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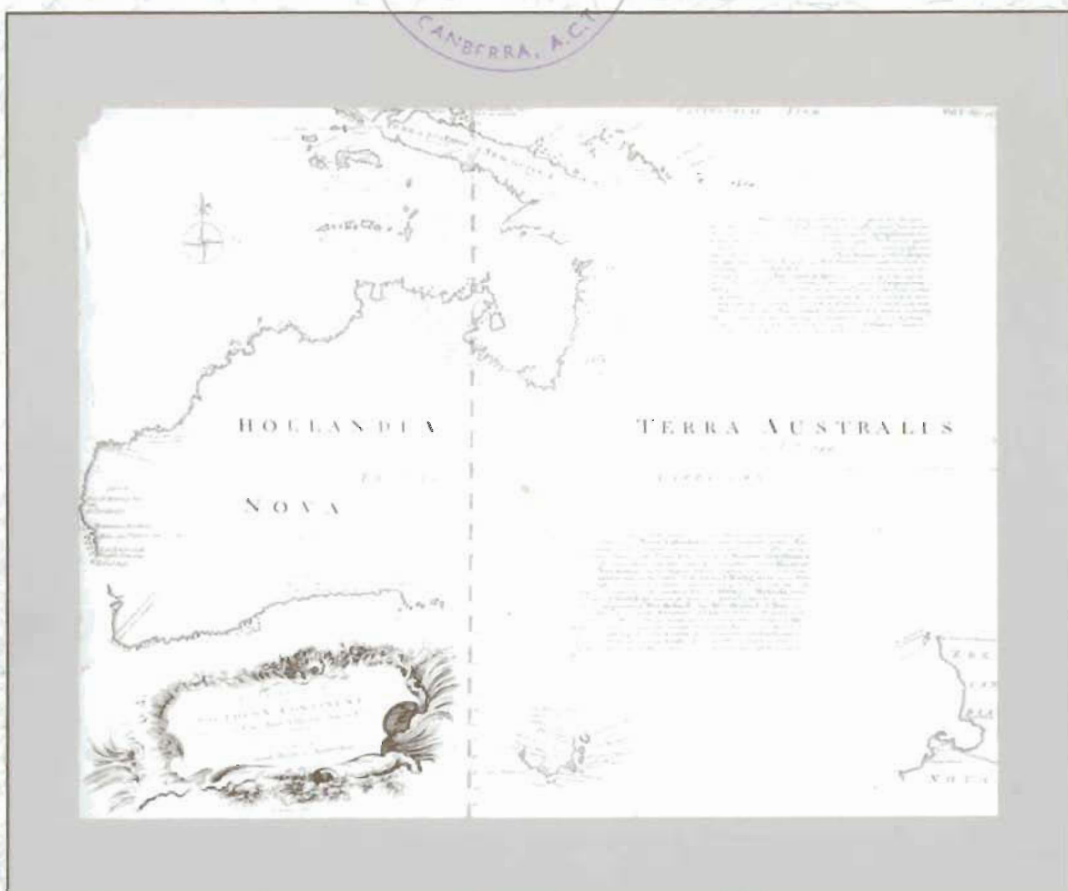

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Emplacement ages of granitic rocks in the Coen Inlier (Cape York): implications for local geological evolution and regional correlation

L.P. Black[1], R.J. Bultitude[2], S-s. Sun[1], J. Knutson[1] & R.S. Blewett[1]

New zircon ion-microprobe U-Pb analyses define two major, short-lived episodes of Palaeozoic magmatism within the Coen Inlier, north Queensland. The younger occurred at about 284 Ma, when the Weymouth Granite and Twin Humps Adamellite were emplaced. Previously published younger K-Ar ages for this event are probably a consequence of radiogenic Ar loss from chlorite-rich biotite concentrates. Most of the granites in the inlier were emplaced during a brief intrusive episode in the Late Silurian - Early Devonian: ages for previously defined units include 402±7 Ma (Flyspeck Granodiorite), 408±6 Ma (Blue Mountains Adamellite), 406±7 Ma (Kintore Adamellite), 407±8 Ma (Morris Adamellite) and 407±5 Ma (Lankelly Adamellite). Restitic (or xenocrystic) zircon ages and Sm-Nd isotopic data are consistent with the derivation of both generations of granites from Precambrian crustal components similar to those which produced granites of closely similar ages in the Georgetown Inlier. Tectonothermal activity at ~1600 Ma was probably part of quasi-continuous activity extending over several hundred million years. A 2500 Ma crustal component is also identified. Despite the similarities in the ages of the Palaeozoic granites in the Coen and Georgetown Inliers, and their closely comparable isotopic characteristics, it is not possible to conclude that the two terranes are part of a single geological entity. This will only be possible if Precambrian metamorphic or igneous rocks, which are so widespread in the Georgetown region, are identified in the Coen Inlier. Although the metasedimentary rocks of the Coen Inlier were derived from weathering and erosion of a Precambrian terrane, the current isotopic data cannot discriminate between Proterozoic, Early Palaeozoic and even Middle Palaeozoic ages of deposition for the metamorphosed sedimentary rocks.

Introduction

The first systematic investigation of the geology of the Coen and Yambo Inliers, north Queensland (Fig. 1), was carried out over the decade following 1958 by the Bureau of Mineral Resources and the Geological Survey of Queensland (de Keyser & Lucas, 1968; Willmott & others, 1973). In 1970 Richards & Willmott published several K-Ar ages for granites from Torres Strait, but it was not until a few years later that a concerted effort was made to understand the temporal evolution of Cape York (Cooper & others, 1975). That study has remained the most authoritative geochronological synthesis of the region until the current investigation.

Cooper & others (1975) presented both K-Ar and Rb-Sr data for two assumed Precambrian terranes, the Coen and Yambo Inliers. Metamorphic rocks from both terranes mostly gave ages of about 400 Ma by both dating techniques. The only exception was a poorly defined 1200—1500 Ma total rock Rb-Sr apparent isochron age for the Holroyd Metamorphics (Coen Inlier). Cooper & others (1975) interpreted the isotopic data for the granites in both terranes in terms of four episodes of Palaeozoic igneous activity, at about 406 Ma, 392 Ma, 377—382 Ma and 250—274 Ma. The youngest ages were derived from rocks in the north and northeast of the Coen Inlier.

Although none of the granites yielded Precambrian ages, the isotopic data did not exclude this possibility. Indeed, the major unanswered question raised by the study was whether the isochrons were recording Middle Palaeozoic emplacement ages or isotopic resetting of older (Precambrian) granites by Middle Palaeozoic metamorphism and deformation. One of the main isotopic arguments for the latter interpretation was the observation that most of the metamorphic rocks yielded considerably younger ages (~400 Ma) than their postulated Proterozoic age of deposition. Another line of evidence was the high to extremely high initial $^{87}Sr/^{86}Sr$ ratios (0.713 to 0.766) of the ~400 Ma granite isochrons. Although these ratios could indicate that the granites were generated at about 400 Ma from the melting of Precambrian source rocks, they could also have resulted from the re-equilibration of Sr isotopes at about 400 Ma in granites emplaced during the Precambrian.

K-Ar and Rb-Sr systems in biotite and muscovite are readily reset at relatively low temperatures (approximately 300°C for all but Rb-Sr in muscovite, which is totally reset at about 500°C; Dodson & McClelland-Brown, 1985), corresponding roughly to those of greenschist-facies metamorphism. Rb-Sr total-rock isochrons are also commonly reset under sub-solidus conditions (Gebauer & Grunenfelder, 1974; Black & others, 1979). In contrast, the U-Pb systematics of zircon are relatively impervious to isotopic resetting. Recent technological advances in U-Pb methodology, particularly the development of the SHRIMP ion-microprobe (Compston & others, 1984), have now made it possible to date different parts of single grains, thereby virtually eliminating the chance of obtaining meaningless, mixed ages (e.g. Black & Sheraton, 1990). The U-Pb SHRIMP analyses of the present study yield unequivocal emplacement ages for selected granites from the Coen Inlier. The results, combined with new Sm-Nd data, clarify some issues, but also generate further questions regarding the geological evolution of this and neighbouring parts of north Queensland.

Geological background

Three inliers generally thought to be of Precambrian age, namely the Georgetown, Coen and Yambo Inliers, occur west of the Palaeozoic Tasman orogen in north Queensland (Fig. 1; Day & others, 1983). Because of their geological similarities to one another these terranes have been regarded by some (e.g. Oversby & others, 1975) as parts of a once continuous geotectonic unit. The subject of this study is the Coen Inlier, a north-trending belt of low- to high-grade metamorphic rocks (the Coen, Holroyd and Sefton Metamorphics), granite and minor felsic volcanics (Willmott & others, 1973).

The igneous rocks of the Coen Inlier were subdivided into two main groups by earlier workers - Middle Palaeozoic granites of the Cape York Peninsula Batholith, and Late Palaeozoic granites and volcanics (Willmott & others, 1973; Cooper & others, 1975). Granitic rocks of the Yambo Inlier were also classified as part of the Cape York Peninsula Batholith. The Willmott & others (1973) terminology is retained here for comparative purposes, although current studies will ultimately lead to re-definition.

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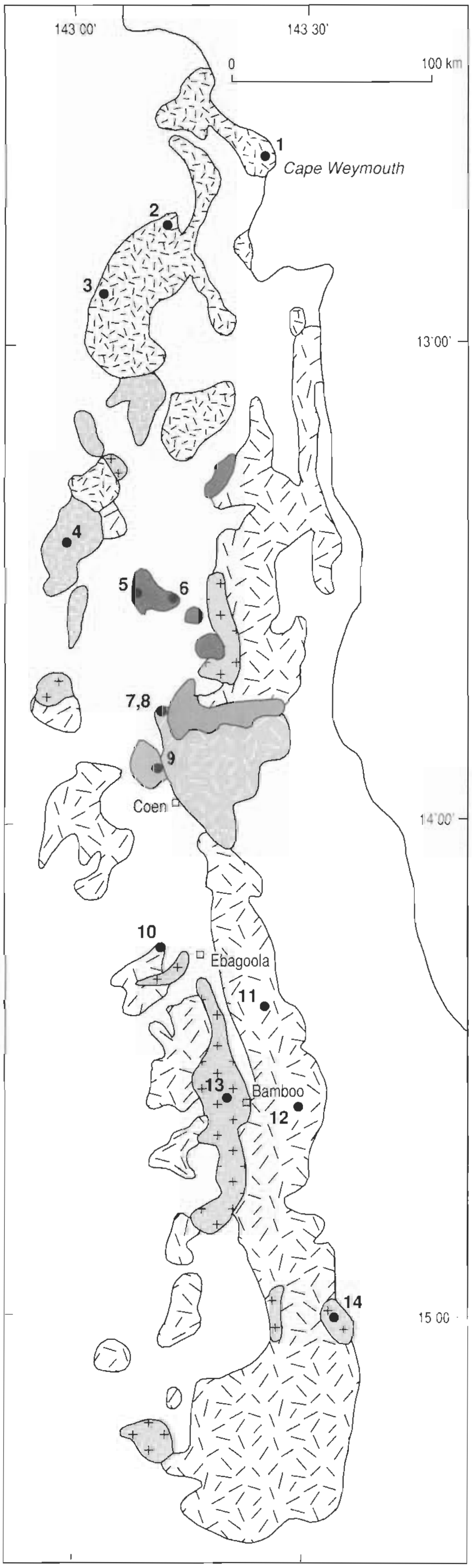

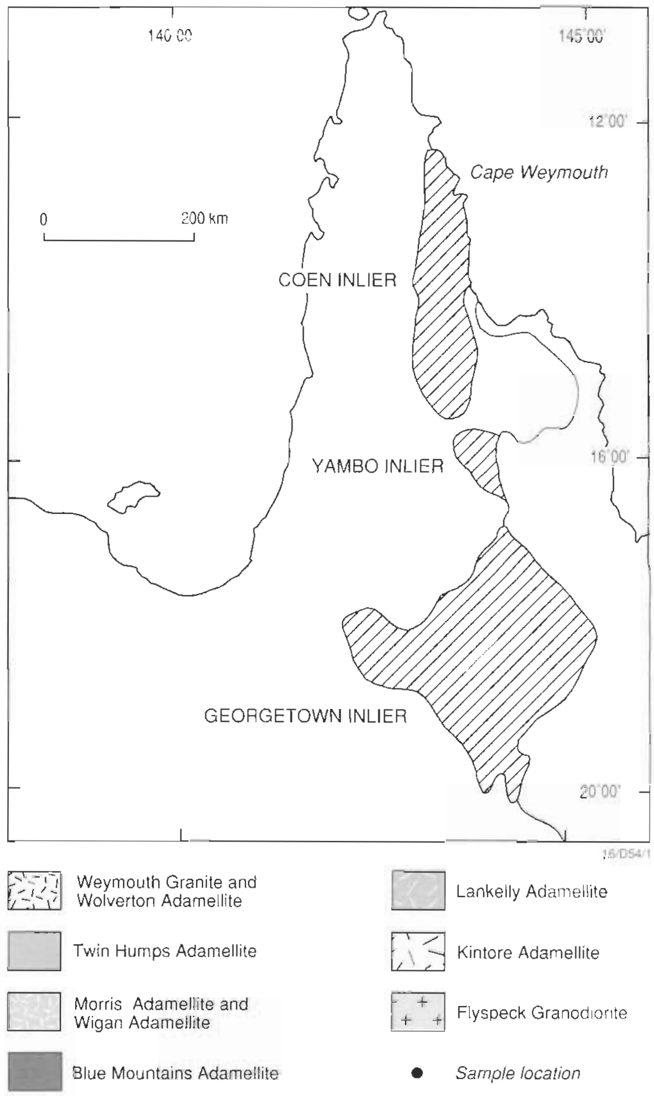

Figure 1. Regional setting, granite distribution and sample locations within the Coen Inlier.

1. Unassigned granite 89837503; 2. Weymouth Granite 89837504; 3. Weymouth Granite 89837502; 4. Morris Adamellite 89837500; 5. Blue Mountains Adamellite 89837507; 6. Blue Mountains Adamellite 89837508; 7. Lankelly Adamellite 89837505; 8. Lankelly Adamellite 89837509; 9. Twin Humps Adamellite 89837506; 10. Unassigned granite 90834330; 11. Kintore Adamellite 89837510; 12. Kintore Adamellite 89837511; 13. Flyspeck Granodiorite 70570190; 14. Flyspeck Granodiorite70570129.

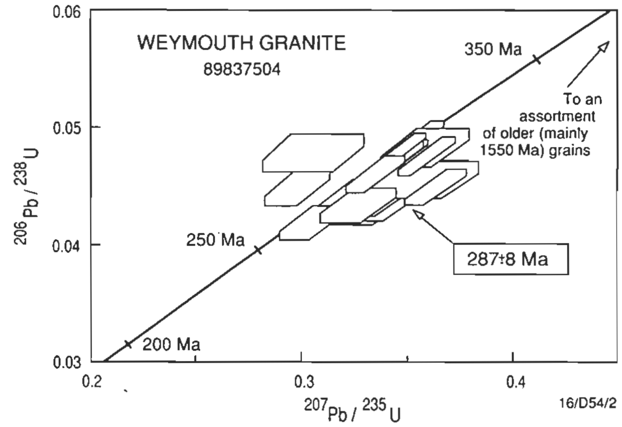

Figure 2. $^{206}Pb/^{238}U$ — $^{207}Pb/^{235}U$ concordia diagram for 23 magmatic zircon grains from the Weymouth Granite (sample 89837504), showing that it crystallised at 287±8 Ma.

The symbols in this and all following concordia diagrams represent 1 s errors.

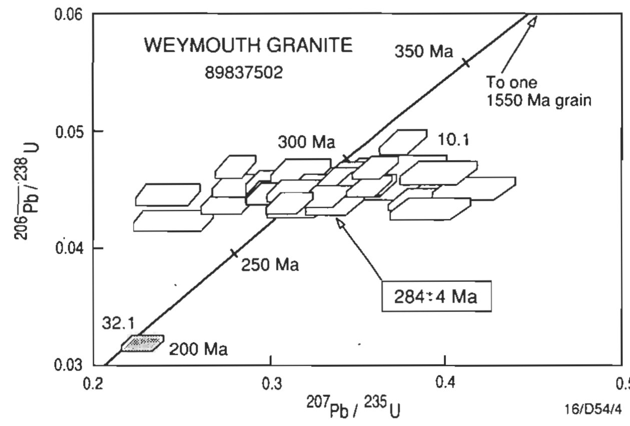

Figure 4. $^{206}Pb/^{238}U$ — $^{207}Pb/^{235}U$ concordia diagram for 36 magmatic zircon grains from the Weymouth Granite (sample 89837502), indicating a crystallisation age of 284±4 Ma.

The shaded symbol represents an analysis which is statistically different from the main group, and is therefore excluded from the age calculation.

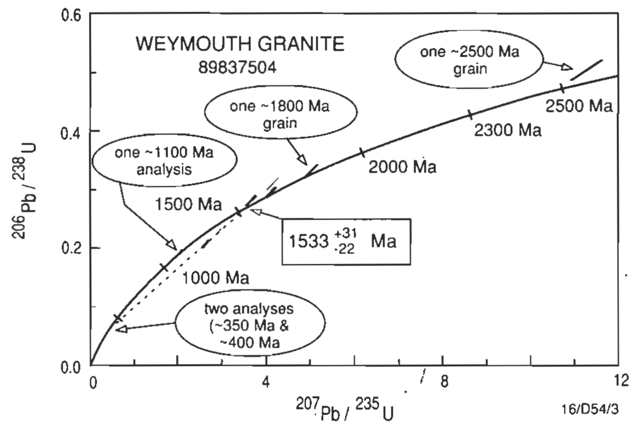

Figure 3. $^{206}Pb/^{238}U$ — $^{207}Pb/^{235}U$ concordia diagram, showing a range of ages for inherited zircon grains from the Weymouth Granite (sample 89837504).

A ~1600 Ma-old component is dominant.

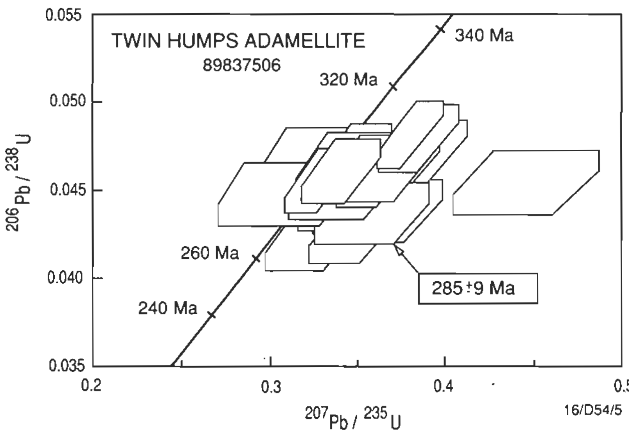

Figure 5. $^{206}Pb/^{238}U$ — $^{207}Pb/^{235}U$ concordia diagram for 29 magmatic zircon grains, which define a crystallisation age of 285±9 Ma for the Twin Humps Adamellite (sample 89837506).

The Cape York Peninsula Batholith (Fig. 1) extends for about 400 km from north to south, and is up to 60 km wide. It crops out over an area of 5500 km², and probably an additional 4000 km² is obscured by Cainozoic sediments. Its elongate form and general concordance with surrounding metamorphics, the presence of a foliation, the occurrence of marginal pegmatites, and the presence of migmatised and partly granitised rocks in the surrounding aureole led Willmott & others (1973) to conclude that the batholith was emplaced at considerable depth, probably in the lower mesozone (Buddington, 1959). The batholith was subdivided by Willmott & others (1973) into seven named lithological units. The most extensive of these is the Kintore Adamellite, which forms about 70% of the batholith, and extends along its entire length. The other units are the Blue Mountains, Morris, Wigan, Lankelly, and Aralba Adamellites (the latter crops out only in the Yambo Inlier) and the Flyspeck Granodiorite. Most of these units show considerable internal chemical and textural variation, and preliminary data from the current mapping show that considerable modification of the existing nomenclature will be necessary. Both S- and I-type granites (Chappell & White, 1974) are present, with the former constituting about 80% of the exposed surface area of the batholith. This contrasts with the Georgetown Inlier, where only I-type granites of Middle Palaeozoic age have been recorded (Bain & others, in press a). A characteristic common to both regions is the lack of preserved Middle Palaeozoic volcanic rocks.

