 1971), is indeed present and in the correct relative position—Ordovician rhyolites and rhyolite tuffs occur in the Grik area, in the Sungei Siput area, in the metasedimentary roof pendants of the Fraser's Hill, Genting Sempah, and Genting Bidai areas of Selangor and Pahang, and in the Dinding Schist of the Kuala Lumpur area (Hutchison, 1973A). A pyroxene micro-granodiorite, occurring immediately east of Genting Sempah in west Pahang, has yielded a Silurian age by the Rb:Sr method (Bignell *et al.*, 1972). This rock may also be considered as part of the Lower Palaeozoic igneous arc of figure 1. The igneous arc in present day distance is only about 100 km behind the trench outcrop. However the actual Lower Palaeozoic distance can be presumed greater, for the Lower Palaeozoic rocks of the eastern foothills and of the Main Range roof pendants are isoclinally folded with steep dips.

Volcanic Igneous Rocks

Analyses of known Lower Palaeozoic volcanic rocks have been extracted from Alexander *et al.* (1964) and plotted on an alkali % versus SiO₂ % diagram (Fig. 2). The two lines on this diagram are after Kuno (1966) and divide the field into an upper alkali olivine basalt series, a middle high alumina basalt series, and a lower tholeiitic basalt series. The usage of the term basalt in this context means all volcanic rocks, whether basaltic, andesitic, or rhyolitic, which are presumed to owe their ultimate origin to basaltic magma evolved in the Benioff Zone. Upward migration of the magma into the arc causes chemical modification through differentiation or interaction with crustal rocks; but the type of magma series depends upon the depth of derivation in the Benioff Zone. Kuno (1966) has shown convincingly that whether or not the rock remains as basalt or evolves to rhyolite, the alkali to silica ratio still reflects the original depth of evolution in the Benioff Zone. The depth of genesis correlates with the distance behind the trench at which the evolved magma eventually comes to rest in the upper crustal levels. Tholeiitic basalts accordingly will outcrop closer to the trench than alkaline basalts. Figure 2 shows that the Malayan Lower Palaeozoic rhyolites are certainly not alkaline, and accordingly originated at moderate depths. Their exclusively acidic character reflects their rise through a strongly sialic continental crust.

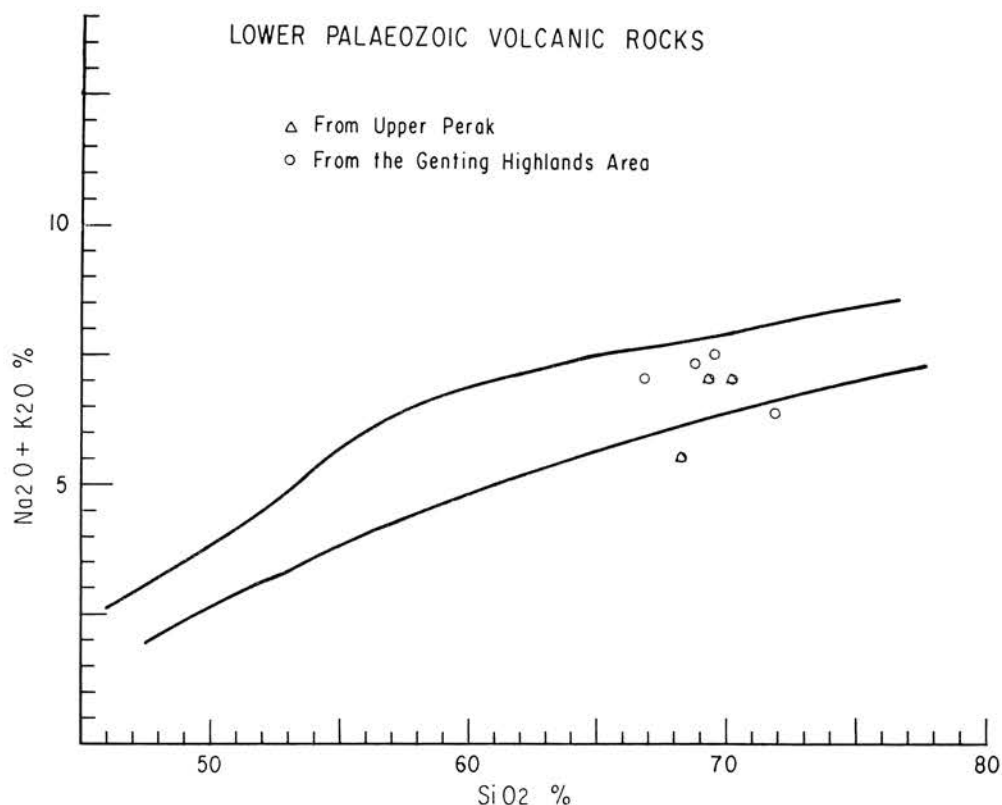


Fig. 2. Plot of total alkalis against silica % for known and presumed Lower Palaeozoic volcanic rocks. The lines are after Kuno (1966) and analyses are from Alexander *et al.*, (1964).

Conditions of Metamorphism

The metamorphic regimes in the arc-trench system should be considered. High heat flow in the active volcanic arc would have given rise to a generally high geothermal gradient type of metamorphism, and the Lower Palaeozoic rocks of the arc region, from Grik to Genting Bidai, have been recrystallized in the high geothermal gradient greenschist facies series (Hutchison, 1973C).

A present day trench area is a region of subduction and hence of low heat flow. Folding and subsequent upthrusting in a trench region would be expected to present outcrops of low geothermal gradient metamorphic rocks characterised by glaucophanite type, accompanied by ophiolites and metabasites in the form of concordant or subcordant sheets. The ophiolites are present along the eastern foothills, and the rocks are indeed isoclinally folded and metamorphosed to give the Schist Series (Hutchison, 1973C) but there remains no sign of the glaucophanite metamorphism which would characterise a trench. However this is not a serious absence, for the presently exposed subduction zone has undoubtedly been successively subjected to different thermal regimes, of higher geothermal gradient, as the arc-trench system moved progressively eastwards and the younger Sumatran subduction system came

into effect. Therefore, even if glaucophanite metamorphism was originally present in the eastern foothills, it is doubtful if it could have survived the Palaeozoic to Mesozoic sequence of higher heat-flow tectonic regimes which subsequently occupied this region.

A general look at the occurrence of glaucophanite type metamorphism in the Earth's crust as a whole shows that it becomes progressively rarer backwards in time through the Phanerozoic, and most of the existing glaucophanite terranes are those that have not been re-deformed or re-metamorphosed since their original glaucophanite type crystallization. It would therefore be unreasonable to expect a Lower Palaeozoic glaucophanite type metamorphism to persist to the present day in the Schist Series of the eastern foothills.

LATE SILURIAN TO EARLY CARBONIFEROUS

From early Devonian to early Carboniferous, there appears to have been a general absence of igneous activity in the Malay Peninsula. Sedimentation continued in northwest Malaya and in the Kinta Valley under rather stable conditions, which would indicate a continuance of the miogeoclinal conditions of the Lower Palaeozoic depicted in figure 1. A Devonian unconformity may have been locally present in the Langkawi islands, but a continuous undisturbed sequence probably exists in the Kinta Valley (Gobbett, 1973).

East of the Lower Palaeozoic ophiolitic and schist belt, Devonian sedimentary formations occur in the neighbourhood of Karak and Lower Carboniferous formations to the north and east, well documented in the neighbourhood of Kuantan. There is no evidence of a depositional break, and continuous sedimentation can be assumed. The earliest authenticated evidence of igneous activity is of contemporaneous volcanic and pyroclastic rocks interbedded with Viséan sedimentary formations of the area around Sungei Lembing, near Kuantan (Fitch, 1952).

It is therefore assumed that throughout the Palaeozoic there was a continual eastwards migration of the trench as it received a supply of sediment from the continental plate and volcanic arc which lay to the west. The geosyncline continued to grow in an eastwards direction by accretion onto the continental plate, causing the subduction zone to be progressively pushed eastwards away from the continental plate of figure 1.

This process is presumed to have caused tension in the sialic plate behind the volcanic arc, eventually causing the continental westerly plate to rift and a marginal basin to form. This situation is analogous to the present day marginal basins of the Western Pacific, such as the Sea of Japan, and the Philippine Sea, for which Karig (1971) has shown that tension in the back arc region results in young and true sea floor spreading. The arc-trench system progresses oceanwards causing a new spreading of basaltic material behind the arc and a break up of the continental plate. In this presumed process, the Malay Peninsula detached itself from its Precambrian continental plate and drifted eastwards away from the foreland. We do not know when this drift began, but it is presumed to have initiated in the mid Palaeozoic.

