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Tectonic settings for emplacement of Southeast Asian tin granites

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Abstract: Most tin-bearing granitic rocks in Southeast Asia occur in one of three main belts: an eastern belt largely of Late Carboniferous to Early Triassic age, a central belt with abundant Late Triassic granites, and a wesetrn belt with widespread Cretaceous to Early Eocene plutons. From the Palaeozoic to Early Triassic four main stratigraphic-structural zones are recognised : the Shan States—Northwest Thailand—Peninsular Burma and Thailand—Western Malaya (Zone 1); the Eastern Foothills of Malaya (Zone 2); medial Malaya and central Thailand (Zone 3) and eastern Malaya and east central Thailand (Zone 4). Lithology and deformation of these Zones indicates that the eastern belt of tin-bearing granites was emplaced in continental crust of Zone 4 above an eastward-dipping Benioff zone; subduction took place beneath an outer arc (Zone 2) to the west of a volcanic arc (Zone 3 and 4). Middle to Late Triassic closure of the ocean basin between Zone 1 and Zones 2 and 3 was accompanied by continental collision resulting in 'the Indosinian orogeny' with emplacement of the central belt syn-collision late-orogenic granites in Zones 1 and 2. The western belt of granites was emplaced in Zone 1 above an eastward-dipping Benioff zone approaching the surface beneath or west of the IndoBurman Ranges, prior to Late Cenozoic northward movement of western Burma with respect to the Shan States. The abundance of tin in Southeast Asia is probably directly related to the fortuitous emplacement within continental crust of the three adjacent belts of subduction and collision-related magmatic rocks; there is little evidence of either a pre-Carboniferous concentration of metal in the crust, or of remobilisation of metal in the older mineralised granites by the younger granites.

INTRODUCTION

The region considered comprises the Shan States and Tenasserim in Burma, most of Thailand and West Malaysia, and the islands extending southeastwards to Billiton Island in Indonesia. This region accounts for nearly 65% of the world's tin production, excluding USSR and China, four times as much as any other region of equivalent surface area in the western world. Many mines are alluvial and related to a fortunate combination of Quaternary sea level changes, topography and bedrock lithology. However, the main reason for the abundance of tin is the presence of a number of belts of tin-bearing granitic rocks.

Tin-bearing granites elsewhere in the world are currently interpreted as having been emplaced in tectonic settings of three main types: in continental crust above shallow dipping Benioff zones (e.g. Alaska) (Reed and Lanphere, 1973); in continent-continent collision belts (e.g. Southwest England) (Mitchell, 1974), and in intra-continental rift zones (e.g. Niger) possibly related to mantle hot spots (Sillitoe, 1974).

The aim of this paper is to consider the tectonic settings in which the Southeast Asian tin associated granites were emplaced, and to show whether the abundance of tin can be explained by analogy with tin belts in similar tectonic settings elsewhere. The tin ores are commonly associated with deposits of wolfram, fluorite and locally molybdenum, bismuth and niobium; in this account, concerned mainly with the tectonic settings of the mineralised plutons, references to tin include these associated deposits where present.

TIN-BEARING GRANITIC BELTS

Granitic rocks with which the tin is commonly associated are distributed in 3 main belts (Fig. 1): the Eastern Belt, comprising eastern Malaya and east central Thailand; the Central Belt, comprising Billiton Island, western Malaya and northwestern Thailand; and the Western Belt comprising Peninsular Burma and Thailand, Tenasserim and western Shan States (east of the Shan Scarp extending from Mandalay to east of Rangoon).

In the Eastern Belt tin production is largely restricted to the eastern Malaya segment. Plutons in the eastern part of this segment include adamellite and granite and produce more tin than plutons in the west. The latter, for example the Boundary Range Granite (Macdonald, 1968), are commonly hornblende-bearing and are less potassic than those in the east. Radiometric ages indicate that most of the plutons are of Late Carboniferous to Permian or Early Triassic age (Hutchison, 1973).

The possible northward continuation of the eastern Malaya segment is found in the granitic plutons near Chantaburi southeast of Bangkok (Hughes and Bateson, 1967) which are at least partly of Early Permian age (Burton and Bignell, 1969) and contain minor tin and molybdenum mineralisation. This belt possibly extends further north to include older plutons west of the Korat Plateau.

In the Central Belt the most productive segment comprises the Indonesian Islands and western Malaya. Granitic rocks form the arcuate mountain belt of the Main Range, and in the north cut across the Lower Palaeozoic rocks east of the Range. Most plutons are mesozonal batholiths of porphyritic biotite granite or adamellite. Radiometric dates indicate a predominate Late Triassic age of crystallisation, although a number of Cretaceous granites also occur. Similar granites extend southwards to Billiton Island, where they are probably of Upper Triassic age (Hutchison, 1973a). Most of the tin and tungsten mineralisation in this belt is associated with the Late Triassic granites. The inferred continuation of the central belt in northwestern Thailand includes numerous granitic plutons (Baum, et al, 1970) associated with many of which are tin and fluorite deposits. Recent rubidium-strontium whole rock determinations on a number of widely spaced granites in northwestern Thailand indicate a Late Triassic age (D. Teggin, pers. commun., 1975).

The granitic rocks with tungsten and minor tin mineralisation which extend from Ko Tao Island southwards and then south-southwestwards into northernmost Malaya lie well to the east of the Main Range. However, they are here provisionally included in the same belt, although they could possibly be of pre-Triassic age.

The most westerly of the three granitic belts extends from the western margin of the Shan States southeast of Mandalay through Tenasserim to Phuket in Thailand. Tin is produced from numerous primary deposits throughout this belt from east of Pyinmana southwards, and alluvial deposits are abundant south of Moulmein. Tungsten deposits include that of the Mawchi Mine, formely the world's largest producer, lying northeast of Rangoon, and other primary wolfran deposits both to the north and south.

