Geol. Soc. Malaysia, Bulletin 28, November 1991; pp. 63 - 95

Cross-border correlation of geological formations in Sarawak and Kalimantan

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Abstract: Recent geological mapping by an Australian/Indonesian team in West and Central Kalimantan has resulted in a revised stratigraphy for the Paleozoic-Tertiary igneous and sedimentary successions in terms of (1) Continental Basement and Platform (Shelf) Sedimentary rocks, (2) Continental Arc intrusives and volcanics, (3) Oceanic Basement and overlying sedimentary rocks and (4) Foreland Rocks (Post-tectonic igneous rocks and sedimentary basins, (5) Tectonic melange and (6) Surficial deposits. Correlation charts are presented to reconcile the stratigraphy across the international border between Sarawak, East Malaysia, and Kalimantan, Indonesia.

INTRODUCTION

The stratigraphy of Central and West Kalimantan has been described recently by Pieters *et al.* (1987), Pieters & Supriatna (1989a) and Williams *et al.* (1988), and for West Sarawak by Tan (1986). All authors have correlated certain individual stratigraphic formations, particularly where they are common to both Sarawak and Kalimantan but no detailed cross-border correlation has been presented to date. This paper attempts to provide a regional correlation between Central and Northwest Kalimantan and South and West Sarawak (Table 1) and, as a result of the new data, to indicate fundamental changes to the interpretation of the geology of this part of Borneo. The completed Indonesian-Australian Geological Mapping Project (IAGMP) covers an area of some 850 km long and 250-300 km wide in Central and West Kalimantan (Pieters & Supriatna, 1989b); twelve preliminary geological maps at 1: 250,000 scale (see key to Fig.1) and a 1:1 million compilation map are published and one 1:250,000 map is in preparation.

Devonian

The oldest fossiliferous rocks in Borneo have been recorded only from one locality in Sg. Telen (116°E, 1°N) in central Borneo (Rutten, 1940). They are composed of Devonian coralline limestone which occurs as allochthonous blocks of dark, recrystallised limestone within a highly disturbed melange zone (Pieters, & Supriatna, 1989b). No autochthonous counter-parts are known. *Heliolites porosus* is clearly identifiable in thin sections of recrystallised limestone, locally impregnated with black matter (?carbon) and the internal structure of the coral is well preserved; *Clathrodictyon cf. spatiosum* occurs in thin and

Presented at GSM Petroleum Geology Seminar 1990

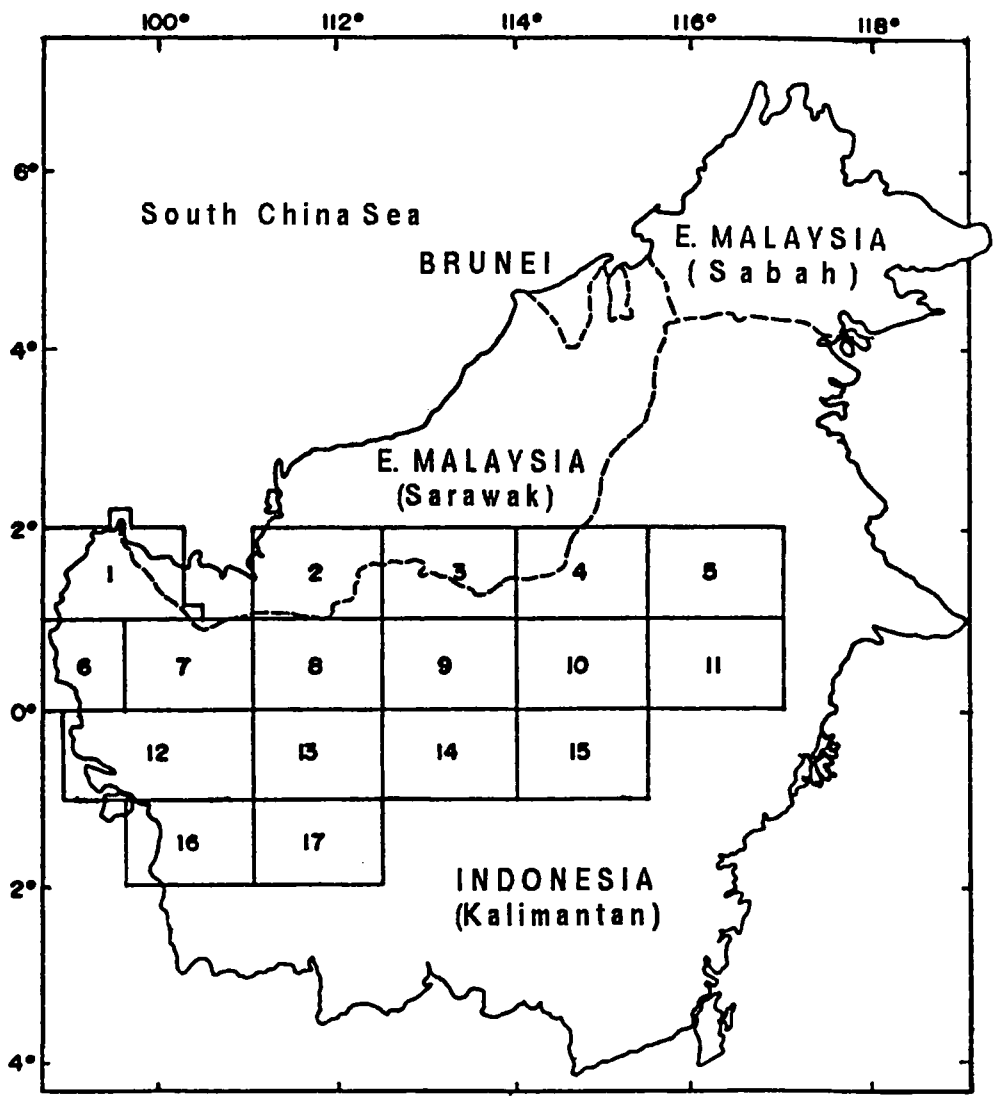
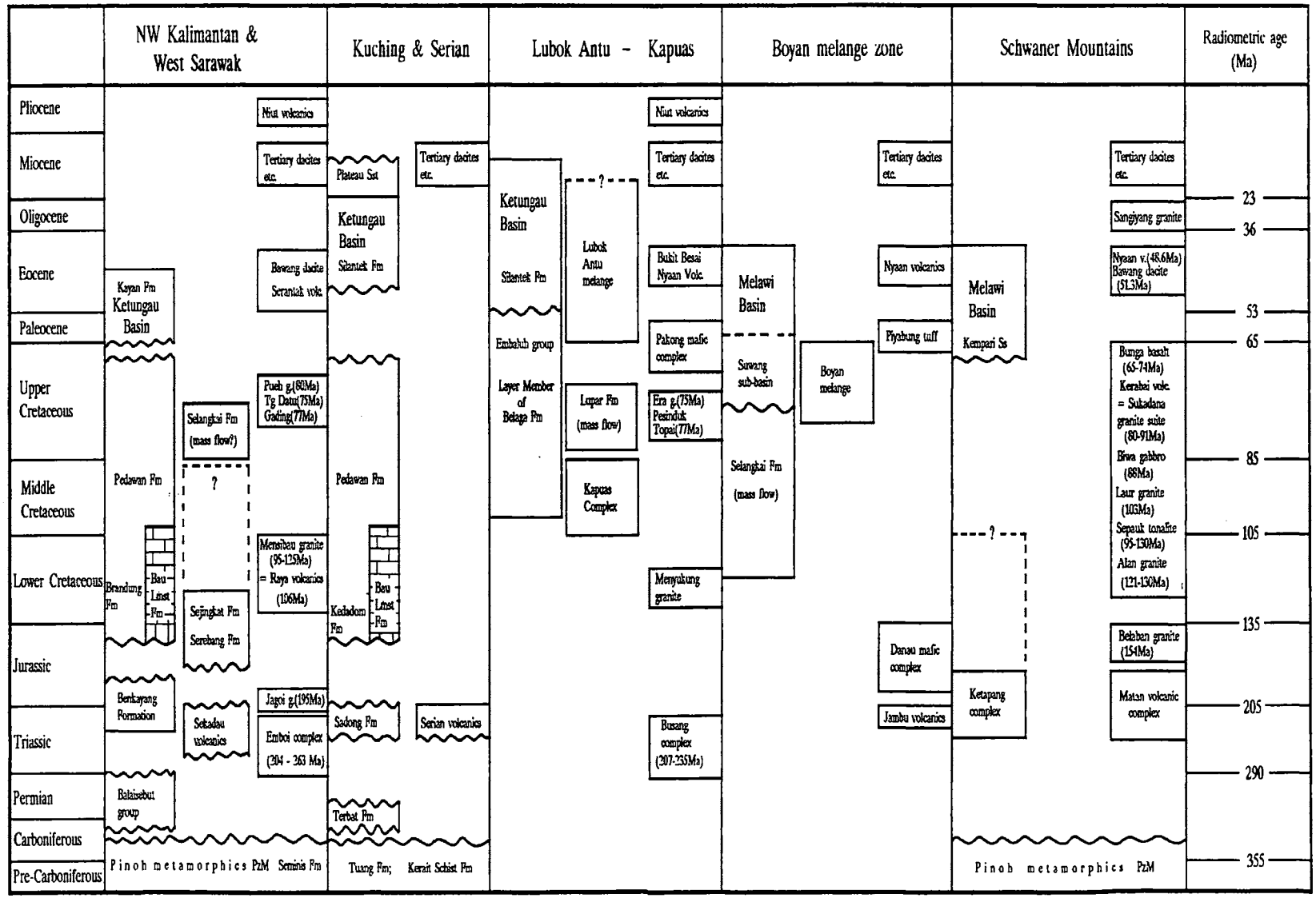


Figure 1: Index of 1: 250,000 geological maps, West, Central and East Kalimantan, Indonesia (after Pieters & Supriatna, 1989a). Key: 1. Sambas & Siluas 2. Nanga Obat 3. Peg. Kapuas 4. Llong Nawan 6. Singkawang 7. Sanggau 8. Sintang 9. Putussibau 10. Long Pahangai 12. Nangataman 13. Nangapinoh 16. Ketapang

Table 1. General correlation chart of the stratigraphy of west, central and east Kalimantan, Indonesia and west Sarawak, Malaysia.



polished section (Rutten, 1940). This isolated occurrence presents a tantalizing enigma which remains to be explained satisfactorily. The nearest Devonian rocks are in NW Malaya and comprise shelf limestones and locally, redbeds (Hutchison, 1989).