Thus today we find the miogeoclinal rock sequence of northwest Malaya divorced and separated from the Precambrian landmass from which it was largely derived, and we do not as yet have any means of knowing to which Precambrian

continent the Malay Peninsula was attached. But in northwest Malaya, under the Machinchang Formation outcrop, that portion of the Precambrian basement which drifted eastwards with the Peninsula should be available for study at a shallow depth: unfortunately it nowhere outcrops. A drilling research programme through the Machinchang Formation to ascertain the lithology and geochronology of this basement would provide significant information relative to the Palaeozoic reconstruction of the Malay Peninsula and its former attachment.

In northern Thailand, west of Chiang Mai, the Cambro-Ordovician formations overlie an outcropping series of Precambrian gneisses (Baum *et al.*, 1970). Since the Lower Palaeozoic stratigraphy of West Malaysia correlates rather well with that of Thailand (Jones, 1973), the Precambrian of the Chiang Mai area must be considered as part of the same basement which underlies the Cambrian of the Langkawi islands. It is open for discussion whether the crystalline schists of northern and southern Sumatra (Bemmelen, 1949) also form part of this Precambrian basement.

There was no subduction along the west of the Malay Peninsula during this time, for the eastwards spreading of the new ocean floor simply pushed the Peninsula ahead of it in the eastwards spreading flow.

LATE CARBONIFEROUS TO EARLY PERMIAN

The established westwards subducting trench had by late Carboniferous time migrated eastwards away from the Peninsula possibly as far as the neighbourhood of Natuna and west Kalimantan, where ophiolitic suites in the Kembajan mountains and in the middle Kapuas region are presumed to be of this approximate age (Bemmelen, 1949; Klompé *et al.*, 1961). The line of these ophiolites seems to agree with what has been named the Serabang Line by Haile (1973). It must, however, be admitted that the evidence for the age of the ophiolites is indirect. Nevertheless there is no evidence for a trench in the Malay Peninsula at this time, and so it can be presumed to have migrated eastwards away from the Peninsula. Its exact location is not critical to the hypothesis being developed here. I have chosen to depict it extending along the axis of the Malaya Basin of Haile (1973). This is the most reasonable location because it lines up with the established Variscan (Carboniferous) ophiolitic belt of Thailand, which lies between Chiang Rai and Chiang Mai (Klompé, 1961; Baum *et al.*, 1970).

Having established the position of the trench (Fig. 3), an igneous arc should now be sought at a suitable distance behind it. It indeed occurs along the eastern belt of the Malay Peninsula, with an extension into west and central Borneo. The arc is shown on figure 3 as including most of the East Coast granite plutons from Kelantan and Trengganu southwards to the neighbourhood of Kuantan. The Upper Carboniferous age of the granites in this belt has been established by Snelling *et al.* (1968), Hutchison *et al.* (1971B), and Bignell *et al.* (1972). Carbo-Permian andesitic to rhyolitic contemporaneous flows and pyroclastic rocks also occur widely in this belt. The southwards extension of this volcano-plutonic arc appears to swing south-eastwards from Kuantan and continue in west Kalimantan, where Klompé *et al.* (1961) have shown extensive occurrences of intermediate to basic lavas intercalated with fossiliferous Carbo-Permian strata. The actual outcrop pattern of the arc-trench as shown in figure 3 must be considered to have been rather different when the important Mesozoic and Cenozoic wrench faults, which have offset the southern end of the Peninsula, are taken into account (Burton, 1973; Tjia *et al.*, 1973).

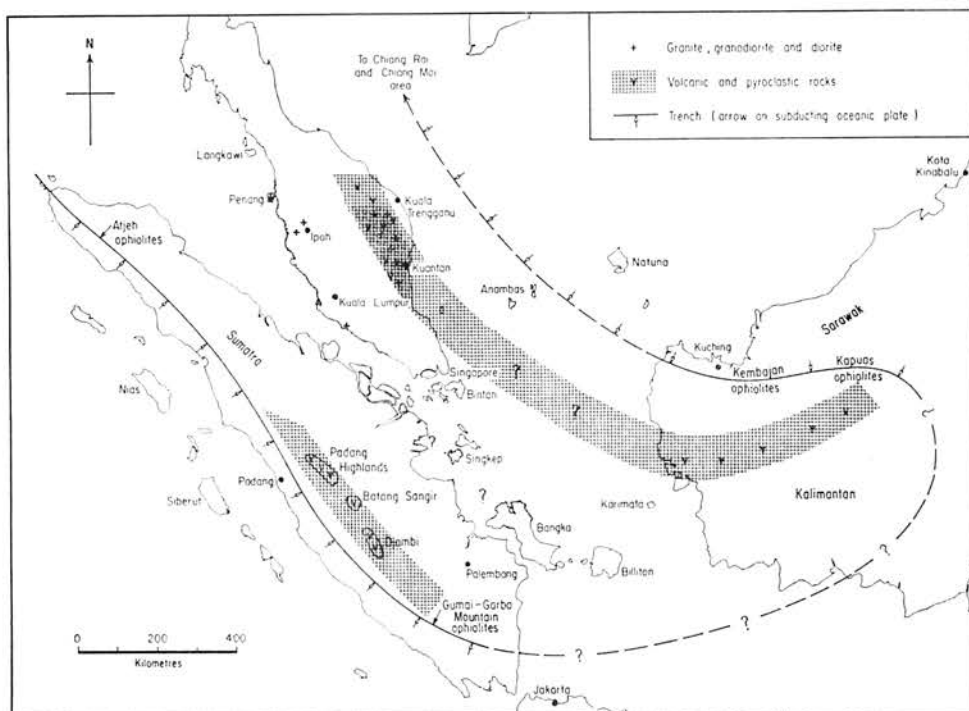


Fig. 3. Palaeo-tectonic scheme for the Late Carboniferous to Early Permian of the Sunda land region.

Carbo-Permian volcanic and pyroclastic rocks, ranging in composition from dacite to andesite, are abundant in the Padang Highlands, Batang Sangir, and Djambi areas of Sumatra (Klompé *et al.*, 1961). Their age is well known from the intercalated fossiliferous strata. Contrary to the view held by Bemmelen (1949) that these rocks have been thrust westwards from the Malay Peninsula in the form of a large Djambi Nappe, Klompé *et al.* (1961) have shown that the Carbo-Permian volcanic rocks occur in a normal sedimentary succession extending from Carboniferous through Permian to Triassic, with no evidence for thrusting. Hence they assume that a volcanic arc did exist in the Sumatran region. In the conference presentation of this article (Hutchison, 1972), I favoured the nappe theory of Bemmelen (1949), but further reconsideration has inclined me to favour the interpretation of Klompé *et al.* (1961).

It thus becomes necessary to postulate the double-sided nature of the region, with opposite-facing arcs, beginning as early as the Carboniferous. This character of the Sunda region continues and appears to have been a permanent feature up to early Tertiary time. From late Carboniferous to early Tertiary the Malay Peninsula, including most of Sumatra and west and central Borneo (Sundaland), must be considered as an established 'continental plate', with eastward and westward subduction on either side. This is not an entirely novel hypothesis, for the regional syntheses of Bemmelen (1949) and Klompé (1961) clearly incorporated the double-sided character of Sundaland in pre-plate tectonic language. I am simply restating

their views and analyses in the new language, with the reinforcement of additional data from radiometric dating.

The position of the Sumatran trench at this time is not certain, but it may be inferred through the outcrops of the Atjeh and Gumai-Garba mountain ophiolitic suites in north and south Sumatra respectively. Although these ophiolites are considered to be of Lower Triassic age (Bemmelen, 1949), it is proposed that this eastwards subducting arc-trench system of Sumatra was initiated in late Carboniferous time.

The proposed palaeo-tectonic scheme is shown in figure 3. The possible continuity of the two opposite-facing arc-trench systems through the region of the Java Sea as a single convoluted system, cannot be established for this time through lack of data. However, as demonstrated below, by Cretaceous time there can be little doubt that a single convoluted arc-trench system wraps around the west, south and east margins of Sunda Land.

Late Carboniferous granites also occur along the western belt of the Malay Peninsula (Bignell *et al.*, 1972), for example in the Bintang and Kledang ranges and the Dindings areas of Perak, and on Penang island. This westerly granitic belt may be regarded as distal granites belonging to either or both of the arc-trench systems. As shown below, these granites are more alkaline than those of the main East Coast arc, supporting their classification, based on Kuno (1966), as distal and formed farther within the continental plate.

Although not proven, the possibility must be entertained that similar late Carboniferous distal granites may occur in the southwards extension of this trend, in the islands of Singkep, Bangka and Billiton.