Late Palaeozoic granitic and volcanic rocks of dominantly felsic composition occur in each of the three inliers. They extend over about 1300 km² of the central and northern parts of the Coen Inlier, where they have been mapped as the Weymouth Granite, and the Twin Humps and Wolverton Adamellites. In contrast to the Middle Palaeozoic intrusives, these granites form discordant intrusions that were emplaced at relatively high crustal levels, as suggested by their commonly porphyritic texture, their close spatial association with (and emplacement into) penecontemporaneous felsic and intermediate volcanics, and the local presence of miarolitic cavities. Hornblende is present in the more mafic varieties, and it appears that all the Late Palaeozoic granites are I-types (S-type granites of this age are also unknown in the Georgetown Inlier). Sn, W, Au, Cu and Pb mineralisation in the Coen Inlier are attributed to the Late Palaeozoic igneous activity.

U-Pb zircon analytical data

Emplacement ages have been derived for 14 granite samples using the U-Pb zircon ion-microprobe (Figs 2—19). Results are summarised in Table 1. The U-Pb zircon ion-microprobe methodology and Sm-Nd analytical technique are summarised in Appendix 1. A discussion of the analytical results and descriptions of the samples are given in Black & others (in press a). The nomenclature of Willmott & others (1973) is used to group the

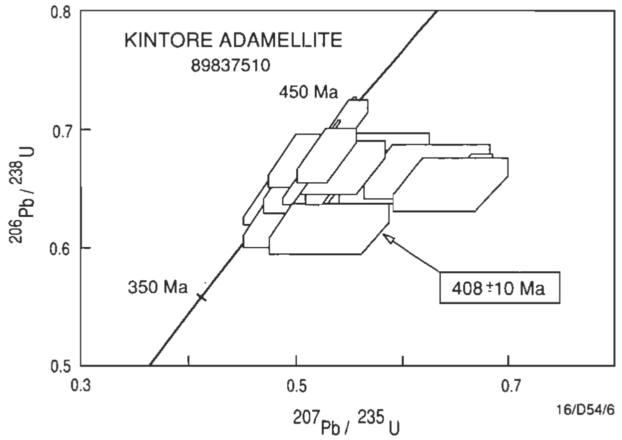

Figure 6. $^{206}Pb/^{238}U$ — $^{207}Pb/^{235}U$ concordia diagram for 27 magmatic zircon grains from the Kintore Adamellite (sample 89837510). These define a crystallisation age of 408±10 Ma.

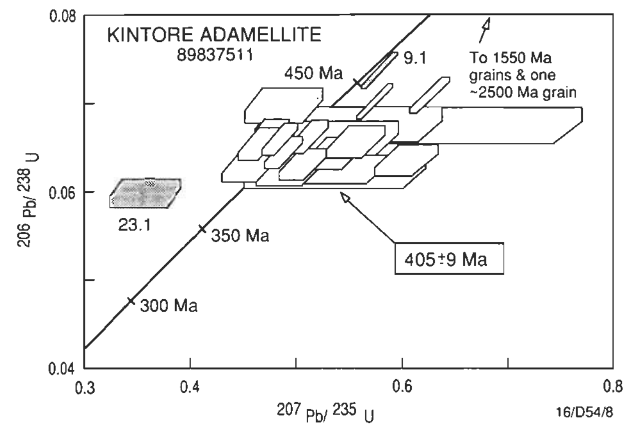

Figure 8. $^{206}Pb/^{238}U$ — $^{207}Pb/^{235}U$ concordia diagram for 21 magmatic zircon grains from the Kintore Adamellite (sample 89837511), indicating that it crystallised at 405±9 Ma.

The shaded symbols represent analyses which are excluded from the age calculation.

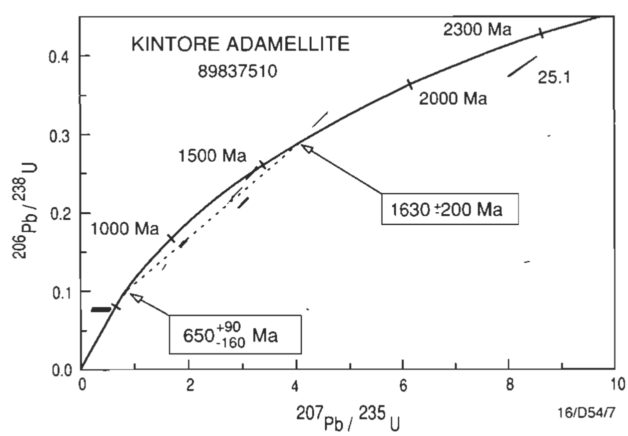

Figure 7. $^{206}Pb/^{238}U$ — $^{207}Pb/^{235}U$ concordia diagram for inherited zircon cores from the Kintore Adamellite (sample 89837510). A ~1600 Ma-old component is dominant.

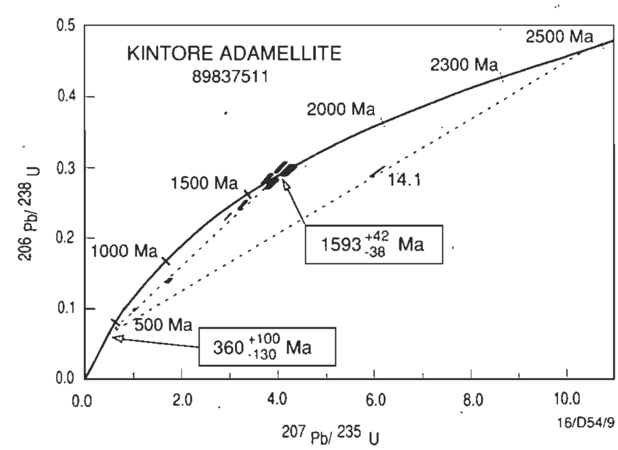

Figure 9. $^{206}Pb/^{238}U$ — $^{207}Pb/^{235}U$ concordia diagram for inherited zircon grains from the Kintore Adamellite (sample 89837511), showing a dominant ~1600 Ma-old component.

samples, with two exceptions. One exception is a biotite granite (89837503) from near Cape Weymouth, originally mapped as part of the Late Palaeozoic Weymouth Granite. Unlike the other analysed samples of Weymouth Granite, it does not contain hornblende, and has yielded a Middle Palaeozoic U-Pb zircon emplacement age. The second currently unassigned sample (90834330) is a strongly deformed granite from the Ebagoola area.

The U-Pb data show that some of the previously reported K-Ar and Rb-Sr ages do not define the time of granite emplacement. The Coen Inlier experienced a simpler Palaeozoic magmatic history than had been realised, with magmatic episodes at about 407 Ma and 285 Ma (see below).

Sm-Nd isotopic data and the origin of the intrusives

Sm-Nd model ages have been derived for all of the granite samples, as well as for several of the metamorphic rocks of the inlier. The interpretation of the significance of such ages is often difficult, but when applied in conjunction with known emplacement ages (from the U-Pb data), some ambiguities can be eliminated. One of the usual ways of presenting Sm-Nd data is by means of an evolution diagram (Fig. 20), in which the development of radiogenic composition (expressed as $^{143}Nd/^{144}Nd$) is plotted against time. Present-day compositions lie on the left side of the diagram. Previous compositions of each rock are estimated from progressive extrapolation backwards in time along trajectories related to individual $^{147}Sm/^{144}Nd$ ratios. Model ages correspond to the point where such trajectories meet those assumed to represent the mantle source of crustal rocks. One of those presumed mantle sources (chondritic or CHUR) is ascribed to an essentially unfractionated mantle. The other (DM) is used for depleted mantle compositions that have been modified by the production and removal of mafic magmas. Several DM models are in vogue; the one used here assumes present-day parameters of 0.225 for $^{147}Sm/^{144}Nd$ and 0.513163 for $^{143}Nd/^{144}Nd$, equivalent to mantle depletion having occurred at 2.7 Ga (Black & McCulloch, 1984).

Perhaps the most obvious feature of Fig. 20 is the relationship between Nd-isotopic composition and emplacement age. Thus, the three Late Palaeozoic granites have more radiogenic Nd than the Middle Palaeozoic granites, indicating that on average they were derived from the melting of more youthful crust. Significantly, the younger granites had Nd isotopic compositions at their time of emplacement (ε_{Nd} = -8, Table 2) very similar to those of I-type temporal equivalents in and immediately east of the Georgetown Inlier (Black & McCulloch, 1990). Those authors proposed that Late Palaeozoic Georgetown granites were the result of a two-

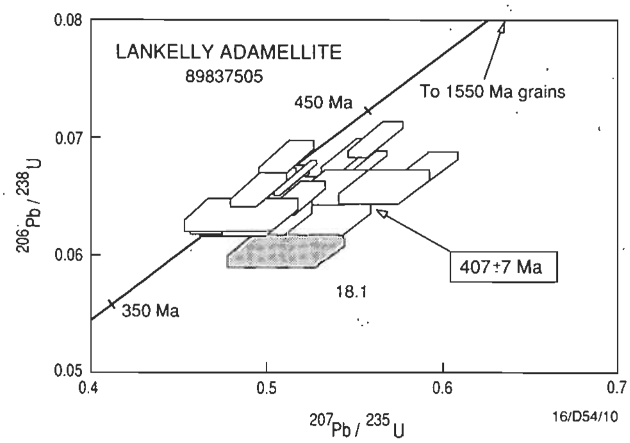

Figure 10. $^{206}Pb/^{238}U$ — $^{207}Pb/^{235}U$ **concordia diagram for 22 magmatic zircon grains from the Lankelly Adamellite (sample 89837505), showing that it crystallised at 407±7 Ma.**

The analysis represented by the shaded symbol is excluded from the age calculation.

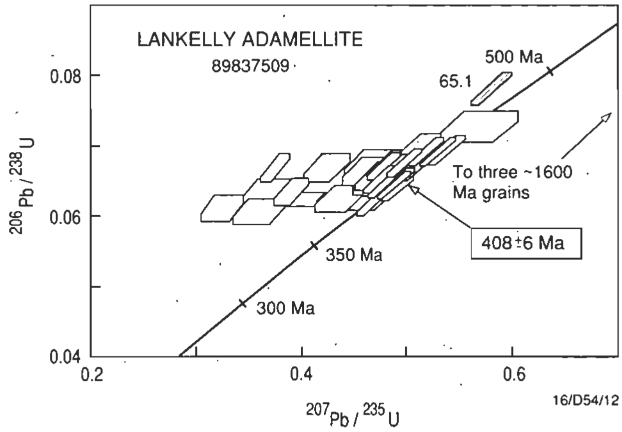

Figure 12. $^{206}Pb/^{238}U$ — $^{207}Pb/^{235}U$ **concordia diagram for 34 magmatic zircon grains from the Lankelly Adamellite (sample 89837509). These indicate that this adamellite crystallised at 408±6 Ma.**

The analysis represented by the shaded symbol is excluded from the age calculation.

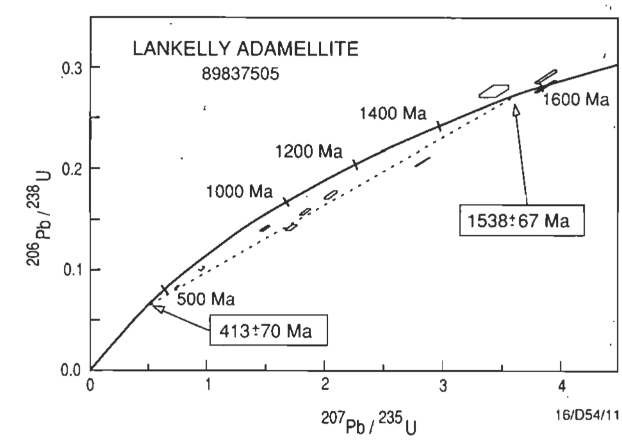

Figure 11. $^{206}Pb/^{238}U$ — $^{207}Pb/^{235}U$ **concordia diagram for ten ~1600 Ma-old inherited zircon cores from the Lankelly Adamellite (sample 89837505).**

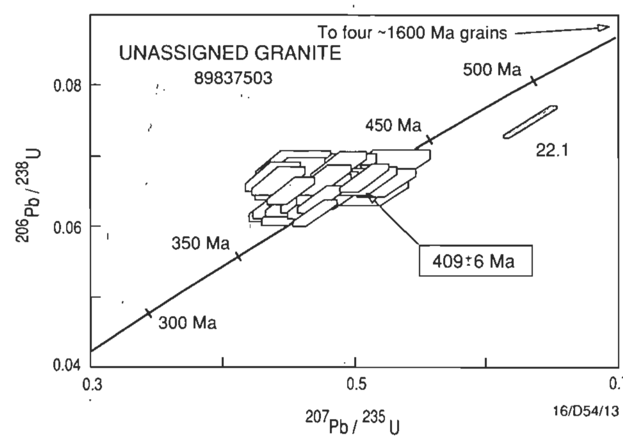

Figure 13. $^{206}Pb/^{238}U$ — $^{207}Pb/^{235}U$ **concordia diagram for 33 magmatic zircon grains from an unassigned granite at Cape Weymouth (sample 89837503).**

These data show that although it occurs in an area thought to have been dominated by Late Palaeozoic igneous activity, this granite crystallised considerably earlier, at 409±6 Ma. The analysis represented by the shaded symbol is excluded from the age calculation.

stage process whereby felsic crust that formed at about 1600 Ma was partially remelted at about 400 Ma to produce more felsic derivatives (similar to the Dido Granodiorite); partial remelting 100 Ma later of this Dido Granodiorite-like precursor(s) then produced the Permo-Carboniferous magmas. The age and isotopic similarities show that the Permo-Carboniferous granites of the Coen Inlier may have similar origin; i.e., the data imply that 1600 Ma-old felsic crust might be present throughout much of north Queensland.

The Middle Palaeozoic intrusives of the Coen Inlier show a much broader range of initial $^{143}Nd/^{144}Nd$ compositions (about 4 epsilon units) than the Permo-Carboniferous granites. The S-type Lankelly and Kintore Adamellites had ε_{Nd} of -14.0 and -14.5, respectively, whereas the I-type granites had higher ε_{Nd} (-11, -12 for the Blue Mountains Adamellite; -11.5 for the Morris Adamellite (a probable I-type according to D.C. Champion, written comm., 1991); -12.5 for the Flyspeck Granodiorite and -13 for an enclosed felsic vein). Nevertheless, there is no clearcut distinction between the two groups, because the enigmatic samples (89837503, from Cape Weymouth, containing neither muscovite nor hornblende, with ε_{Nd}= -13.5, and the garnet-bearing, highly deformed 90834330, with ε_{Nd} = -13.8) effectively link the two groups.

Unlike the Permian intrusives, Middle Palaeozoic granites in the Coen Inlier have ε_{Nd} characteristics different from those of their temporal equivalents in the Georgetown Inlier. The latter are characterised by a distinct dichotomy of compositions (Fig. 20), one of which is defined by the Dido Granodiorite (ε_{Nd} = -5.6), and the other (ε_{Nd} = -16) by the Dumbano Granite, and White Springs and Robin Hood Granodiorites. Black & McCulloch (1990) interpreted this isotopic dichotomy in terms of different episodes of felsic crust formation. They deduced that the Dido Granodiorite formed by the melting of approximately 1600 Ma-old crust. In contrast, they concluded that the much less radiogenic compositions of the other three granites resulted from the melting of much older, possibly composite, crust that formed about 2000—2500 Ma ago.

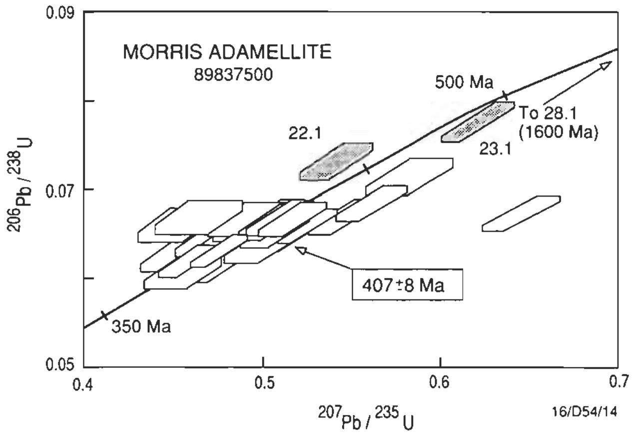

Figure 14. **$^{206}Pb/^{238}U$ — $^{207}Pb/^{235}U$ concordia diagram for 33 magmatic zircon grains from the Morris Adamellite (sample 89837500), which define a crystallisation age of 407±8 Ma.**

The shaded symbols represent analyses which are excluded from the age calculation.

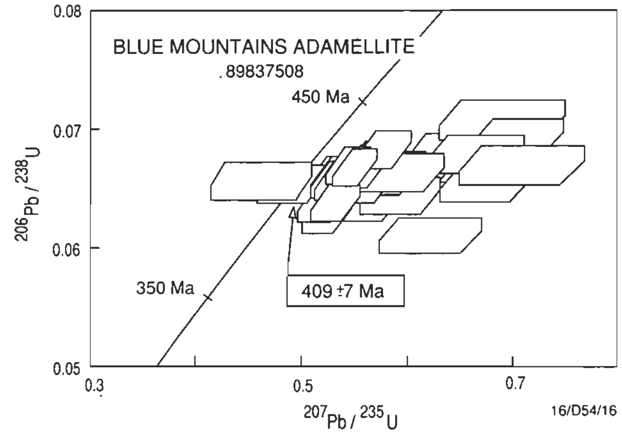

Figure 16. $^{206}Pb/^{238}U$ — $^{207}Pb/^{235}U$ concordia diagram for 35 magmatic zircon grains from the Blue Mountains Adamellite (sample 89837508). These define an emplacement age of 409±7 Ma.

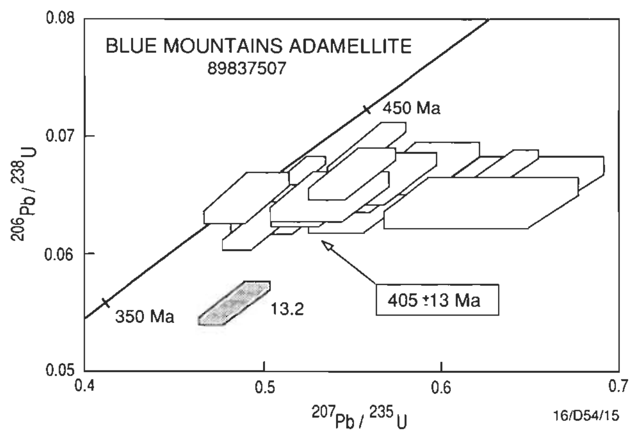

Figure 15. $^{206}Pb/^{238}U$ — $^{207}Pb/^{235}U$ concordia diagram for 16 magmatic zircon grains from the Blue Mountains Adamellite (sample 89837507). These define a crystallisation age of 405±13 Ma.

The analysis represented by the shaded symbol is excluded from the age calculation.

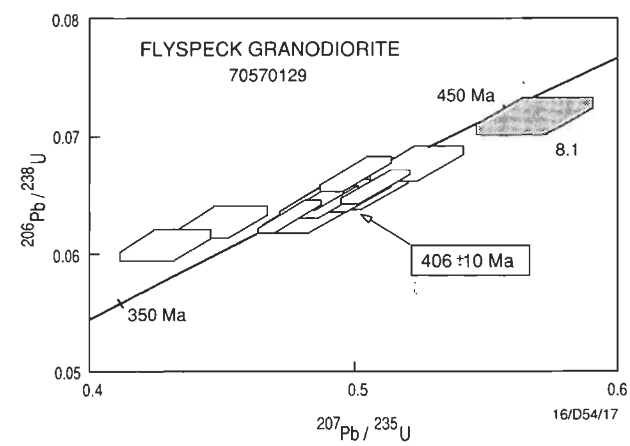

Figure 17. $^{206}Pb/^{238}U$ — $^{207}Pb/^{235}U$ concordia diagram for 19 magmatic zircon grains from the Flyspeck Granodiorite (sample 70570129). These define a crystallisation age of 406±10 Ma.