"Continental Basement" and the Sunda Shield

It has been customary to refer to the largely granitic terrain occupied by the Schwaner Mountains in west Borneo as "continental" basement which forms part of a larger area termed "Sunda Shield" implying a largely ancient continental core. Recent chemical and radiometric data now show that there would appear to be no ancient cratonic continental rocks in that part of West Borneo known as the "Sunda Shield". The Schwaner Mountains composite batholith forming the largest plutonic mass in Borneo is a Cretaceous volcano-plutonic arc which is linked probably to the Boyan and Lubok Antu - Kapuas subduction zones 100 - 200 km to the north. The granitoids intrude the Pinoh metamorphics, the oldest autochthonous rocks which have not been dated radiometrically but are thought to be Carboniferous-Permian or earlier in age. The term "Continental Basement" would therefore appear to be a misnomer as is the term "Sunda Shield" for which Haile (1969) suggested the term "west Borneo hinterland". Perhaps a more appropriate term would be "Pre-Carboniferous Basement" to remove the continental affiliation and the term "Sunda Shelf" would be more appropriate than "Sunda Shield" as the area comprising Malaya, west Borneo and between has been emergent during the late Cenozoic. Although a small number of late intrusions tend to be alkaline, there is a difference between the onshore, predominantly I-type (Chappell & White, 1974), calc-alkaline, volcano-plutonic rocks of West Kalimantan and the apparently rift-related granites on the islands further west in the South China Sea (Karimata, Natuna and Anambas) which are distinctly alkaline and give slightly younger radiometric ages. Hutchison (1989) questions whether the Late Cretaceous radiometric ages obtained from the rift-related granites represent emplacement ages or a subsequent hydrothermal modification and remarks that the Late Cretaceous epizonal granites may be included in the Late Yenshanian rifting province which extends from south China to the environs of the South China Sea.

?Carboniferous or Pre-Carboniferous Basement

The term "Pre-Carboniferous Basement" refers to a sequence of regionally metamorphosed, schistose rocks of largely indeterminate origin occurring as relatively small, detached inliers in Kalimantan and West Sarawak. The oldest *in situ* rocks in Kalimantan (and probably Borneo) are the Pinoh metamorphics which outcrop in a 50 km-wide latitudinal belt extending discontinuously across the northern flank of the granitoid Schwaner Mountains from near Pontianak eastwards to the margin of the West Kutei basin (Fig. 1). A smaller area, mapped as Seminis Formation, occurs in NW Kalimantan

South of Sambas. The Pinoh metamorphics comprise slate, hornfels, phyllite, quartzite, schist, gneiss, migmatite and minor metavolcanics and amphibolite; some areas contain distinctive calcareous psammites and pelites. The type locality is situated in the Nangapinoh quadrangle, in the area of Sg. Pinoh (111°45'E, 0°30'S) (Amiruddin & Trail, 1989). There are two metamorphic grades, a low, greenschist facies and a higher, garnet facies. In addition to the regional metamorphism, thermal metamorphism related to the subsequent intrusion of Schwaner Mountains granitoid plutons has imposed an imprint in the form of andalusite hornfels. The strike of the schistosity and cleavage ranges from ENE through E to SE and trendlines on aerial photographs trend SE. Major faults have been mapped between metamorphics and plutons in several places and trend generally ESE and SE. Others trend S and a few trend NE. Contacts between the Pinoh metamorphics and other pre-Mesozoic rocks are faulted and contacts between Tertiary sediments are moderately dipping unconformities (Amiruddin & Trail, 1989).

The Seminis Formation is poorly exposed (Rusmana *et al.*, 1989) and comprises well-cleaved slates and phyllites cut by quartz veins and indurated, micaceous meta-sandstones and there are indications of deep water turbidites. Intruding and overlying the Seminis Formation are the widespread intermediate to basic Sekadau Volcanics which are thought to be equivalent to the Late Triassic Serian Volcanics in Sarawak. In mapping the Sambas-Siluas 1:250 000 quadrangle, Rusmana *et al.* (1989) remark that the age of the Seminis Formation is poorly constrained and assumed tentatively a ?Late Paleozoic-Early Triassic age based on structural and stratigraphic evidence. They state that the Seminis Formation is overlain unconformably by relatively unmetamorphosed, mainly tuffaceous and carbonaceous clastics and possible turbidites of the ?Late Triassic to Lower Jurassic Bengkayang Group which would indicate that the Seminis Formation is older than Late Triassic. Rusmana *et al.* (1989) also suggest that some of the volcanics in the southern part of Sambas may be related to the Lower Cretaceous Raya volcanics (marked as Kl4 on 1:1 million map) which outcrop widely to the E and SE. Perhaps the Seminis Formation is equivalent to the pre-Lower Carboniferous Tuang Formation around Kuching which has deep water affinities. The inter-relationships of metasediments and volcanics and detailed nature of the various volcanic sequences associated with the Seminis Formation need to be pursued further to establish a reliable age and stratigraphic position for the Seminis Formation. For the purposes of the present correlation, the Seminis Formation is regarded as Lower Carboniferous or older, a stratigraphic position used on the IAGMP 1:1 million preliminary geological map.

The age of the Pinoh Metamorphics is uncertain; no critical contacts have been found with rocks other than Cretaceous granitoids and it has been assumed that the stratigraphic position is older than Lower Triassic and most likely Lower Carboniferous or pre-Carboniferous. No radiometric dating has been done, probably due to the difficulty in finding suitable samples free of the

thermal effects of later plutonism.

In Sarawak, Pre-Carboniferous strata are confined to two Formations, the Tuang and the Kerait Schist. The former occurs in a more or less contiguous area around Kuching and to the south around Kuap and consists of highly deformed, greenschist-grade metamorphic rocks comprising basic and possibly ultrabasic rocks together with boudinaged metasandstones interbedded with graphitic phyllites. The metasandstones show graded bedding and are probably turbidites (Hon, in manuscript). The Formation is thought to be Pre-Carboniferous on the evidence of a dubious fossil tentaculid. The Kerait Schist Formation (Pimm, 1965) occurs as inliers in relatively small isolated areas E and SE of Serian and comprises muscovite-quartz schists and muscovite-tremolite-quartz schists. It has not been dated and is thought to be contemporaneous with the Tuang Formation. There would appear to be no rocks equivalent to the Kerait Schist Formation in Kalimantan.

The turbiditic and associated basic / ?ultrabasic nature of the Tuang and Seminis Formations suggests that they may have been formed in an oceanic environment; certain aspects of the Pinoh metamorphics could also be classified as oceanic especially if the quartzites show grading and the meta-volcanics,amphibolites and migmatites are derivatives of sub-seafloor metamorphism as Hutchison & Dhonau (1971) have proved in eastern Sabah.

Permo-Triassic igneous and metamorphic rocks

A number of Permo-Triassic igneous and metamorphic fault-bounded inliers from 10-40 km across occur in a latitudinal belt just north of the equator. The Embuoi Complex (PTR on the 1:1 million geological map) forms part of a Permo-Triassic igneous assemblage in the Sanggau quadrangle (Supriatna *et al.*, 1989a, b) and comprises basic volcanics, amphibolites and schists, the latter being possibly mylonitised granitic rocks as there are zones of intense shearing within the Complex. The rocks are strongly foliated. K-Ar dating indicates two separate crystallization events, a primary one 263-230 Ma, Late Permian-Early Triassic, and a secondary recrystallization from 214-201 Ma, Late Triassic-Early Jurassic (Bladon *et al.*, 1989). In the east, more acidic igneous and metamorphic rocks are encountered in the Long Pahangai (Abidin & Sudana, 1989) and Putussibau (Pieters *et al.*, 1988; Surono & Noya, 1989) quadrangles where they are mapped as the Busang Complex comprising foliated granitic rocks together with schists, gneiss and quartzite. K-Ar determinations on granite rocks range from 207-235 Ma. The Busang Complex is fault-bounded against less metamorphosed Cretaceous Selangkai Formation and forms a structural complex of uncertain origin. The Busang-Murung Crescent containing the Busang Complex (Doutch, H.F. *in:* Abidin & Sudana, 1989) and the Kebayan (Embuoi Complex) inliers are positioned at either end of the Semitau inlier (Doutch, H.F. *in:* Abidin & Sudana, 1989) and Trail (pers. comm. Trail to Doutch *in:* Abidin & Sudana,1989) noted the possibility that they are detached

bodies 'floating' within the melange. If so, the bodies are extremely large, being up to 40 km across.

The genetic origin of the rocks forming the Embuoi and Busang Complexes is obscure and in the absence of geochemical data, the structural units are classified as undifferentiated basement. Further petrologic and chemical studies may show that they were originally ultrabasic complexes as in eastern Sabah where migmatitic rocks are derived from ophiolite suites by sub-seafloor metamorphism (Hutchison & Dhonau, 1971). If so, they could be associated with the Danau Ultramafic Complex or be genetically allied with the Late Triassic Serian and Sekadau Volcanics further west.

SHELF SEDIMENTARY AND VOLCANIC ROCKS

?Carboniferous-Permian metasediments

The oldest fossiliferous rocks found *in situ* in central and west Kalimantan are located in structural inliers located south and SSE of Kuching and 30 km south of the border and termed the Balaisebut Group (CP) in the Sanggau quadrangle. The Group comprises locally carbonaceous slate and phyllite, schist and quartzite and minor limestone, marble and chert. These rocks are ascribed to shelf deposits rather than the IAGMP designation of platform sediments which implies deposition over a much wider area. The metamorphic grade is garnet-greenschist and there are several phases of deformation each with a cleavage. Zeijlmans van Emmichoven (1939), identified Permo-Carboniferous fusulinid faunas as well as Late Triassic faunas but neither has been reconfirmed in the recent mapping. The total thickness is estimated to exceed 1,000 m.

The equivalent of the Balaisebut Formation in Sarawak is the less-metamorphosed Terbat Formation (Pimm, 1965), a fusulinid calcareous succession of restricted extent close to the border. The rocks of the Terbat Formation are mostly recrystallised, dolomitised and silicified, moderately fossiliferous limestones with thin interbeds of highly sheared sericitic shale. The original sediment was composed of a mixture of calcareous mud and fossil debris in a shallow water, shelf environment devoid of terrigenous material. Although some of the fossils are distorted by subsequent tectonism, the overall metamorphic grade appears to be much lower than that in the Balaisebut Group. The rocks are generally steeply dipping and the total thickness is of the order of 600 m.