Plutonic igneous rocks

There is compelling evidence that the granites of the East Coast batholiths in this arc were epizonal. A late Carboniferous age for some of between 280 and 300 m.y. (Snelling *et al.*, 1968), combined with the knowledge that they were emplaced into Lower Carboniferous (Viséan) sedimentary rocks in some places (Hutchison *et al.*, 1971B), implies that they were emplaced close to the surface. Although much of the common amphibole content of these granites has been attributed to contamination by sedimentary country rocks (Hutchison, 1973B), euhedral primary amphibole frequently occurs, bearing witness that the magma was relatively dry, for amphibole is unstable in a wet granitic magma (Tuttle *et al.*, 1958) and is characteristic of high level granites. Dry magma has the ability to rise high in the crust, whereas a wet magma is forced to crystallize by boiling off of its water long before it approaches the surface (Cann, 1970). Distinct contact aureoles around the East Coast granite batholiths, especially in the Sungei Lembing (Yeap, 1966) and Gambang (Lim, 1971) areas, also bear witness to the high level nature of these granite emplacements (Hutchison, 1973B).

A plot of normative quartz of the available analyses of East Coast granites taken from Alexander *et al.* (1964) against crystallization index (Poldervaart *et al.*, 1964), using norms calculated by the programme of Hutchison *et al.* (1971A), indicate (Fig. 4D) that the East Coast granites form a continuous series, which has evolved from an initial dioritic magma (crystallization index about 24), towards a highly

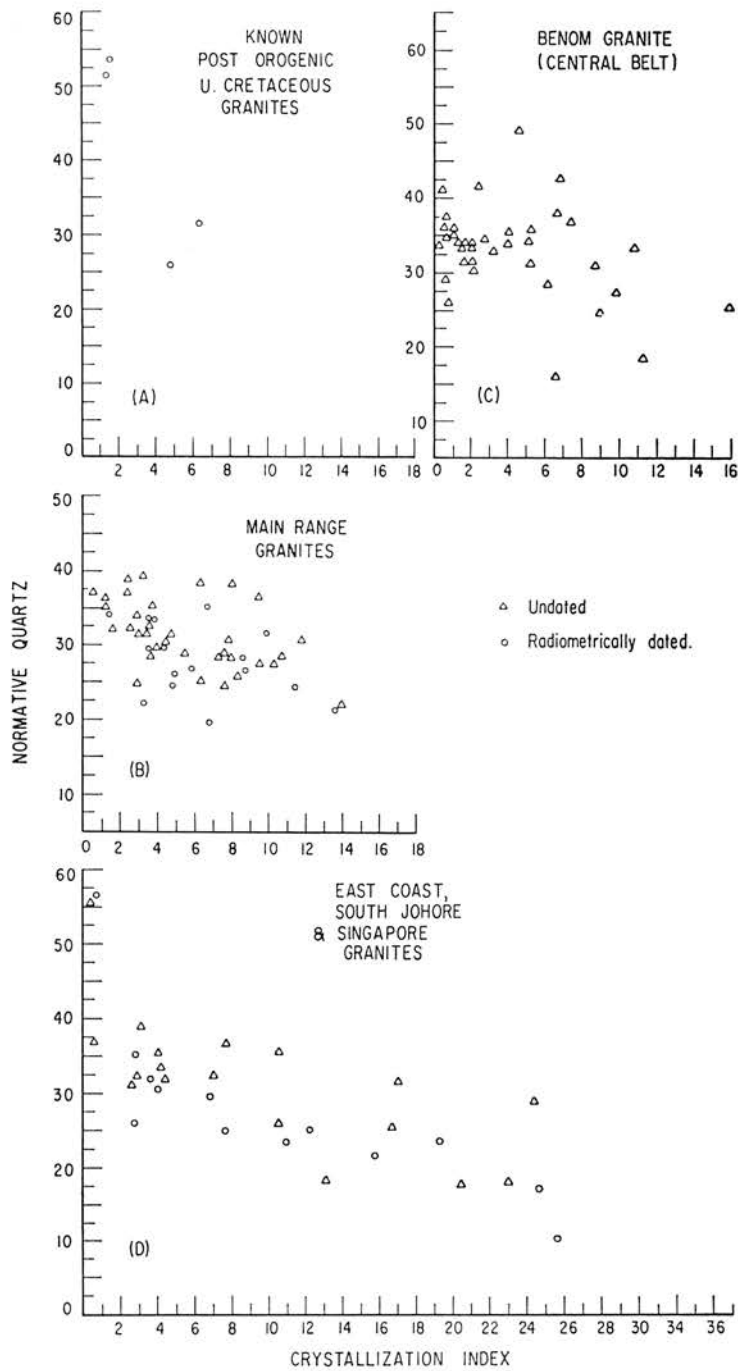


Fig. 4. The relation between normative quartz and crystallization index (Poldervaart *et al.* 1964) for granites of A- known post-orogenic Late Cretaceous age; B- The Main Range; C- Gunong Benom; and D- The East Coast, South Johore, and Singapore.

evolved granite of crystallization index approaching 0. These granites must have differentiated upwards through the crust during emplacement. The dioritic parent indicates a high melting temperature relative to a truly granitic magma, and hence a dry magma of dioritic composition would experience no difficulty in rising to high crustal levels (Brown, 1971). The parental dioritic nature of the magma, as indicated by figure 4D, is in keeping with the postulated tectonic scheme of figure 3 in which the magma is initially derived from the Benioff Zone as basalt, modified upon upward migration; but it has not been modified nearly as much as in the case of the Lower Palaeozoic rhyolitic magma, because in the late Carboniferous case the sialic material formed only a relatively thin veneer over the oceanic plate.

One should also consider that a primary hot melt ascending in the crust will transfer heat to higher crustal levels. Lower temperature truly granitic liquids, resulting from partial melting of the crustal rocks, showing little intrusive capacity, might then appear at the higher levels (Brown, 1971). Hence granite plutons could result at similar crustal levels as earlier granodiorites and diorites and we must presume that the focus of activity gradually moved away from the trench inwards into the continental plate.

The late Carboniferous granites of the West Coast belt of the Peninsula are therefore classified as distal (from the trench). Some analyses of these western granites have been plotted on figure 4B. Their more truly granitic character, in comparison with those of the East Coast (Fig. 4D), is clearly shown. A comparison of figures 13B with 13D also shows that they are more alkaline.

It would be a mistake to say that all granites of the East Coast belt originated at a deep level, and all were emplaced epizonally. What can be said with confidence is that they ultimately originated as a dioritic primary magma (Fig. 4D) which rose to a high level in the crust. If this is the correct interpretation, then one would expect these plutons to display prominent contact metamorphic aureoles, since they are presumed to have been hot magma emplacements into epizonal country rocks. This can indeed be shown to be true, for well defined aureoles have been mapped in the Kuantan and Gambang areas with widths of approximately 1 mile or less, outside of which the Lower Carboniferous sedimentary rocks are unmetamorphosed and abundantly fossiliferous (Lim, 1971; Yeap, 1966).

PERMIAN TO EARLY TRIASSIC

The volcanic and plutonic rock occurrences indicate little overall change in the positions of the arcs from late Carboniferous time. The arc-trench system (Fig. 5) is therefore shown to be rather similar to that for Late Carboniferous to Early Permian (Fig. 3). The eastern trench is shown passing through Natuna to account for ophiolites there of this presumed age (Bemmelen, 1949). Abundant andesitic to rhyolitic volcanic and pyroclastic rocks occur in the same regions of Sumatra and in west and central Kalimantan (Klompé *et al.*, 1961), with an indication that the arc has moved slightly northwards closer to Sarawak than it was in the Carbo-Permian. Abundant and widespread andesitic to rhyolitic volcanic and pyroclastic activity characterised the region of the Malay Peninsula east of the Main Range. This was formerly referred to as the Pahang Volcanic Series (Hutchison, 1973A).

Plutonic activity also occurs in this broad Malayan arc, in which granites of Permian and early Triassic age have been determined both in the East Coast belt and in the Main Range, and early Triassic granites characterise the region of Singa-