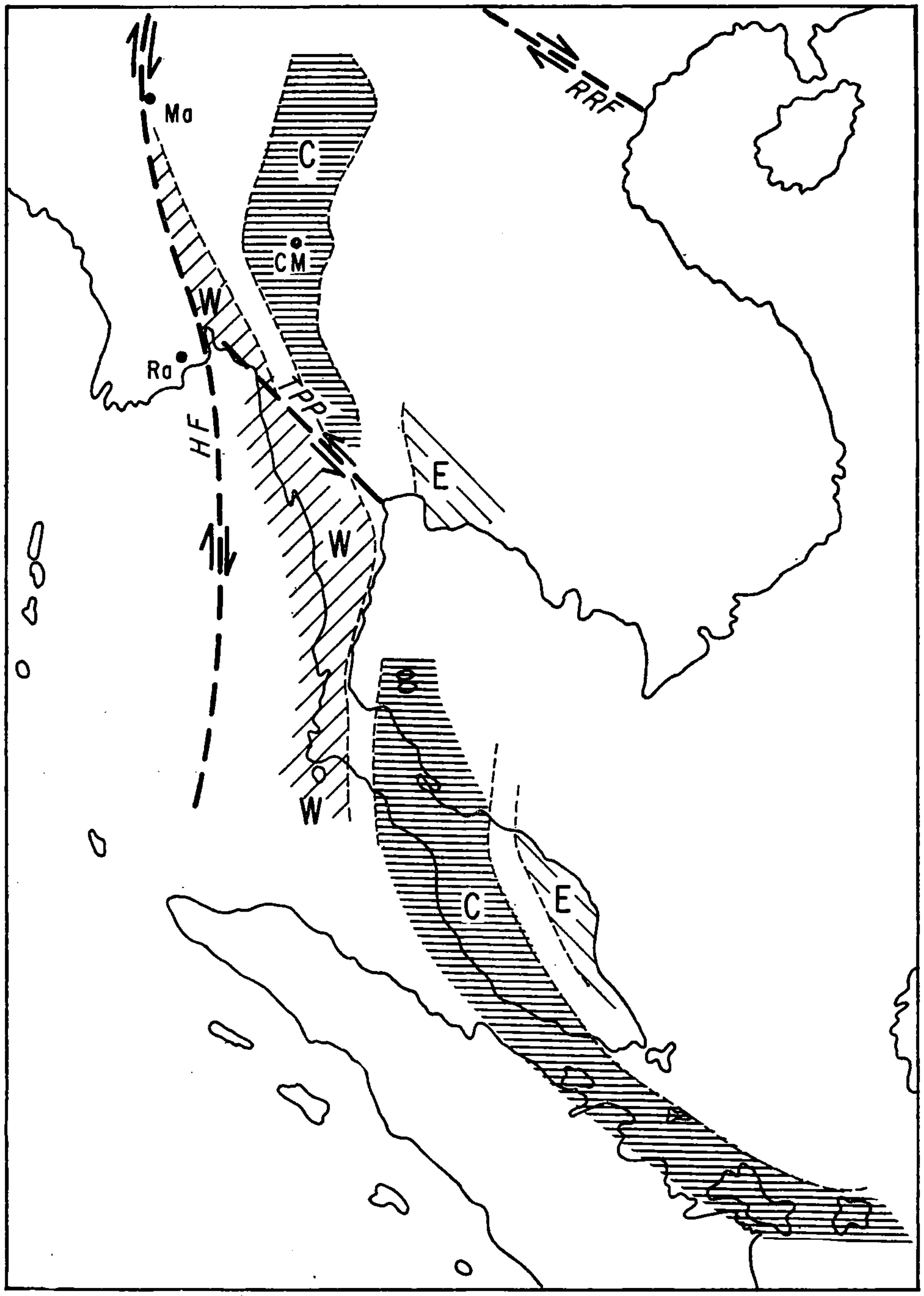

Fig. 1. Belts of tin-bearing granitic plutons, and major faults discussed in this paper. Tin-bearing granitic Belts: E Eastern; C Central; W Western. CM Chiang Mai; Ma Mandalay; Ra Rangoon. HF Hninzee-Sagaing Fault System; RRF Red River Fault; TPP Three Pagodas Pass Fault.

Rb/Sr whole-rock determinations indicate an Early Cretaceous age for two of three dated granites near Ranong (Burton and Bignell, 1969), and four granites from the Phuket area have yielded Late Lower Cretaceous Rb/Sr ages (Snelling, Hart and Harding, 1970). A mineralised granite east of Pyinmana in Burma has yielded an Early Eocene Rb/Sr age, and a similar K/Ar age has been determined for an adamellite to the north (N.J. Snelling, pers. commun. 1975). This suggests that a major episode of granite emplacement took place in the western belt, during the Cretaceous to Early Eocene, and that at least part of the tin is associated with plutons of this age.

MAJOR STRATIGRAPHIC-STRUCTURAL ZONES

Determination of the tectonic settings in which the granitic rocks of the three belts were emplaced requires an understanding of the Palaeozoic and Early Mesozoic geological history of the region, and locally of the Late Mesozoic and Cenozoic history. (Fig.2)

From Palaeozoic to Early Triassic the region can conveniently be divided into four main zones, each characterised by particular lithostratigraphic units and in some cases also by style of deformation. Zones 3 and 4 are now divided into northern and southern segments, separated by the Gulf of Thailand. That the segments of each zone were at one time continuous is, however, suggested by the closely comparable lithologies of the same age in the two segments. Two to three hundred kilometers northwestward movement of the Malay Peninsula relative to Thailand would result in the segments becoming relatively continuous, supporting the suggestion of Ridd (1971) that major sinistral movement along faults of this trend lying west and northwest of the Gulf of Thailand took place in the Early Tertiary.

Zone 1. Shan States – northwestern Thailand – Peninsular Burma and Thailand – western Malaya.

Stratigraphic correlations suggest that throughout this zone similar geological events occurred at similar times during the Palaeozoic to Early Mesozoic, and that the zone lay on but near the margin of a continent not subject to magmatism after the Early Ordovician. Several widely distributed lithostratigraphic units can be recognised.

Acid volcanic rocks and quartzites of Late Cambrian to Earliest Ordovician age in the Shan States (La Touche, 1913) can be correlated with the Late Cambrian quartzites (Machinchang Fm) of the Langkawi Islands, and with the Cambrian Papulut quartzite and Late Cambrian to Ordovician acidic lavas and tuffs of western Malaya. Overlying limestones and shales of the Northern and Southern Shan States (Naungkangyi Stage) (La Touche, 1913; Myint Lwin Thein, 1973) extend through South Thailand and the Langkawi Islands (Setul Limestone) into north-western Malaya (Sungei Patani Limestone). Early Silurian graptolitic shales, widespread in the Shan States (Pang-hsa-pye Fm) also occur within an extensive unit in northwest Malaysia (Makang Fm) (Jones, 1973).

The Late Devonian to Early Permian succession of turbidites, pebbly mudstone and slumped units passing up into quartzites and shales in south Thailand (Phuket Gp, Garson, et al, 1975) extends northwards through Tavoy and Moulmein (Taunggyo Gp, Brunnschweiler, 1970) to northeast of Pyinmana in Upper Burma; southwards (Gobbett, 1973) similar facies extend into the Langkawi Islands (Singa Fm) and the mainland to the east (Kampong Sena Fm).