The analysis represented by the shaded symbol is excluded from the age calculation.

The Middle Palaeozoic granites of the Coen Inlier therefore cannot be precise genetic equivalents of their temporal counterparts in the Georgetown Inlier. Nevertheless, it is possible to explain them in terms of crustal components similar to those postulated for Georgetown, because the Nd isotopic compositions of the Georgetown rocks lie each side of the limits of the Coen Nd isotopic array (Fig. 21). Individual Middle Palaeozoic intrusions in the Georgetown Inlier could have formed essentially by the melting of only one of the two sources, whereas those in the Coen Inlier could have formed from mixtures of the same two felsic source components. If this was the case, the Middle Palaeozoic I-type Coen intrusives would contain a higher proportion of 1600 Ma-old crust than the S-types (which is consistent with being derived from greater depths, as underplating produces inverted stratigraphy). However, because all the Middle Palaeozoic granites in the Georgetown Inlier are I-type (i.e. derived from igneous sources), whereas those in the Coen Inlier comprise both S- (i.e. derived from sedimentary source rocks) and I-types, the postulated sources of the two granite provinces cannot be identical, even though they may have the same mantle extraction age. Nevertheless, it is logical to surmise that the 2000—2500 Ma source component of the Georgetown Middle Palaeozoic granites is of igneous origin, and that of contemporaneous Coen granites is the sedimentary derivative from such crust. Suitable metasedimentary rocks do exist at Georgetown, where they form the source for 1600 Ma S-type granites and volcanics. Comparable Sm-Nd isotopic compositions for the Coen Metamorphics and Holroyd Metamorphics (Table 2) indicate that most metasediments of the Coen Inlier were probably derived from source rocks either similar to metasediments exposed in the Georgetown Inlier, or to the source from which those rocks were derived.

Relevance of isotopic data to intra-crustal Sm/Nd fractionation

The isotopic trajectories have been extrapolated beyond the emplacement ages of the granites to the CHUR and DM evolution curves (Fig. 20). The locus of intersection with these curves yields the respective model ages for those rocks. These model ages are geologically meaningful only if there was no significant fractionation of Sm/Nd during the processes that produced the granites from their crustal precursors (or at any other stage of their crustal evolution). It is generally accepted (McCulloch & Wasserburg, 1978; Black & McCulloch, 1984) that intra-crustal

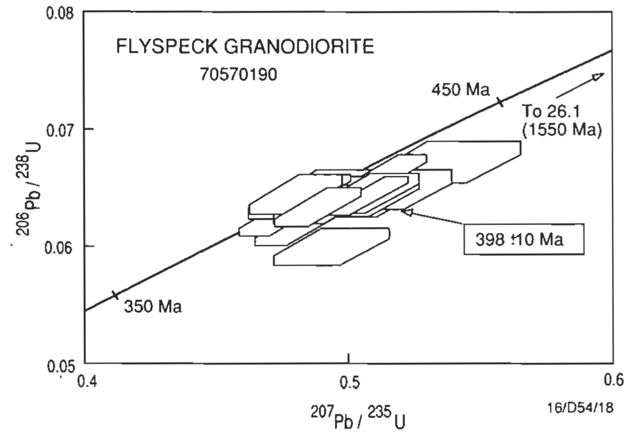

Figure 18. $^{206}Pb/^{238}U$ — $^{207}Pb/^{235}U$ **concordia diagram for 18 magmatic zircon grains from the Flyspeck Granodiorite (sample 70570190). The indicated crystallisation age of 398±10 Ma is indistinguishable from that of the other Flyspeck Granodiorite sample.**

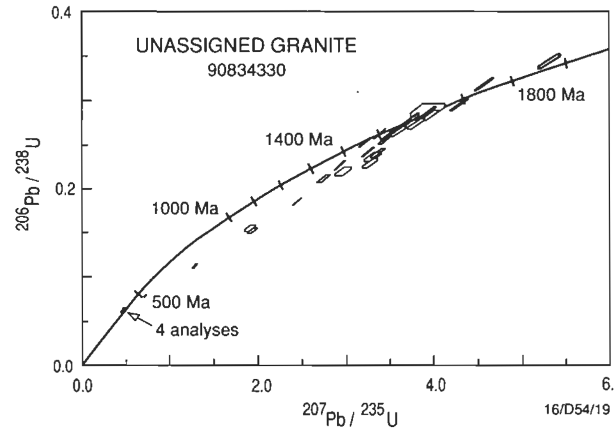

Figure 19. $^{206}Pb/^{238}U$ — $^{207}Pb/^{235}U$ **concordia diagram for zircon from unassigned granite sample 90834330.**

Most of the grains grew at about 1600 Ma. They are thought to have been inherited by the magma, a common occurrence of some S-type granites (see text). Only the four analyses at 400 Ma are interpreted as magmatic grains.

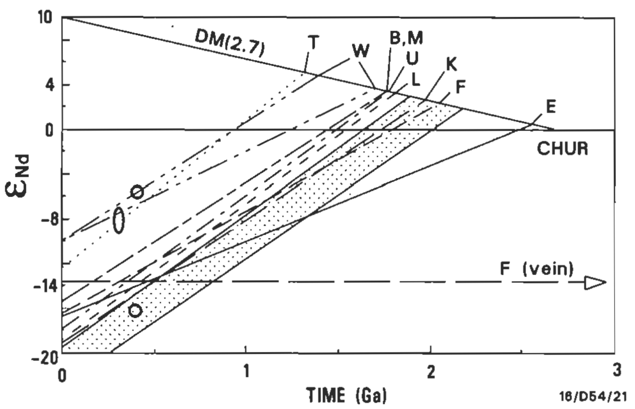

Figure 20. $^{143}Nd/^{144}Nd$ **evolution diagram for the rocks of the Coen Inlier. The shaded field encloses the compositions of the three metamorphic rocks. The evolving compositions of the granites are shown by variously dashed lines.**

T, Twin Humps Adamellite; B, Blue Mountains Adamellite; M, Morris Adamellite; W, Weymouth Granite; L, Lankelly Adamellite; K, Kintore Adamellite; U, unassigned granite from Cape Weymouth; E, unassigned deformed granite from Ebagoola; F, Flyspeck Granodiorite). DM(2.7) is the trajectory of mantle depleted at 2700 Ma, CHUR is the trajectory of primitive mantle. The small circular (400 Ma) and oval (300 Ma) fields are shown for reference to the Palaeozoic granites of the Georgetown Inlier. The upper circle represents the Dido Granodiorite; the lower represents the Dumbano and Robin Hood Granites and the White Springs Granodiorite. The oval field represents the composition of many of the Late Palaeozoic igneous rocks near the eastern margin of the Georgetown Inlier. Refer to the text for a more detailed explanation of this diagram.

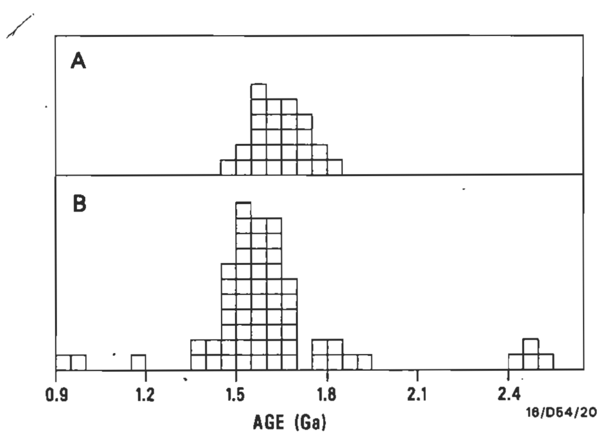

Figure 21. a. Histogram showing the age distribution of zircon grains of assumed inherited origin in sample 90834330. b. Age distribution of inherited zircons from the other analysed granites.

All ages were calculated by the extrapolation through each analysis to concordia of a chord from the 400 Ma concordia locus (because the individual sample data indicate that this was a time of significant Pb mobilisation).

fractionation of Sm/Nd is mostly insignificant, and that a relatively constant fractionation of about 40% occurs when the mantle is melted to produce continental crust. However, some studies have shown that intra-crustal fractionation does occur under certain conditions. For example, Black & McCulloch (1987) demonstrated its occurrence during deformation and granulite-facies metamorphism.

The present study probably provides at least one example, and possibly two (providing 90834330 was emplaced at about 400 Ma, as seems likely), of such fractionation. The less definitive example is provided by the most deformed of the analysed granites (90834330) which had $^{143}Nd/^{144}Nd$ similar to that of the other Siluro-Devonian S-type granites at the time of their generation. Its composition rapidly diverges from them as it is progressively extrapolated further back in time, until it yields a CHUR model age over 500 Ma older than the oldest value for the other granites. An even more pronounced enrichment of Sm/Nd appears to have occurred in sample 70570129a, a leucocratic vein from within the Flyspeck Granodiorite sample (70570129) analysed for U-Pb. At its time of formation (400 Ma) the $^{143}Nd/^{144}Nd$ in this vein was only about one epsilon unit more negative than that in the other Flyspeck sample (and indistinguishable from that in the S-type granites), consistent with the vein being primarily the product of extended fractional crystallisation of its host granite. Before 400 Ma its extrapolated isotopic composition rapidly deviates from those of the other analysed rocks. Indeed, its inordinately high $^{147}Sm/^{144}Nd$ for a felsic rock is identical to that of CHUR, which means that it has an infinitely old (and obviously meaningless) model age. Clearly, the present $^{147}Sm/^{144}Nd$ of the vein was established at about 400 Ma as a result of dramatic enrichment of Sm over Nd, probably in response to extensive crystal fractionation involving the removal of accessory minerals such as monazite and/or apatite (Miller & Mittlefehldt, 1982). Fluid activity might also have played a role.

The enrichment of Sm/Nd deduced above is not typical of crustal processes. If the $^{147}Sm/^{144}Nd$ of felsic rocks markedly diverges from the normal crustal value of about 0.12, it is most commonly offset to lower values, as is often the case for highly fractionated rocks such as pegmatite or aplite (e.g. Black & others, in press b). As long as Sm/Nd is not increased by successive crustal processes, any resultant model ages will represent a younger limit for the time of mantle extraction. The above two examples exhibit the opposite behaviour (cf. the study of Miller and Mittlefehldt, 1982), documenting one more reason for treating Sm-Nd model ages with caution.

Geological significance of the new data

Unlike the previous Rb-Sr and K-Ar data (Cooper & others, 1975), which could be interpreted in terms of isotopic resetting, the new U-Pb zircon ages clearly define emplacement ages for the granitic rocks of the Coen Inlier. The three Permo-Carboniferous ages are within error of each other (Table 1), signifying that each of these granites was emplaced at about 285 Ma, in Permian times (the Carboniferous—Permian boundary occurs at about 298 Ma: Hess & Lippolt, 1986). In contrast, Cooper & others (1975) determined a range of ages for Permo-Carboniferous igneous activity in this area. When corrected for current decay constants (Steiger & Jager, 1977) and for slight changes in analytical calibration (Richards & Singleton, 1981), these are 277 Ma (Wigan Adamellite, Rb-Sr biotite), 285 Ma (Weymouth Granite at Cape Weymouth, K-Ar biotite), 273 Ma (Weymouth Granite at Restoration Island, K-Ar biotite) and 263 Ma (Twin Humps Adamellite, K-Ar biotite). Even though we have not studied the same outcrops as Cooper & others (1975), their proposed age range is probably more apparent than real. The three K-Ar biotite ages show a marked positive correlation with K contents (4.7%, 6.3% and 7.1%) of the analysed biotites, consistent with the presence of the poorly retentive mineral, chlorite. Only the sample with 7.1% K can be a relatively pure separate, and therefore be expected to yield a meaningful age. This age (285 Ma) is indistinguishable from that produced by the U-Pb data. In the absence of new data for the Wigan Adamellite it is not possible to assess whether its published Rb-Sr age of 277 Ma has also been affected by loss of radiogenic daughter product.

The U-Pb data indicate that the Siluro-Devonian granites were also emplaced during a short-lived intrusive episode (Table 1). The two Flyspeck Granodiorite samples yield a pooled age of 402±7 Ma, the Blue Mountains Adamellite samples yield 408±6 Ma, the Lankelly Adamellite samples 407±5 Ma and the two Kintore Adamellite samples yield 406±7 Ma. The Morris Adamellite and the unassigned granite (sample 89837503) yield ages of 407±8 Ma and 409±6 Ma, respectively. All ten of the Siluro-Devonian ages are indistinguishable from one other, and indicate an age of about 407 Ma for the episode of granitic emplacement. This age is close to that of the Siluro-Devonian boundary (Harland & others, 1989).

Although the U-Pb zircon data broadly support the K-Ar and Rb-Sr ages of Cooper & others (1975) for the Middle Palaeozoic intrusives, there are some important differences in detail (as for the Permo-Carboniferous granites). It was concluded from the earlier data that there were three episodes of Middle Palaeozoic igneous activity in the Coen Inlier, at about 406 Ma, 392 Ma and 377-382 Ma. The current study conclusively supports the oldest of those events, but fails to support the other two. This is presumably because the earlier ages were derived from non-robust isotopic systems which were partly reset during Permo-Carboniferous igneous activity.

The new U-Pb results are also at variance with the recent study of Blewett & von Gnielinski (1991), who suggested, on the basis of similar structural style, that the first two major tectonothermal events in the Coen Inlier were synchronous with D_1 and D_2 in the Georgetown Inlier. Black & others (1979) had derived a Rb-Sr age of about 1470 Ma for D_2 at Georgetown, and recent conventional (Black & McCulloch, 1990) and ion-microprobe U-Pb zircon data (L.P. Black, unpublished analyses) suggest that it might be even older. As Blewett and von Gnielinski (1991) recorded that D_2 structures in the Coen Inlier overprint some of the granites now dated at about 400 Ma, it is clear that at least this deformation should not be correlated with D_2 in the Georgetown Inlier. Additional mapping and re-assessment of some of the original observations have now led to a structural interpretation (Blewett & von Gnielinski, *in* Bain & others, in press b) that is compatible with the new isotopic data.

Whatever specific interpretation is attached to the numerous isochrons obtained by Cooper & others (1975), their very high initial $^{87}Sr/^{86}Sr$ ratios are testament to the presence of Precambrian crustal components within the Coen Inlier. With the benefit of the confirmatory U-Pb and Sm-Nd data it is now possible to partly quantify the age of this old crust. By comparing the Sm-Nd data with those from the Georgetown region, it can be speculated that ~1600 Ma and ~2000—2500 Ma crustal components dominate the Coen Inlier. Restitic (or xenocrystic) zircons in the granites support this conclusion, for they produce a dominant, but imprecisely defined ~1450—1800 Ma population with a maximum at 1600 Ma, and a minor 2500 Ma component (Fig. 21).

Although inherited zircons occur in both the S- and I-type granites, they are generally far more abundant in the S-types, a relationship which has also been found to apply to the granites of the Lachlan Fold Belt (Chappell & others, 1990). Sample 89837504 (284±7-Ma I-type Weymouth Granite) is a notable exception (Black & others, in press a; many of the Siluro-Devonian granites in the Georgetown Inlier also contain large quantities of inherited zircons). Possible reasons for the generally more common occurrence of inherited zircon in S-type magmas are (1) their lower temperature, (2) their higher viscosity, and (3) the lower solubility of zircon in peraluminous melts (Watson, 1979).

Table 1. U-Pb emplacement ages for the analysed samples.

Sample	*Rock*	*Grid reference*	*Age*	*Pooled ages*
89837504	Weymouth Granite	735885921	287±8 Ma	
89837502	Weymouth Granite	719085725	284±4 Ma	285±4 Ma
89837506	Twin Humps Adamellite	735384615	285±9 Ma	
89837410	Kintore Adamellite	754684070	408±10 Ma	
89837511	Kintore Adamellite	764283813	405±9 Ma	406±7 Ma
89837505	Lankelly Adamellite	734484766	407±7 Ma	
89837509	Lankelly Adamellite	733784768	408±6 Ma	407±5 Ma
89837503	Unassigned granite	759186037	409±6 Ma	
89837500	Morris Adamellite	710185138	407±8 Ma	
89837507	Blue Mountains Adamellite	736185001	405±13 Ma	
89837508	Blue Mountains Adamellite	730585005	409±7 Ma	408±6 Ma
70571029	Flyspeck Granodiorite	774483416	406±10 Ma	
70570190	Flyspeck Granodiorite	749483863	398±10 Ma	402±7 Ma
90834330	Unassigned granite	739784247	~400 Ma	

Table 2. Sm-Nd isotopic compositions of granites and metamorphic rocks from the Coen Inlier.

Classification	*Type*	*Sample no.*	*Sm (ppm)*	*Nd(ppm)*	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	εNd 0 Ma	εNd 400 Ma	T^{Nd}_{CHUR}	T^{Nd}_{DM}
Lankelly Adamellite	S	89837509	11.28	66.1	0.1032	0.511717±9	-18.20	-13.4	1.52	1.80
Lankelly Adamellite	S	89837505	12.19	73.1	0.1008	0.511697±7	-18.60	-13.7	1.52	1.79
Kintore Adamellite	S	89837510	5.66	32.2	0.1062	0.511670±6	-19.12	-14.5	1.65	1.91
Kintore Adamellite	S	89837511	4.08	21.5	0.1145	0.511679±6	-18.93	-14.8	1.80	2.04
Unassigned granitoid	S	90834330	2.96	12.45	0.1436	0.511805±7	-16.49	-13.8	2.41	2.53
Unassigned granitoid	S	89837503	7.43	44.37	0.1013	0.511727±9	-18.00	-13.1	1.47	1.76
Morris Adamellite	I	89837500	8.33	43.11	0.1168	0.511888±8	-14.87	-10.8	1.46	1.79
Morris Adamellite	I	89837501	10.48	56.6	0.1119	0.511859±9	-15.43	-11.1	1.42	1.75
Blue Mountains Adamellite	I	89837507	8.67	46.4	0.1129	0.511871±6	-15.20	-10.9	1.42	1.75
Blue Mountains Adamellite	I	89837508	9.22	53.6	0.1041	0.511811±6	-16.37	-11.6	1.38	1.70
Flyspeck felsic vein	I	70570129	1.07	3.30	0.1966	0.511943±7	-13.79	-13.8	—	—
Flyspeck Granodiorite	I	70570190	5.76	28.15	0.1237	0.511808±6	-16.43	-12.7	1.75	2.03
Twin Humps Adamellite	I	89837506	13.0	87.9	0.0895	0.512011±7	-12.47	-7.0	0.91	1.29
Weymouth Granite	I	89837502	5.72	30.0	0.1152	0.512152±5	-9.71	-5.6	0.93	1.40
Weymouth Granite	I	89837504	6.31	28.7	0.1328	0.512139±8	-9.96	-6.8	1.23	1.70
Coen Metamorphics		70570264	4.44	26.7	0.1008	0.511639±8	-19.72	-14.8	1.60	1.86
Holroyd Metamorphics		68480231	9.10	49.9	0.1104	0.511646±6	-19.58	-15.2	1.77	2.01
Holroyd Metamorphics		68480232	9.83	57.5	0.1033	0.511435±6	-23.71	-19.0	1.98	2.16

S Granite apparently derived by the melting of a dominantly sedimentary source

I Granite apparently derived by the melting of a dominantly igneous source

The U-Pb data, although considerably simplifying the previously advocated igneous chronology of the Coen Inlier, create a new dilemma. Extensive field and laboratory studies have until now indicated that the Coen and Georgetown Inliers are time and lithological equivalents. The U-Pb and Sm-Nd data reinforce the similarities in Middle and Late Palaeozoic igneous history between the two regions. However, there is no evidence in any of the currently available data for the presence of Precambrian granites in the Coen Inlier. Until Precambrian rocks are discovered and dated, it will not be possible to equate the two inliers convincingly. Although the U-Pb, Sm-Nd and Rb-Sr data indicate the subsurface crust of the Coen Inlier is mainly Precambrian, there is (as yet) no isotopic evidence that the exposed metasediments of the Coen Inlier were deposited in the Precambrian, as they were in the Georgetown Inlier (at some time before 1550 Ma). The isotopic similarities between the two regions could be explained by derivation of the meta-sedimentary rocks of the Coen Inlier from the weathering and erosion of an old terrane, such as the Georgetown Inlier. Deposition of the sedimentary precursors to the metamorphic rocks in the Coen Inlier could have occurred at any time up to about 400 Ma. This issue is not clarified by the Precambrian Rb-Sr age reported for the Holroyd Metamorphics by Cooper & others (1975) because this age was derived by the inclusion on a single 'isochron' of samples from three different localities. When the analyses from each locality are considered in isolation, they yield no evidence of an age older than about 400 Ma. The Rb-Sr data for the Holroyd Metamorphics are thus equivocal. Although they may indicate an age of deposition at about 1500 Ma (very approximate), they could have resulted from deposition at a considerably later time of poorly sorted Precambrian detritus. Future work will investigate zircons within these and other metasedimentary rocks. When this avenue of research has been examined in detail it may be possible to make a more definitive statement on the depositional age of the Coen Inlier.