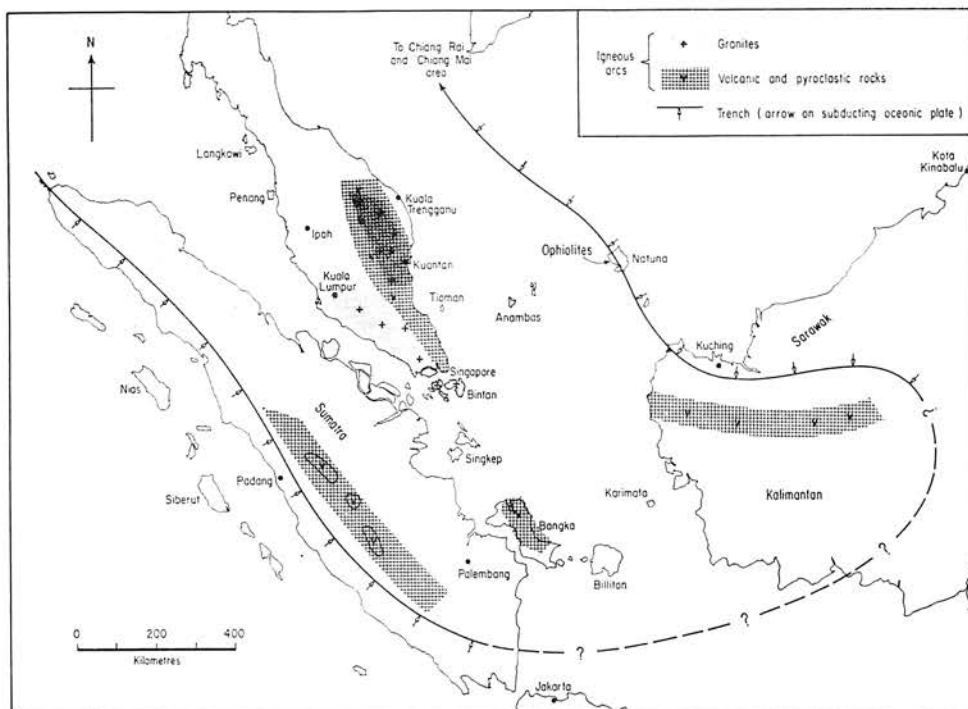


Fig. 5. Palaeo-tectonic scheme for Permian to early Triassic for the Sundaland region.

pore and south Johore (Bignell *et al.*, 1972). The possibility that granites of this age occur in west Kalimantan must be entertained, though there is no radiometric confirmation as yet.

Interaction between the opposite-facing subduction zones can be considered as the cause of uplift of the Malay Peninsula resulting in shallow marine depositional environments for most of the Triassic sedimentary formations (Burton, 1973). The igneous arc of the Malay Peninsula is rather broad, logically to be expected from the merging together in one central zone of the arcs of both the eastern and western arc-trench systems. High heat flow in this arc, centred on the Malayan Geosyncline, can be considered to have caused catazonal metamorphism in its deeper parts, resulting in recrystallization of the deeper or tectogene parts, which will eventually form, upon later uplift, the Taku Schist, Stong Complex, and Benta Complex (Hutchison, 1973C).

Volcanic Igneous Rocks

Figure 6 is an alkalis versus $\text{SiO}_2\%$ plot for known and assumed volcanic rocks of this arc system. Most of them are from Pahang and Trengganu. It should be noted that they are exclusively basaltic to andesitic and range considerably in alkalinity. The polarity of the subduction system can be inferred from the fact that those rocks from the east coast of Trengganu are tholeiitic, and hence derived from a shallow level on the Benioff Zone, while those inland and from central Pahang are predominantly alkaline, and hence derived from a deeper tectonic level (Kuno, 1966). However this is only a generalization, for no systematic progression in alkalinity

PERMIAN TO TRIASSIC VOLCANIC ROCKS

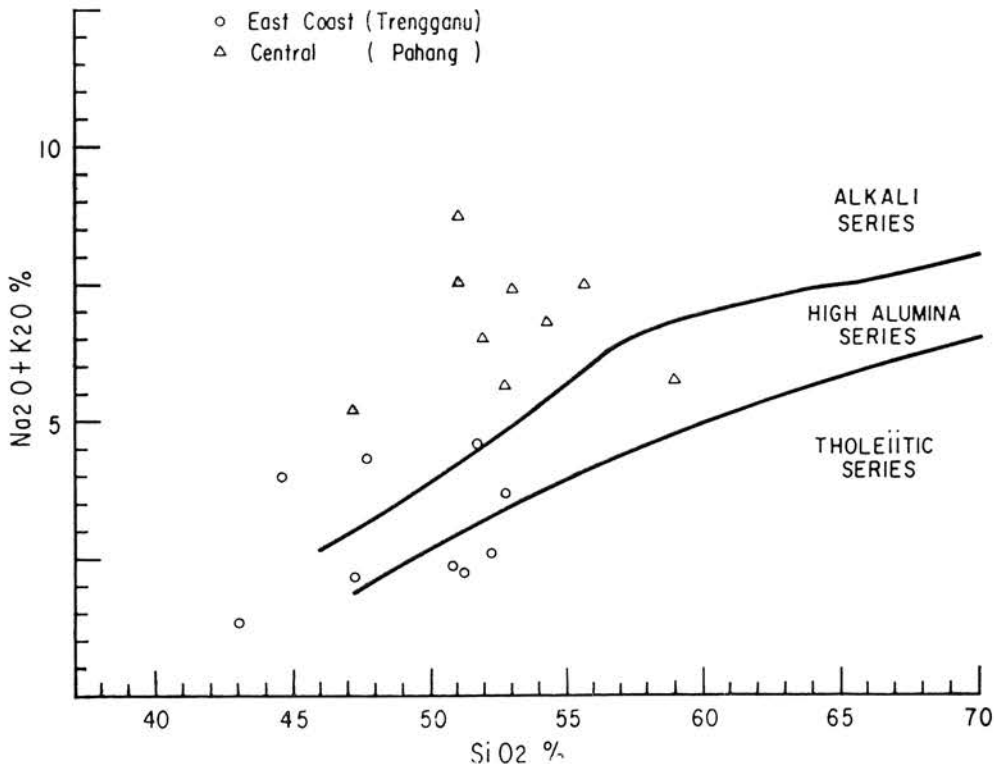


Fig. 6. Alkalis% versus silica% diagram for known Permian and Triassic volcanic rocks (Alexander *et al.*, 1964). The westwards dip of the Benioff Zone may be inferred from the tholeiitic nature of rocks closer to the east coast, while those from Pahang are alkaline.

has been observed from east to west, and that all the specimens analysed are exactly of the same age is not known with certainty. Such a systematic study has yet to be done, but the preliminary deduction from figure 6 does justify the conclusion that the main Benioff Zone dipped westwards for the Trengganu-Pahang volcanic arc.

Plutonic Igneous Rocks

As with the Late Carboniferous, granites of Permian to Early Triassic age (Bignell *et al.*, 1972) occurring in the East Coast belt, including Singapore and south Johore (Fig. 4D), have a wider compositional range throughout granodiorite to diorite (Fig. 4D) than do those belonging to the Main Range (Fig. 4B). Figure 13 also shows that the Main Range occurrences are more alkaline than their East Coast counterparts. All this points to the Main Range occurrences being distal when compared with the East Coast granites of the main igneous arc, and is in agreement with the alkaline polarity of Kuno (1966).

Along the Central belt of the Peninsula are several elongate bodies of microgranite and 'quartz porphyry' which may also be tentatively ascribed to this system (e.g. at Raub and Lanchang), though there is nothing definitely known of their age.

It is nevertheless important to know more about the plutonic and volcanic relationships in this Central belt, for this is a part of the Peninsula characterised by gold and by the general absence of tin mineralization. The Benom granite occurs in this region, but petrographic, geochemical and radiometric evidence suggests it is related to the majority of the Main Range granites of Late Triassic age.

LATE TRIASSIC TO EARLY JURASSIC

A similar palaeo-tectonic scheme can be proposed for this period (Fig. 7). The Borneo arc-trench system can be precisely located. The trench position is depicted