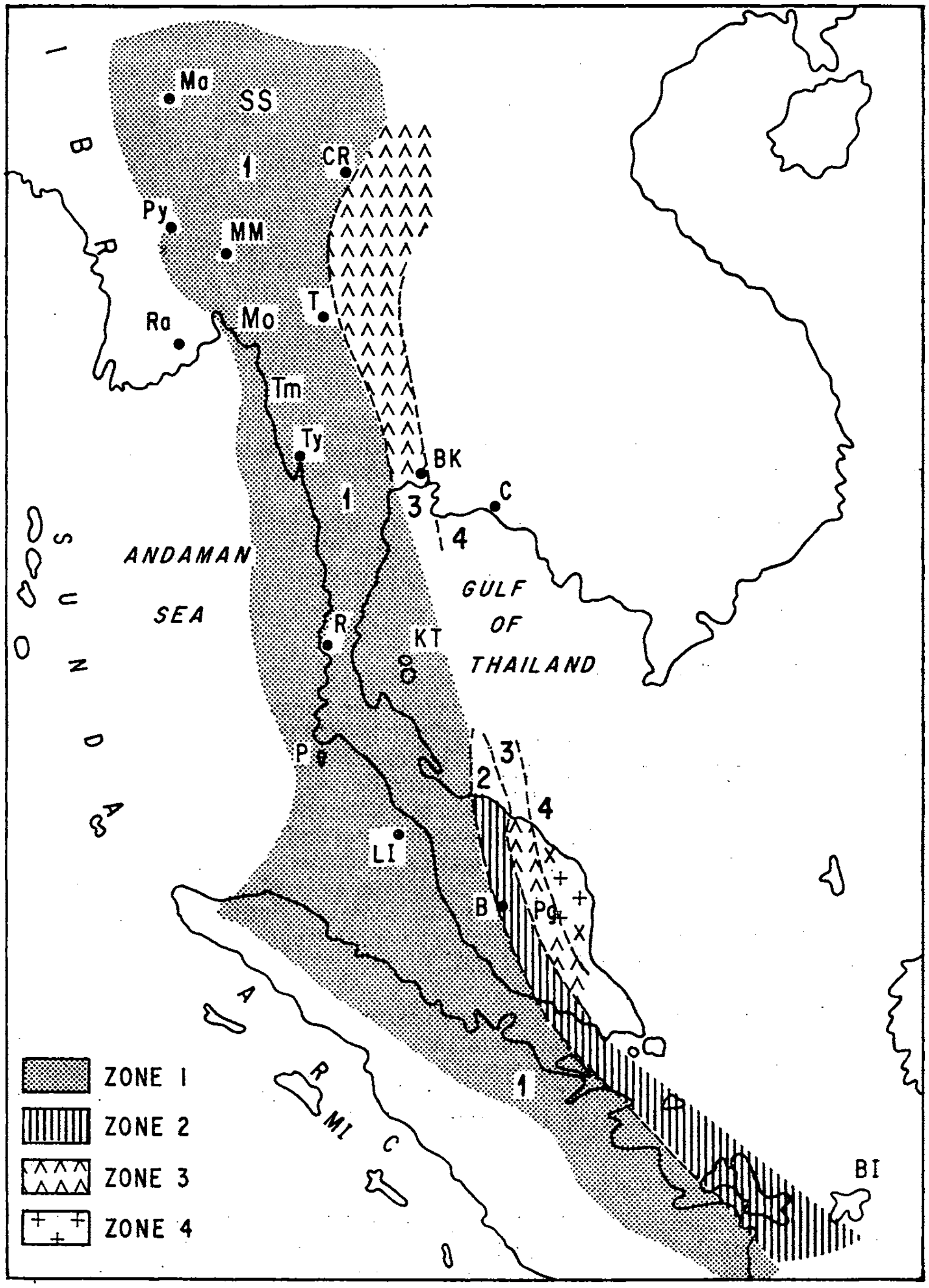

Fig. 2. Stratigraphic-structural zones. dots=Zone 1; vertical dashes=Zone 2; inverted v's=Zone 3; crosses=Zone 4. Bk=Bangkok; B=Bentong; BI=Billiton Island; C=Chantaburi; CR=Chiang Rai; IBR=Indo-Burman Ranges; KT=Ko Tao Island; LI=Langkawi Islands; Ma=Mandalay; MI=Mentawai Islands; MM=Mawchi Mine; Mo=Moulmein; P=Phuket; Pg=Pahang; Py=Pyinmana; Ra=Rangoon; R=Ranong; SS=Shan States; Ty=Tavoy; T=Tak; Tm=Tenasserim.

Middle or Upper Permian to Middle Triassic limestones and dolomites are the most morphologically distinct and widely traceable unit, forming the Shan Dolomite Group (formerly Plateau Limestone) in the Shan States (Amos 1975; Garson et al, 1976). Upper Permian carbonates continue through Tenasserrim and the Thai Peninsular as the Moulmein Limestone and into the Langkawi Islands (Chuping Fm) and Kedah (Kodiang Limestone); eastwards they extend into northwestern Thailand, and locally into Zone 3 in Malaya where they are of Late Permian to Early Triassic age (Ga Musang Fm). Tightly folded turbidites in the western part of the Shan States are possibly of the same age as the Middle to Upper Triassic flysch and cherts (Semmanggol Fm) in northwestern Malaya (Gobbett, 1973; Gobbett and Tjia, 1973; Burton, 1973).

Zone 1 includes the granitic plutons of the Central Belt, most of which are probably Late Triassic, and were therefore all emplaced within a broadly similar stratigraphic succession.

The eastern edge of Zone 1 extends through central Malaya, west of the Main Range Granites, and continues from Tak northeastwards through Chiang Rai to beyond the Laos border. Palaeozoic rock units east of this line are significantly different from those to the west.

Zone 2. The Eastern Foothills

Zone 2 is a relatively narrow and restricted zone lying immediately east of the Main Range granites, perhaps including roof pendents within the granites, and also occurring west of the granite in Malacca. The succession has been interpreted as an eugeosynclinal basin facies (Burton, 1970). Near Bentong schists, slates and minor amphiboles are overlain by more than 2000 m of flysch-type sediments; above this are radiolarian cherts, shales, quartzites and conglomerates and tuffs, but mappable units have not been recognised; in South Pahang the sedimentary rocks are around 5000 m thick. Lower Palaeozoic faunas are absent, but Devonian fossils in a shale suggest that the succession is of Lower and Early Upper Palaeozoic age. Further south in the same zone sandstones and schists are considered to be either Upper Palaeozoic to Triassic or Lower to Upper Palaeozoic (Jones, 1973).

Roof pendents in the Main Range show near-vertical to easterly dips (C.S.Hutchison, pers. commun., 1974), and in general the isoclinally folded succession east of the Range also dips easterly. Elongate bodies of basic and ultrabasic rock, mostly serpentinites but including peridotities, pyroxenites and dolerites, and possible basaltic lava flows, occur within this succession (Hutchison, 1973a, 1975).

Zone 3. Medial Malaya and north central Thailand

In general the succession within Zone 3 (medial Malaya and north central Thailand) contrasts with that of Zones 1 and 2 to the west in lacking Early Palaeozoic rocks and in the abundance of Late Palaeozoic and Triassic volcanic rocks. However as noted above Upper Permian to Lower Triassic limestones characteristic of Zone 1 occur locally west of Zone 3.

The southern, or Malayan, segment corresponds to the eugeosynclinal furrow of the west Malaysia geosyncline of Burton (1970, 1973). Calcareous rocks of Lower Carboniferous are present but shales with minor cherts are more abundant, particularly in the south, and contain Middle Permian to Middle Triassic faunas (Jelai Fm.) (Burton, 1973; Gobbett, 1973). Volcanic rocks are mostly marine and consist largely of rhyolitic pyroclastics although trachytic and andesitic lavas are locally abundant, mostly in the west. Pyroclastics are widespread in the Permian to Lower Triassic succession, and also occur in the Middle and Upper Triassic; rhyodacitic tuffs of probable Early Triassic age form a major unit in Johore (Hutchison, 1973a).