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Appendix 1. Experimental techniques

The U-Pb zircon analyses were made using the ion-microprobe SHRIMP (Compston & others, 1984; Williams & others, 1984) at the Research School of Earth Sciences, Australian National University. The instrument was operated at a mass resolution of more than 6500 to remove all significant isobaric spectral interferences. Absolute values for Pb/U were normalised to a mean $^{206}Pb/^{238}U$ value of 0.0928 (corresponding to an age of 572 Ma) for a standard zircon fragment (SL13). Systematic inter-element fractionation was corrected by a Power Law relationship determined between Pb^+/U^+ and UO^+/U^+ for the zircon standard. The reproducibility of reduced Pb/U ratios for the standard analyses interspersed with zircons analysed from each rock ranged from about 2% to 3% (1Σ). This uncertainty is added to that resulting from fundamental counting statistics in the errors displayed on the concordia diagrams, and is taken into account in the calculation of all age uncertainties (which are given at the 95% confidence level, tΣ).

In keeping with the normal procedures used in the SHRIMP laboratory, the relatively precise ^{208}Pb method was used for common Pb correction of the youngest of the analysed grains — the syn-magmatic zircon within both the Middle and Late Palaeozoic granites. $^{206}Pb/^{238}U$ ages, which are least affected by uncertainties in common Pb correction, are reported for these grains. These ^{208}Pb-corrected data are depicted on the various concordia diagrams and reported in the OZCHRON database, because they best allow an appraisal of data quality. However, in order to minimise the (relatively small) uncertainties resulting from common Pb correction, all Palaeozoic ages have been derived from the ^{207}Pb correction technique. Based on the assumption that all of the appropriate analyses are concordant, the use of this technique allows more meaningful age comparison than does the ^{208}Pb technique.

Common Pb correction for the older zircon analyses was by the ^{204}Pb method, because there was commonly evidence that the U-Th-Pb systematics of those grains had been disturbed by post-crystallisation processes. There is no evidence that the non-radiogenic Pb component in either the Precambrian or Palaeozoic grains is unrepresentative of contemporaneous common Pb (Cumming & Richards, 1975).

The U-Th-Pb isotopic data are presented throughout this article only in graphical form. Raw numerical data are too bulky to be presented here. Readers wishing to see the numerical data are referred to OZCHRON, the Australian Geological Survey Organisation geochronological data base.

Sm-Nd chemical procedures are based on the technique of Richard & others (1976). Mass-spectrometric analysis was performed on a Finnigan-Mat 261 instrument using a system of calibrated Faraday cup collectors in static mode. $^{146}Nd/^{144}Nd$ was normalised to 0.7219. Present day values of 0.513163 and 0.225 for $^{143}Nd/^{144}Nd$ and $^{147}Sm/^{144}Nd$, respectively, were used to calculate the depleted mantle (DM) model ages. All errors are quoted at the 95% confidence level.

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A new local magnitude scale for southeastern Australia

Marion Michael-Leiba[1] & Kim Malafant[2]

Measurements of maximum trace amplitudes from 181 short-period vertical seismograms recorded at hypocentral distances of 3—1500 km from 36 earthquakes in the magnitude range 0.8—4.3 were used to derive a new preliminary ML scale for southeastern Australia ML = log A + (1.34±0.09)log(R/100) + (0.00055±0.00012)(R-100) + 3.13 + S where ML is local magnitude, A (mm) is equivalent Wood-Anderson trace amplitude not corrected for the measurement having been made on a vertical component, R (km) the hypocentral distance and S the station correction.

Introduction

Richter (1935, 31) defined the magnitude of an earthquake as 'the logarithm of the calculated maximum trace amplitude, expressed in microns, with which the standard short-period torsion seismometer (T_0=0.8, V=2800, h=0.8) would register that shock at an epicentral distance of 100 kilometers'. T_0 is the undamped free period of the seismometer, V is the static or geometric magnification, and h is the coefficient of damping (Anderson & Wood, 1925). Thus a magnitude ML 3.0 earthquake would have a maximum trace amplitude of 1 mm (1000 μm) on a Wood-Anderson seismograph at a distance of 100 km from its epicentre. The corresponding amplitude of a magnitude ML 0.0 shock would be 0.001 mm (1 μm).

Clearly not all earthquakes are conveniently located 100 km from a seismograph, so Richter (1935) drew up an attenuation curve for Southern California based on a group of 11 events which occurred in January 1932. He plotted the logarithm of the observed amplitude against the epicentral distance. A single curve, representing the attenuation for an arbitrary event, was drawn parallel to the individual attenuation curves. From this he constructed a table of the logarithms of the maximum trace amplitudes (mm) with which a magnitude zero event would be recorded on a standard Wood-Anderson seismograph at epicentral distances in the range 0—600 km (Richter, 1958). He called these values log A_0, and defined the magnitude, ML, as

$$ML = \log A - \log A_0 \quad (1)$$

where A (mm) is the maximum trace amplitude of an event, measured on a standard Wood-Anderson seismograph at a certain distance, and A_0 is the corresponding amplitude which would have been recorded for a zero magnitude shock at that distance. The amplitudes are measured zero to peak.

Richter (1935, 1958) also applied empirical corrections, S, to the ML determination from each station or preferably from each instrument (each station consisting of a pair of horizontal seismographs) to give

$$ML = \log A - \log A_0 + S \quad (2)$$

Richter (1958) pointed out two limitations of his scale. One was its dependence on the Wood-Anderson seismograph. The other was that the table of log A_0 values cannot be assumed to apply outside the Californian area because of possible differences in mean focal depth, geology and crustal structure.

Despite Richter's warnings, his local magnitude scale was widely applied with little or no modification for many years in various parts of the world. Recently, Hutton & Boore (1987) redetermined the attenuation function in Southern California using thousands of observations and modern computing methods. Similar work has been done in other parts of the United States (e.g. Bakun & Joyner, 1984), Japan (e.g. Takeo & Abe, 1981), Greece (Kiratzi & Papazachos, 1984), South Australia (Greenhalgh & Singh, 1986) and Western Australia (Gaull & Gregson, 1991). Our paper gives a new preliminary attenuation function and station corrections for the Australian Geological Survey Organisation's (AGSO) short-period vertical seismographs in southeastern Australia.

Method

The seismograph stations used in the study (Fig. 1) were Canberra (CNB), Australian Capital Territory; Cobar (CMS), Cooney (COO), Stephens Creek (STK), Riverview (RIV) and Dalton (34.726°S,149.177°E) in New South Wales; Roma (RMQ) in southern Queensland; and Bellfield (BFD) and Toolangi (TOO) in Victoria. In May 1985, the Toolangi photographic recorder (designated TO1 in this study) was converted to hot stylus recording (TO2).

The maximum trace amplitude and corresponding period on the AGSO seismograms were measured wherever possible for 36 events in southeastern Queensland, New South Wales, Victoria and Tasmania (Table 1). This gave a total of 181 observations at hypocentral distances of 3—1484 km. The earthquakes were chosen to give a range of magnitudes, geographic localities and hypocentral distances. The number of measurements for each event varied from two to nine with a mean of five. Those earthquakes with only two measurements were selected because one of the hypocentral distances was less than 50 km. This was to give definition to the attenuation curve at short distances. The amplitudes were converted to Wood-Anderson trace amplitudes, A (mm), making no correction for the measurements having been made on a vertical component, and assuming a maximum Wood-Anderson magnification of 2800. Because the formula which would result from this study was intended for routine use, it was not considered practical to try to decide which oscillation on the seismogram would actually represent the maximum trace amplitude on a Wood-Anderson.

Gaull & Gregson (1991) found that maximum trace amplitudes read from a horizontal component seismograph were a mean of 1.34±0.05 times those read from the vertical component. This is equivalent to applying a correction of +0.13 to the magnitude determined from the vertical component, because the magnitude is proportional to the logarithm of the amplitude (log 1.34 is 0.13).

Following Hutton & Boore (1987),

$$-\log A_0 = n \log(R/100) + K(R-100) + 3.0 \quad (3)$$

where R is hypocentral distance (km), n is the geometric spreading coefficient and K the attenuation coefficient. Combining (2) and (3),

$$ML = \log A + n \log(R/100) + K(R-100) + 3.0 + S \quad (4)$$

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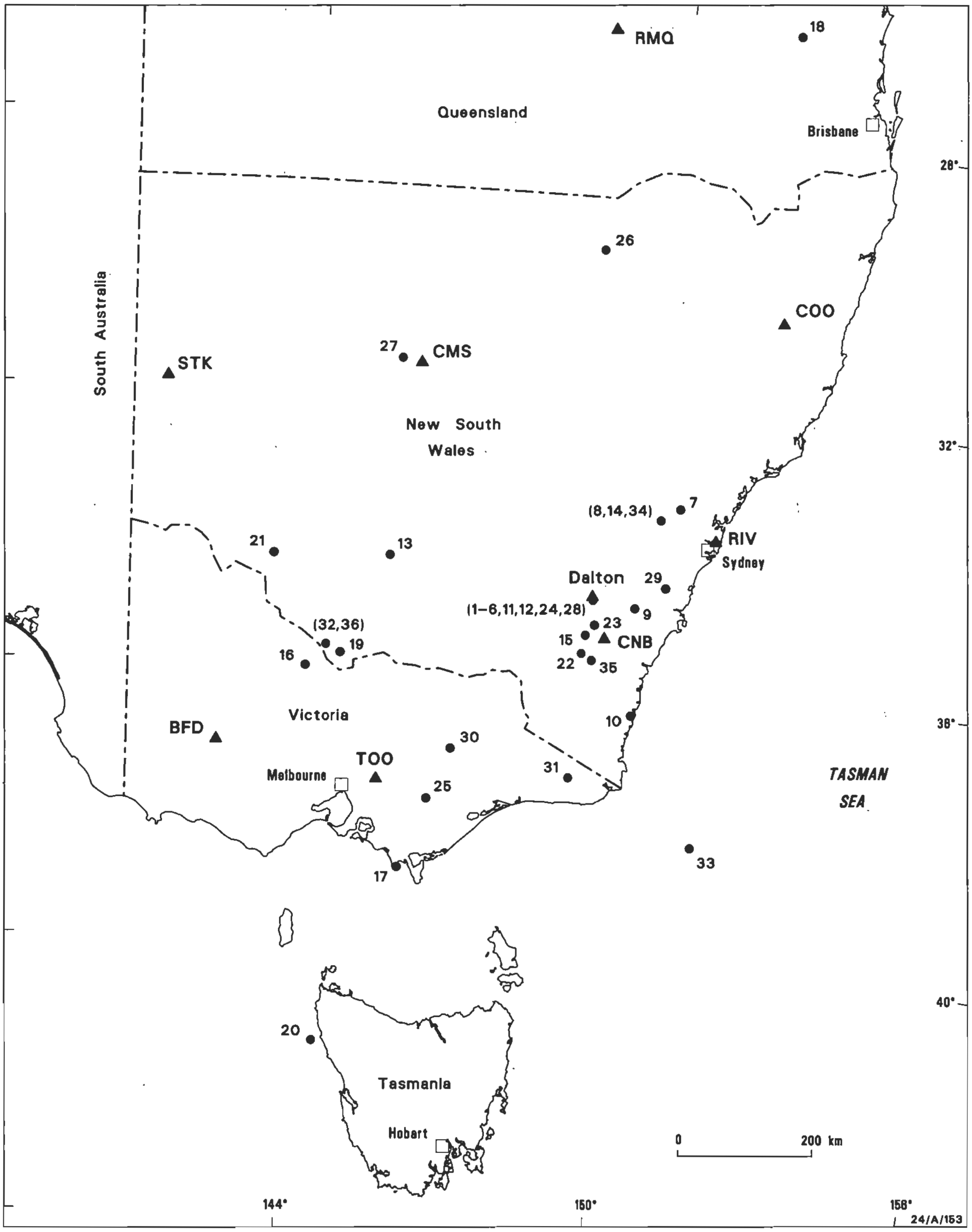

Figure 1. Seismograph stations (triangles) and epicentres (dots) of earthquakes used in the southeastern Australian magnitude study. The numbers are the Id numbers in Table I.

Equation (4) reflects the assertion that a magnitude ML 3.0 earthquake has a maximum trace amplitude of 1 mm on a Wood-Anderson seismograph 100 km distant. Because our measurements were made on vertical component instruments,

$$ML = \log A + n \log(R/100) + K(R-100) + 3.13 + S \quad (5)$$

where the 0.13 added to the 3.0 from equation (4) is the correction mentioned above. Gaull & Gregson's (1991) value was adopted because it was very similar to the ad hoc correction of 0.15 which had been used traditionally by the Australian Seismological Centre in Canberra. As magnitudes are routinely rounded to one decimal place, the difference is immaterial.

Rearranging (5), the model fitted to the data was

$$-3.13 - \log A = n \log(R/100) + K(R-100) - M_i + S_j \quad (6)$$

Table 1. Earthquakes used in the southeastern Australian magnitude study.

Id no.	*locality*	*year*	*month*	*day*	*hour*	*min*	*lat. (°S)*	*long. (°E)*	*new ML*
1	Oolong NSW	1984	08	09	06	30	34.82	149.19	4.0
2	Oolong NSW	1984	08	09	10	01	34.82	149.19	3.1
3	Oolong NSW	1984	08	09	10	33	34.82	149.19	2.9
4	Oolong NSW	1984	08	09	14	01	34.82	149.19	2.9
5	Oolong NSW	1984	08	10	01	29	34.82	148.19	3.0
6	Dalton NSW	1984	01	07	10	06	34.76	149.18	2.8
7	Upper Colo NSW	1986	02	20	21	43	33.33	150.60	3.6
8	Lithgow NSW	1985	02	13	08	01	33.49	150.18	4.0
9	Inveralochy NSW	1986	06	23	06	29	34.92	149.86	2.5
10	Bermagui NSW	1986	08	01	07	57	36.43	149.99	2.5
11	Oolong NSW	1986	07	18	03	28	34.79	149.16	1.4
12	Oolong NSW	1986	07	29	14	42	34.78	149.16	1.7
13	Griffith NSW	1986	09	22	14	21	34.31	145.55	3.6
14	Lithgow NSW	1986	10	19	15	52	33.53	150.16	2.5
15	Canberra ACT	1985	11	28	20	51	35.28	149.11	2.3
16	Pyramid Hill Vic	1986	07	14	10	36	36.05	144.16	3.1
17	Cape Liptrap Vic	1984	10	20	05	16	38.94	146.00	4.3
18	Murgon Qld	1984	10	30	06	29	26.34	151.82	3.8
19	Mathoura NSW	1986	04	10	18	53	35.78	144.85	3.7
20	Off W coast Tas	1986	03	16	01	53	41.45	144.63	3.8
21	Balranald, NSW	1986	08	03	05	47	34.36	143.55	2.9
22	Tharwa ACT	1987	04	04	03	20	35.62	149.05	2.2
23	Sutton NSW	1987	04	29	17	05	35.21	149.25	1.2
24	Oolong NSW	1987	05	17	01	57	34.77	149.19	1.2
25	Deep Creek Vic	1987	05	30	14	44	37.88	146.52	3.7
26	Moree NSW	1988	01	15	10	25	29.72	148.91	2.9
27	Cobar, NSW	1988	02	23	21	56	31.47	145.60	2.8
28	Oolong NSW	1988	03	10	04	51	34.75	149.17	0.8
29	Mittagong NSW	1988	03	21	13	40	34.53	150.45	2.1
30	Bonnie Doon Vic	1988	04	07	22	57	37.06	145.90	2.9
31	Mt Ellery Vic	1988	04	19	06	24	37.41	149.00	3.1
32	Caldwell NSW	1988	04	21	16	45	35.72	144.52	3.1
33	West Tasman Sea	1988	04	24	04	21	38.22	151.35	3.5
34	Lithgow NSW	1988	04	30	17	00	33.50	150.15	2.8
35	Williamsdale NSW	1988	05	15	00	48	35.65	149.17	2.1
36	Bunnaloo NSW	1988	07	03	08	23	35.73	144.49	3.8

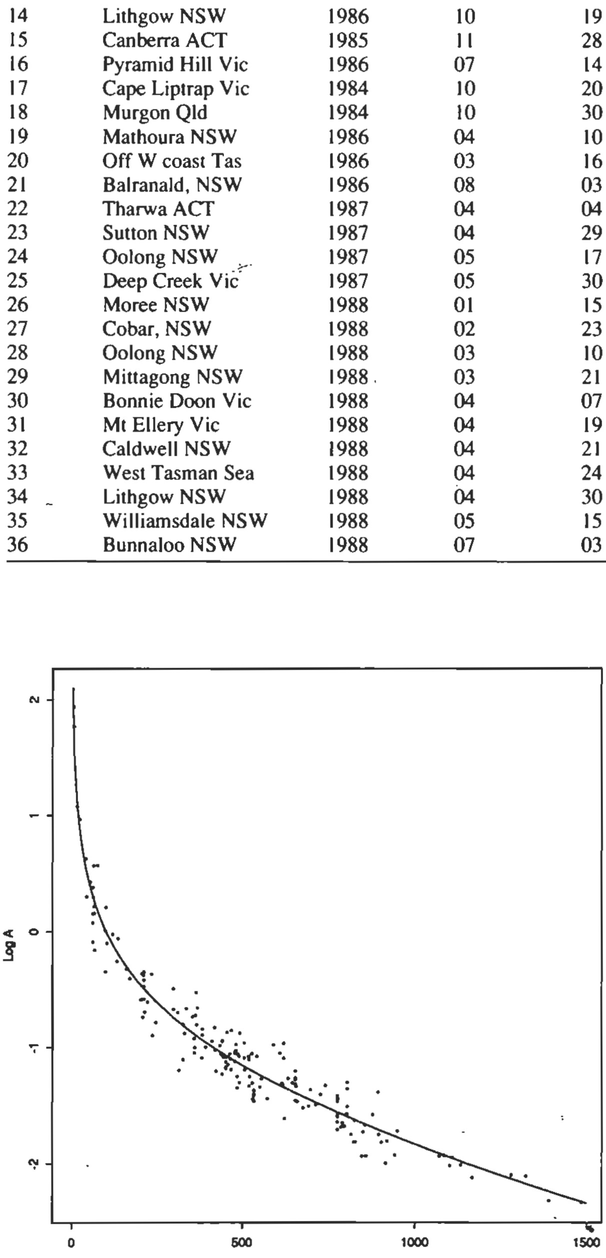

Figure 2. Amplitude, A (mm), normalised to ML 3.0, with the vertical component and station corrections included, plotted against hypocentral distance, R (km).

where M_i is the individual earthquake magnitude and S_j are the station corrections. The model was fitted using the GLIM package (Baker & Nelder, 1978) as a linear (in the parameters) regression with normal error distribution. The earthquake and station corrections were treated as qualitative variables or factors, while the variables log(R/100), (R-100) and (-3.13 - log A) were treated as quantitative variables (McCullagh & Nelder, 1983). The goodness of fit and significance of each parameter can be estimated using a Student t statistic for each parameter and a multiple-correlation coefficient for overall goodness of fit.

Results

The model fits extremely well, accounting for 94% of the variation in the data - the square of the multiple-correlation coefficient being 0.94. All variables give a highly significant reduction in deviance (sums of squares) with the parameter, n, being highly significant. Analysis of variance indicates significant ($P<0.001$) earthquake and station adjustments as well as attenuation effects.