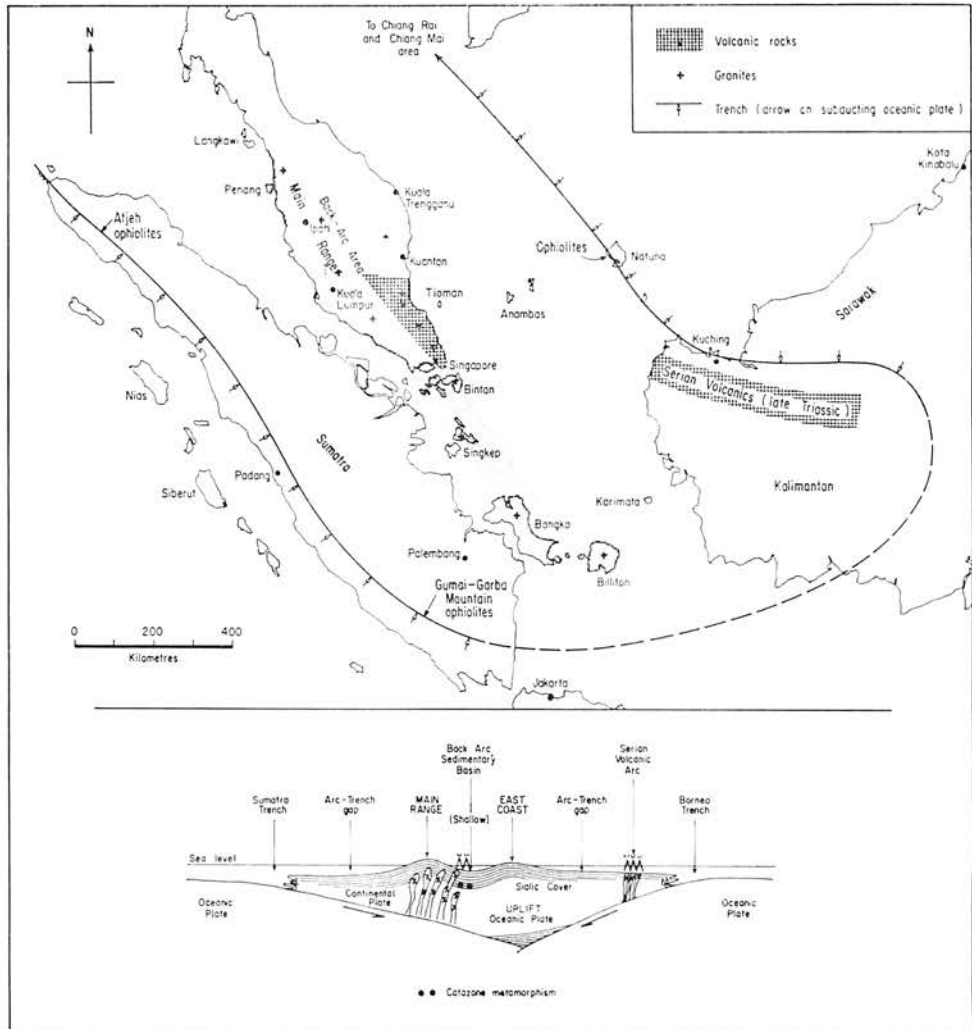


Fig. 7. Palaeo-tectonic scheme for Late Triassic to Early Jurassic for the Sundaland region. The diagrammatic cross section shows the two igneous arcs in relation to the opposite-facing subduction pattern.

along the Lupar Line of Haile (1973) which separates the Sibu Zone of the north from the Kuching Zone of the south. The volcanic arc is composed of Late Triassic predominantly andesitic formations, which lie behind the ophiolitic zone in the Kuching Zone, both in south Sarawak as the Serian Volcanic Series (Kirk, 1968), and in north Kalimantan as the Matan and Ketapang Volcanic Series (Bemmelen, 1949).

The Sumatran trench, as shown in Figure 7, can be located along the axis of the island passing through the Triassic ophiolitic complexes of Atjeh in the north, and the Gumai-Garba mountains in the south. The age of these ophiolites is taken from Bemmelen (1949).

Rhyolitic and dacitic volcanic rocks occur in the Triassic sedimentary formations of south Pahang and Johore, and Burton (1973) holds that they are contemporaneous and consanguinous with the granites. The Peninsular arc of Figure 7 may therefore be considered as of volcano-plutonic character.

Interaction between the two opposite-facing subduction zones can be considered to have been the cause of uplift along the East Coast zone and the Main Range zone of the Peninsula, as shown in the diagrammatic cross-section of Figure 7. The uplift is represented by an important unconformity between isoclinally folded metasediments of Upper Palaeozoic age along the eastern part of the Peninsula and the overlying generally flat-lying rhyolitic volcanic rocks which characterise the region from Pekan through Mersing to southeast Johore (Grubb, 1968). There can be little doubt that the eastern part of the Peninsula emerged at this time, for the acid volcanic rocks of this region have all the characteristics of sub-aerial ignimbritic eruptions. The exact age of the unconformity is not presently known, but the overlying volcanic rocks are assumed to be Triassic (Hutchison, 1973A).

Main Range Granitic Arc

Let us now look at the nature of the Main Range granites. Available analyses (Alexander *et al.*, 1964) are shown plotted in Figure 4B. This batholith system is shown to be highly evolved and of rather restricted range of crystallization index (Poldervaart *et al.*, 1964), and of a very restricted granitic nature. This fact, in conjunction with the absence of amphibole and its country rock envelope of isoclinally folded greenschist facies metasediments, indicates that the Main Range granite was evolved within the crust as a wet magma and therefore had very poor capacity to rise. It is therefore a typical mesozonal granite, characterised by a dynamothermal greenschist facies envelope and a general absence of a hornfels facies thermal aureole; and accordingly quite distinctly different from the Upper Carboniferous epizonal granites of the East Coast belt. The present level of exposure of the Main Range granite is close to its original roof. One must conclude that there was originally a considerable thickness of Upper Palaeozoic to Lower Mesozoic sedimentary and volcanic rocks on top of the batholith, which subsequent erosion has removed.

The strongly evolved nature of the Main Range granite (Fig. 4B) is in keeping with its position above the remnant of the original Precambrian continual plate (Fig. 7). The granitic magma which gave rise to the Main Range resulted from anatexis of strongly sialic rocks, in part Precambrian, and in part of the Lower Palaeozoic cover on the Precambrian sialic plate. The zone of high heat flow in the igneous arc supplied the necessary heat for anatexis at deeper levels, and for greenschist facies metamorphism of the sedimentary formations of the shallower levels.

The reason for ascribing the Main Range to the Sumatran subduction system, rather than to the Natuna system, is the radically different petrologic nature of the Main Range and East Coast granites. The mineralization of the two ranges is also vastly different, so that any system proposed to relate the two granite ranges to a similar origin, will be basically unsound. It is possible that the Main Range granite belt includes the east coast of Sumatra and the islands of Singkep, Bangka and Billiton, which have yielded similar Late Triassic radiometric ages (Hutchison, 1973B).

The Benom granite of central Malaya (Fig. 4C) is similar chemically and petrographically to the Main Range granites (Fig. 4B) and radiometric evidence points to its Triassic age.

Volcanic igneous rocks

The Late Triassic Serian Volcanic Series of Sarawak (Kirk, 1968) ranges in composition from basalt to rhyolite and exhibits a considerable alkali to silica percentage range (Fig. 8) over the fields of tholeiitic, high alumina to alkaline basalt. The geographic distribution of the analysed specimens has not permitted the polarity of the arc to be deduced on the basis of the scheme of Kuno (1966).

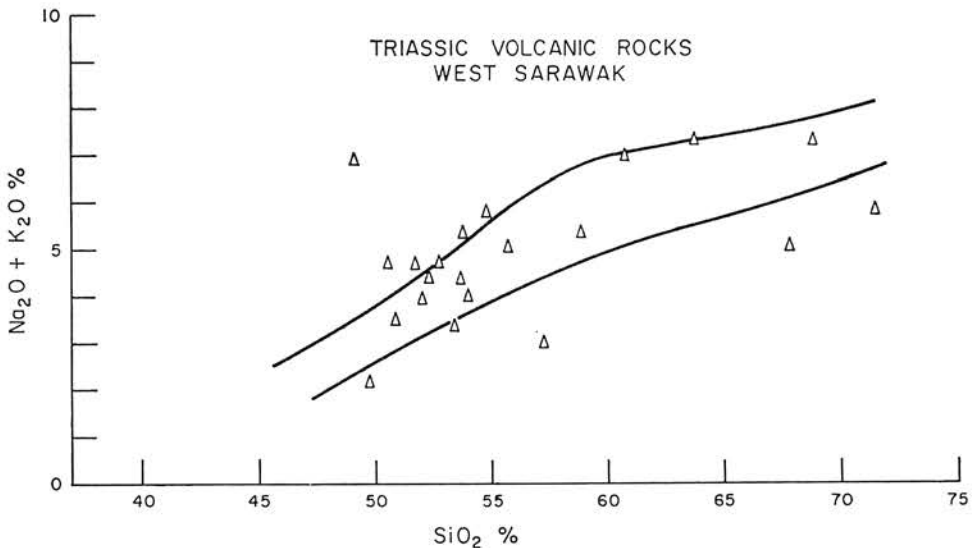


Fig. 8. Alkalis% versus silica% diagram for Late Triassic volcanic rocks of West Sarawak. The lines are from Kuno (1966) and the analyses from Kirk (1968).