The Upper Palaeozoic and Triassic succession is isoclinally folded, mostly dip east and is overturned to the west; stratigraphic relationships within the succession are obscure. In the eastern part of the segment, 3000 m of Upper Triassic and Jurassic gently folded cross-bedded sandstones and conglomerates (Tembeling Fm), mostly red beds with red shales near the top of the succession, rest unconformably on Permian and Triassic rocks (Burton, 1973).

Metamorphic rocks occur in four main masses, the three southern ones in the west of the segment. The northernmost mass (Taku Schist) consists of schists, amphibolite, granite gneiss and minor serpentinite, metamorphosed in the almandine amphibolite facies. Further south two areas of migmatitic rocks (Stong and Benta Complexes are separated by an elongate belt of meta-rhyolite (Hutchison, 1973a).

Small north-trending granitic plutons of probable Triassic age and lacking tin mineralisation occur in the central part of the segment, and in the north granites continous with those of the Main Range are present.

In north central Thailand, small areas of Carboniferous to basal Permian sediments and acid volcanic rocks are overlain by Middle Permain massive limestone (Rat Buri Limestone) and other marine sediments. The thickest and most characteristic unit is the volcanic and sedimentary succession of Permian and Triassic age (Lampang Gp.) which extends northwards from near Tak to the Burma border. Volcanic rocks are most abundant in the Late Permian and Early Triassic, and consist mostly of rhyolites and silicic tuffs associated with cognlomerates and marine shales. These are overlain by a massive limestone unit which passes up into a red bed sequence(Pitakpaivan and Piyasin, 1971; Baum, et al, 1970).

Zone 4. Eastern Malaya – east central Thailand

The oldest rocks in the Malayan segment of Zone 4 are a thick succession of clastic sediments with predominant shales mostly of Lower Carboniferous to Middle Permian age and minor Carboniferous limestone (Gobbett, 1973). Late Palaeozoic rhyolitic and andesitic volcanic rocks occur both in the north and south of the zone, and in the southeast extensive Triassic rhyolites are present. The succession is folded and stratigraphic relations among the rock units are poorly understood (Hutchison, 1973a). The area probably underwent Late Permian and Triassic uplift but there is no evidence for post-Palaeozoic folding.

The East Central Thailand segment comprises a north-trending arcuate belt of tightly folded Devonian to Carboniferous clastic sediments and Permo-Carboniferous carbonates overlain by Triassic and younger sediments (Hughes and Bateson, 1967). In the possible northward extension of the segment in southwestern Laos, volcanic rocks are interbedded with Upper Palaeozoic sediments (Workman and Page, 1967). Volcanic rocks of Triassic age also occur in southwestern Laos, and Triassic acid porphyry intrusive rocks are present in Thailand.

Near Chantaburi the presence of Late Triassic plutons and absence of volcanic rocks suggest that the area forms an eastern extension of Zone 1. However, in the absence of known Lower Palaeozoic rocks, it is included in Zone 4.

EASTWARD SUBDUCTION AND CARBONIFEROUS TIN-GRANITES

The tin-bearing Late Carboniferous to Permian granitic rocks of eastern Malaya have been interpreted as a magmatic arc emplaced above a southwestward dipping Benioff zone with the subduction zone to the northeast (Hutchison, 1973b). However, northeastward subduction, with the subduction zone lying southwest of Zone 4, is suggested by the relative positions of Zones, 1, 2 and 3, by the lithology and deformation of Zone 2, and the variation in mineralisation and composition of plutons across Zones 3 and 4 as described below.

The eastern edge of Zone 1 is reasonably well defined by the eastern limit of several Palaeozoic rock units; Lower Palaeozoic units do not extend eastwards into Zones 2, 3 or 4, and in general the facies of Late Palaeozoic and Triassic sedimentary rocks in Zone 4 differ from those in the other zones. This, together with the widespread Late Permian-Early Triassic carbonate platform facies of Zone 1, suggests that the zone lay on the margin of a continent and that the eastern limit of the zone was probably the eastern continental margin during the Permian and Early Triassic.

In Zone 2 the association of tightly folded slates, radiolarian cherts and flysch, with verticle or overturned isoclinal folds, and minor ophiolitic bodies resembles that of modern outer arcs on the ocean side of active volcanic arcs, for example, the Late Mesozoic and Cenozoic rocks of the Mentawi Islands and Indo-Burman Ranges of the Outer Sunda Arc, and the Late Mesozoic to Eocene of Barbados. On modern outer arcs other than Barbados either ultrabasic or ophiolitic rocks commonly occur mostly on the volcanic arc side of the deformed sediments, and metamorphic rocks are found either associated with or on the landward side of the ultrabasics. This distribution is analogous to that of the ultrabasic rocks of Zone 2 and metamorphics of Zone 3.

Outer arcs are considered to have formed by scraping up above a subduction zone of oceanic crustal rocks and overlying pelagic and flysch-type sediments in successive imbricate thrust slices, with thrust or axial planes of isoclinal folds commonly dipping towards the volcanic arc. In Zones 2 and 3, the fold axes and thrusts commonly dip east, suggesting that during deformation the ocean lay to the west and the magmatic arc to the east.

The Late Carboniferous to Early Triassic plutonic rocks of Zones 3 and 4, interpreted together with the volcanic rocks as a subduction-related magmatic arc by Hutchison (1973b), are more silicic and potassic in the east of Zone 4, where most of the tin deposits occur. In Zone 3 there is no tin but considerable gold mineralisation. This variation in composition and in distribution of mineral deposits is analogous to that of a number of other arc systems where tin-bearing granites within continental crust are bordered by tin-barren plutons closer to the subduction zone, for example, Bolivia (Turneaure, 1970) and the Aleutian arc (Reed and Lanphere, 1973).

The above features of Zone 2 can most easily be explained by Late Carboniferous to Early Triassic eastward subduction of oceanic crust (Fig, 3 and 4), as suggested by Stauffer (1973) and later favoured by Hutchison (personal commun., 1975). The sub-