There are no faunal comparisons with the Terbat Formation fusulinid assemblages described from Sarawak (Sanderson, 1964), but it seems likely that they could be equivalent although with slightly different age ranges. The paleo-environment of both Formations is largely shallow marine. The differences in metamorphic grade and possibly also structural style between the Balaisebut

and Terbat Formations may perhaps be related to the Upper Permian-Middle Triassic orogeny, during which the igneous and volcanic rocks of the Embuoi Complex and Sekadau volcanics were emplaced. The orogeny seems to have had a greater intensity in Kalimantan.

Two major unconformities within the Paleozoic-Lower Mesozoic of Sarawak (Pimm, 1965), pre-Permo-Carboniferous and Upper Permian-Middle Triassic, are thought to exist in the Sanggau area of NW Kalimantan (Supriatna *et al.*, 1989b) but the nature of the unconformities above and below the Balaisebut group is unclear as contacts with the Embuoi Complex are invariably faulted.

Upper Triassic volcanic rocks

The Serian Volcanic Formation comprising generally andesitic lavas and tuffs occurs widespread in Sarawak (Wilford & Kho, 1965; Pimm, 1965) and continues south for 10 km across the border into the Sanggau quadrangle. The silicified Jambu Volcanics are lithologically similar to the Serian Volcanics and occur at the western end of the Boyan zone some 25-50 km to the SE. The relationship of the Serian and Jambu Volcanics with older units in Kalimantan is unknown but in Sarawak, there is an angular unconformity with Permo-Carboniferous rocks (Terbat Formation). In Kalimantan, volcanics are interbedded with sediments of the Sadong Formation as in Sarawak.

The Sekadau Volcanics lie to the NW, in Sambas-Siluas and their stratigraphic position, as already mentioned, is problematical and speculative. They are reported to intrude and overlie unconformably the Seminis Formation and are in turn overlain unconformably by the Bengkayang Group. They are probably equivalent to the Serian Volcanics although in the south they show affinities with the younger Raya Volcanics which outcrop in Singkawang (Suwarna *et al.*, 1989) and western Sanggau (Supriatna *et al.*, 1989b).

Chemical analyses of the Serian Volcanics (Kirk, 1965) indicate calc-alkaline to high-K calc-alkaline characteristics. Hon (1975) shows that the predominantly basalt-andesite (with extension to rhyodacite) association has tholeiitic affinities indicating that they formed on the oceanic side of an island arc (Hall, 1987).

The Jagoi granodiorite which straddles the border has been dated by the K-Ar method, at 195 Ma (Early Jurassic) (Bladon *et al.*, 1989). If the K-Ar age represents the time of intrusion, the Jagoi granodiorite would appear to be younger than the extensive Upper Triassic Serian Volcanics and perhaps also partly equivalent in age to the basic volcanics and intrusives of the Serabang and Sejingkat Formations. There is some doubt concerning the validity of the age determination on the Jagoi samples as previous determinations give younger ages on samples collected near fault/shear zones. The granite mass is strongly sheared along the northern margin (Ting, 1991) and shearing is also reported on the Indonesian side of the border. The Early Jurassic age may therefore be

spurious as a result of argon loss due to shearing and the pre-Triassic stratigraphic age given by Kirk (1965) may be still valid. The presence of hornblende and magnetite suggests it is an I-type granite. Relationships with other rocks are poorly known; in Kalimantan, the Jagoi granite has a faulted contact with the Pedawan Formation and the shearing is thought to be Tertiary (Rusmana *et al.*, 1989). In Sarawak, Ting (1991) has shown that the Bau Limestone forms fringing reefs around the Jagoi hills and the Pedawan Formation was deposited mostly in deeper water.

Hamilton (1979) noted that the Jagoi pluton is overlain by unmetamorphosed Upper Jurassic strata and is perhaps correlative with the Upper Triassic volcanic rocks and Hamilton's argument seems plausible. The oceanic nature of the Serian Volcanics as indicated from geochemistry and the I-type nature of the Jagoi granodiorite indicate that they formed in an island-arc setting with the Sadong Formation shelf sediments being deposited concomitantly in an emergent volcanic chain. However, the occurrence of continental clasts in the conglomerates is anomalous. Subsequent development of fringing reefs and basinal sediments occurred in the Upper Jurassic and Cretaceous.

Hutchison (1989) was tempted to assign the Serian Volcanics to a continental arc relationship. The inter-relationships of the Serian/Jambu andesites and the Jagoi I-type granite would repay further study and analysis of the volcanic rocks further south may show a clearer polarity and reveal whether there is a Late Triassic volcano-plutonic island arc.

Late Triassic-Lower Jurassic shelf sediments

The Late Triassic Sadong Formation is a shallow marine sedimentary facies associated with the Serian Volcanics, mainly in Sarawak and comprises moderate to steeply folded shale, feldspathic sandstone, conglomerate and tuffaceous sediments with thin beds of coal, chert and limestone. A distinctly arkosic sequence forms a separate member. The conglomerates contain clasts of gneiss, mica granite, mica schist, carbonaceous phyllite, chert and limestone. The thickness is at least 2,300 m. Shoreline deposits occur SW of Serian and contain chert debris from the Lower Permian Terbat Formation. Kon'no (1972) has identified Late Triassic (Late Carnian) plant remains from just above the basal conglomerate at Krusin, near the border (1°4'N, 110°30'E). The floral assemblage is characteristic of the SW Pacific floral province in Late Triassic times and there are no European or Siberian floral elements present. The Krusin flora is different to that on Bintan island but there are similarities with the Tonkin flora in N. Vietnam (Kon'no, 1972). The base of the Sadong Formation is probably unconformable with the Terbat Formation and the top is overlain unconformably by the Kedadom Formation, the Upper Jurassic part of the Bau Limestone Formation and elsewhere by the Lower Cretaceous Pedawan

Formation.

The equivalent, in part, of the Sadong Formation in Kalimantan is the Bengkayang Group which outcrops extensively in NW Kalimantan SE of Sambas where it unconformably overlies the Seminis Formation. The lower part of the Benkayang Group consists of sandstone and minor conglomerate overlying carbonaceous sandstone and shale with tuffaceous and lithic sandstone and acidic tuff at the base. The upper part, locally tuffaceous, comprises fossiliferous sandstone, siltstone and mudstone with graded bedding, low-angle, trough cross-bedding, parallel and convolute lamination, indicating turbiditic deposition. The upper part is 1500 m thick and dated by Early Jurassic (Toarcian) fossils and the lower part is more than 1000 m thick and is probably Late Triassic (Norian) from a reported occurrence of *Monotis sp.* by Wing Easton (1904). The basal tuffaceous and lithic clastics, tuffs and black sandstones may correlate with the near-shore marine sandstones of the Sadong Formation (Wilford & Kho, 1965).

There was a period of sedimentary non-deposition from Middle Permian to Middle Triassic in Sarawak and in Kalimantan and marked in Sarawak by a major unconformity representing a period deformation and possibly of uplift; the Permo-Triassic, igneous-metamorphic Embuoi and Busang Complexes appear to have been formed at this time.

Another unconformity between Late Triassic and Lower Jurassic has been recorded in West Sarawak but the break is probably a period of non-deposition as the ?Late Triassic-Lower Jurassic shallow marine Bengkayang Group was deposited 50 km to the SW in Kalimantan.

The Late Triassic/Jurassic unconformity has not been identified with certainty in the Bengkayang Group, although it may be present between the upper and lower parts in Sanggau. In Singkawang, there is a conformable relationship between the two. The turbiditic nature of the upper part of the Bengkayang Group indicates a deepening of the paleoenvironment prior to the onset of a period of tectonism which deformed the Benkayang Group sediments during the middle Jurassic.

The Bengkayang Group is unconformably overlain by the Cretaceous Pedawan Formation and Raya Volcanics and intruded by Cretaceous, Miocene and Pliocene igneous rocks.

The Ketapang Complex in the SW part of the Schwaner Mountains occurs as small inliers within Cretaceous granitoids (De Keyser & Rustandi, 1989). The rocks comprise thin-bedded pelites and psammites, siltstones, sericitic sandstones, lithic and volcanigenic arenites, grits, shales and slates. Calcareous horizons are transformed to calcsilicate rocks by contact metamorphism. The rocks are strongly folded with moderate to steep dips. The age and stratigraphic position of the Ketapang Complex are ambiguous. The rocks resemble the

Upper Triassic-Lower Jurassic Bengkayang Group but a mid-Cretaceous microflora was identified in shales collected from the Ketapang Complex (Haile, 1974).

Late Triassic-Lower Jurassic volcanics and intrusives

Associated with the Ketapang Complex are a series of volcanic rocks termed the Matan Complex introduced originally by van Bemmelen (1939) to include all the volcanic rocks within the Ketapang and Kendawangan quadrangle areas. The preliminary report of the Ketapang quadrangle area (De Keyser & Rustandi, 1989) retains the term for volcanics regarded as older than most of the Cretaceous granitoid plutons. They are highly altered and weathered in outcrop and show a wide variety of rock types ranging from andesites and basalts to rhyodacites, rhyolites and quartz keratophyres and are tentatively placed between Upper Triassic-Lower Cretaceous. The JICA (1982) report correlated the Matan volcanics with volcanics in the Bengkayang area and were assigned to an Upper Triassic-Jurassic age. Unaltered and clearly younger volcanics in the same quadrangle (and formerly included in the Matan Complex of Van Bemmelen) are the Bunga basalt and Kerabai volcanics which have been shown be to be related chemically and mineralogically to the Upper Cretaceous phase of granitoid plutonic activity and radiometric dates confirm a Cretaceous age.

The Belaban granite, a hornblende-quartz monzodiorite/monzonite located at Bukit Belaban Tujoh, (2° 10'N, 110°30'E) lies within the Matan Complex area and has yielded a date of 154 Ma (Upper Jurassic) (Haile *et al.*, 1977). The granite appears to be a separate and earlier intrusive event and older than the main Cretaceous plutonism which is widespread in this part of Kalimantan. Whilst petrologically similar to the other plutonic granitoids, the Belaban granite contains sedimentary xenoliths, unlike the other plutons where the xenoliths are igneous. The genetic relationships of the Belaban granite and the Matan volcanics are difficult to determine due to the absence of detailed field, chemical and radiometric data.

The Ketapang and Matan Complexes may be, in part, time equivalents of the Bengkayang, Sadong and Serian volcanics.