The estimate of n is 1.34 with a standard error of 0.09. The estimate of K is 0.00055 with a standard error of 0.00012. The station correction which should be added to a single station ML estimate to approximate the mean ML is -0.3 for RIV, -0.1 for CNB, 0.0 for CMS, TOO, BFD and Dalton, +0.1 for COO and RMQ, and +0.2 for STK. The mean magnitudes, determined by regression, for the 36 earthquakes are given in Table 1. The

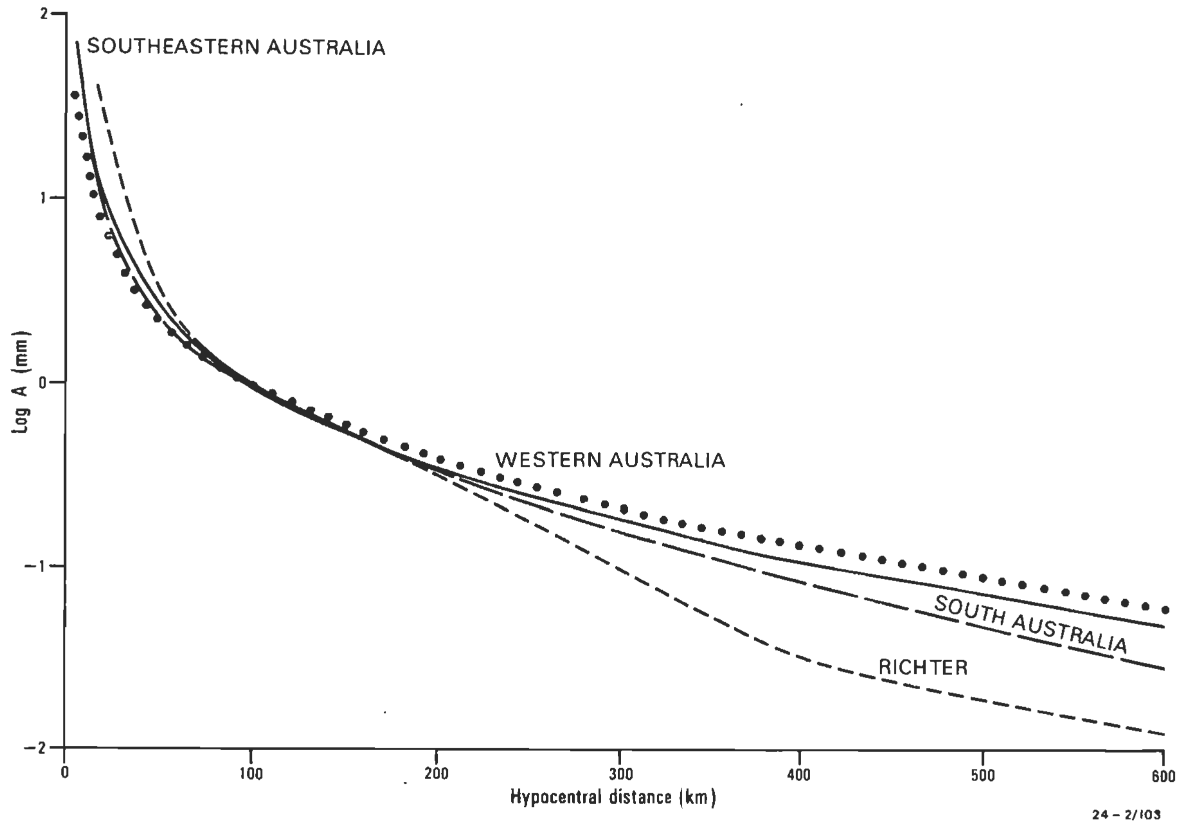

Figure 3. Theoretical maximum trace amplitude from a magnitude ML 3.0 earthquake on a Wood-Anderson seismograph at hypocentral distances up to 600 km according to Richter (1958), and the attenuation functions for South Australia, Western Australia and southeastern Australia.

amplitude data normalised to ML 3.0 (with the vertical component and station corrections included) are plotted against hypocentral distance in Figure 2.

Discussion

Because this study is based on a relatively small number of observations (181 measurements on 36 earthquakes), the results should be regarded as preliminary. Table 1 shows that 10 of the 36 events have epicentres in the Oolong-Dalton area. Four of these events (numbers 11, 12, 24 and 28) were included because they were the only ones which were recorded on two of the stations at distances of less than 10 km from one of them (Dalton). Their distances from the other (CNB) were 60—65 km and they were not recorded on any of the other stations. Consequently, they provided important information on the attenuation at small hypocentral distances.

To see whether the inclusion of a high proportion of larger Oolong-Dalton events in the analysis had biassed the results unduly, four of them (numbers 2, 3, 4 and 5) were eliminated and the analysis redone. The values of n and K (1.34 and 0.00056 respectively) were again highly significant, but did not differ significantly from those obtained previously. The station corrections remained unchanged except for TO1 and COO which became -0.2 and 0.0 respectively. As eliminating the four events reduced the number of observations at TO1 to only two, the 0.0 station correction based on six measurements is preferred. The change at COO was actually from +0.07 to +0.03, and it is probably preferable to adopt a zero station correction for COO.

The value of 1.34 for n, the geometric spreading coefficient, is higher than for most other studies. For example, in Gaull & Gregson (1991) an n of 1.14 was obtained. However, Kiratzi & Papazachos (1984) derived attenuation functions for Greece with n equal to 2.00 for ML exceeding 3.7, and 1.58 for smaller magnitudes. The theoretical value of the geometric spreading coefficient in a semi-infinite, vertically stratified medium, is 1.00 for body waves, 2.00 for head waves, and 0.50 for surface waves (Brekhovskikh, 1960). The n of 1.34 obtained in our study may be attributed to head waves, as well as body waves, giving rise on occasion to the greatest amplitude on the records. Deviation of the geology from the theoretical model may also be a contributing factor.

Figure 3 shows the theoretical maximum trace amplitude from a magnitude ML 3.0 earthquake on a Wood-Anderson seismograph at hypocentral distances up to 600 km according to Richter (1958), Greenhalgh & Singh (1986), Gaull & Gregson (1991) and this study. Both Richter and Greenhalgh & Singh used epicentral distance, so focal depths of 16 and 10 km were assumed for Southern California (Richter, 1958) and South Australia (Gaull & others, 1990) respectively in converting epicentral to hypocentral distances. The four attenuation functions are very similar in the range 52—210 km. However, taking the mean focal depth of earthquakes in California to be 16 km, as stated in Richter (1958), then at distances less than 52 km, use of Richter's attenuation will cause southeastern, Western and South Australian magnitudes to be underestimated. This discrepancy is probably an artefact of the assumed 16 km focal depth. Most of the 106 central Californian earthquakes used in Bakun & Joyner's (1984) study had depths in the range 5—10 km. If these depths are applicable to Richter's data, his attenuation at hypocentral distances less than 52 km is similar to the Australian functions. However, at distances greater than 210 km, Richter's attenuation deviates increasingly from the Australian results, and use of it will cause local magnitudes of Australian events to be overestimated.

Conclusions

The new preliminary ML scale adopted by the Australian Seismological Centre for southeastern Australia is

$$ML = \log A + (1.34\pm0.09)\log(R/100) + (0.00055\pm0.00012)(R-100) + 3.13 + S$$

where A (mm) is equivalent Wood-Anderson trace amplitude, 0.13 is the vertical component correction, R (km) is hypocentral distance (3—1500 km) and S the station correction. The attenuation is very similar to Richter's (1958) over distances of 52—210 km and probably also when closer to the focus, but lower over longer distances. At a hypocentral distance of 600 km, Richter's attenuation will overestimate ML by 0.6.

The station correction which should be added to a single station ML to approximate the mean ML is -0.3 for RIV, -0.1 for CNB, 0.0 for COO, CMS, TOO, BFD and Dalton, +0.1 for RMQ, and +0.2 for STK.

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Ferricrete in Cape York Peninsula, North Queensland

C.F. Pain[1] & C.D. Ollier[2]

In Cape York Peninsula ferricrete is found in a wide variety of locations, including scarp edges, lower valley slopes, around surface depressions, on gently sloping interfluves and on recently eroded surfaces. Ferricretes are not associated with any particular geomorphic surfaces, but rather occur where conditions are suitable for iron accumulation and hardening. In general, these conditions are found in the mottled zones of deep weathering profiles, where the mottled zones cement after exposure at the surface, and in lower parts of the landscape, where iron moves laterally to the surface and cements whatever regolith materials may be present. There is no evidence for former extensive covers of ferricrete, nor is there any evidence for particular periods of ferricrete formation. Ferricrete continues to form at present. It is therefore unreliable for determining either relative ages of geomorphic surfaces, or correlating widespread bodies of regolith.

Introduction

Duricrusts in the landscape have been used in many attempts to identify and correlate isolated occurrences of particular geomorphic surfaces (e.g. Twidale, 1983). In particular, ferricrete has been used in northern Queensland by several workers to construct a history of landscape evolution involving several cycles of weathering separated by periods of erosion (e.g. Doutch, 1976; Grimes, 1979).

In this paper we describe different kinds of ferruginous duricrusts and ferricrete types that occur in Cape York Peninsula north of 16° (Fig. 1) and show that ferruginous cementing of regolith materials occurs in several types of geomorphic location in the study area. As a result of our studies, we conclude that ferruginous cemented materials are not a reliable indicator of the age of either landforms or regolith, and are not useful for correlation.

Terminology

There is a considerable literature, and much disagreement, on the terminology of 'laterite' and 'ferricrete' (e.g. McFarlane, 1987; Ollier & Galloway, 1990; Ollier, 1991). We side with those who conclude that 'laterite' is a widely misused term that should be confined to meaning 'reddish-coloured saprolite of the mottled zone in a deep weathering profile which is sufficiently hard to be used for building purposes' (Ollier, 1991). In this paper we use the term only when quoting from other authors. Instead we use the terms defined below.

Mottles are spots, blotches or streaks of colour different from the matrix colour of the material in which they occur, and forming less than 50% of the material. Ferruginous mottles are commonly reddish, and may be somewhat indurated. A mottled zone commonly forms part of a deep weathering profile, and when it is hard, is perhaps closest to the 'laterite' defined above.

Nodules are distinct units of material within a matrix. They have sharp boundaries with the matrix, and can vary from irregular to spherical in shape. The more spherical nodules may be better termed pisoliths. Internally they can vary from matrix fabric to concretionary fabric.

Duricrust refers to a mass of hard material formed in sediment or saprolite by either relative or absolute accumulations of natural cements. The use of 'crust' implies that duricrusts form layers at or near the ground surface.

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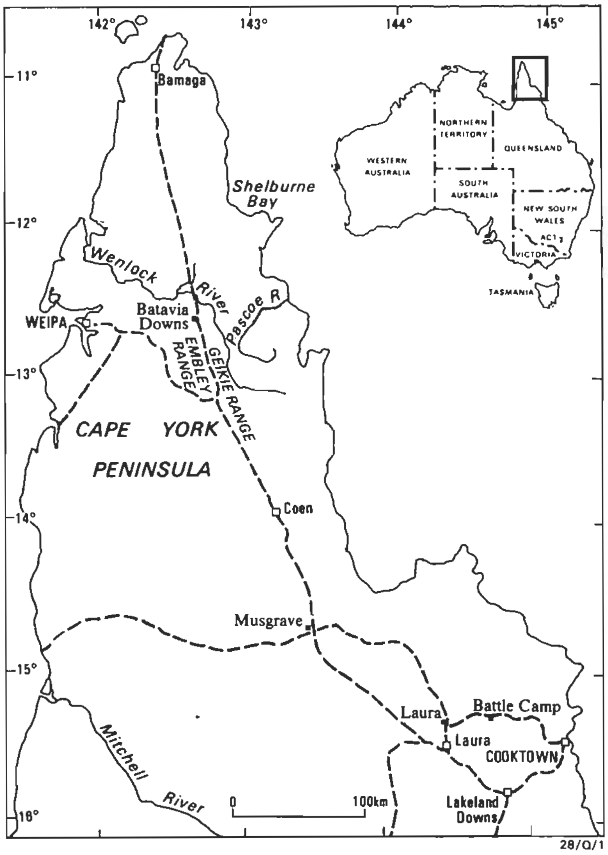

Figure 1. Cape York Peninsula location map.

Ferricrete is regolith material strongly cemented mainly by iron. We use the term to refer to iron-cemented masses of regolith, not necessarily part of a duricrust layer, including the iron-cemented portions of large mottles. It does not include uncemented, isolated iron pisoliths, or 'buckshot' gravels. Moreover, in our view, the term has no genetic connotations beyond the fact of iron accumulation and cementing.

The term *laterite profile* is commonly used to refer to a deep weathering profile which, if complete, has the following sequence of layers from the surface down: residual surface material (commonly sand), ferricrete, mottled zone, pallid zone, and bedrock. This usage is continued here. However, our findings suggest that the occurrence of ferricrete in such a profile is the exception rather than the rule.

Previous work

The first account of ferricrete in Cape York is probably that of Jackson (1902) who noted the occurrence of 'pisolitic iron ore' in many locations, mainly on the eastern side. Simonett (1957), in a study of 'laterite and other ironstone soils' in the southern part of the Cape York Peninsula, concluded that 'ironstone' (ferricrete) occurred at or near the top of deep weathering profiles, and also on lower valley slopes in various locations. He thus noted the existence of at least two types of geomorphic location for ferricrete. However, he associated ferricrete in the deeply weathered horizons with the existence of a widespread Late Tertiary peneplain.

Connah & Hubble (1960, 373) gave an account of laterites in Queensland. They defined laterite as 'a massive, vesicular, or concretionary ironstone formation nearly always associated w... uplifted peneplains and undoubtedly originally formed o... of low relief subject to high water tables'. This definition, after Prescott & Pendleton (1952), includes not only descriptions of material, but also many assumptions about geomorphology, hydrology and tectonic history. These assumptions make their definition a positively dangerous starting point. For the Cape York region they describe ferruginous grits up to 2 m thick on flat-topped hills near the east coast, and the very extensive eastern area where 'the low lateritic plateaux ... are probably remnants of a much more extensive and continuous Tertiary peneplain' (Connah & Hubble, 1960, 373).

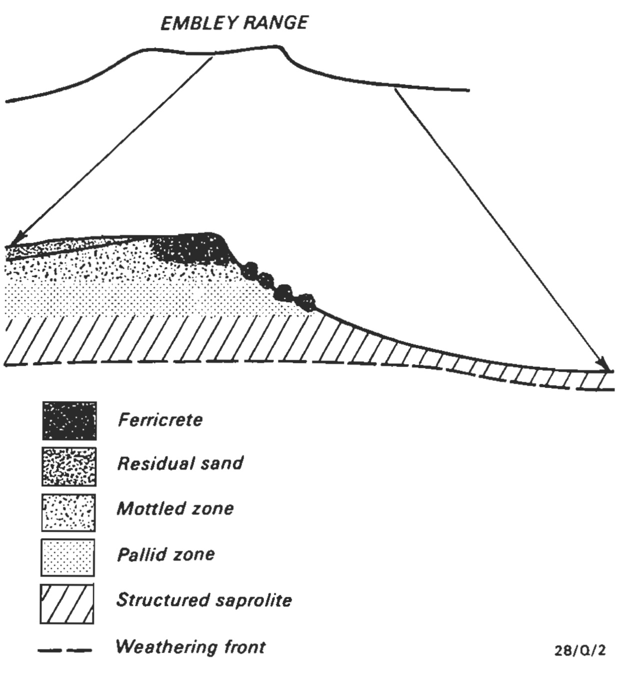

Figure 2. Ferricrete occurrence at a plateau edge or scarp.
The scarp surrounding the Embley Range, near Batavia Downs, is a good example of this.

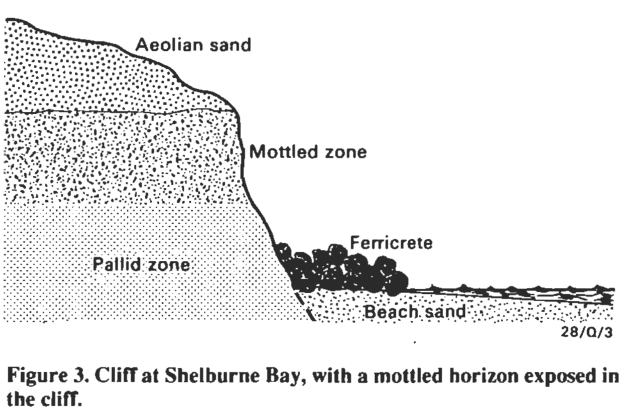

Figure 3. Cliff at Shelburne Bay, with a mottled horizon exposed in the cliff.
Ferricrete on the beach is derived from a former ferricrete occurrence on the cliff edge. Key as for Figure 2.

Connah & Hubble (1960) also describe three kinds of laterite identified by Malcolm & Summers (1959). These are angular and sub-angular ironstone fragments as ridge cappings formed by breakdown of massive laterite in situ; massive laterites up to 6 m thick in stream outcrops, probably younger than the first kind; and pisolitic laterites associated with poor present-day drainage, probably of recent origin.

The unpublished account by Malcolm & Summers (1959) fits very well with our own observations of ferricrete distribution, but it is the obsession with lateritised erosion surfaces that has dominated most previous work. The most extreme position is probably that of Allen & others (1960, 341), who stated 'a basis of division [of the Cenozoic of Queensland] is provided by the State-wide sheet of laterite that developed on early Cainozoic and older rocks'. More recently, Doutch (1976), Grimes & Doutch (1978), and Grimes (1979) described an Aurukun Surface which was lateritised and bauxitised in an Oligocene phase of weathering and no erosion, and younger, Plio-Pleistocene surfaces and deposits such as the Bulimba Formation. Their account is followed by Isbell (1983, 190) who wrote 'The most important factor in relation to landscape and soil history since the Late Cretaceous has been the formation and partial destruction of a number of widespread erosional and depositional surfaces, together with associated deep weathering which has produced thick laterite profiles'.

An account of regolith and landscape development in the area will be presented elsewhere, but here we can say that the existence of simple surfaces completely covered in ferricrete is now doubted.

Ferricrete occurrences

Scarp edges

Ferricrete commonly occurs along scarp edges (Fig. 2). In a few places the ferricrete is massive at the scarp edge, and may be up to 2 or 3 m thick. In many locations, however, the ferricrete is only part of a horizon which consists of large red and white mottles, the white material filling 'tubes' of ferricrete up to 50 cm in diameter. Our observations suggest that the ferricrete extends no more than a few tens of metres back from the scarp edge, and in many cases it extends back for only a few metres.

In some instances there is a scree of ferricrete blocks below the scarp at the edge of a plateau. This scree consists of broken ferricrete blocks that have fallen from the scarp. In a few cases the blocks are re-cemented into a more continuous surface layer.

An extreme case of this type of ferricrete occurrence is found along cliffed coasts. Rapid coastal erosion has undermined the ferricrete which has then collapsed onto the beach at the foot of the cliff (Fig. 3). At first sight the source of the fallen ferricrete is a mystery, as it is not present on the cliff. Instead, the uncemented mottled horizon extends right to the cliff edge. The entire width of the ferricreted zone has collapsed.

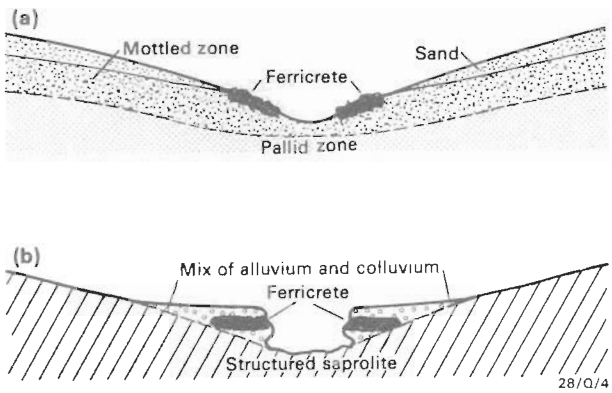

Figure 4. Valley floor ferricrete. a. Cemented mottled zone material, common in valley floors on Rolling Downs Group sandstone, and on granite. b. Cemented alluvium/colluvium, common in areas of metamorphic rock.
Key as for Figure 2.