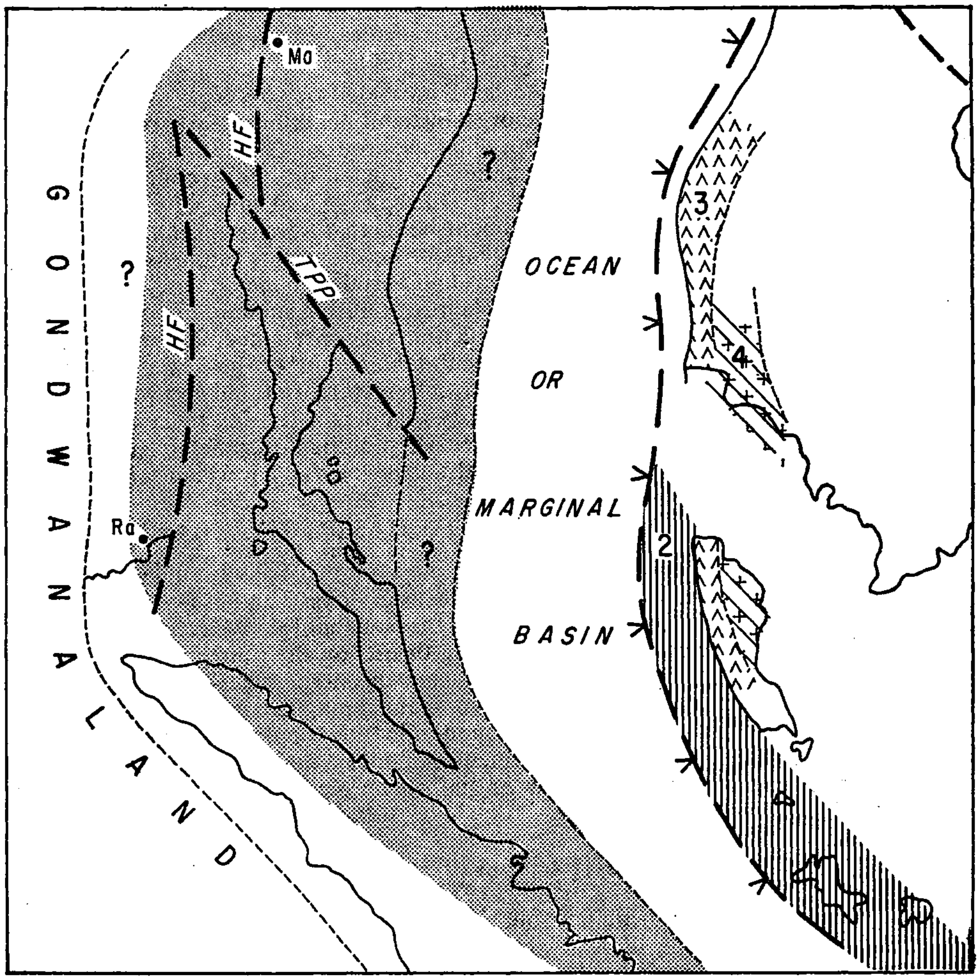

Fig. 3. Schematic palaeogeography: Late Permian; subduction of ocean floor, emplacement of Eastern Belt granites. Subduction zone; other symbols as in Figs. 1 and 2.

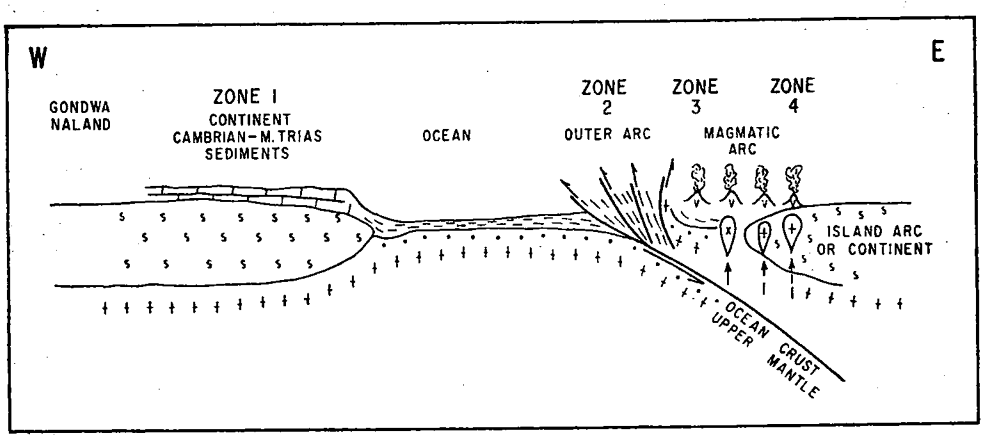

Fig. 4. Schematic cross-section: Late Permian; emplacement of Eastern Belt granites.

ducting ocean basin separated a passive or stable continental margin (Zone 1) from a subduction zone to the east (Zone 2); an outer arc trough (Zone 3) on the overiding plate lay between the zone and the magmatic arc situated mostly on continental crust further to the east (Zone 4, part of Zone 3). During eastward subduction in the Carboniferous and Permian, ocean floor sediments and crust were scraped up to form an outer arc (Zone 2). The Lower to Upper Palaeozoic deformed sediments of Zone 2, are at least as old as the Late Carboniferous and Permian magmatic arc. This is consistent with their having accumulated either before or during subduction, subsequently becoming tectonised in and above the subduction zone. Metamorphic rocks of Zone 3 can be interpreted either as uplifted continental 'basement' of the western margin of the overiding plate, or as uplifted Palaeozoic rocks metamorphosed as a result of subduction beneath them. By analogy with Tertiary granitic tin-bearing rocks of the Aleutians, and perhaps also of Bolivia, the eastward dipping Benioff zone above which the mineralised granites of Zone 4 were emplaced was inclined at a low angle.

CONTINENTAL COLLISION AND TRIASSIC TIN GRANITES

Termination of subduction towards the close of the Trias is suggested by the scarcity of Late Triassic and younger volcanic rocks in Zones 3 and 4. The Late Triassic was a period of major tectonism, indicated by the isoclinal folds affecting Early Triassic and older rocks in Zone 3, easterly dipping thrusts on the Langkawi Islands, and numerous other westerly directed overthrusts shown on the schematic cross section (Gobbett and Tjia, 1973). That orogeny accompanied magmatism is indicated by the change from predominantly marine to predominantly continental sedimentation the end of the Trias. In the northern segment of Zones 3 and 4 in Thailand the Late Triassic is characterised by the widespread Indosinian orogeny, recently reviewed by Workman (1974).

The granitic 'post orogenic' (Hutchison 1973a) batholiths of the Main Range and northwestern Thailand, occurring mainly in Zone 1 but extending locally into Zone 2, were emplaced during or immediately following tectonism and orogeny. These granitic rocks, although comparable in their high potash content and associated tin mineralisation to plutons on the continental side of some magmatic arcs, are associated neither with a parallel belt of granodioritic rocks, nor with eruptive rocks of similar age, and are thus unlikely to be related to subduction of oceanic crust. Their tectonic position relative to adjacent ultra-basic rocks and deformed sediments is comparable to that of Southwest England Hercynian tin-bearing granites, interpreted as post-collision plutons within continental crust of the subducting plate emplaced in a similar tectonic setting to the Tertiary granites south of the Indus suture in the Himalayas (Mitchell, 1974).

The cessation of volcanism, orogeny with westerly directed overthrusts, and emplacement of granitic plutons can be explained by a continental collision in Malaya and northern Thailand during the Late Trias (Fig. 5,6). The continental margin of Zone 1, separated from the subduction zone and related outer arc (Zone 2) during the Carboniferous and Permian, approached the subduction zone and overiding plate of Zones 3 and 4 during the Trias, and eventually collided with and underthrust the outer arc and overiding continental margin to the east. Permian to Middle Triassic carbonates present locally in Zone 3 in Malaya are possibly the eastern margin of the underthrusting continent of Zone 1, elevated following underthrusting beneath Zone 2.