Jurassic-Cretaceous shelf sediments

The Bau Limestone covers an area of about 280 km^2 is up to 900 m thick in Sarawak and comprises massive, poorly to moderately fossiliferous limestone with thin calcareous shales and conglomerate near the base (Malaysia, 1988). The Bau Limestone Formation continues marginally across the border into NW Kalimantan. The paralic to shallow marine Pedawan Formation is more widespread and is about 4,500 m thick in Sarawak and comprises thick sequences of marine shale, mudstone and sandstone with subordinate beds of conglomerate, limestone, chert and andesitic to rhyolitic lavas and tuffs. In

Kalimantan, the Pedawan Formation is more than 2,000 m thick. (Marked K on the 1:1 million composite map). Underlying the Bau Limestone and Pedawan Formation in Sarawak is an arenaceous paralic to shallow marine sequence with tuffs and carbonates termed Kedadom Formation containing Late Jurassic faunas but the sequence has not been found further south in Sambas-Siluas. However, the Brandung Formation in Sanggau forms isolated outcrops of fossiliferous, calcareous shallow marine deposits with a total thickness of more than 100 m and is probably the lateral equivalent of either the Kedadom or Bau Limestone Formation.

Late Cretacaceous shelf margin sediments

The Selangkai Formation occurs poorly exposed in east Sanggau and widespread in Sintang (Williams & Heryanto, 1985, 1986)and Long Pahangai where there are thick marine sequences of tightly folded calcareous mudstone with intercalations of pebbly and bouldery mudstone, graded sandstone, rare limestone and conglomerate. The conglomerate contains a wide variety of rock types including quartzite, granite, volcanic rock and rare gneiss. Some areas are dominated by turbidites and/or mass flow deposits including large limestone blocks (olistostromes) in a calcareous mudstone matrix. The limestones consist of algal and coralline micrites with *Orbitolina* species of Cenomanian age. The total thickness of the Formation is estimated to be about 3,000 m. Fossils identified from samples of sandstone and mudstone indicate a Turonian (Late Cretaceous) age. The age of the Selangkai Formation ranges from Lower Cretaceous (Valanginian) to Upper Cretaceous (Turonian) based on fossil assemblages collected by Zeijlmans van Emmichoven (1939) and the IAGMP survey. The turbidite and olistolithic mass flow deposits suggest an unstable shelf area at the edge of a steep slope. Paleocurrents indicate transport from the SE. The field descriptions show much similarity to the Lupar Formation in Sarawak but the latter is somewhat younger (Maastrictian) and paleocurrents indicate a source from the SW (Tan, 1979). Williams & Heryanto (1986) indicate that the Selangkai Formation appears to young towards the north and perhaps the Lupar Formation represents a slightly younger equivalent. Tight folding indicates a period of tectonic deformation and the overlying sediments rest with unconformity.

VOLCANO-PLUTONIC ARC ROCKS

Lower Cretaceous granitoids

The Laur and Sepauk granitoids of Lower Cretaceous age occur widely in Pontianak-Nangataman, Nangapinoh (Pieters & Supriatna, 1989a) and Ketapang in the SW and the Alan granite of the same age in Long Pahangai. The Laur and Sepauk granitoids are closely associated and form the larger part of the Schwaner Batholith. Petrologically, the Laur is a monzonite and Sepauk a tonalite/granodiorite and K-Ar radiometric ages obtained from the

Sepauk and Laur plutons are in the 130-95 Ma range. The granitoids are calc-alkaline and I-type in character and emplaced at a mid-crustal level over an area of 600 km long and 180 km wide. They were formed from igneous material near the base of the crust during subduction in the Lower Cretaceous. The Alan granite intrudes altered volcanic rocks of unknown age and lie within disturbed zones. K-Ar radiometric ages range from 121-130 Ma but the genetic origin is unclear.

In NW Kalimantan, the Mensibau Granitoid occurs widely in W Sanggau and Singkawang and forms an extension to the large Schwaner Batholith. It varies in composition from hornblende-biotite granodiorite to tonalite. K-Ar dates range from 95-125 Ma and geochemical analyses indicate a calc-alkaline, I-type composition (JICA, 1982; Suwarna *et al.*, 1989). The Biwa Gabbro forms numerous stocks and plugs in Nangataman and Nangapinoh and intrudes the Mensibau Granodiorite and also perhaps the Raya Volcanics. A K-Ar radiometric age of 87.9 Ma (Haile *et al.*, 1977) suggests the intrusions are Late Cretaceous.

The Lower Cretaceous Menyukung granite which occurs in the Kapuas Lakes District in Sintang quadrangle is unusual as it is an alkali feldspar granite rich in K-feldspar, accessory ilmenite and trace element tin. Anomalous tin values occur in streams draining the two main granite bodies suggest that the granite is a member of the S-type, ilmenite series (Chappell & White, 1974). The nearest tin-bearing granites lie almost 500 km to the east and are Miocene.

Lower Cretaceous volcanics

The Raya Volcanics form a suite of altered basalt-andesite-dacite intrusives and associated pyroclastic deposits occurring widely in Singkawang and extend east to Sanggau. A K-Ar radiometric date from a single sample yielded an age of 106 Ma, suggesting that the volcanics are probably Lower Cretaceous. Trace element analyses (Harahap, 1987) show that the Raya Volcanics have a typical island-arc association and are probably co-magmatic with the Mensibau Granodiorite (Suwarna *et al.*, 1989).

Upper Cretaceous Granitoids

Upper Cretaceous granitoids and related volcanic rocks occur in the Schwaner Batholith in Pontianak-Nangataman, Nanga-pinoh and Ketapang and comprise the Sukadana Granite Suite and Kerabai Volcanics. The Sukadana granitoids are widely distributed and form igneous masses of batholithic dimensions and a distinct NE alignment as well as smaller plutons and stocks. Petrologically, they range from rare gabbros and diorites to abundant quartz monzonites, monzogranite and syenite to alkali-feldspar granite and syenite. Chemically and mineralogically, the rocks are predominantly calc-alkaline with hornblende and orthopyroxene. Riebeckite was reported by van Bemmelen (1939) but De Keyser & Rustandi (1989) found arfvedsonite in one of their thin

sections and suggested that van Bemmelen's riebeckite may also be arfvedsonite. In plotting all available analyses of the Sukadana Granite Suite, De Keyser & Rustandi conclude that although chemically the analyses fall narrowly within the alkali-calc series, mineralogically the rocks belong to the calc-alkali series as there is abundant common hornblende and ortho- pyroxene. Trace element analyses show no definite trends. The Sukadana granitoids are typical I-type, magnetite series granites and De Keyser & Rustandi (1989) suggest they may have formed by partial melting of a fractionated basic igneous source in the lower crust. Radiometric ages obtained mainly from K-Ar determinations supplemented by few U/Pb dates range mostly in the Upper Cretaceous.

A number of Upper Cretaceous granitoids forming relatively small, isolated intrusions occur in an arcuate belt 75-100 km wide from Tg. Datu on the border in the west to the Nieuwenhuis Mountains in the east. In Sarawak, they comprise the adamellite intrusions at Tg. Datu and Tinting Bedil, the granodiorites at Sebuyau (Lupar estuary) and Gading, near Lundu. Smaller bodies of gabbro are sometimes present. The Tinting Bedil intrusion contains hornblende and magnetite and is possibly an I-type granitoid. K-Ar radiometric ages range from 75-101 Ma (Kirk, 1965). The Pueh granite straddles the border region in the NW and elsewhere in Kalimantan, the Era granite (75 Ma) and the minute Pesinduk altered granodiorite occur in Kapuas and the Topai hornblende-biotite granite (76 Ma) in the Long Nawan quadrangle (Baharuddin & Andimangga, 1989) in the NE. Williams *et al.*, (1988) has noted that the small granitic bodies of Late Cretaceous age form a discontinuous arcuate belt parallel to the regional trend of the melange belts. The rocks are generally biotite monzogranite or syenogranite and show no evidence of deformation. The convergent ages of all the intrusions and somewhat similar chemistry suggest they are all genetically related but the relationship is with the melange belts and granitoid batholiths further south remains unclear. Perhaps a trace element study would resolve the issue.

Upper Cretaceous volcanics

The Bunga basalt and Kerabai volcanics which were formerly considered as part of the "Matan Complex" in Ketapang comprise a wide variety of compositional and eruptive types ranging from andesite to basalt with dacite, trachy-andesite, rhyodacite and rhyolite and quartz keratophyre. Geochemically the basic varieties of the Bunga basalt are high K/Na, calc-alkaline basalts suggesting that the Bunga basalt formed in a mature, volcanic-arc setting. The rocks have yielded Upper Cretaceous radiometric ages. The age and 250-300 km separation from the Lubok Antu-Kapuas melange suggests that they are more likely to be linked with Lubok Antu-Kapuas rather than the Boyan subduction zone. An arc-trench distance of 200-300 km is of the correct order, according to modern examples (Hutchison, 1975a). Alternatively, perhaps the paired subduction lies to the SE in subduction zones of the Meratus area but the arc-trench separation is much greater.

The Kerabai Volcanics are a suite of Upper Cretaceous volcanics and subvolcanics which crop out extensively in S Nangataman, SW Nangapinoh and N Ketapang. They consist of lava, lava breccia, pyroclastics, and shallow intrusive dykes and sills and stocks and are composed of andesite, dacite-granodiorite, monzonite and basalt-gabbro. Chemically, they plot in the same fields as the Sukadana Granite suite and are probably co-magmatic. Stratigraphic relationships indicate an age younger than the emplacement of the Sepauk Tonalite and Laur Granite although isotopic analyses indicate the granites are about 15 Ma older than the volcanics.

Hutchison (1989) remarks on the present high heat flow of the SE Asian region and the preponderance of hot springs, particularly in the Sinoburmalaya part. Hot springs in west Borneo appear to be limited in extent or have not been recorded on the recently published preliminary geological maps as only two hot springs are shown, one in the Jagoi granite (109° 58'E, 1°17'N) and the other in northern Putussibau (113°20'E, 00°57'N). In west Sarawak, eight hot springs are reported from seven areas between Serian and Lundu (Sulong Enjop, 1990). Four are associated with faults adjacent to the Serian volcanics, three are in Bau Limestone/Pedawan Formations and one at Lundu is close to the Pueh granodiorite intrusion. Those at Paku, ENE of Bau and Senah, 32 km South of Bau are thought to be associated with limestone and igneous rocks at depth (Wilford, 1955; Wilford & Kho, 1965). The waters are mostly calcium bicarbonate with a temperature range from 32-69°C. The geothermal gradient map (Rutherford and Qureshi, 1981) has no data between Pontianak and Singapore. High heat flows (3° - 3.5°/100 ft) occur in the South China Sea, E of Natuna and in the Java Sea, S of Belitung Island; the Luconia Platform is moderate (2° - 3°/100 ft) and the Barito Basin mostly low (1°-2°/100 ft). The apparent rarity of present day thermal activity, particularly in the largely granitic Schwaner Mountains, suggests that this part of Borneo may be geothermally cooler than the Sunda platform further west.