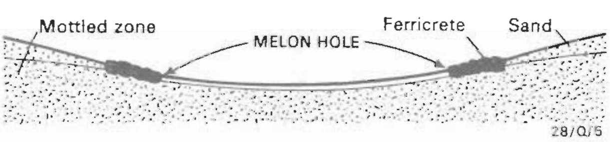

Figure 5. Ferricrete around the edge of a melon hole depression.
Key as for Figure 2.

Lower valley slopes and valley floors

Ferricrete commonly occurs along lower valley slopes (Fig. 4a). There may be a low break of slope, making a scarp in the landscape, or the ferricrete may simply occur as a layer on the surface, or as exposed blocks. Usually the ferricrete can be followed along the edge of the valley, at a consistent height above the valley floor. In most places there is little evidence that the ferricrete continues at depth away from the lower valley side. On the contrary, it is often clear from gully and road exposures, or exposures of bedrock farther up slope, that the ferricrete is confined to a narrow belt along the valley side. The ferricrete commonly grades laterally into the upper part of a mottled horizon away from the lower valley slopes (Fig. 4a).

Ferricrete is also found in valley floor sediments (Fig. 4b). This is particularly the case with valleys in areas of metamorphic bedrock. Again, the iron accumulation is confined to the valley floor.

'Melon holes'

Ferricrete is present around some, but not all, melon holes. 'Melon hole' is a local name used to refer to shallow (about 1 m deep) depressions in generally flat terrain. The origin of the depressions is not known, but may result from solutional removal of material on flat surfaces, or along prior shallow valley floors. The depressions are generally oval to circular, and range from a few tens of metres to more than a kilometre in diameter. They usually contain water during the wet season.

The ferricrete is confined to a band up to 10 m wide in the vicinity of the high water mark. It may form a continuous ring around the depression, or may occur in localised patches. This type of ferricrete is also shallow, usually less than 1 m in thickness. A mottled horizon occurs below surface materials both inside and outside the depression (Fig. 5).

Figure 6. Nodular ferricrete overlain by packed but loose iron nodules, near Battle Camp.
1. Loose iron nodules. 2. Nodular ferricrete. This arrangement suggests concentration of the nodules by termite activity, and then cementing of the nodules to form ferricrete.

Interfluve areas

We have observed ferricrete scattered in surface patches up to several hundred metres across on broad interfluve areas. The patches are discontinuous, and separated by areas of sand. Some of the ferricrete patches are the cemented upper part of a mottled horizon that usually occurs below a sandy topsoil, but is exposed in an irregular pattern across the landscape. Elsewhere, nodular ferricrete is found beneath residual sand, and resting on the mottled zone. The residual sand may contain abundant iron nodules, which in some cases are concentrated at the base of the sand (Fig. 6).

Stream and gully walls

Ferricrete has been observed along vertical walls formed by stream incision. This includes modern gully erosion initiated by disturbance of regolith surfaces, most commonly associated with roads. The incision first strips a loose sandy cover, and then cuts into a horizon which consists of sandy material with large red and white mottles (the mottled zone of a deep weathering profile). The reddish parts are coloured by iron, and only when they are exposed do they become hardened to give a form of ferricrete (Fig. 7). This ferricrete is usually discontinuous and vermiform, with skins and tubes up to 30 cm across surrounding white saprolite.

Good examples of this type of ferricrete are found along the Wenlock River, especially where retreat of waterfalls creates gorges up to 20 m deep downstream of the falls. In these locations the white saprolite is removed from the cemented tubes leaving a labyrinth of ferricrete (Fig. 7). Another example caused by gully formation following road construction is near the Pascoe River (Fig. 8). Here the ferricrete is a 'skin' only a few tens of centimetres thick, and must have formed in historic times.

Intra-regolith ferricrete

At Weipa, within the bauxite weathering profile on Rolling Downs Group fine sandstones, ferricrete is found in up to three separate and distinct horizons. The first is within the zone of bauxite pisoliths. The second is within the otherwise pallid zone consisting largely of kaolin. The third lies at the top of recognisable Cretaceous Rolling Downs Group fine sandstone. The details of this weathering profile are described by Evans (1976) and Schaap (1990). The ferricrete layers each have different characteristics. The upper one is the iron rich part of a thick mottled zone, where the red parts of the mottles are cemented. This is similar to ferricretes seen elsewhere. The middle ferricrete layer consists of a series of pods several tens of square metres in size, but only 1-2 m thick (Mike Morgan, COMALCO geologist, pers. comm., July 1990). The third layer appears to be a ferruginised layer in the upper part of little-weathered Rolling Downs Group sandstone.

Ferricrete formation

General points

There is considerable debate over the formation of ferricrete, much of it centred on the relationship between ferricrete and the landscape. Workers who have decided on a particular model of landscape evolution are constrained by their chosen model when they come to explain the origin of ferricrete. However, instead of adopting a single model, it may be more profitable to separate the formation of ferricrete into stages, as follows:

1. Relative or absolute accumulation of iron.
2. Cementing of the 'parent' material by the iron to form the ferricrete.
3. The series of geomorphic processes that leads to the present position of the ferricrete in the landscape.

Of these, the first two form the ferricrete. The nature of iron accumulation depends on position in the landscape. In broad low relief areas iron moves up from the weathering front by chemical diffusion and accumulates in the mottled zone (Mann & Ollier, 1985). In lower parts of the landscape (valley slopes and melon holes) lateral movement of water is a major factor in iron accumulation.

Figure 7. Ferricrete developed after exposure of a mottled layer by incision along the Wenlock River, east of Batavia Downs.
1. Mottled zone. 2. Mottled zone ferricrete. 3. Pallid zone material, partly covered by fallen blocks of ferricrete near the water.

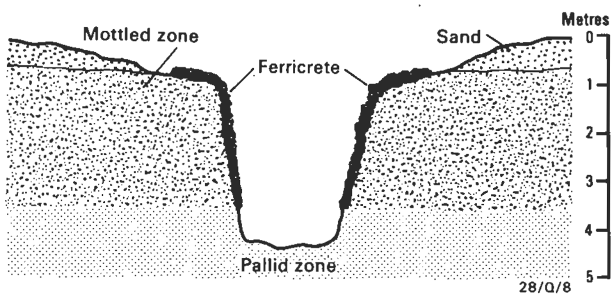

Figure 8. Ferricrete formed along a post-European gully near the Pascoe River.
Key as for Figure 2.

Cementing of the iron to form ferricrete requires oxidising conditions. In northern Cape York Peninsula the watertable varies annually over a range of several metres, in some locations tens of metres. This allows drying out of the iron-rich zone every year, with consequent cementing of iron where it has concentrated.

Geomorphic changes in the landscape can lead to two results relevant here. First, ferricrete which is already formed below the surface by wetting and drying can be exposed at the surface. Second, a zone of iron concentration can be exposed, or brought into the zone of wetting and drying, at which time the ferricrete forms.

The following sections illustrate the observed complexity that results from the various weathering, hydrological and geomorphic processes noted above.

Induration of mottled zones

The location and nature of ferricrete sometimes suggests that its formation follows exposure of a mottled zone. When it is exposed, the iron-rich part of the mottled zone can become very hard. The light coloured material may then be eroded out leaving tubular ferricrete either as a distinct layer or as a series of blocks or lumps.

The mottled zone forms within a zone of fluctuating water levels, and is common on most broad flat or gently undulating areas. Ferricrete formation from the mottled zone is thus a function of exposure, and not a distinct weathering period, or age of land surface. This is emphasised by ferricretes formed on surfaces developed by post-European settlement gullying, and by wagon tracks preserved in materials that are now cemented (Colin Simpson, AGSO, pers. comm., October 1990).

Ferricretes at scarp edges, on some interfluve areas, and on eroded surfaces probably developed in this way.

Cementing of surface materials

In other cases ferricrete appears to form where the fluctuating watertable reaches the surface. Here iron moving laterally through sub-surface horizons reaches the surface, accumulates and cements the regolith. In some of these cases the ferricrete can be demonstrated to have formed in detrital materials, especially alluvium and colluvium. Occurrences of this type are described by Ollier & Galloway (1990), who note in particular the unconformable nature of the lower boundary of many ferricretes. However, it is iron accumulation and cementing rather than the nature of the cemented material which is important.

Again, this process can take place on surfaces of any age. Ferricretes found on lower valley slopes, valley floors and around melon holes are formed in this way.

Formation from nodules

Iron nodules are almost ubiquitously associated with the sandy topsoils found over much of the study area. These nodules are found as lag gravels on the surface, scattered through the residual soil, and as accumulations at the base of the residual sand. Although we have no firm evidence, it appears that the nodules form as localised concentrations throughout the residual sand. Lag accumulations at the top occur as a result of removal of sand from the surface. Concentration of nodules at the base of the residual sand probably occurs as a result of biological activity, particularly that of termites, and tree fall. Where ferruginous nodules accumulate at the base of the residual sand, they often become cemented to give nodular ferricrete (Fig. 6).

Formation within the regolith

The only ferricretes that appear to have formed, or are forming, at depth are those found in the bauxite weathering profile at Weipa. Because the upper part of the bauxite profile, especially the pisolite layer, is very porous, the zone of watertable fluctuation may dry out sufficiently for iron cementing of the bauxite to take place. The lower 2 layers are more problematic, but may represent horizons of past wetting and drying.

Discussion

With the exception of the 'Weipa' ferricretes, ferricrete formation is limited in horizontal and vertical extent to zones of surface exposure of iron-rich regolith material. This can and does occur on surfaces of any age. There is no evidence in the study area to suggest that there is any genetic relationship between the occurrence of ferricrete and deep weathering. The presence or absence of ferricrete is therefore not a reliable indicator of surface age, and cannot be used to correlate surface remnants. The presence of ferricrete known to have formed since initiation of erosion following the advent of the motor car underlines this conclusion.

Ferricrete does not occur as a uniform sheet as was often implied in previous attempts to decipher landscape history in Cape York Peninsula. It is not limited to high plateaus, but occurs in many other locations. It is unrealistic to cast 'ferricrete surfaces' between observed outcrops. Ferricrete can occur in a number of locations, nearly always restricted, and once it forms it becomes a prominent and persistent feature in the landscape, and exerts some control on landscape development. The ferricrete seldom occurs in large sheet-like bodies, but rather as scattered patches. Where it is fairly continuous the distribution supports the 'inversion of relief' hypothesis (see summary by Ollier & Galloway, 1990), and the ferricrete on some plateau edges and ridge tops may have formed originally on valley floors. However, in determining the overall evolution of a landscape, the ferricrete is something of a red herring—the landscape would probably look much the same if the ferricrete was not there. The main geomorphic function of the ferricrete is to make the break of slope more pronounced at the 'breakaway'.

Similar conclusions have been reached from work in other parts of Australia, including Western Australia (Ollier & others, 1988) and southeast Australia (Milnes & others, 1985; Bourman, in press). Bourman concludes that 'different types of ferricretes, mottled and bleached zones developed in specific sites in response to local environmental conditions' and 'The fact that different facies of ferricrete may have formed synchronously in different parts of the same landscape, and that identical ferricretes occur on land surfaces of widely disparate ages, restricts the utilisation of ferricretes as reliable morpho-stratigraphic markers'. We concur with his conclusion. Ferricrete should thus be used with care when determining landscape history. The evidence does not support old models based on a succession of sequential surfaces of great perfection, each with a distinct duricrust, ferricrete or 'laterite'.

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Analysis of conodont apparatus organisation and the genus *Jumudontus* (Conodonta), a coniform—pectiniform apparatus structure from the Early Ordovician

Robert S. Nicoll[1]

A classification of conodont apparatus structure is set out, based on the type of element (coniform, ramiform or pectiniform) found in the discernens and contundens groups of elements. Of a possible nine organisational structural configurations, only four (coniform—coniform, coniform—pectiniform, ramiform—ramiform and ramiform—pectiniform) have been reported in the literature. The coniform—ramiform configuration is possible but has not yet been recognised; all other apparatus configurations are regarded as biologically improbable. The genus *Jumudontus* Cooper from the Early Ordovician (Arenig), represented by *J. gananda* Cooper, is shown to have a septimembrate coniform—pectiniform apparatus configuration. *Jumudontus brevis* sp. nov. is described, based on a partial apparatus reconstruction, using specimens from the Emanuel Formation of the Canning Basin, Western Australia.

Introduction

The nature and range of elements of late Cambrian and early Ordovician conodont apparatuses, outlined in an early study by Barnes & others (1979), is only now being comprehensively investigated. In recent studies (Chen & Gong, 1986; Ji & Barnes, 1990; Nicoll, 1990, 1991; Nicoll & Shergold, 1991) a wide range of element morphologies have been delineated and multielement apparatuses recognised, but no attempt has been made to categorise the basic configurations of the apparatus structures. As an outgrowth of biostratigraphic investigations of conodont faunas of Late Cambrian and Early Ordovician age in central Australia, a number of observations have been made on the basic structure of a wide variety of conodont taxa. By looking also at post-Ordovician faunas, it is now possible to present a classification of conodont apparatuses based on the various types of elements in the discernens and contundens groups, the two subsets of element types in the apparatus structure (Nicoll, 1985).

The recovery of elements of the full apparatus of the genus *Jumudontus* from samples of the Early Ordovician Horn Valley Siltstone of the Amadeus Basin in central Australia (Cooper, 1981; Shergold & others, 1991; Elphinstone & Gorter, 1991) has documented an earlier appearance of an apparatus style that had previously not been identified in the Ordovician. This septimembrate apparatus consists of coniform M and S elements and pectiniform P elements. This type of apparatus structure has previously been associated only with genera of the family Icriodontidae of Silurian and Devonian age.

Apparatus structure

Conodont elements can be divided into three main types: coniform, ramiform and pectiniform (Sweet, 1981). Recovery of bedding plane assemblages (Aldridge & others, 1987), fused clusters (Nicoll & Rexroad, 1987) and traces of the whole animal (Aldridge, 1987) indicate that the elements are located in the head region and have a linear pattern of distribution. In the organisation of the apparatus structure in the conodont animal (Fig. 1) the elements appear to fall into two functional groups (Nicoll, 1977, 1985) an anterior discernens group, composed of M, Sa, Sc, Sb and Sd elements, and a posterior contundens group, composed of pairs of Pb and Pa elements. Some Cambrian and Ordovician coniform taxa lack M elements in their apparatus and thus have only S elements in the discernens group. The Late Ordovician genus *Promissum* Kovács-Endrödy has an octimembrate apparatus and the contundens group is composed of pairs of Pc, Pb, and Pa elements (Theron & others, 1990). Most conodont animals have sexi- or septimembrate apparatus structures that contain 13 or 15 elements (Nicoll, 1985), but some taxa may have had as many as 200 discrete elements (Nicoll, 1982).

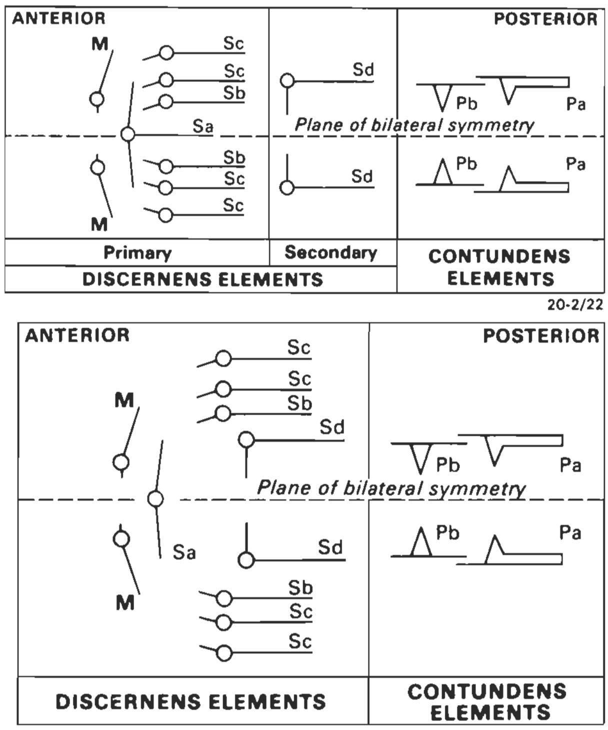

Figure 1. Generalised organisation and arrangement of elements in the discernens and contundens groups of the conodont apparatus structure.

Precise positioning of the elements varies, especially the placement of the Sd elements. a (upper), based on *Polygnathus*. b (lower), based on *Ozarkodina*. After Nicoll (1977, 1985, 1987) and Nicoll & Rexroad (1987).

Within either the discernens or contundens functional group of elements, there appears to be only one basic type of element. Thus all elements of the discernens group will be of either a coniform, ramiform or pectiniform type, and the same is true of the contundens group. No apparatus is known to contain more than two basic types of elements.

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Table 1. Organisational structural types of conodont apparatuses with examples of genera.
The discerns group is composed of M, Sa, Sc, Sb & Sd or Sa, Sc, Sb & Sd elements. The contundens group is composed of Pb & Pa or Pc, Pb & Pa elements.

Element type Discerns group	*Contundens group*	*Examples of genera*
coniform	coniform	*Teridontus, Hirsutodontus, Drepanodus*
coniform	ramiform	None known, possible configuration
coniform	pectiniform	*Jumudontus, Icriodus, Pelekysgnathus*
ramiform	coniform	None known, improbable configuration
ramiform	ramiform	*Cordylodus, Erraticodon*
ramiform	pectiniform	*Prionidus, Ozarkodina, Polygnathus*
pectiniform	coniform	None known, improbable configuration
pectiniform	ramiform	None known, improbable configuration
pectiniform	pectiniform	None known, improbable configuration

For purposes of this discussion the M element is considered to be neither coniform or ramiform in morphology. Most M elements are assigned to the makellate shape category (Nicoll, 1990); they may or may not have an outer lateral process. All M elements associated with coniform—coniform apparatuses lack a process, or have only a rudimentary and very short adentate process. M elements with ramiform—ramiform apparatuses usually, but not always, have a denticulate lateral process. M elements associated with ramiform—pectiniform apparatuses almost always have denticulate processes. The M elements associated with coniform—pectiniform apparatuses are variable, but usually lack a denticulated lateral process.

Of the nine possible combinations of element type in the apparatus, only four have thus far been recognised in bedding plane assemblages, clusters or reconstructed apparatuses (Table 1). In the following discussion, the discernens group elements are listed first and the contundens group elements are listed second. This corresponds to their location in the conodont animal (Aldridge, 1987), the contundens group being the posterior.

Coniform—coniform apparatuses are recognised from the Cambrian to the end of the Devonian. Both seximembrate (without M elements) and septimembrate (with M elements) styles are known. This form of apparatus structure is the earliest type to have evolved, but becomes progressively less abundant through the Ordovician, rare in the Devonian and unknown in the Carboniferous.

No apparatuses are presently known to have a coniform—ramiform configuration. It is possible that this type of apparatus will ultimately be recognised in taxa from Cambrian or Ordovician rocks.

Coniform—pectiniform apparatus structures are the least common type yet reported. Formerly only species of the family Icriodontidae, of Silurian to Devonian age, were known to have this type of structure. Coniform—pectiniform apparatuses are now recognised in the Ordovician genera *Jumudontus* and *Histiodella*. Some species of *Icriodus* may have as many as 200 elements in their apparatus structure (Nicoll, 1982), but the low abundance of *Jumudontus* elements indicates that only the normal 15 element apparatus probably occurs in this genus.

Ramiform—coniform apparatus configurations are not known and are unlikely to have evolved. The elements of the contundens group appear to have evolved toward denticulated complexity more rapidly than the elements of the discernens group, and no species appears to have reverted to a coniform element after developing denticulation.

Ramiform—ramiform apparatuses appear to be less common than either coniform—coniform or ramiform—pectiniform apparatus configurations. They are found from the latest Cambrian (*Cordylodus*) into the Ordovician (*Erraticodon*), but progressive evolution of the contundens group elements to the pectiniform level of element morphology appears to have limited the number of examples of this type of apparatus.