The distribution of tectonic units in the region during the Late Trias hsa been compared to that of the Alpine chains (Aubouin, 1965) during the Late Mesozoic and

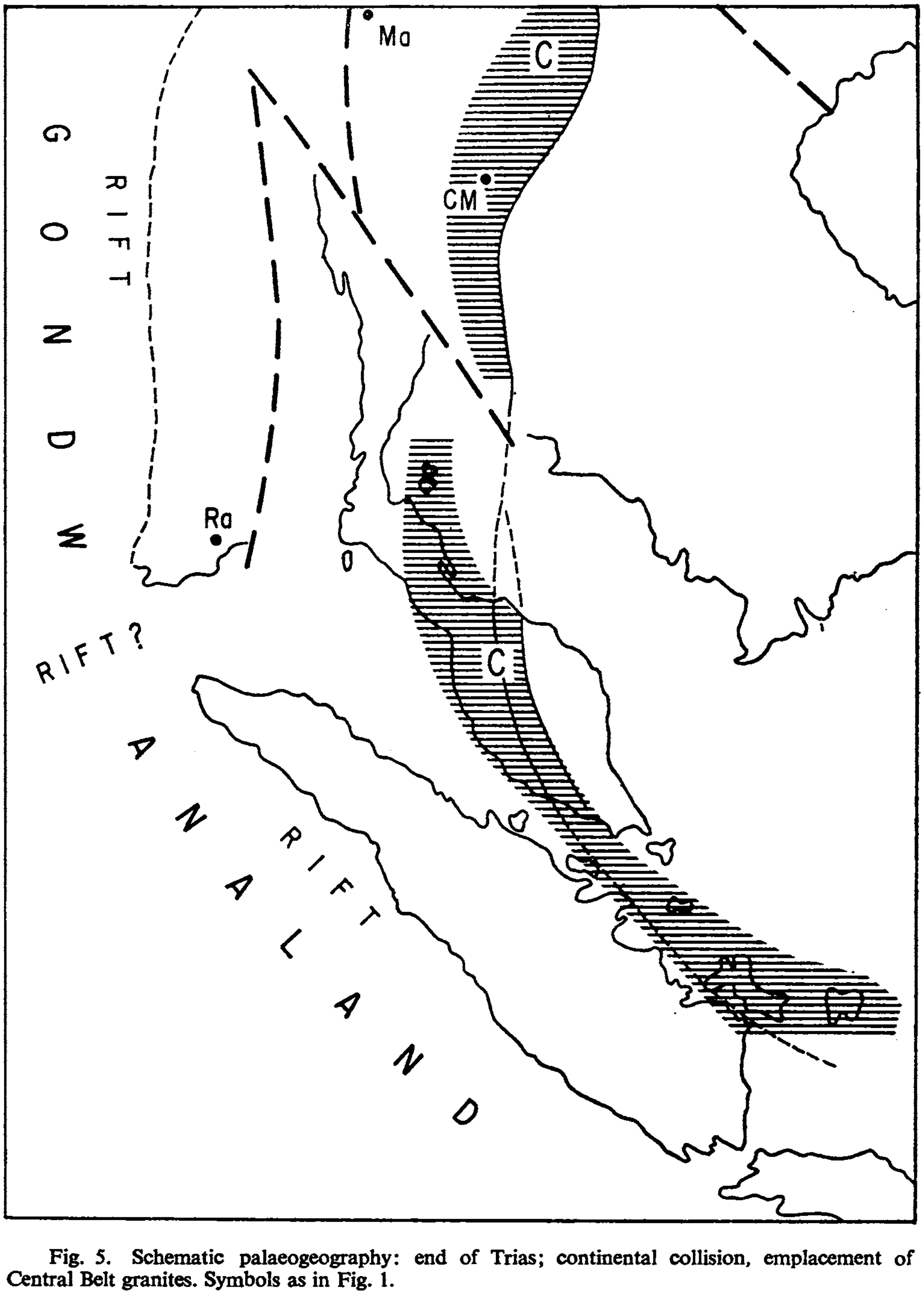

Fig. 5. Schematic palaeogeography: end of Trias; continental collision, emplacement of Central Belt granites. Symbols as in Fig. 1.

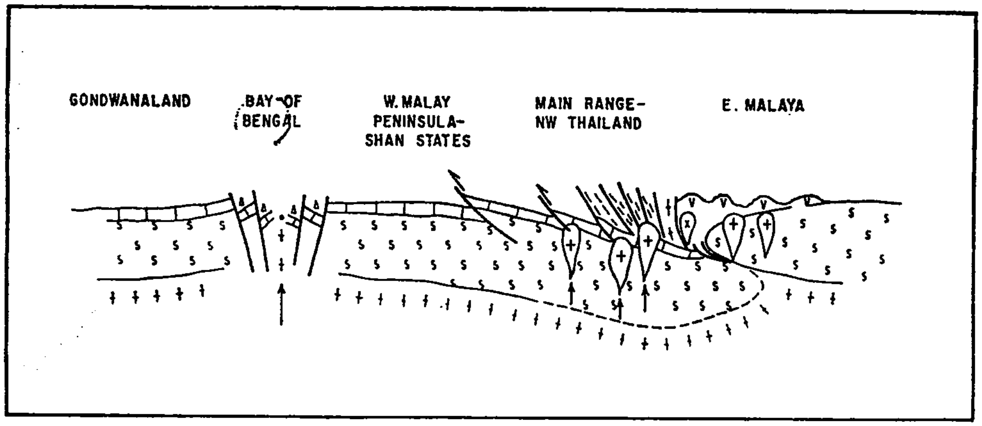

Fig. 6. Schematic cross-section: end of Trias; emplacement of Central Belt granites. Age of rifting of Southeast Asia from Gondwanaland is probably end Triassic or Carboniferous.

Early Cenozoic (Burton, 1967, 1970; Jones, 1973). Zone 1, comprising the shelf and miogeosynclinal succession, corresponds to the Alpine foreland and miogeosyncline on the external side of the orogenic belt or geosyncline; Zone 2, part of the eugeosynclinal furrow of Burton (1970), corresponds to the flysch-ophiolite and flysch nappe zone of the Alpine chains, and Zone 4, the eugeosynclinal ridge of Burton, occupies an equivalent position to the cordillera on the internal side of the Alpine chains. As the Alps themselves, and the geosynclinal models based on them, can now be interpreted in terms of collision tectonics, the geosynclinal interpretation of the sedimentary and tectonic belts in the four zones described here can easily be reconciled with the plate tectonic subduction and collision model.

The extensive pre-collision subduction-related magmatism of Zones 3 and 4 is absent or poorly developed in the equivalent tectonic positions in the Alps, and equivalents of the Late Triassic collision-related granites of Zone 1 are represented only by minor post-tectonic granitic bodies (Adamello, Bergamo granites) of the Alpine chains. However, in the Himalayan collision belt abundant Neogene potassic igneous rocks in Tibet north of the Indus suture have been interpreted as the result of collision of India with Asia (Dewey and Burke, 1973), and Tertiary granites in the Himalayas south of the Indus suture (Gansser, 1964; Hamet and Allegre, 1976) occupy a tectonic position broadly analogous to that of the Main Range Granites of Malaysia.