The volcanism in the Peninsula was essentially rhyolitic and figure 9 shows that the rocks, although rhyolitic, are essentially of tholeiitic type, and non-alkaline, and were probably derived from a basaltic parent rising from a shallow horizon relatively close to the trench. These rhyolites and rhyolite tuffs were extruded with a strong unconformity over isoclinally folded Permo-carboniferous metasediments. They are generally flat lying or may have gentle primary dips in contrast to the steeply dipping underlying metasediments. A prominent conglomerate locally characterises the unconformity, for example in Mersing Bay, and this may be correlated with the Murau

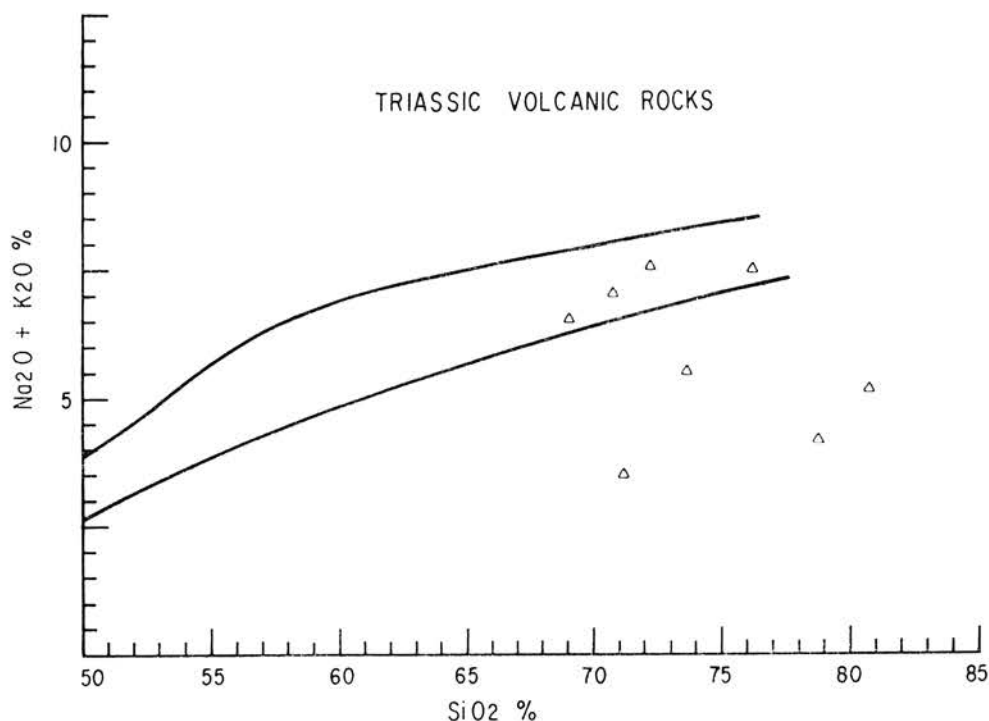


Fig. 9. Alkalis% versus silica% diagram for Triassic volcanic rocks of east Johore. The lines are from Kuno (1966) and the analyses from Alexander *et al.* (1964) and Grubb (1968).

Conglomerate. One has therefore to conclude that the east coast zone was uplifted before the rhyolitic rocks were extruded. At the same time the back-arc area of the central Peninsular zone was the only region to have continuous sedimentation from Permian to Triassic (Burton, 1973).

Some General Comments

Epeirogenic uplift of the Malay Peninsula at this time, and subsequently, can be accounted for by the hypothesis that it was by this time a sialic or 'continental' plate between two opposite-facing arc-trench systems. The subduction zones of the two systems (or of one convolute system) interfered underneath the Peninsula (Fig. 7), upsetting the simple subduction of mantle and oceanic material, and, with upward diversion of one subducting block, causing uplift in certain zones of the Peninsula according to the nature of the interference of the Benioff Zones. Imbrication of the Benioff Zone after the style of Lipman *et al.* (1971) may also play a part in the cause of the rather wide volcano-plutonic arcs which characterise the Malay Peninsula.

The Late Triassic uplift of the Main Range is well corroborated by the major maximum of K:Ar radiometric dates at 185 m.y. on the Main Range granites (Hutchison, 1973B); but this maximum is not considered to indicate an important magmatic event, for Rb:Sr dates on the same granites generally indicate the true magmatic ages as within the range 200 to 230 m.y.

Only the central belt of the Peninsula continued to be an area of major sedimentation through Triassic into Jurassic; but about this time it also became uplifted and transformed from a marine deposition area to one in which continental molasse-type red beds of the Tembeling Formation took the place of the marine flysch deposition.

The deeper parts of the central deposition belt, which may be called the Malayan 'Geosyncline', were metamorphosed in the amphibolite facies when the volcanic arc, with its high heat flow, was centred on the sedimentary trough, and it later began to uplift as a result of the interplay or imbrication of the Benioff Zone. It is imagined that the catazone uplifted in the form of rheid flows to form gneiss domes into the overlying greenschist facies terrane (Hutchison, 1973C; 1973D).

MID JURASSIC TO MID CRETACEOUS

This period is characterised by general uplift and conversion of the Malay Peninsula from an area of marine sedimentation to a landmass on which continental molasse-type and fluvial sedimentation became progressively restricted to zones in the Central and east-Central deposition belt (Gobbett, 1972; Burton, 1973). By Cretaceous time the sedimentary depositional pattern was controlled by important wrench and block faults (Burton, 1973; Tjia *et al.*, 1973).

Igneous activity appears to have been relatively insignificant. Some of the Tembeling Formation is weakly tuffaceous, and minor basalt and trachyte flows occur in the Gagau Formation. Lamprophyre and basalt dykes were abundant along the East Coast region. But these are all of minor significance and no volcano-plutonic arc appears to have existed in the region during this rather long period.

The general absence of major igneous activity may be interpreted to indicate that the region, which we may now call the Sundaland plate, was not being actively subducted by the surrounding oceanic plate(s). Whatever the cause, the pulsing nature of plate movements must be considered, for although igneous activity appears to have been nearly evenly distributed on the time scale from mid-Carboniferous to late-Triassic, most of the Jurassic and Cretaceous is characteristically a period of igneous quiescence for this region. It may be considered as a period when Sundaland became cratonized and a major system of strike-slip and block faulting developed (Tjia *et al.*, 1973). The most important of these faults are shown on figure 10.

Despite the long period of quiescence, the renewal of igneous activity in Late Cretaceous largely followed the same arc-trench pattern that was already established in the Palaeozoic and early Mesozoic. Therefore one must conclude that the tectonic quiescence over most of the Jurassic and Cretaceous did not signal the end of one regime and the beginning of a new system; it seems rather to indicate a period when tectonic forces in this region were momentarily (geologically speaking) at rest.

LATE CRETACEOUS TO EARLY TERTIARY

The evidence for the double-sided nature of the Sundaland area becomes even more clear for this period. The Sumatra trench is well located along the line of islands which lie to the west of Sumatra, the largest of which is Siberut (Fig. 10). The age of the ophiolites in these islands is presumed by Bemmelen (1949) to be Late Cretaceous to Early Tertiary. The igneous arc of this system includes, in order of

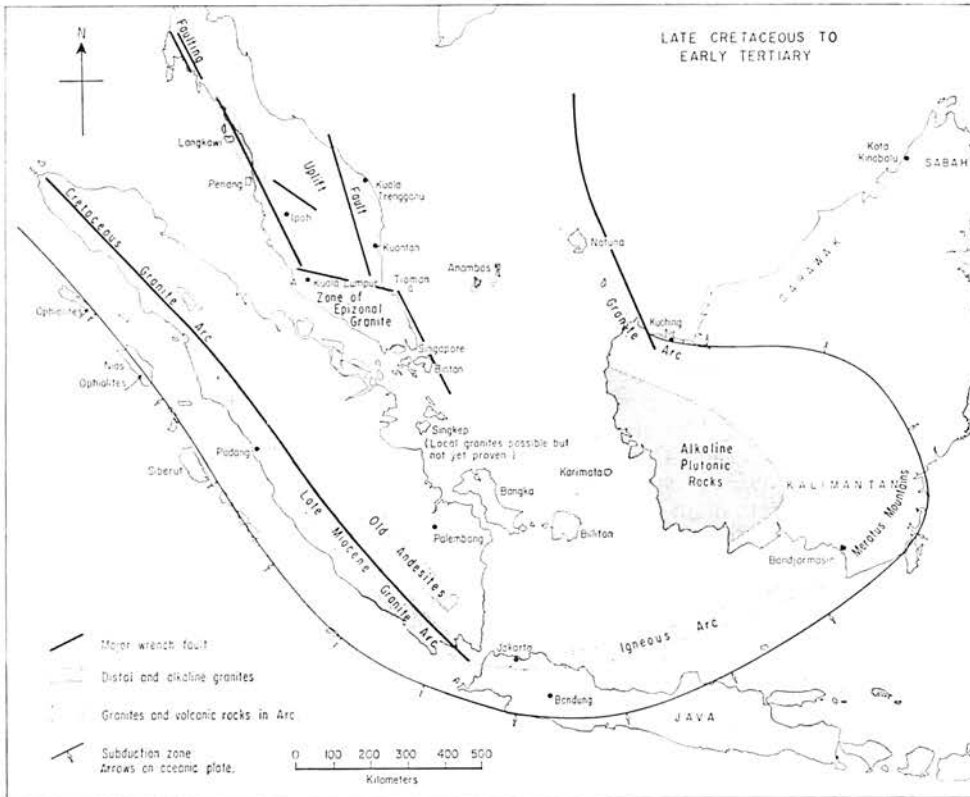


Fig. 10. Palaeo-tectonic scheme for Late Cretaceous to Early Tertiary for the Sundaland region.

time, Cretaceous granites of north Sumatra, Old Andesites, and Late Miocene granites of south Sumatra (Bemmelen, 1949). Katili (1971) has presented an identical pattern for the arc-trench system as is shown on Figure 10. Katili (1972) has also given details of 100 m.y. radiometric dates of granitic rocks from Central and South Sumatra.