Ramiform—pectiniform apparatuses are known from the Ordovician to the Triassic and are represented in the majority of conodont genera. Early pectiniform elements with simple angulate or carminate morphology rapidly developed complex planate or scaphate surfaces. Pastinate and stellate morphologies were also well developed by the Early Ordovician.

Discussion

No apparatus with pectiniform elements in the discernens group position has been recognised. This is attributed to the possibility that the function of the elements of the discernens and contundens groups was so distinct that the morphologies of the elements are not interchangeable. This may not have been the case with the very early primitive coniform conodonts of the Cambrian (like *Protohertzina* or *Hertzina*) but, at a very early stage (early Late Cambrian or earlier), the specialisation of function by the elements in both the discernens and contundens groups was such that element morphologic differentiation was, in most species, clearly recognisable.

Both discernens and contundens group elements exhibit trends towards progressively more complex morphology, but the direction and rate of change differ in the two groups (Fig. 2). Nicoll (1992) discussed some possible reasons for the development of element denticulation, but the effect of this increase in element complexity on apparatus classification was not addressed. The rate of evolution of elements in the contundens group (Pa, Pb and Pc elements) has long been accepted as having been more rapid than that expressed by the M and S elements of the discernens group. This is demonstrated by the almost exclusive use of P elements in both classic and modern conodont biostratigraphy.

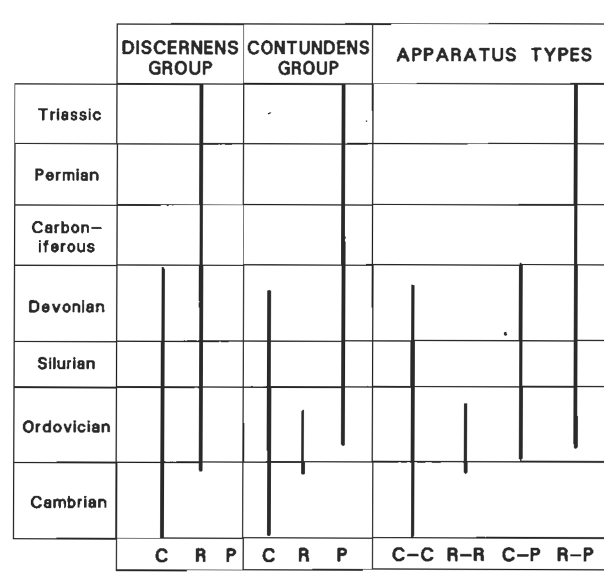


Figure 2. Range of coniform, ramiform and pectiniform element in the discernens and contundens groups through time.
C coniform, R ramiform, P pectiniform.

Ramiform elements, developed from coniform conodont species, first appear in the genera *Eodentatus* and *Cordylodus* in the latest Cambrian. The apparatus structure of *Eodentatus* is not known, but ramiform elements in *Cordylodus* developed simultaneously in both the discemens and contundens groups (Nicoll, 1990).

Pectiniform elements appear to have developed from a different group of coniform conodont species with the essentially synchronous development of both denticulation and pectiniform morphology. Early ramiform—pectiniform genera, such as *Prioniodus* and *Oepikodus*, appear to have developed from a number of different ancestral lineages that may not have been closely related. Thus the precursors of *Prioniodus* and *Oepikodus* were not ramiform—ramiform type apparatus, but coniform—coniform apparatus. Because the Sa elements of *Prioniodus* and *Oepikodus* are distinctly different, their ancestral coniform precursors were probably also not closely related.

The evolutionary consideration here is that a number of coniform—coniform lineages have independently crossed the denticulation barrier and given rise to lineages which are morphologically similar but not necessarily closely related. Thus coniform—pectiniform *Jumudontus* is not closely related to ramiform—ramiform *Cordylodus* or ramiform—pectiniform *Prioniodus*, nor are ramiform—pectiniform *Prioniodus* and *Oepikodus* necessarily closely related. The evolutionary progression of apparatus development has not been a simple coniform → ramiform → pectiniform progression.

The genus *Jumudontus*

The Early Ordovician (Arenig) conodont genus *Jumudontus* is a structurally interesting and biostratigraphically useful taxon with a distinctive apparatus composition. The apparatus has a coniform—pectiniform structure. Two species of the genus are now recognised, *J. gananda* Cooper (1981) and *J. brevis* sp. nov., both based on material from Australia.

Distribution of *Jumudontus*

Jumudontus, under a number of generic designations (see synonymies below), is a common, but never abundant, element in conodont faunas of the early Arenig of most parts of the world. Cooper (1981) described the type species from the Horn Valley Siltstone of the Amadeus Basin, but Pa elements of the two recognised species have been illustrated from numerous localities. In Australia elements of *Jumudontus* have been reported from the Amadeus Basin (Cooper, 1981), western New South Wales (Kennedy, 1976) the Georgina Basin (Druce *in* Cooper, 1981) and the Canning Basin (this paper).

Jumudontus has been reported from the San Juan Formation of Argentina in South America (Serpagli, 1974). The genus has been recovered from numerous localities throughout North America, from Scotland (Ethington & Austin, 1991) and from Baltoscandia by Bergström (1988). The genus has yet to be recorded from China or Korea. *Loxodus asiaticus* Abaimova from Siberia cannot be confirmed as a P element of *Jumudontus*, despite the suggestions of Cooper (1981) or Ethington & Clark (1981). Most of these reports are of material assignable to *Jumudontus gananda* Cooper, but *J. brevis* sp. nov. has been reported from Texas and Utah (Ethington & Clark, 1964, 1981), Newfoundland (Stouge & Bagnoli, 1988) and Baltoscandia (Bergström, 1988).

In all cases except Ethington & Clark (1981), only the Pa element has been illustrated. Now that the rest of the elements of *J. gananda* have been recognised, it is easy to see why they have not previously been identified or associated with the Pa elements. First, the Pa and Pb elements are much larger than the M and S elements. Secondly, the M and S elements are even less common in collections than the P elements. Thirdly, the combination of coniform and carminate pectiniform morphologies is an unexpected association in an apparatus structure. However, fine details of the morphology of all of the element types strongly support the reconstructed apparatus.

Examination of two samples from the upper part of the Eleanor River Formation (one from the Heim Peninsula of southern Ellesmere Island, GSC Loc. C-110513; the second from Mount Hawker, Grinnell Peninsula, Devon Island, Ph.D. thesis material) in the collections of Godfrey Nowlan (GSC-ISPG, Calgary, Alberta) have revealed both P element and several of the S elements of *J. gananda*. However, the illustration of the Pa and Pb elements of *J. brevis* (as New Genus 2) by Ethington & Clark (1981) is the only published record of any other elements except the Australian material from the Horn Valley Siltstone and Emanuel Formation recorded in this study.

Phylogenetic relationships

The phylogenetic affinities of *Jumudontus* are unclear and no form ancestral to *J. brevis* has yet been identified. Cooper (1981) thought that the genus might be related to *Loxodus* or *Histiodella*. It is unlikely that *Loxodus* is closely related because the element structure is dissimilar. However, the identification of the additional element types of *J. gananda* in this study indicate a possible, if distant, relationship between *Jumudontus* and *Histiodella*. Both genera have coniform (or modified coniform)—pectiniform apparatus structures. The gross morphologies of the seven element types are also similar and the Pa and Pb elements of both genera

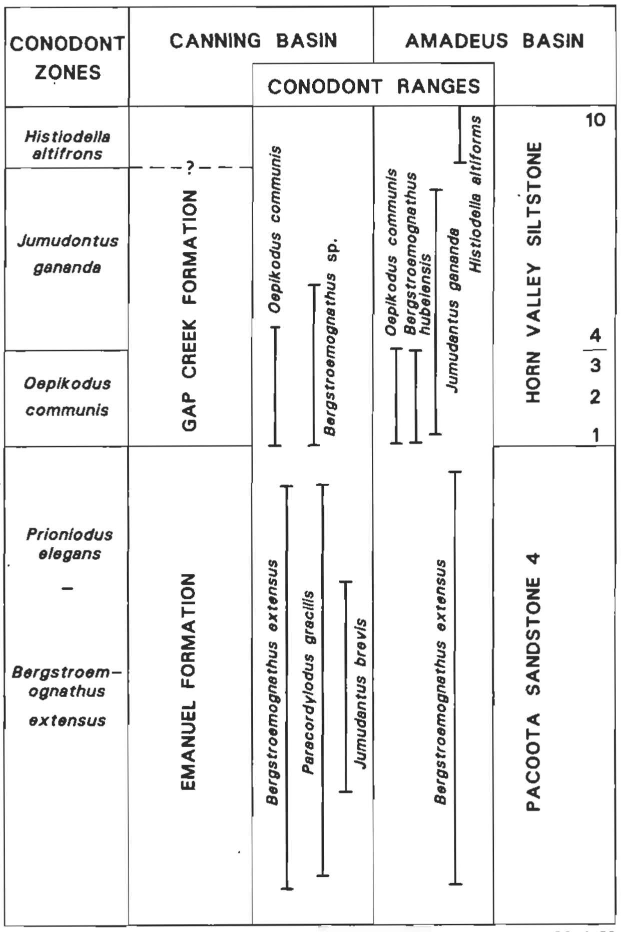


Figure 3. Biostratigraphic distribution of *Jumudontus brevis* and *J. gananda* in the Early Ordovician of the Amadeus and Canning Basins in Australia.

Table 2. Samples of Horn Valley Siltstone from the Amadeus Basin, central Australia, containing more than one type of element of *Jumudontus gananda*.
One sample with a single Pb element and 19 samples with a total of 41 Pa elements are not included.

Sample number	*M*	*Sa*	*Sc*	*Sb*	*Sd*	*Pb*	*Pa*
	Conodont element type and abundance						
2003/14						1	1
2004/14C	1		1	2			
2020/E					2	5	
2020/F	1			6	9	4	
2020/G	1	1	3	4	2	3	20
2021/C					1	3	11
2021/L	3		4	1	7	50	
2031/A	1	3	9	10	20	59	108
Total	7	4	12	19	32	84	199

Table 3. Distribution of elements of *Jumudontus brevis* from the Emanuel Formation, Canning Basin, Western Australia.

Sample number	*M*	*Sa*	*Sc*	*Sb*	*Sd*	*Pb*	*Pa*
	Conodont element type and abundance						
WCB 705/212				1	3		
WCB 705/177A		2	1	1			
WCB 705/175D				1	?1		
WCB				1	1		
Total	0	2	0	1	0	3	5+?1

are carminate. Both genera have white matter, but in *Jumudontus* it is usually confined to the denticles and in *Histiodella* it is found throughout most of the crown.

The stratigraphic ranges of *Histiodella* and *Jumudontus* overlap slightly. The oldest unquestioned species of *Histiodella, H. altifrons*, co-occurs with the youngest examples of *J. gananda*. In addition there are a number of major differences to be found between the two genera. *Jumudontus* P elements tend to be, at least on ontogenetically older specimens, very robust, and the P elements of *Histiodella* are delicate. The stratigraphically younger species of *Jumudontus*, *J. gananda* has large and well developed denticles defined by hyaline and white matter distribution. The oldest species of *Histiodella*, *H. altifrons*, lacks discrete denticles.

No transitional forms between the two genera have been identified. If the genera are related, they are related because both species have developed from a common coniform ancestral stock.

Biostratigraphy

Both *Jumudontus brevis* and *J. gananda* can be used for biostratigraphy (Fig. 3) in the Arenig (Early Ordovician). *Jumudontus brevis* is the older of the two species and is confined to the *Prioniodus—Bergstroemognathus extensus* Zone where it is associated with species such as *Paracordylodus gracilis, Prioniodus elegans* and *Bergstroemognathus extensus*.

Jumudontus gananda is found in the *Oepikodus evae* and *Jumudontus gananda* Zones where it is associated with forms such as *Oepikodus evae, O. communis, Bergstroemognathus hubeiensis* and *Erraticodon patu*.

Systematic palaeontology

Genus *Jumudontus* Cooper, 1981

Type species. *Jumudontus gananda* Cooper, 1981.

Revised diagnosis. Septimembrate apparatus with a coniform—pectiniform structure. The M element is makellate, and lacks denticles on the outer lateral process. The S elements are coniform or modified coniform, and are asymmetrical except for the Sa element. The P elements are carminate pectiniforms with a large cusp, and may have denticles on the anterior blade. Some Pa elements may also have rudimentary denticles in the posterior blade. All elements have white matter; the Pa elements may have well defined albid denticles in the anterior process. The P elements are usually much larger than their associated M and S elements.

Remarks. *Jumudontus* is a rare but widespread species in conodont faunas of this age from Australia and both North and South America. The genus has been reported from Baltoscandia (Bergström, 1988) and Scotland (Ethington & Austin, 1991). In the Horn Valley Siltstone *J. gananda* Pa elements are usually physically the largest elements in the fauna.

In *Jumudontus*, there is the imbalance of Pa element abundance relative to that of the rest of the elements (Tables 2, 3) in most samples. This is probably related to the size disparity of the Pa, and to some degree the Pb element, when compared with the relatively smaller M and S elements. Current sorting may have had a major effect by separating the larger P elements from the smaller M and S elements.

Jumudontus gananda Cooper, 1981
Figs 4—8

Synonymy

v. 1971 *Jumudontus gananda* n. sp. Cooper, pp. 170—172, pl. 31, fig. 13
1964 ?*Spathognathodus* sp. Ethington & Clark, p. 201, pl. 2, fig. 5
1970 ?*Spathognathodus* n.sp. Fåhraeus, fig. 31
1974 New Genus B. Sweet & others, pl. 1, fig. 34
1974 New Genus B. Barnes, pl. 1, fig. 9
1974 *Spathognathodus* sp. Serpagli, p. 87, pl. 19, fig. 11a—b, pl. 29, fig. 16
1976 *Spathognathodus* sp. Landing, p. 640, pl. 4, fig. 15
1977 New Genus B n. sp. s.f. Barnes, p. 104, pl. 1, figs 16—18
1978 *Histiodella* n. sp. s.f. Fåhraeus & Nowlan, p. 460, pl. 3, fig. 14
1981 *Jumudontus gananda* Cooper; Ethington & Clark, pp. 51—52, pl. 2, figs 9, 10
1982 ?*Spathognathodus* sp. s.f. Ethington & Clark; Repetski, p. 53, pl. 25, figs 8—10

Material studied. 399 elements: 240 Pa, 85 Pb, 7 M, 4 Sa, 12 Sc, 19 Sb, 32 Sd. All from the Horn Valley Siltstone, Amadeus Basin, central Australia.

Diagnosis. Septimembrate coniform—pectiniform apparatus with adentate makellate M elements, coniform S elements and carminate P elements. The Pa element has well developed erect anterior denticulation, a large erect or slightly posteriorly inclined cusp over the basal cavity, and a posteriorly directed inner lateral spur on the basal margin. The Pb element is similar but lacks anterior denticulation and lateral spur. The M element with well developed carinae on both faces of the cusp and the S elements are slightly modified coniform types. Fine striae are well developed on the element surfaces.

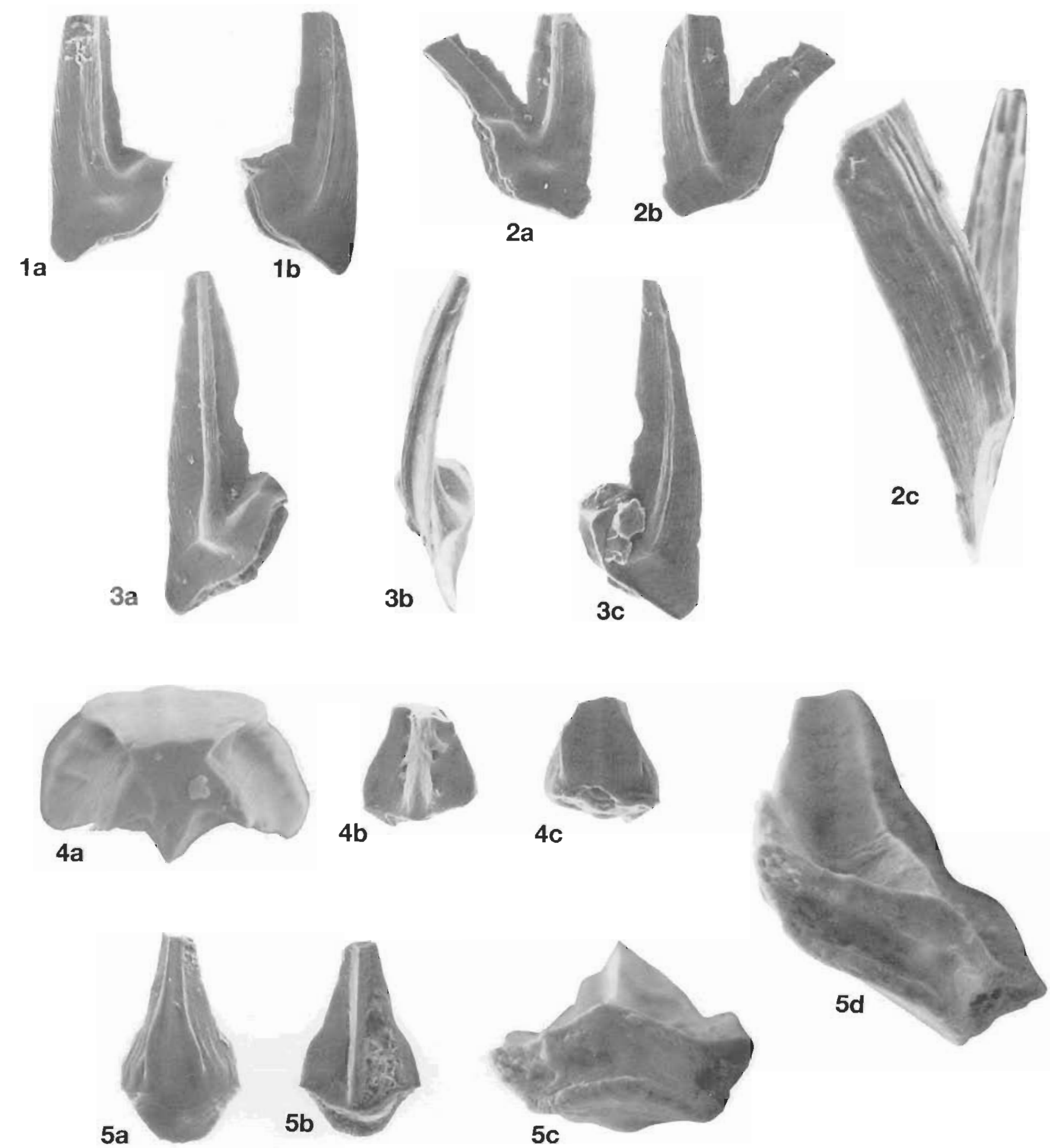


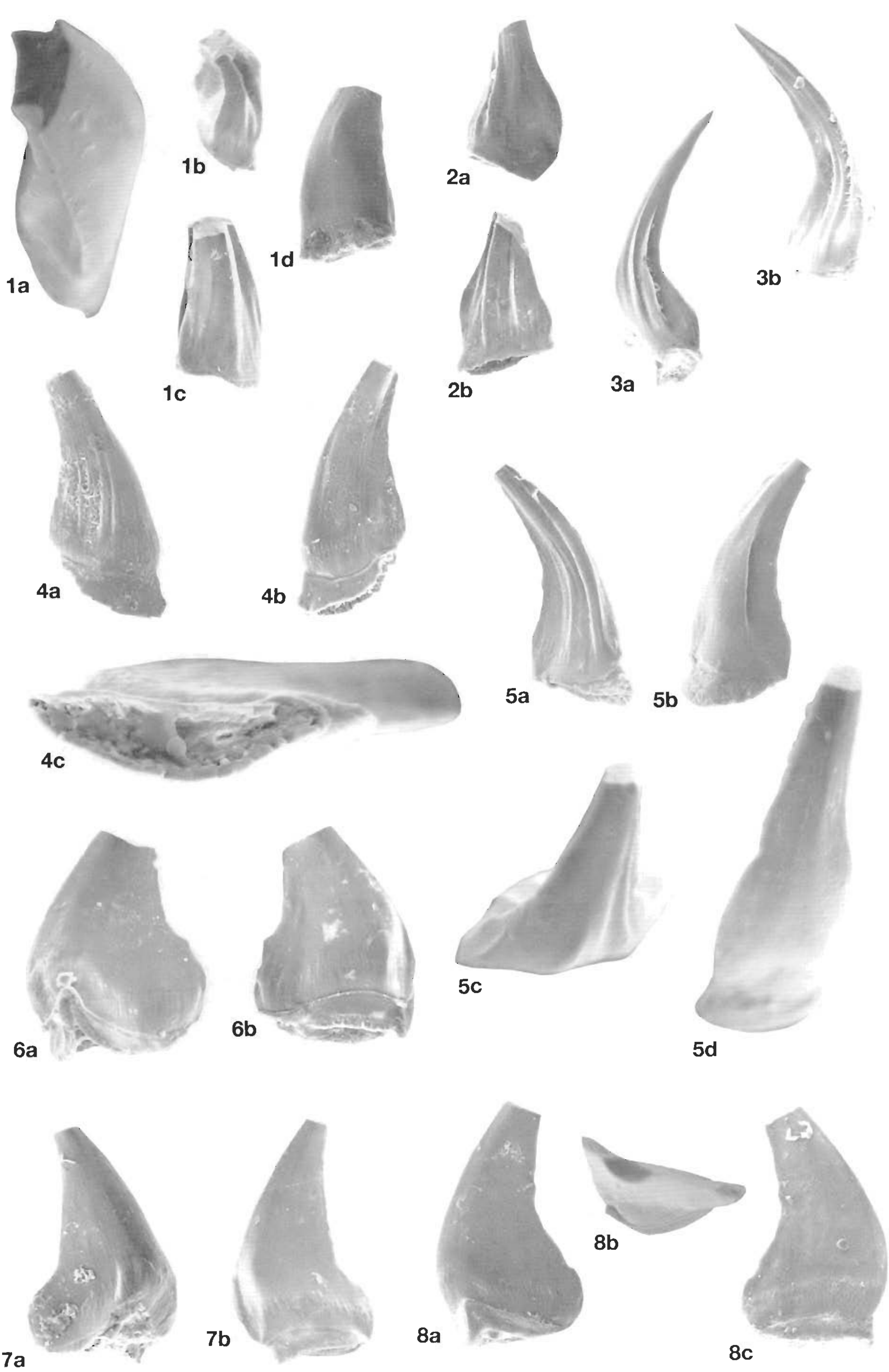
Figure 4. *Jumudontus gananda* M and Sa elements.