The large volume of granites in the Malaya - Thai collision belt can possibly be explained if underthrusting in the collision belt was not restricted to the collision or suture zone beneath Zone 2, but also took place along thrust zones within the underthrusting continent of Zone 1, as indicated on the schematic cross section (Fig. 4). These postulated thrusts are then analogous to those present in the underthrusting Indian continent south of the Indus suture and Late Tertiary granites of the Himalayas. Generation of granitic magmas in this type of setting is presumably related to tectonic thickening and depression into the mantle of lower continental crust.

The southwestern termination of the Western Belt of tin-bearing granitic rocks in Billiton Island coincides approximately with the southwestern limit, between Sumatra and Java, of continental crust of Zone 1 on the subducting plate. Beyond Billiton Island subduction of ocean floor may have either continued or ceased, but no continental collision took place.

TRIASSIC-EARLY JURASSIC BLOCK FAULTING AND POSSIBLE RIFTING

Although it is widely accepted that Southeast Asia was attached to another continental mass, probably within Gondwanaland, during much of the Palaeozoic and possibly the Early Mesozoic, the age of separation and the present position of this continental margin are uncertain (Stauffer, 1973).

Stratigraphy and sedimentary facies in Zone 1 provide some evidence for the age of separation. In the Shan States the Late Permian and Early Triassic carbonate sedimentation was succeeded by later Trias or Early Jurassic evaporite sedimentation and accumulation of thick clastic carbonate red beds, red siltstones, limestones lacking marine faunas and local carbonaceous shales (Kalaw Red Beds and Namyau Fm). Rather similar red beds comprise the Tembeling Fm in Malaya. These facies could be explained as the result of break up of the Triassic carbonate platform with block faulting and uplift of Western Burma and perhaps Sumatra as they rifted and separated from Gondwanaland in the early Jurassic. Possibly western Burma and the Mentawai Trough west of Sumatra formed two arms of a trilete rift junction, with a third (failed) arm extending southwestwards into Gondwanaland (Fig. 5,6).

Alternatively, a pre-late Triassic age for the rifting is suggested by the presence of a thick flysch-type succession of Late Triassic age in the east of the IndoBurman Ranges (Gramman, 1974), which implies the presence of a continental margin or fault trough rather than a stable continental interior to the west of Burma in the early Mesozoic. Early Carboniferous rifting could best explain the thick pebbly mudstones and flysch type sediments of Carboniferous age in Zone 1 although these could have been related to rifting to the east rather than west of Zone 1.

The association elsewhere of tin-bearing granites with aborted rift zones and in some cases with rifts which subsequently developed into marine basins, suggests that similar granites might have been emplaced during the Carboniferous or Early Mesozoic rifting in Burma or Sumatra. However, in the west of Zone 1 igneous rocks of this age appear to be scarce or absent; minor Jurassic volcanic rocks occur in Zones 1and 3 in Thailand, but there is here little evidence of contemporaneous rift tectonics.

EASTWARD SUBDUCTION AND CRETACEOUS-EOCENE TIN GRANITES

The tin-bearing granitic rocks of the Western Belt (Shan Scarp-Tenasserim-Phuket) are mostly of Cretaceous to Eocene age. The abundance of potash-rich granite plutons and absence of associated volcanic rocks could be explained if, like the Central Belt to the east, they were emplaced in a continent-continent collision zone. However, there is no tectonic evidence for a collision and no evidence of a continent to the west of Burma during the Eocene which this collision would require. It is therefore inferred here that the granites were emplaced in continental crust above a shallow dipping Benioff zone, in an analogous tectonic setting to the tin-bearing plutons of Alaska, and to the Carboniferous-Early Triassic granites of Zone 4 described above.

As there is no evidence of a Late Mesozoic subduction zone east of the granite Belt, the most probable position of the zone was to the west beneath the present-day outer arc of the IndoBurman Ranges and Andaman-Nicobar Islands. The Ranges include Triassic sediments in the east (Gramman, 1974) but consist mostly of a very thick folded and cleaved succession of flysch-type sediments and mudstones, probably of Cretaceous to Early Eocene age, repeated by faults and mostly dipping east and striking parallel to the length of the Ranges (Brunnschweiler, 1966; Win Swe, in press).