The arc-trench system, however, does not continue along Java but swings through it towards the Meratus Mountains of southeast Kalimantan. This is well documented by the dating of 100 m.y. granites from the offshore areas of Java and a late Cretaceous subduction melange in central Java (Katili, 1972). The trend shown on Fig. 10 is after Katili (1971). Klompé (1961, p. 110), however, had already shown on his Southeast Asian synthesis a line of Laramic folding passing from south Sumatra, through Central Java, into the Meratus Mountains of south Kalimantan. The new radiometric evidence and the new framework of plate tectonics therefore simply confirms the early enlightenment of Klompé, whose understanding of the region as a whole was without equal.

The arc-trench system had its outcrop in the region of Sarawak (Fig. 10), in which the Lupar Line (Haile, 1973) may still be regarded as the trench outcrop, and the igneous arc located along a line behind this in west Sarawak and west Kali-

mantan, extending seawards into Anambas and Natuna. The granites of this arc are well dated as late Cretaceous (Haile *et al.*, 1971; Kirk, 1968). The tie-up from Sarawak to the Maratus Mountains is uncertain, but major rivers in east Kalimantan have prominent arcuate courses which can be taken to indicate the continuance of the arc-trench system as shown on Figure 10. The convolute nature of the arc-trench outcrop seems, therefore, to be fairly well documented, and it is of interest to note that this system (Fig. 10) is not significantly different from that which has been proposed for the region beginning in late Carboniferous and continuing to the early Tertiary.

Distal granites and faulting

During this time, the Malay Peninsula was uplifted and cratonized. It occupied the back-arc area of both sides of the convoluted arc-trench system and was now thoroughly uplifted because of continuing interaction of the opposite-facing Benioff Zone. As the arc-trench outcrops moved respectively away from each other, the back-arc Peninsular region became one of extension, resulting in numerous important deep-seated faults within the region (Tjia *et al.*, 1973; Katili *et al.*, 1971). It was along this fault system, especially the important one along the western margin of the Main Range, that an important episode of localised late Cretaceous to early Tertiary granitic activity occurred. Authenticated granites of this age occur in the region of Gunong Pulai in Johore and Mount Ophir in Malacca (Bignell *et al.*, 1972). Others may occur along this line, but have not yet been established. However along this belt of country (Fig. 10), K:Ar dates often indicate this important tectonic episode (Hutchison, 1973B).

This zone of epizonal post-orogenic granites of the Peninsula cannot in a simple manner be related to any igneous arc of either the eastwards or westwards facing subductions. The granites occur too far behind the known arcs, and at this time the Peninsula must be considered as a landmass, far removed from any subduction. If the subduction zone is of a shallow dip, then the granites can be considered as distal, belonging to a broad igneous arc. However they are not particularly alkaline (Fig. 13A) as would be required by this hypothesis. It may therefore be necessary to regard them as resulting from imbrication of the subduction zones under the Peninsula, producing distal granites which are not necessarily alkaline (Lipman *et al.*, 1971). The alkaline plutonic rocks of west Kalimantan should also be considered as distal, for they occupy a wide area behind the main arc outcrop. The evidence is that most of the granites of this region are late Cretaceous (Katili, 1972).

The granites of Mount Ophir and Gunong Pulai have many features of high level emplacements, as would be expected from their young ages. The K-feldspar is usually monoclinic, in contrast to the high triclinicity in all other granites of the Peninsula. These epizonal granites would be expected to exhibit a strong thermal aureole on the country rocks in view of their high temperature of emplacement; and a contact aureole, characterised by spotted cordierite hornfels, has recently been discovered on the north slopes of Mount Ophir around the reservoir.

Figure 4A is a Plot of normative quartz against crystallization index for the known late Cretaceous granites of the Mount Ophir and Gunong Pulai areas of the Peninsula. They are highly evolved and have a high enrichment in silica. They can therefore be regarded as residual in nature from a magma resulting from anatexis of strongly sialic material. The zone in which these granites occur continues to the present day to be one of high heat flow as witnessed by the numerous hot springs.

LATE CENOZOIC

To bring the palaeotectonic scheme up to date, Figure 11 shows the distribution of the important igneous features of the late Cenozoic. The convolute arc-trench system outcrop has straightened considerably to a gentle arc extending through Sumatra and Java. The Sumatran trench of the Present day is located off the west coast of the islands of west Sumatra extending eastwards to the south of Java, and its volcanic arc is in the Barisan Mountains of Sumatra and along the mountains of south Java.

During this period, the only activity in the Peninsular area, in the back arc region, was the extrusion of highly alkaline basalt flows at Kuantan and Segamat (Hutchison, 1973A). Similar basalt flows occurred in south Sumatra at Sukadana, in west Kalimantan at Niut, and in the region of Midai island (Fig. 11). These basalt flows can be related to deep extension faulting as the Malayan craton (Eurasian Plate) moves south, the Indian Ocean-Australian Plate moves north, and the Pacific Plate moves westwards (Katili, 1971).

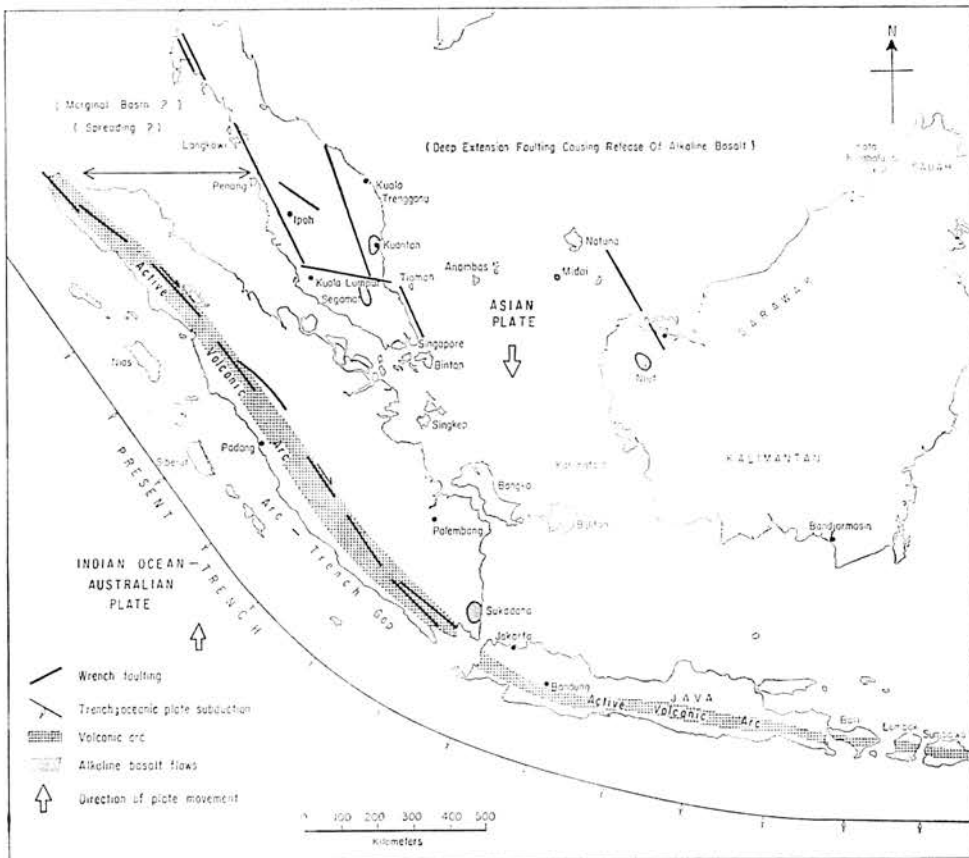


Fig. 11. Tectonic scheme for the present day and the Late Cenozoic of the Sundaland region.

Basalts

Figure 12 shows the highly alkaline nature of the basalts of the Malay Peninsula. The plot is on a diagram after Kuno (1966), and the analyses include rocks from the Kuantan area (Fitch, 1952) and the Segamat area (Grubb, 1965). Both occurrences of basalt are extremely alkaline, as would be expected if they originated deep on a Benioff Zone under a sialic or continental plate. This highly alkaline nature is in keeping with their occurrence a long distance behind the volcanic arcs of this time. They are strongly continental in nature. The description in van Bemmelen (1949) also indicates that the Indonesian occurrences of young basalts as shown on Figure 11 are also highly alkaline.

In sharp distinction to the highly alkaline nature of these basalts, Kuno (1966) has shown that the active volcanoes of the main parts of Sumatra, Java, Flores, and those of Halmahera are predominantly either tholeiitic or of the high alumina type, but that strongly alkaline types do occur farther away from the trenches in the northern group of the Celebes and in the northern coasts of Java.