OCEANIC BASEMENT & OVERLYING SEDIMENTARY ROCKS

Jurassic-Cretaceous ophiolites

The slate, quartzite, chert, basalt, gabbro and dolerite melange rocks of the Serabang and Sejingkat Formations in West Sarawak extend as isolated outcrops into NW Kalimantan north of Sambas. No additional confirmation of the Jurassic-Cretaceous ages obtained from radiolarian cherts in Sarawak has been obtained from Kalimantan, neither are the structural relationships with other Formations clear. The rocks are steeply dipping, highly deformed and sheared and the thickness is unknown. They represent possibly a Jurassic subduction zone which may be paired with the volcanic rocks in the Matan Volcanic Complex and the high-level, plutonic Belaban granite some 200 km SE in central Kalimantan.

The Danau Mafic Complex extends in relatively widely dispersed outcrop in Sintang, Putussibau, Kapuas and Nangaobat (Surono & Noya, 1989) and comprises gabbro, dolerite, basalt, diorite and ultramafics. Geological contacts with most other formations are obscure and probably tectonic. The age from stratigraphical evidence is probably Jurassic to Lower Cretaceous and the Complex is associated intimately with the Boyan and Kapuas melange zones. The thickness is estimated at least 1,000 m. In Sintang, the Danau Mafic Complex is intruded by the Lower Cretaceous Menyukung Granite and is therefore Early Cretaceous or older. Remnants of oceanic basalt and brecciated basalt lavas represent the upper part of oceanic crust and the more mafic members (harzburgite, etc.) deeper levels of crust.

In Sarawak, the Pakong Mafic Member is a diminutive and incomplete ophiolite sequence (the most basic rock is gabbro) of Late Cretaceous-Paleocene age (Tan, 1979). Few petrologic details are available of the strike equivalent of the Pakong Mafic Member, the Danau Mafic Complex, which occurs sporadically across the border in Kalimantan and it is unclear whether the ophiolite sequences there are similarly incomplete. A large, positive, WNW-ESE Bouguer gravity anomaly beneath the Lakes area in Kapuas (C.A.Foss *in:* Surona & Noya, 1989) is attributed to a basic mass at depth. The greater density of such a large mass is thought to have caused a subsiding basin after the relaxation of compressive forces and the basin is infilled with Quaternary and possibly Tertiary sediments.

Late Cretaceous-Paleocene accretionary prism

Monotonous, turbiditic sediments of deep marine origin representing an accretionary prism comprising slate, meta-sandstone and siltstone, metamorphosed pebbly sandstone, phyllite, shale and argillite occur as the Embaluh Group of Late Cretaceous-Eocene age (KT on the 1:1 million map). They are distributed widely across Kapuas, E Nangaobat and N Putussibau. In Long Nawan, there are up to 2,000 m of turbiditic sediments intruded by the Late Cretaceous Topai Granite dated between 75-77 Ma and in Kapuas by the Era granite of the same age (Baharuddin & Andimangga, 1989). They are in tectonic contact with the Kapuas Complex melange and the Danau ultrabasic rocks. The Embaluh Group is not subdivided into members. The structure of the Embaluh Group, dominated by strike ridges easily recognised on aerial photographs, enables the Embaluh Group to be classified as a separate tectonic unit, the Embaluh Fold Belt. The structural grain varies from westerly in the W to eastnortheasterly in the E and folding is apparently tight about axes parallel to the strike of the bedding (H.F.Doutch *in:* Surona & Noya, 1989). The Embaluh Group in the SE corner of Nangaobat north of Martinus (112° 22'E, 1° 5'N) is deformed into melange but the lateral equivalent in Sarawak, the Lupar Formation, is a coherent sedimentary sequence and no melange has been found.

The equivalents of the Embaluh Group in Sarawak are the Lupar Formation and the Layar and Kapit Members of the Belaga Formation (Liechti *et al.*, 1960; Tan, 1979, 1982) consisting of mostly turbidity/mass flow deposits of Upper Cretaceous-Paleocene/Lower Eocene age. The Upper Cretaceous Lupar Formation is the oldest coherent stratigraphic sequence of the Rajang Group (Liechti *et al.*, 1960) and is, in part, the time equivalent of the Layar Member. The Lupar Formation comprises rhythmically interbedded shale, mudstone, slate and graywacke exhibiting graded bedding and load structures indicative of turbidites. The Lupar Formation is more arenaceous than the Layar Member which in turn, is more arenaceous than the younger Kapit Member. The latter is characterised by red and green shales of somewhat lower metamorphic grade than the phyllites in the Layar Member. The structure of the Belaga Formation shows strike-dominated features similar to those in the Embaluh Group and the structural grain trends predominantly WNW.

TECTONIC MELANGE ZONES

There are two belts of tectonic melange in Kalimantan. In the south, the Boyan Melange (Williams & Heryanto, 1986; Williams *et al.*, 1988) extends in an E-W direction for over 200 km in a 5-20 km belt bordered by prominent faults. It is composed of a polymict tectonic breccia composed of a wide variety of rocks in a pervasively sheared dominantly shale matrix.

Further north, the Kapuas Complex (Kk on Putussibau & Kapuas, Telm on Sintang 1:250 000 Quadrangle sheets) is a new term taken from the Kapuas river which flows through the Complex, to describe a sequence of unknown thickness comprising sheared and faulted spilite, chert, slate and red claystone occurring principally in NE Putussibau and SE Kapuas between 113°30'E and 114°E at latitude 1°N, and Nangaobat. Substantial chert sequences occur in an area 20 km long and 10 km wide on the Kalimantan side of the border in Nangaobat but it is unclear whether they are coherent sequences or tectonic blocks as in Sarawak. The Kapuas Complex is intimately associated with melange. In Putussibau and Nangaobat, it is in tectonic contact with the Embaluh Group and is probably overlain by the Selangkai Formation. The Complex contains mid-Cretaceous fossils (Surono & Noya, 1989).

The Kapuas Complex continues NNW across the border in Sarawak where its equivalent is the Lubok Antu Melange (Tan, 1979). Williams *et al.*, (1988) refer to the continuation of the Lubok Antu Melange as the Kapuas Melange in Kalimantan. Chert occurs as tectonic blocks up to 5 km in length within the Lubok Antu Melange and appears to be less widespread than in Kalimantan. Blocks of fossiliferous limestone, volcanic conglomerate and sandstone, shale and calcareous shale are also present. Chert has not been found in the adjacent Lupar Formation (Tan, 1979).

Cross-border correlation of the geology of the Lupar valley with the rocks in Kalimantan is not entirely reconcilable. On the Sarawak side of the border, there is a clear distinction between non-coherent rocks, the Lubok Antu Melange containing chert and coherent sediments, the Lupar Formation and the Layar Member, Belaga Formation. In Kalimantan, the Kapuas Complex which is disrupted and contains chert appears to be same as the Lubok Antu Melange. However, parts of the Embaluh Group are also disrupted into melange, apparently without chert and the Embaluh melange extends across central Borneo for at least 350 km to Sg.Boh (115°20'E,1°30'N).

Associated with the melange rocks is the Danau Mafic Complex which occurs as fault-bounded masses up to 40 km long on the N margin of the Semitau Inlier. Equivalents of the Pakong Mafic Complex in the Lupar valley (Tan, 1979) are found in isolated outcrops in the Quaternary sediments of the Kapuas Lakes depression.

The age of the Lubok Antu Melange is thought to be younger than the Boyan melange on the presence of early Eocene foraminifers and Paleocene - Miocene nannofossils in the matrix (Tan, 1982). The age of the Kapuas Complex has yet to be defined satisfactorily; it is shown as Jurassic-Cretaceous on the 1:1 million map and mid-Cretaceous fossils have been found (Surona & Noya, 1989). The age of the Boyan Melange is difficult to establish with certainty due to the scarcity of diagnostic fossils in the matrix and the few determinations which have been made indicate the age is younger than Cenomanian (mid-Cretaceous) and older than a Middle Miocene intrusion (Williams & Heryanto, 1986).

POST SUBDUCTION VOLCANISM AND SEDIMENTARY BASINS

Eocene volcanic rocks

Eocene magmatic activity following the end of Cretaceous subduction in central Kalimantan is recorded by the presence of a series of early Eocene intrusives and extrusives of relatively restricted radiometric age range, between 48-50 Ma and occur sporadically in the Singkawang, Sintang, Putussibau, Kapuas & Nangaobat, Long Pahangai and Long Nawan quadrangles.

In Singkawang, the Bawang Dacite (51.3 Ma) and associated dacitic pyroclastics termed Serantak Volcanics unconformably overlie the Upper Triassic-Lower Jurassic Bengkayang Group. The Serantak pyroclastics are less than 300 m thick.

In Sintang, the Piyabung Tuff is a new name (Williams & Heryanto, 1986) for a sequence of acid to intermediate tuff and agglomerate which crops out over a distance of some 40 km within the Semitau inlier. The type locality is in the Boyan river, E of Gunong Piyabung (112° 16'E, 00° 18'N). The rocks are

composed of mainly air-fall, gently dipping, lithic and vitric tuff and agglomerate up to 200 m thick. Williams & Heryanto (1986) were unable to establish with certainty the age of the Piyabung Tuff and stratigraphic relationships with other formations were also difficult to establish (see below and compare the various relationships in Table 2). A K-Ar radiometric age of 49.9 Ma has been obtained from the Piyabung Tuff but the age is regarded as a minimum age due to extensive carbonate replacement (Bladon *et al.*, 1989).

The felsic Piyabung Tuff in W Putussibau and Sintang and the Nyaan Volcanics in Putussibau and Kapuas are unconformable on Late Cretaceous Embaluh Group and Selangkai Formation and the melange/ultramafics of the Kapuas the Boyan areas. They are sub-aerial, ash-flow deposits with graded bedding and laminations.