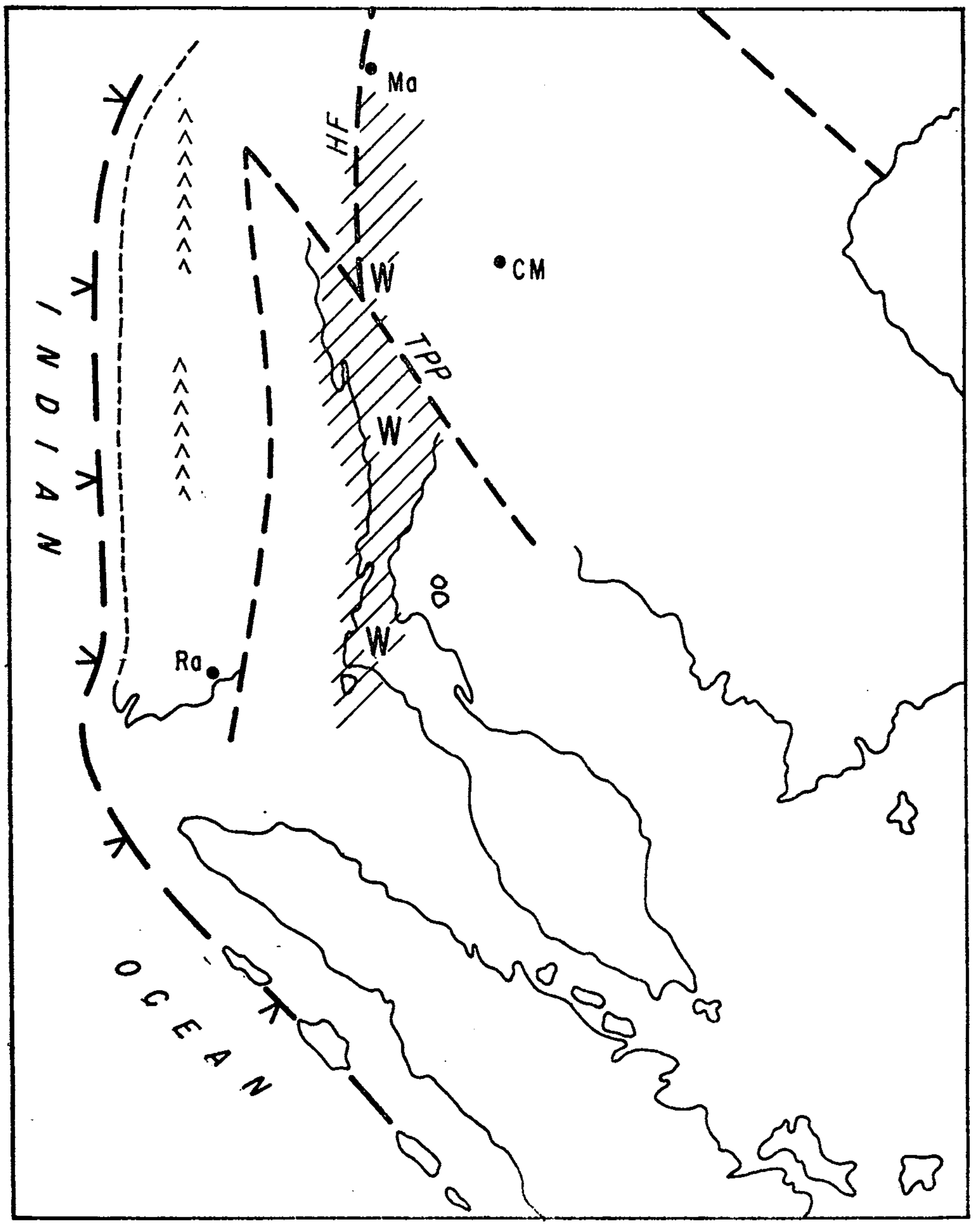

Fig. 7. Schematic palaeogeography: Early Eocene; eastward subduction of Indian Ocean, emplacement of Western Belt granites. V—Burma magmatic arc; other symbols as in Figs. 1 and 3.

In the east serpentinites, dunites pyroxenites and pillow lavas are probably thrust westwards over the flysch together with metasedimentary rocks (Brunnschweiler, 1966). The Ranges can now be interpreted broadly as an imbricate stack of sediments scraped up above a subduction zone, and underthrust eastwards beneath ophiolites and the leading edge of the western overiding plate. The Mesozoic to Early Eocene age of the deformed sediments is compatible with Cretaceous and Eocene subduction (Fig.7 and 8).

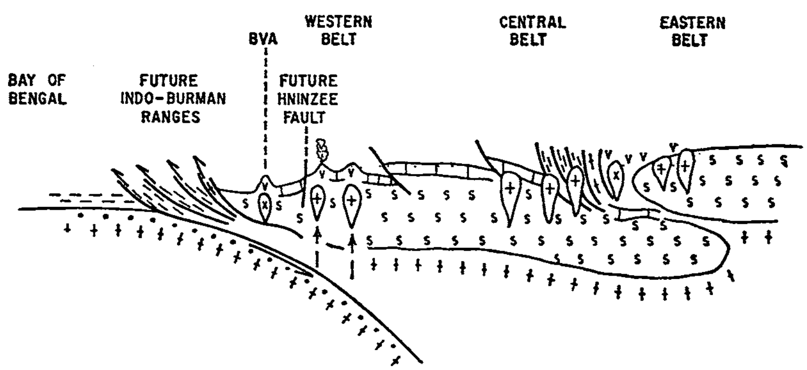

Fig. 8. Schematic cross-section: Early Eocene; emplacement of Western Belt granites. BVA—Burma magmatic arc.

Relative to the granitic rocks the positions of the subduction zone was different from the present position of the Andaman-Nicobar arc, partly because of subsequent inferred sinistral movement along the 3 Pagodas Pass Fault and faults of similar trend to the north and south, but mostly because of probable dextral movement along the Hninzee-Sagaing Fault.

The Hninzee-Sagaing Fault (Dey, 1968; Win Swe, 1972) extends from west of Mandalay along the Shan Scarp, east of the Pegu Hills, and thence probably southwards towards northern Sumatra (Fig. 7 and 8). It shows considerable evidence of Late Cenozoic dextral movement (Win Swe, 1972), and offsets in structural units of northern Burma suggest that at least 300 km of dextral movement has taken place in the Late Cenozoic. Thus since the Oligocene or earlier, western Burma has behaved as a separate plate between the Indian plate to the west and the Asian plate to the east.

Before this dextral movement, the Andaman Basin was occupied by the present Pegu Yomas, and the Cretaceous magmatic belt of northern Burma lay west of the Western Granitic Belt. Therefore in the Late Mesozoic and Early Eocene the tin-bearing granites were bordered on the west by a predominantly andesitic and granodioritic magmatic belt; west of this lay a sedimentary trough and the rising outer arc of the Indo-Burman Ranges above or immediately east of the subduction zone.

The granodiorite and granitic magmatism need not have been contemporaneous although both were emplaced within the Cretaceous to Eocene interval. Possibly the granite belt magmas were emplaced above a shallow-dipping Benioff zone, which either previously or subsequently dipped at a steeper angle and resulted in emplacement of the granodioritic plutons (Mitchell and Garson, 1972; Mitchell, 1973).

SOURCE OF TIN AND REGIONAL CONSIDERATIONS

The above speculative interpretation explains the granitic rocks in the three belts as subduction-related magmas emplaced within continental crust of the overiding plate (Eastern Belt), syn-collision magmas emplaced in continental crust of the subducting plate following closure of the ocean basin and continental collision (Central Belt), and subduction-related magmas emplaced within continental crust of the overiding plate above subducting Indian Ocean floor (Western Belt). The abundance of tin in the region is evidently closely related to the emplacement in adjacent belts of these subduction and collision-related silicic and potassic magmas and related volatiles able to transport, concentrate and deposit the metal.

Possibly the tin was present in initial pre-Carboniferous concentrations in the lower crust, and was further concentrated by the granites, although there are two arguments against this hypothesis. Firstly, detrital tin has not been reported from any of the lower Palaeozoic clastic sedimentary units in the region. Secondly, Triassic closure of the ocean basin between the two areas of continental crust now occupied respectively by the Eastern and Western Belts of tin-bearing granites implies that prior to this closure any pre-existing concentrations of tins were separated by an area of oceanic crust. However, it is possible that this crust occupied a marginal basin rather than a major ocean basin, (P. Stauffer, pers. commun., 1975) and that the marginal basin opened in the Carboniferous following rifting of a previously single continent, approximately along the line of the subsequent collision zone. Deposition of the widespread Carboniferous clastic unit of Zone 1 could perhaps have been related to this rifting. In this case, a single pre-Carboniferous area of continental crust with abnormal concentrations of tin would have been split into two continental fragments which were subsequently welded together in the late Trias collision.

In the absence of both evidence of an initial crustal concentration of tin, and any explanation for the origin of this hypothetical concentration, it seems more probable that the metal was present only in 'average' trace amounts in the crust, and that its abundance is related directly to emplacement of the granitic magmas and associated volatiles.

Permian-Triassic eastward subduction of ocean floor beneath Zone 2 was contemporaneous with subduction beneath the future Red River Fault between Southeast Asia and China (Hamilton, 1973) and northward or northeastward subduction beneath the future Indus suture; possibly the three subduction zones met at a migrating complex triple junction situated east of Assam. Late Triassic continental collisions terminated subduction beneath Zone 2 and along the Red River Fault, but subduction probably continued along the future Indus suture. In the Cretaceous and perhaps Eocene, prior to dextral movement along the Hninzee-Sagaing Fault, this subduction zone was possibly joined to that of the Indo-Burman Ranges and Outer Sunda Arc by a subduction zone situated along the arcuate belt of ophiolitic rocks of unknown age (Hutchison, 1975) in northeastern Burma.

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