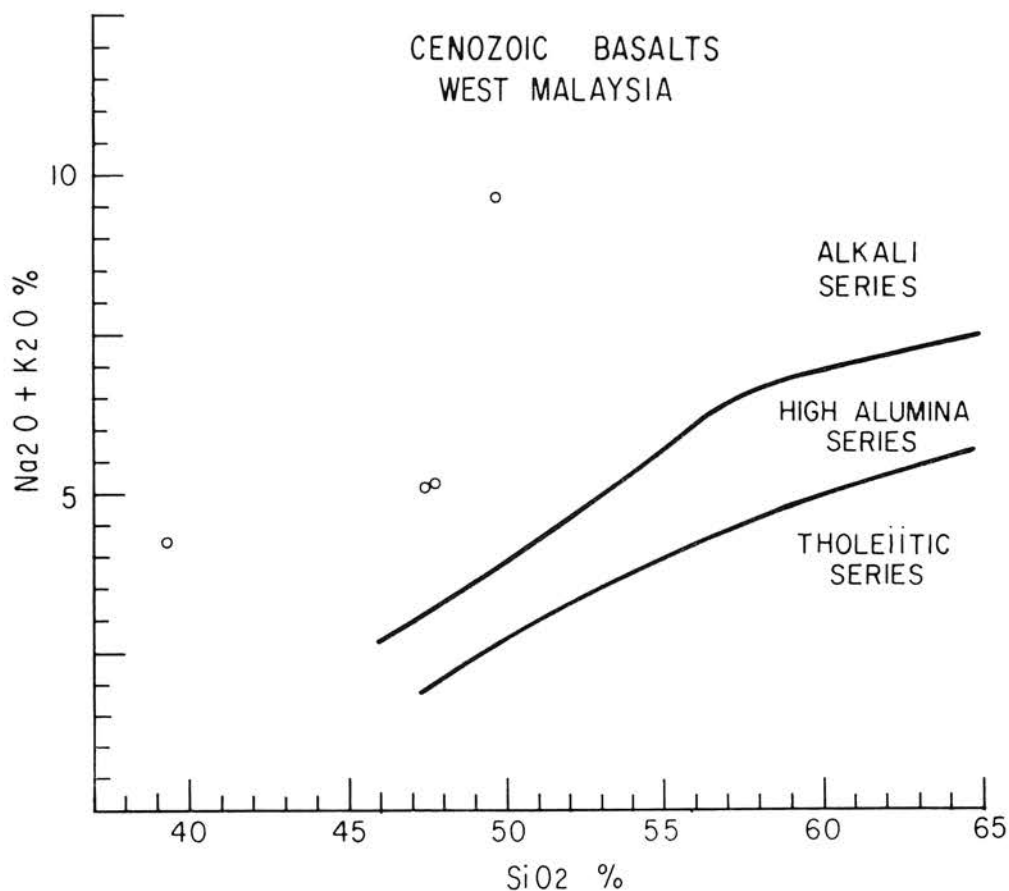


Fig. 12. Alkalis% versus silica% diagram for the Cenozoic basalt of Kuantan and Segamat. The lines are from Kuno (1966) and the analyses from Fitch (1952) and Grubb (1965).

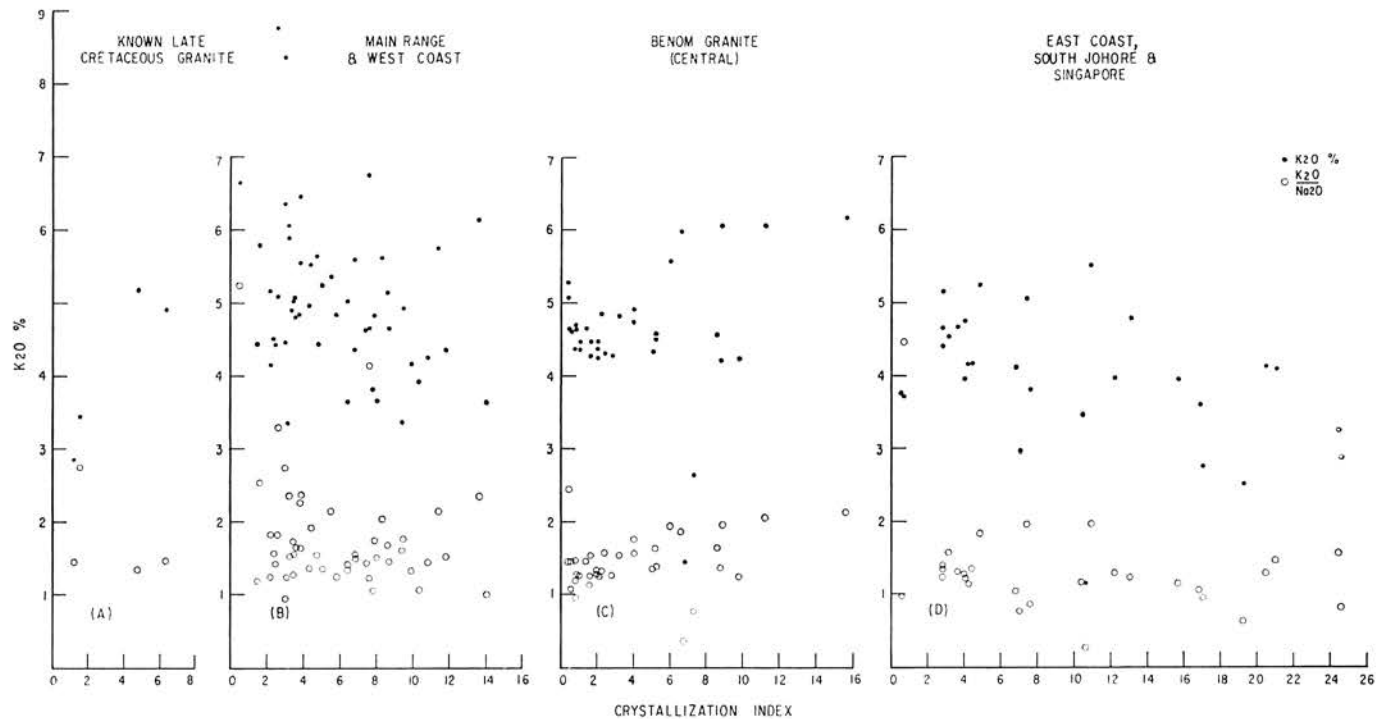


Fig. 13. Relationship of K₂O% and $\frac{K_2O\%}{Na_2O\%}$ versus crystallization index for A- known Late Cretaceous granites; B- Main Range and west coast granites; C- Benom central granite; and D- East Coast, South Johore and Singapore granite.

FINAL DISCUSSION OF MALAYAN GRANITES

One of the most important conclusions of this study is the difference between the granites of various ages in the Peninsula. The earlier (Late Carboniferous) granites are less mature and appear to have evolved from a dioritic ancestor, whereas as one approaches the present, the granites become more and more highly evolved. This has already been shown in Figure 4, and is better displayed on Figure 13, which is a plot of $K_2O\%$ and $\frac{K_2O}{Na_2O}$ versus crystallization index (Poldervaart *et al.*, 1964).

The oldest granites of the Malay Peninsula occur predominantly along the eastern zone of the Peninsula, in what has been called the East Coast granite belt. Analyses of these granites are shown in figure 13D. Although some granites included in this group are undoubtedly Permian, many are Upper Carboniferous in age. It is important to note in this figure that there is a range of crystallization index from dioritic to extremely granitic and that the trend is single with no branching towards alkali enrichment. One can conclude that the differentiation therefore was from a dioritic ancestor and proceeded uniformly. The basic ancestor is in keeping with the origin of these granites in a crustal area which was largely oceanic. The dioritic nature also has been used above to explain why most of these granites are high level.

In contrast, the granites of Gunong Benom (Fig. 13C) and the Main Range (Fig. 13B) are highly evolved with a rather restricted range of crystallization index, as might be expected if these rocks were derived by anatexis of geosynclinal sedimentary rocks. They are to be considered as wet magmas and to have had rather poor ability to rise to higher levels. The Main Range granite follows a similar differentiation trend to all the others, but its most highly differentiated members (those with the lowest crystallization indices) become somewhat enriched in K_2O , but not to the extent of a syenitic evolution.

The known post orogenic Late Cretaceous granites (Fig. 13A) are too few in number for drawing any definite conclusions. The known ones are strongly evolved, with low crystallization indices, but are not unusual in respect of alkali contents, and resemble the Main Range granite.

The sequence from D, through C, through B to A in figure 13 is considered to be a time sequence. It may be concluded that with time, the Malayan granites have become more highly evolved, showing greater maturity. In other words, with time, the Malayan plutonic activity trends towards a more granitic (*sensu stricto*) character, perhaps indicating the progressive change from an oceanic to a continental environment.

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