In Long Pahangai and Long Nawan, the Nyaan Volcanics are from 200-900 m thick and are unconformable on the Cretaceous turbiditic Embaluh Group. The volcanics are composed of tuff, agglomerate, ignimbrite and dacite. A K-Ar radiometric determination gives an age of 48.6 Ma. In Long Pahangai, the Nyaan is at the base of Tertiary shallow water, marine sedimentary successions of the West Kutei basin.

In Sarawak, there are a number of igneous rocks which have been attributed to Eocene magmatic activity but most are basic to intermediate in composition and are generally intrusive. No radiometric ages are available and the stratigraphic evidence is ambiguous. A gabbro forming Bukit Kunang in the Lupar valley intrudes Early Cretaceous cherts and the Upper Cretaceous Eocene Lubok Antu Melange. Tan (1979) is of the opinion that the intrusion is probably early Tertiary although the Geological Survey of Malaysia prefer an Oligocene age (Malaysia, 1990). It could be Miocene and coincident with the Miocene dacites and subordinate gabbros in West Sarawak and the Sintang Intrusive Suite in Kalimantan.

Elsewhere in the Lupar valley, the Bukit Besai basalt/andesite intrusions are post-Upper Eocene as they have thermally metamorphosed the Upper Eocene Basal Sandstone Member of the Silantek Formation. Tan (1979) remarks that they are different from the Pakong Mafic Complex basalts and although he considers the Bukit Besai basalts are of oceanic origin the chemical evidence is ambivalent. He concludes they are probably mid-upper Tertiary in age. At the top of the Rajang Group in the Balingian valley 200 km NNE of the Lupar valley, the Arip Volcanics comprising andesitic and rhyolitic lavas and pyroclastics as well as the Bukit Piring granodiorite intrusion are probably Late Eocene from stratigraphic evidence.

The Eocene igneous activity in Sarawak appears to have little connection with the Eocene volcanic activity in Kalimantan. The acid-intermediate, sub-aerial tuffs and high level intrusions of the Balingian area are probably related to cessation of subduction caused by the arrival of a rifted continental block

derived from SW China underlying the Luconia carbonate platform (Hutchison, 1989). The igneous activity in the Lupar valley is probably not Eocene and quite unlike the scattered, air-fall volcanics in the Lower Tertiary basins of central Kalimantan basin which are attributed to a change from compressional to extensional tectonic regime and the resultant basin formation (Williams & Heryanto, 1986; H.F.Doutch *in:* Surona & Noya, 1989).

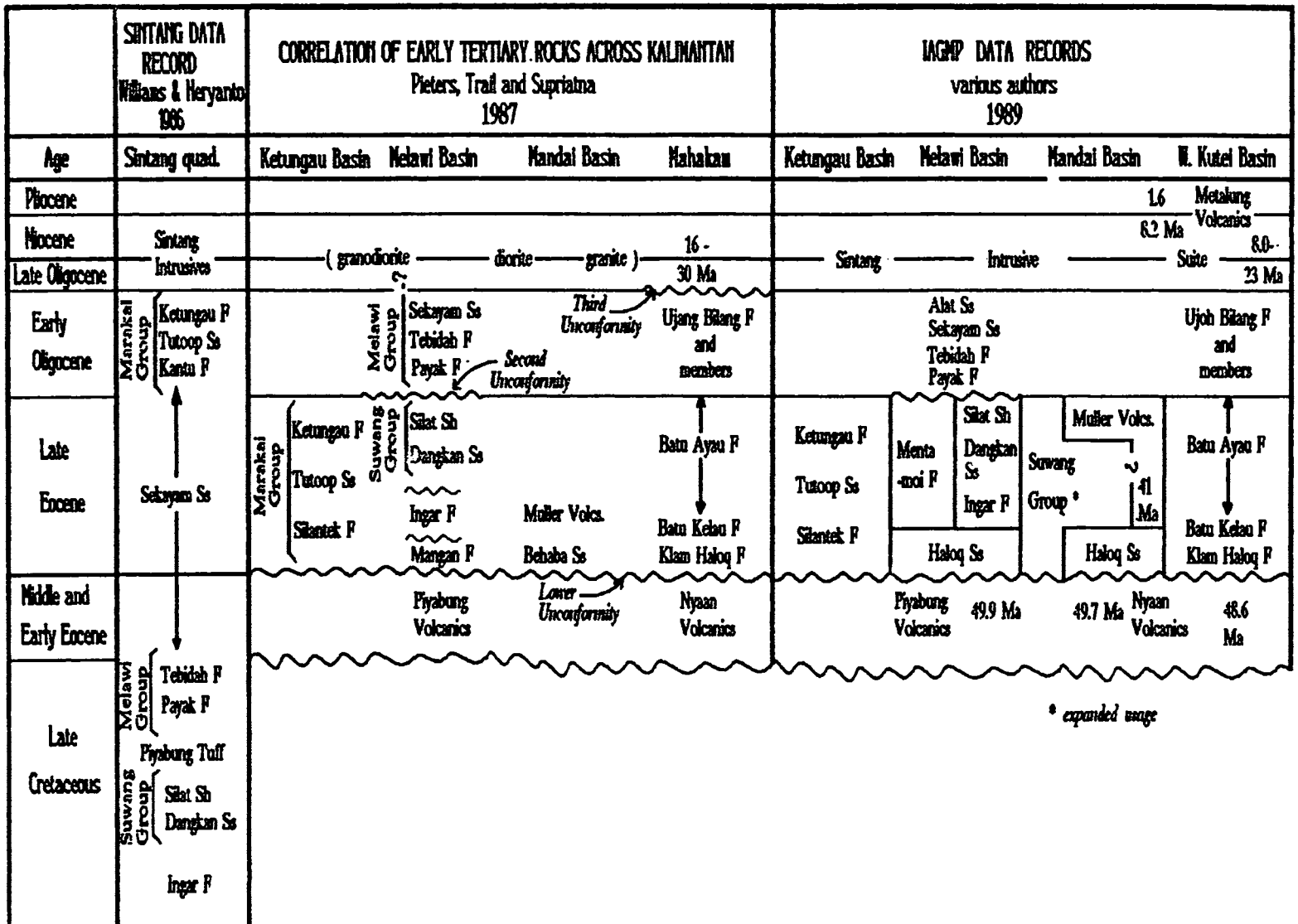
Lower Tertiary sedimentary basins

Subduction in central Kalimantan probably ceased in the Late Cretaceous although Williams *et al.* (1988) implies that subduction ceased in the Early Cretaceous. Growth of an accretionary prism and the uplift of the new granitoids, melange and flysch deposits together with post-tectonic volcanism provided the source sediments for a series of Lower Tertiary basins developing both N, S and E of the Semitau Inlier and known as the Melawi, Ketungau and Mandai basins (Fig. 2). H.F.Doutch (*in:* Surono & Noya, 1989) is of the opinion that all three basins as well as the West Kutai Basin further E were originally one continuous sedimentary basin. The relevant correlation chart is shown in Table 2 (after Williams & Heryanto, 1986; Pieters, *et al.*, 1987, & IAGMP Data Records; various authors; Pieters & Supriatna, 1989).

The lack of diagnostic fauna and flora deposits which are mostly of terrestrial or lacustrine origin has led to different interpretations and confusion in early attempts to correlate the stratigraphy. For example, the calcareous Ingar Formation was assigned to the Late Cretaceous by Williams & Heryanto on the presence of foraminifera which were thought subsequently to have been reworked (Pieters *et al.*, 1987). Williams & Heryanto (1986) placed the Dangkan sandstone and lacustrine Silat shale forming the Suwang Group below an important volcanic marker, the Piyabung Tuff, which together with the Tebidah and Payak Formations forming the Melawi Group, were assigned to the Late Cretaceous. Pieters *et al.* (1987) subsequently assigned the Piyabung (and Nyaan) Volcanics to the Early-Middle Eocene based on radiometric dating and ALL later basin sedimentation was designated younger.

Pieters *et al.* (1987) indicate that a major unconformity at the base of the Tertiary sequence has been traced across Kalimantan for 600 km between longitudes 111½° and 115°. The unconformity is truncated by a second unconformity in the SW which forms the base of a sedimentary sequence of probable Oligocene age. A third unconformity occurs in the lower Mahakam drainage system. A basal Late Eocene sandstone (Haloq Sandstone & synonyms, Table 2) associated with the lowest unconformity is reported by Pieters *et al.*, (1987) to be physically continuous over a distance of 400 km from the Mahakam river to the Sintang area. West of Sintang, the basal unit is onlapped by younger formations. The Late Eocene basal sandstone correlates with the Late Eocene Silantek Formation in Sarawak (Tan, 1979) and is probably continuous beneath the Quaternary Kapuas Lakes.

Table 2. Correlation of Late Cretaceous to Lower Tertiary post-tectonic sedimentary basins across Kalimantan (after Williams & Heryanto, 1986; Pieters *et al.*, 1987; and IAGMP Data Records by various authors, 1989).



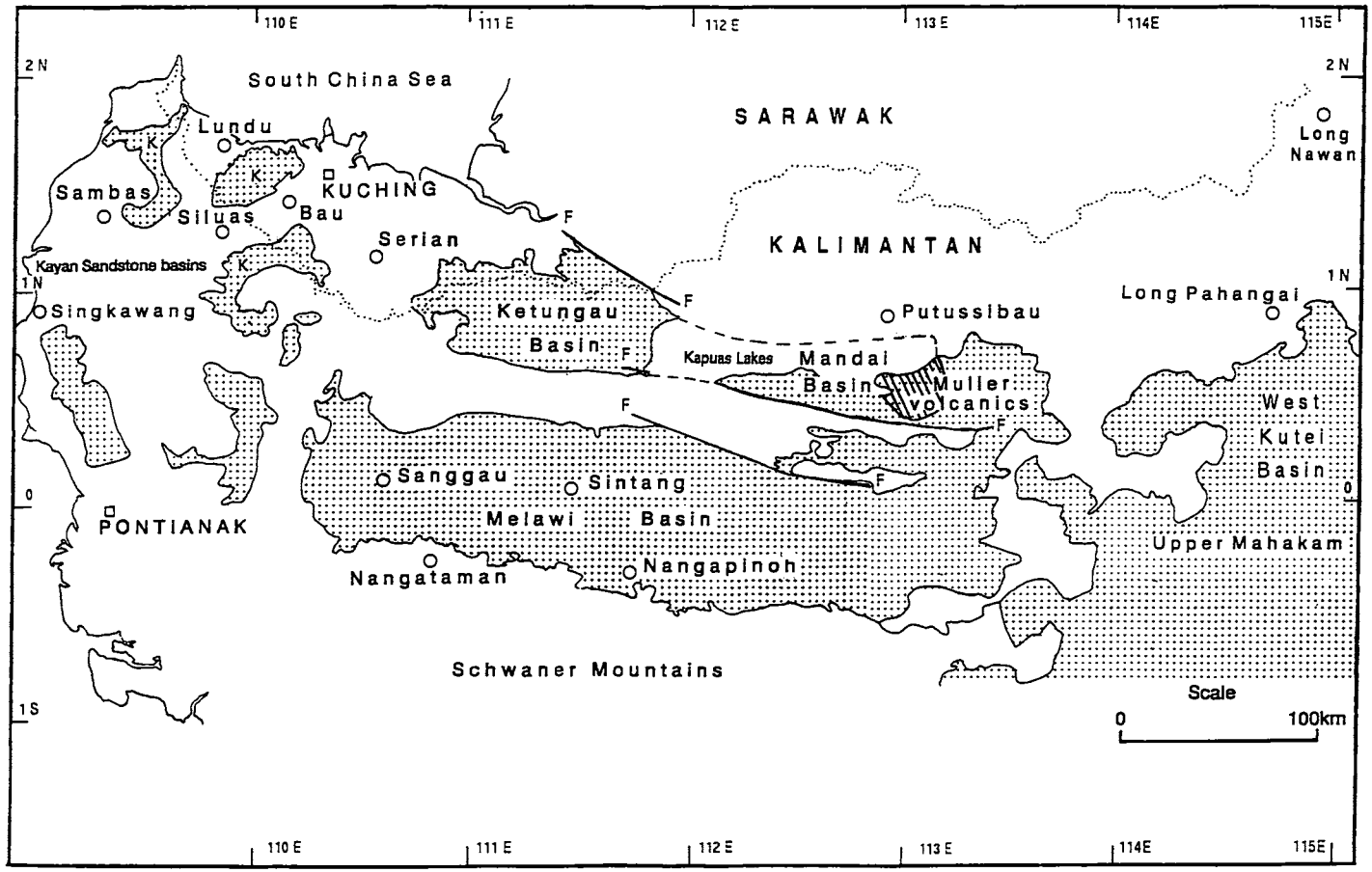


Figure 2: Geological sketch map of the post-tectonic sedimentary basins in NW Kalimantan and W Sarawak. (after Williams *et al.*, 1988).

The Eocene-Oligocene succession in Long Pahangai comprises shallow to open marine sediments with some reef limestone of the Haloq Sandstone, Batu Kelau and Ujoh Bilang Formations and Members which have a total thickness of about 2,750 m and form the western part of the Kutei basin. According to Williams & Heryanto (1986, & Table 2) sedimentation commenced earlier in the Melawi Basin in Sintang with the calcareous Ingar Formation unconformably underlying the fluviatile Dangkan Sandstone and lacustrine Silat Shale forming the Suwang Group. The Suwang Group is succeeded by the Melawi Group comprising the Piyak and Tebidah Formations totalling 5500 m which occurs widely across Sintang. To the south in Nangapinoh, the Suwang Group is several thousand metres thick but the overlying Melawi Group is only about 2,250 m, all sediments being of fluviatile or rarely shallow marine origin and ranging in age from Eocene to Oligocene, i.e. younger than further north.

In Sanggau, there are three sedimentary basins, the Kayan Basin in the NW, the Ketungau Basin in the NE and the Melawi Basin in the S. The synformal Kayan Basin comprises in excess of 1000 m of coarse felspathic and lithic sandstones, siltstone and shale polymict conglomerate overlying unconformably upon the Late Cretaceous Pedawan/Selangkai Formations; the age of the Kayan Formation here is questionably Late Cretaceous-Early Tertiary. The Ketungau Basin comprises Late Eocene Kantu Formation (=Silantek Fm.) of unknown thickness overlying Triassic sediments and forming a synclinal half graben thickening northwards. The Kantu Formation is succeeded conformably by the Tutoop and Ketungau Formations with a total thickness exceeding 2500 m and also Late Eocene in age. Sedimentation in the Melawi Basin commences with the calcareous Ingar Formation (=Silantek Fm.) of unknown thickness, succeeded unconformably by more than 1500 m of fine grained sandstones and mudstones of the Payak Formation. The Tebidah Formation overlies conformably the Payak Formation and is about 1000 m in thickness and the uppermost unit of the Melawi Basin is the coarse-grained Sekayam Sandstone more than 150 m in thickness. Due to the absence of diagnostic fossils, the age of the Payak-Sekayam sequence is tentatively assigned to the Early Oligocene (Supriatna *et al.*, 1989b). The structure of the Melawi Basin is that of a gentle, regional syncline with thrust faulting along the northern margin. The coarseness of the Sekayam Sandstone is thought to imply regional uplift in the middle Oligocene (Supriatna *et al.*, 1989b). The paleo-environment of all three basins is largely shallow water, fluviatile with a paucity of diagnostic fossils.

In Pontianak-Nangataman, the lagoonal and brackish-water Tebidah and Sekayam Formations represent the western margins of the Melawi basin and have a combined thickness of 1500 m. Of about the same age, further south in the Schwaner mountains, the Kempari Sandstone occurs as a 50 m thick series of light-coloured, quartz arenites and conglomerates separating the underlying Sukadana Granite suite and the overlying comagmatic Kerabai Volcanics. The

composition of the pebbles in the conglomerates is largely related to the underlying granite suite. The rocks are unfossiliferous and probably deposited in a fluviatile environment. Dips in the sandstones are steep and fault contacts with the Sukadana granites are common. It has no counterpart elsewhere.

The topmost Tertiary sequences in central Kalimantan are the youngest strata of the Melawi Basin comprising the Alat Sandstone occurring in Sintang and Nangapinoh. The Alat Sandstone consists mostly of unfossiliferous, massive bedded chert breccia, conglomerate and quartz lithic arenites totalling 250 m. The age of the Alat Sandstone Formation is questionable. In the Sintang Data Record, Williams & Heryanto indicate that the Alat Sandstone is intruded by the Sintang Intrusive Suite of Miocene age and a (Late) Oligocene or early Miocene age would appears probable. H.F.Doutch (personal communication) has not found any direct evidence of Oligocene ages for the Melawi Group or basin, including the youngest unit, the Alat Sandstone.

In West Sarawak, from Lundu eastwards to Serian, the dominantly terrestrial Kayan Formation ranges in age from Upper Cretaceous to Middle Miocene although in a recent revision by Tan (1986), deposition stopped in late Eocene, coinciding with the Second Unconformity in central and west Kalimantan where the Kayan Sandstone Formation lies above the Late Cretaceous unconformity in Sanggau and Sambas- Siluas. The Kayan Sandstone in West Sarawak comprises predominantly terrestrial sediments and fluviatile deposits with intercalations of paralic and shallow marine sediments and forms marked geomorphology in the form of plateaux, cuestas and generally mountainous terrain. The structure is overall synformal and the upper surface is erosional.

According to Tan (1986), a shift of depocentres to the east of Serian took place with deposition of the Silantek Formation commencing in Lower-Middle Eocene (or perhaps later, in Late Eocene?) and continuing into the Miocene with a transition to the Plateau Sandstone. Tan (1979) indicated the Silantek Formation to be a shallow marine near shore deposit grading northwards into proximal and distal turbidites and the Schwaner Mountains in the south forming a primary source. The Silantek Formation continues south into Kalimantan and should be considered as part of the more widespread Ketungau Basin which, according to H.F.Doutch, continues beneath the Holocene Putussibau Depression to join the Mandai Basin.

There would appear to be a break in deposition across Kalimantan between Late Oligocene and Upper Miocene during which the Sintang Intrusive Suite was emplaced.

Oligocene-Middle Miocene intrusive rocks

The Sintang Intrusive Suite is a magmatic, calc-alkaline series of mafic and felsic high-level plutons and stocks often forming distinctive topographic

features and is distributed across central Borneo in an arcuate belt 150 km wide from NW Kalimantan and West Sarawak to the West Kutai basin. In the latter area, at Kelian, they form the source of the largest gold deposit in Indonesia (Van Leeuwen *et al.* 1990). There are many intrusions in the Sintang and Putussibau quadrangles where they intrude most of the older Formations and form hornfels contact metamorphic zones. In Ketapang, the Sangiyang granite forms distinctive, steep-sided, domed peaks and is composed of fine-grained, leucocratic granophyric and perthitic alkali-felspar granite (Rustandi & de Keyser, 1988). Petrographically, the rocks range from pyroxene andesite and dolerite to microgranite and microdiorite. Most contain phenocrysts of hornblende, plagioclase and quartz in a very fine grained groundmass. Geochemically, the have characteristics of I-type granitoid rocks and have generally moderately to high magnetic susceptibility with magnetite as the dominant accessory. K-Ar determinations show that they are mostly Middle Miocene. The genetic origin is ascribed by Williams and Heryanto (1985) to crustal melting as a result of downwarping due to the great thicknesses of sediment (up to 6 km) which accumulated in the Melawi, Ketungau and Mandai Tertiary basins coupled with a rise in geothermal temperature following cessation of subduction in the Eocene. The combined effect of great thickness and higher geothermal temperature resulted in a partial melting of the basaltic crust giving rise to acid magmas intruded as post-tectonic, differentiated, I-type, calc-alkaline suite.

In West Sarawak, there are many high-level small stocks, dykes, sills and laccoliths which are subdivided by Kirk (1965) into two main petrologic groups. Porphyritic microgranite, adamellite and granodiorite occur mainly in the Klingklang Range along the border SE of Serian, and in the Bau-Kuching area. Diorite, gabbro and dolerite occur mainly in the Klingklang and Bungo Ranges and N and W of Kuching. In the Bau area, the intrusives are aligned NNE and are the cause of gold mobilisation forming workable deposits. K-Ar radiometric determinations from stocks near Kuching have yielded ages between 16-19 Ma. Elsewhere in Sarawak, at Bukit Piring in the Upper Balingian valley SE of Tatau, alkali granite and adamellite intrude Eocene-Oligocene sediments.

The Miocene hypabyssal intrusives in West Sarawak have been assigned by Tan (1982) as arc-related and paired with a subduction marked by the Lupar line. Although the intrusives are calc-alkaline and with I-type affinities, the West Sarawak intrusives are located too close to the subduction line and considerably younger than the alleged age of subduction to have any genetic connection. Williams *et al.* (1988) interpretation seems to be a more feasible explanation as post-orogenic sub-crustal melting. The Miocene intrusives seem to prefer to intrude into and through the Lower Tertiary basin strata and an exceptionally high number of stocks are found in three areas between longitude 113°-114°E.

Geologically and geochemically different are subvolcanic granitic intrusions with K-Ar radiometric ages in the range 17.5-26 Ma which occur in a longitudinal belt trending north from about 116°30'E, 1° 50' N. They continue further north where tin mineralization is associated with porphyritic leuco-adamellites which fit an isochron age of 26 Ma (Lefeuvre *et al.*, 1982; Bambang Setiawan and Le Bel, 1988). The genesis is thought to be partial melting of arc-derived material during an Oligo-Miocene collision episode; the adamellites are subalkaline and have S-type characteristics but a low initial isotopic Sr ratio indicates a mantle source, either derived directly or promptly reworked from mantle derived material (Bambang Setiawan & Le Bel, 1988). Equivalent rocks in Sarawak have not been reported although it is possible that related dykes, etc. may yet be found in the Eocene-Paleocene Rajang Group in Ulu Rajang.

Upper Miocene-Pliocene volcanic rocks

Widespread volcanic extrusives and associated stocks, dykes and sills occur in Kapuas, Long Nawan and Long Pahangai quadrangles. They are termed the Metulung Volcanics or Lapung Volcanics, are up to 1250 m thick and composed of lava, lava breccia, tuff, agglomerate ranging from basaltic to andesitic in composition. There are several large volcanic cones especially in the east. Pliocene eruptives termed the Niut Volcanics are widespread in Sambas-Siluas and to a lesser extent in Sanggau. They form flood basalts composed of pyroxene andesite and trachy-basalt. K-Ar determinations from various areas range between 1.6 and 8 Ma.

Similar extrusives together with feeder stocks, dykes and sills occur in the Upper Rajang and Upper Baram valleys in Sarawak, notably the Usan Apau (Banda, 1989), Linau-Balui (Banda, 1990) and Hose Mountains and the Nieuwenhuis Mountains on the border with Kalimantan. Vents are common and up to 1.4 km across. The thickest deposits occur in the Hose Mountains where tuffs and lavas are up to 1,400 m thick and the most widespread deposits occur in the Usan Apau. They have not been dated radiometrically in Sarawak but are clearly the equivalents of Pliocene explosive vulcanicity in Kalimantan and represent the final stages of post-magmatic activity in Central Borneo. Some are clearly related to a dominant NE or NNE structural trend as exemplified by the similar alignment of volcanic cones.

CONCLUSIONS

There is no ancient continental basement in west Borneo and the Schwaner Mountains comprises a Cretaceous arc-related plutonic complex. The plate tectonic setting of the volcano-plutonic arc is as yet unresolved and it is debatable whether the arc formed at a continental margin or as an island arc in an oceanic environment. Williams *et al.* (1988), Fig. 8., gives cogent palinspastic reconstruction diagrams indicating various correlative relationships

between Borneo and Vietnam and Vietnam should be considered as a possible continent. For example, the proto-Mekong river would solve the source problem for the Crocker Formation-Rajang Group as has been suggested by Hutchison (1989) except that the paleocurrent directions indicate a source to the SW (Stauffer, 1968) whereas the grainsize varies conversely, the coarsest and thickest bedsets are in the Crocker.

The relationships between west Borneo and the rest of the Sunda Shelf are unclear. There may be a separate petrologic province in west Borneo, distinct from the alkaline granites of Natuna, Anambas and other islands between Borneo and Malaya, even though minor alkaline granites occur in the Sukadana suite in the Schwaner Mountains. There would seem to be differences in thermal activity between Borneo and the Sunda platform further west perhaps indicating there are two separate geologic provinces although heat flow data in Borneo is limited mainly to measurements from Tertiary basins.

The oldest coherent rocks in Borneo are probably of deep water origin but further investigations are required to establish the correct age and relationships with other rocks, e.g. the Seminis Formation and the Sekadau volcanics. In west Sarawak, new petrologic and geochemical studies may show that the Serebang, Tuang and Sebangan Hornstone Formations are the same age and origin; the Serebang Formation is both regionally and thermally metamorphosed. The age of the Serebang and Sejingkat Formations as presently defined is unsatisfactory as the evidence was obtained from thin-section examination of radiolaria. A re-examination using modern methods of dissolving out specimens for identification would probably give a more reliable result which would probably help to resolve the present ambiguity of deepwater, oceanic deposits in close proximity to the shallow marine Bau/Pedawan Formations as mentioned by Haile (1991). The rock assemblages in the Tuang and Serebang Formations seem to indicate generation in an oceanic rather than a continental environment. A radiometric age determination on the Tuang Formation would clarify its position viz-a-viz the Triassic and pre-Triassic geology in west Sarawak and perhaps enable a better correlation with the Pinoh Metamorphics which are unsuitable for radiometric dating. Further petrologic and geochemical studies may resolve the origin of the Permo-Triassic Buang/Embuoi Complexes. Chemical analyses of the Jambu volcanics would help to establish a clearer polarity of a possible Upper Triassic island arc represented by the Serian/Jambu volcanic succession. The Ketapang Complex is unresolved and the ambiguous dates and stratigraphic relationships invite further attention. A trace element study of the Upper Cretaceous granitoids in West Sarawak would perhaps provide additional information concerning the relationship of those intrusions with the Schwaner Mountains batholiths of the same age in addition to formulating a genetic origin.

Williams *et al.* (1988) have indicated that evidence for underthrusting beneath the accretionary wedge on either side of the Boyan zone is absent in NW Kalimantan and have interpreted the geological and gravity boundaries between the accretionary domain and NW Kalimantan domain as a transcurrent fault aligned NNE. The transcurrent fault is coincident with the NNE – trending boundary of the gravity domains (Williams *et al.*, 1988, fig. 3) and aligned with the abrupt swing in the coastline at the Lupar estuary. The transcurrent fault also marks the eastern boundary of the Jurassic-Cretaceous sedimentary basin and the Upper Triassic Serian volcanics also lie on this line. Deep structural discontinuities trending NNE are also evident across much of offshore NW Borneo (Bol & van Hoorn, 1980) and there is evidence of NE or NNE shear zones onshore, notably the Mulu shear zone (McManus & Tate, 1976; Tate, 1991).

In linking subduction zones and island arc magmatism, spatial relationships are easier to ascertain than chronological alignment. For example, what does a fossil age determination from the matrix of a subduction melange represent? Is it the age of the last moments of subduction? What evidence should be taken to represent the beginning of subduction, the oldest radiometric age determined from a calc-alkali granitoid? If the Lubok Antu subduction zone ranges from Paleocene to Miocene, should Paleocene-Miocene, calc-alkali granitoids be expected to occur 200 km to the south? Perhaps subduction was relatively short lived and hence an extensive plutonic arc complex was not formed. The time-lag between the initiation of subduction and the first melting of crust at a depth of 90 km is about 3.6 m.y., assuming a plate convergent rate of 5 cm/yr and an angle of 30° for the subducting slab. Assuming the rate at which magma rises through the lithosphere is of the same order, 5 cm/yr (a generous estimate as Maale (1985) calculates the rate of ascent of plumes and diapirs to be 30 cm/yr!) the time taken to rise from 90 km is about 1.8 m.y., thus the total time lag is of the order of 5.4 m.y., or about two per cent of the spread in radiometric ages obtained from the Schwaner batholiths. The time lag between the advent of subduction and the subsequent high-level intrusion of related granitoids of a paired system would seem to be geologically insignificant.

In West Borneo, the stratigraphic age obtained from a melange and the radiometric age of its linked plutonic arc appear disparate, the arc is usually older than the melange and this has raised doubts concerning the validity of linkage. For example, subduction represented by the Boyan melange (?Upper Cretaceous) caused intrusions of Lower Cretaceous age (Alan granite, Sepauk tonalite etc.) and subduction by the Lubok Antu melange (Paleocene - Miocene) caused the Upper Cretaceous intrusions (Sukadana Suite and associated comagmatic Kerabai volcanics). There may be other granitoids linked to the Lubok Antu subduction, for example, the calc-alkaline, I-type, Late Cretaceous Pueh granitoid, although the arc-trench separation is inadequate. The Pueh intrusion is perhaps tectonically displaced by the right-lateral transform

postulated by Williams *et al.* (1988), to separate the geologically distinct provinces of central and NW Kalimantan.

The stratigraphy of the Tertiary sedimentary basins may be resolved better when fossils and pollen collected during the IAGMP survey are investigated and reported. A number of problems remain unresolved; for example, the upper part of the Silantek Formation and the Plateau Sandstone E of Serian are the youngest Tertiary sediments in West Sarawak and currently assumed to be Upper Oligocene-Middle Miocene. The youngest Tertiary sediments in central Kalimantan are the ?Miocene Payak-Alat fluviatile sequences further south in the Melawi basin. In Eastern Kalimantan, the youngest sequences are the Oligocene Ujoh Bilang Formation in the West Kutei Basin. The deposition of the Silantek/Plateau Sandstone sequences appears to be concomitant with the Miocene intrusions of the Sintang Intrusive Suite which, although predominant across central Kalimantan, also occur sporadically across most of West Sarawak.

It seems likely from regional evidence, that the Kayan Sandstone Formation in West Sarawak is probably Late Eocene and not, as presently assigned on palynological evidence, Late Cretaceous-Middle Miocene. The Kayan Sandstone is equivalent probably to the Ketungau Basin sediments further east. The palynological determinations by Muller (1968) may need re-examination since recent trends in palynology have shown that pollen distribution of specific floral elements can be quite localised (Morley, 1990) and age ranges of some pollens have been re-designated. If Trail *et al.* (1987) and Doutch (*in:* Surono & Noya, 1989) are correct in suggesting that initially the Lower Tertiary sediments were deposited across most of central Borneo, and subsequently modified by major, latitudinal faulting, there are important structural implications for the post-subduction evolution of this part of Borneo.

ACKNOWLEDGEMENTS

The author is grateful to Dr. Rab Sukamto, Director-General, Geological Research & Development Centre, Bandung, Indonesia for access to the results of the IAGMP surveys in Kalimantan and to Professor C.S.Hutchison, University of Malaya and Dr. H.F.Doutch (BMR, Canberra) for reading critically the manuscript and offering helpful suggestions.

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Manuscript received 14th June 1991