All figures x 110, except as noted.

1. M element (CPC 23269)[85-2021/L] right element. **a,** posterior view; **b,** anterior view. **2. M element** (CPC 23270)[85-2021/L] left element. **a,** posterior view; **b,** anterior view; **c,** inner lateral view (x 245). **3. M element** (CPC 23271)[85-2021/L] right element. **a,** posterior view; **b,** inner lateral view; **c,** anterior view. **4. Sa element** (CPC 23272)[86-2031A]. **a,** oral view, x 245; **b,** posterior view; **c,** anterior view. **5. Sa element** (CPC 23273)[86-2031A]. **a,** anterior view; **b,** posterior view; **c,** basal view, x 245; **d,** oblique basal view, x 245.

Description. The P elements and some of the S elements may have a very narrow flange parallel to and just above the basal margin that has numerous small pustules on its surface. The P elements have solid white matter in some denticles and dispersed white matter in the blades of some elements. The M and S elements have white matter in the cusps. Fine striae are well developed on the element surfaces.

The Pa element is carminate with four to six denticles in front of a cusp that is both slightly taller and larger than the rest of the denticles. Behind the cusp a short blade, about a third the length of the anterior blade, contains a highly variable number of suppressed denticles that are not usually expressed on the oral margin. The anterior and posterior blades are both straight but the base of the posterior blade is twisted outward. A short spur on the inner side of the element flares posteriorly and inward from the axis of the cusp. White matter in the anterior blade is confined to the denticles. From the cusp forward each successive denticle contains less white matter at its base, giving the element an inverted staircase impression (Fig. 8.4), and the anterior denticle may lack white matter completely. The suppressed denticles of the posterior blade may be discretely defined by white matter or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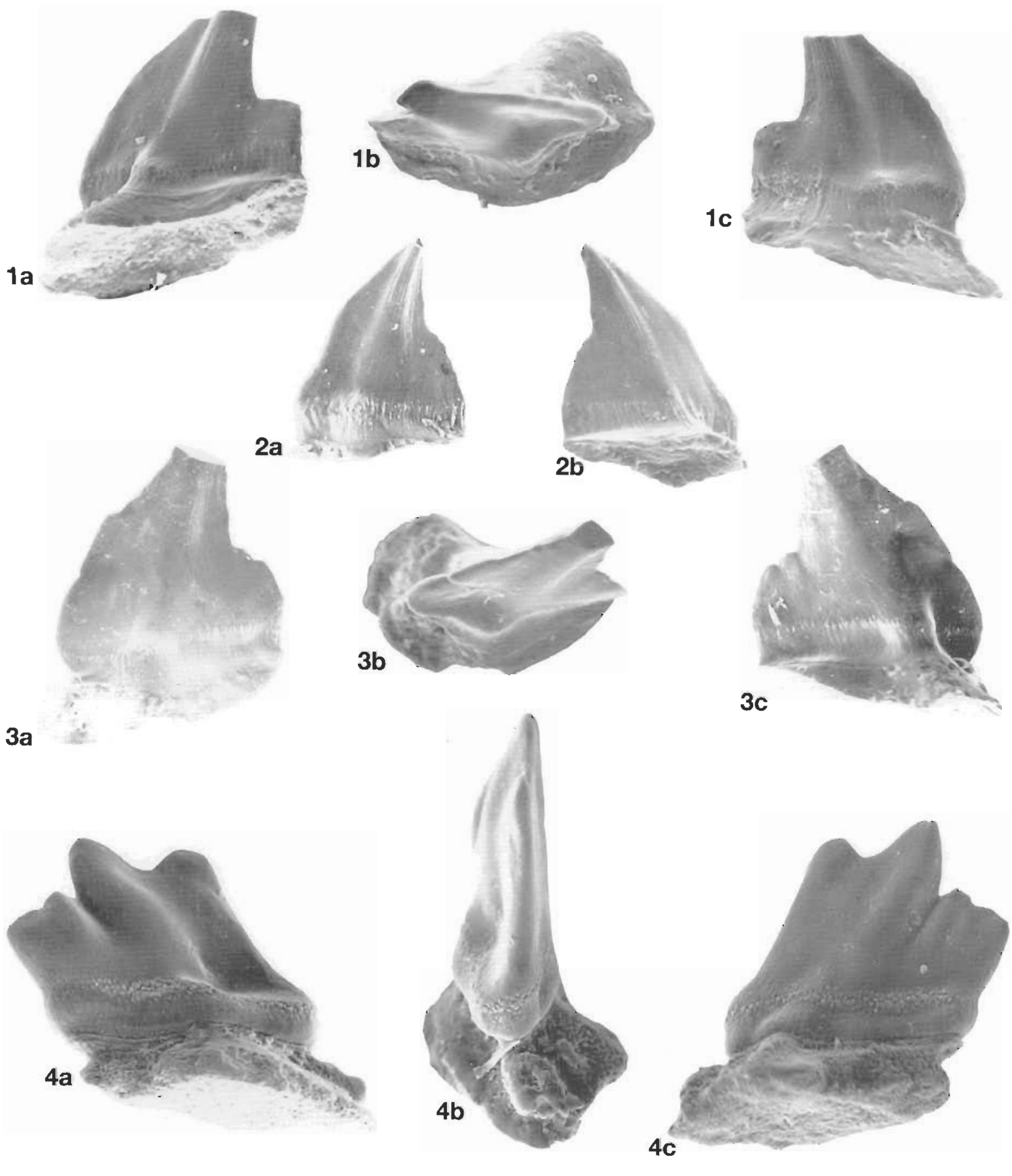


Figure 6. *Jumudontus gananda* Pb element.

All figures x 110.

1. Right element (CPC 23282)[86-2031A]. **a,** inner lateral view; **b,** oral view; **c,** outer lateral view. **2. Left element** (CPC 23283)[86-2031A]. **a,** outer lateral view; **b,** inner lateral view. **3. Left element** (CPC 23284)[86-2031A]. **a,** outer lateral view; **b,** oral view; **c,** inner lateral view. **4. Right element** (CPC 23285)[85-2021/L]. **a,** outer lateral view; **b,** anterior view; **c,**. inner lateral view.

Figure 5. Jumudontus gananda Sc, Sb & Sd elements.

All figures x 110, except as noted.

1. Sc element (CPC 23274)[86-2031A] right element. **a,** oral view (x 330); **b,** oblique oral view; **c,** inner lateral view; **d,** outer lateral view. **2. Sc element** (CPC 23275)[86-2031A] left element. **a,** outer lateral view; **b,** inner lateral view. **3. Sc element** (CPC 23276)[86-2031A] right element. **a,** outer lateral view; **b,** inner lateral view. **4. Sb element** (CPC 23277)[85-2021/L] right element. **a,** outer lateral view; **b,** inner lateral view; **c,** basal view, x 200. **5. Sb element** (CPC 23278)[86-2031A] left element. **a,** inner lateral view; **b,** outer lateral view; **c,** oral view, x 220; **d,** oblique anterolateral view, x 220. **6. Sd element** (CPC 23279)[86-2031A] left element. **a,** outer lateral view; **b,** inner lateral view. **7. Sd element** (CPC 23280)[86-2031A] right element. **a,** outer lateral view; **b,** inner lateral view. **8. Sd element** (CPC 23281)[852021/L] left element. **a,** outer lateral view; **b,** oral view; **c,** inner lateral view.

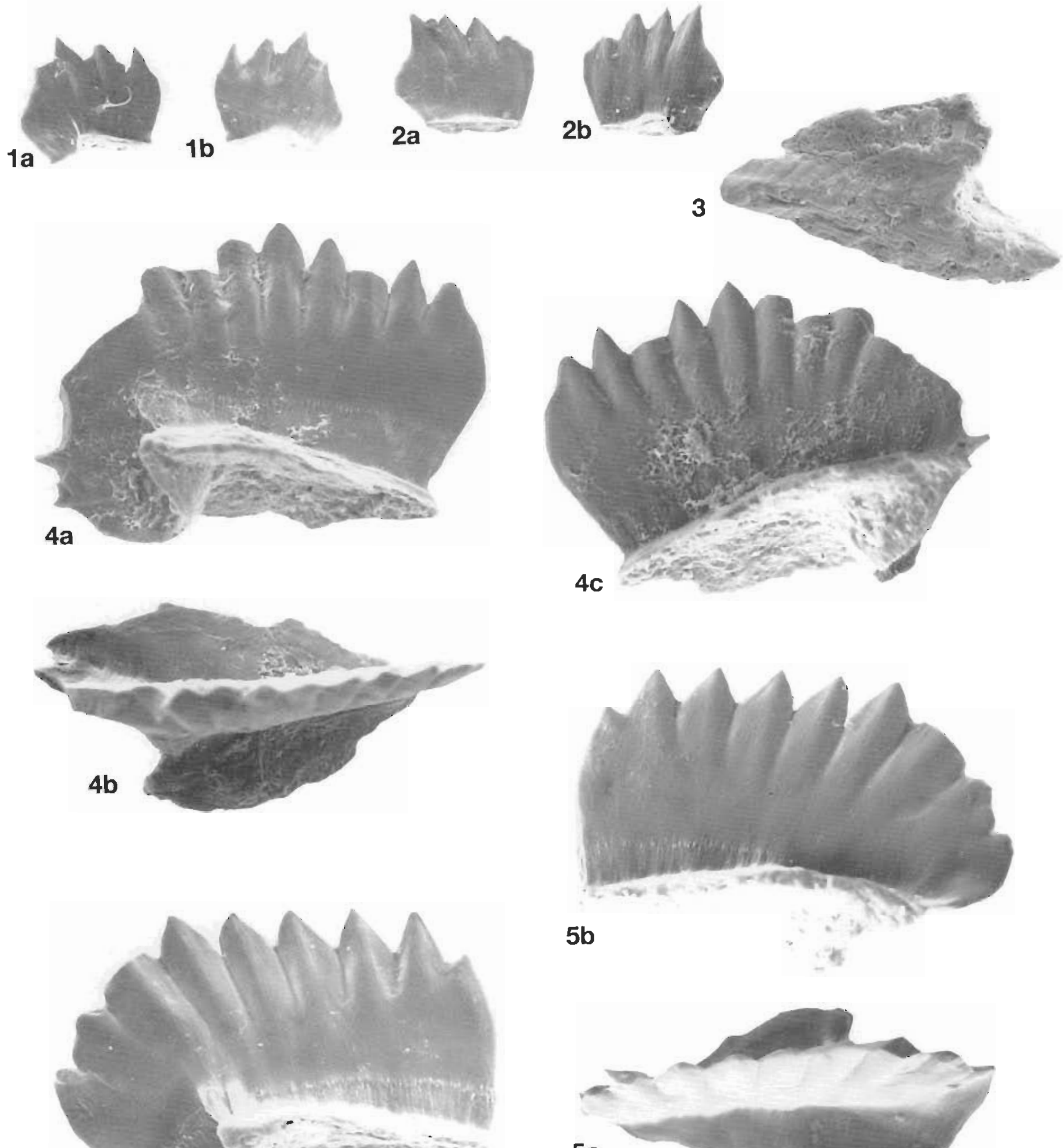


Figure 7. *Jumudontus gananda* Pa element.

All figures x 110.

1. Left element (CPC 23286)[86-2031A] juvenile. **a,** inner lateral view; **b,** outer lateral view. **2. Right element** (CPC 23287)[86-2031A] juvenile. **a,** outer lateral view; **b,** inner lateral view. **3. Basal plate** (CPC 23288)[85-2021/L] upper surface of detached plate. **4. Left element** (CPC 23289)[86-2031A]. **a,** inner lateral view; **b,** oral view; **c,** outer lateral view. **5. Left element** (CPC 23290)[86-2031A]. **a,** inner lateral view; **b,** outer lateral view; **c,** oral view.

the white matter may be dispersed. In lateral view the element has an overall rectangular shape. The anterior denticles are erect, the cusp is either erect or slightly posteriorly inclined and the posterior denticles fan out from the base of the cusp. The basal cavity is broad and shallow. Well preserved basal plates expand laterally and accentuate the morphology observed on the base of the crown.

The Pb element is also carminate with a large posteriorly inclined cusp forming more than half of the element. The anterior blade is reduced to a short adentate flange. The posterior blade is similar to that of the Pa element and some elements may show a number of suppressed denticles that radiate from the base of the cusp but are not apparent on the margin. White matter is confined to the cusp and denticles. The element is straight, lacking the inner spur and outer posterior twist of the posterior blade in the Pa element. The cusp has fine striations on the lateral faces. The basal cavity is broad and shallow. Well preserved basal plates are very broad and rounded on the anterior margin and narrow posteriorly.

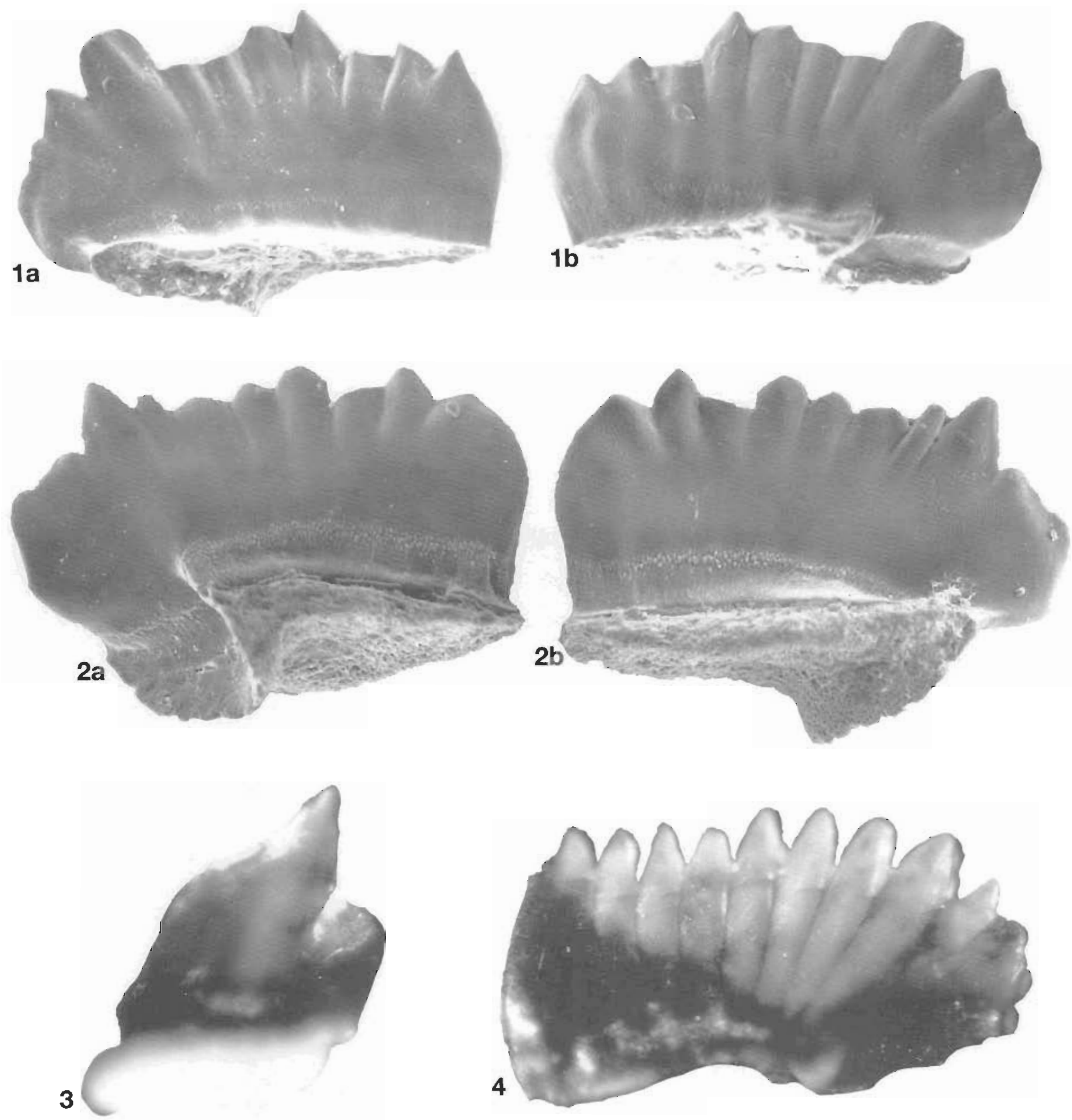


Figure 8. ***Jumudontus gananda*** **Pa and Pb elements.**

All figures x 110 except as noted.

1. Pa element (CPC 23291)[86-2031A] right element. **a,** outer lateral view; **b,** inner lateral view. **2. Pa element** (CPC 23292)[85-2021/L] left element. **a,** inner lateral view; **b,** outer lateral view. **3. Pb element** (CPC 23293)[85-2021/L] left element; outer lateral view showing distribution of white matter. **4. Pa element** (CPC 23294)[85-2021/L] right element, inner lateral view showing distribution of white matter, x 90.

The M element is makellate with an adentate anticusp and outer lateral process. The posterior flange is of moderate size. The basal cavity is widest at the flange and narrows toward both anterobasal and posterobasal corners. The cusp has sharp keels and a single large costa on each face. The faces of the cusp have fine striations. White matter is confined to the cusp.

The Sa element is coniform with a complex pentameral cross-section. A central keel on the posterior margin is symmetrically flanked by major postero-lateral costae on either side. There are two symmetrical antero-lateral costae on the anterior face of the element. The base of the element lacks white matter but the cusp is white. The basal cavity is very shallow.

The Sc element is coniform with both costae and striations prominent. The element is laterally compressed and an anterior margin flange is directed slightly inward. The upper part of the cusp is twisted slightly out of the axial plane of the base. The element is widest near the rounded anterior margin, and narrows to a sharp posterior margin. The basal cavity is deep, extending 1/2 to 1/3 of the height of the cusp, and white matter is restricted to that part of the element above the cavity.

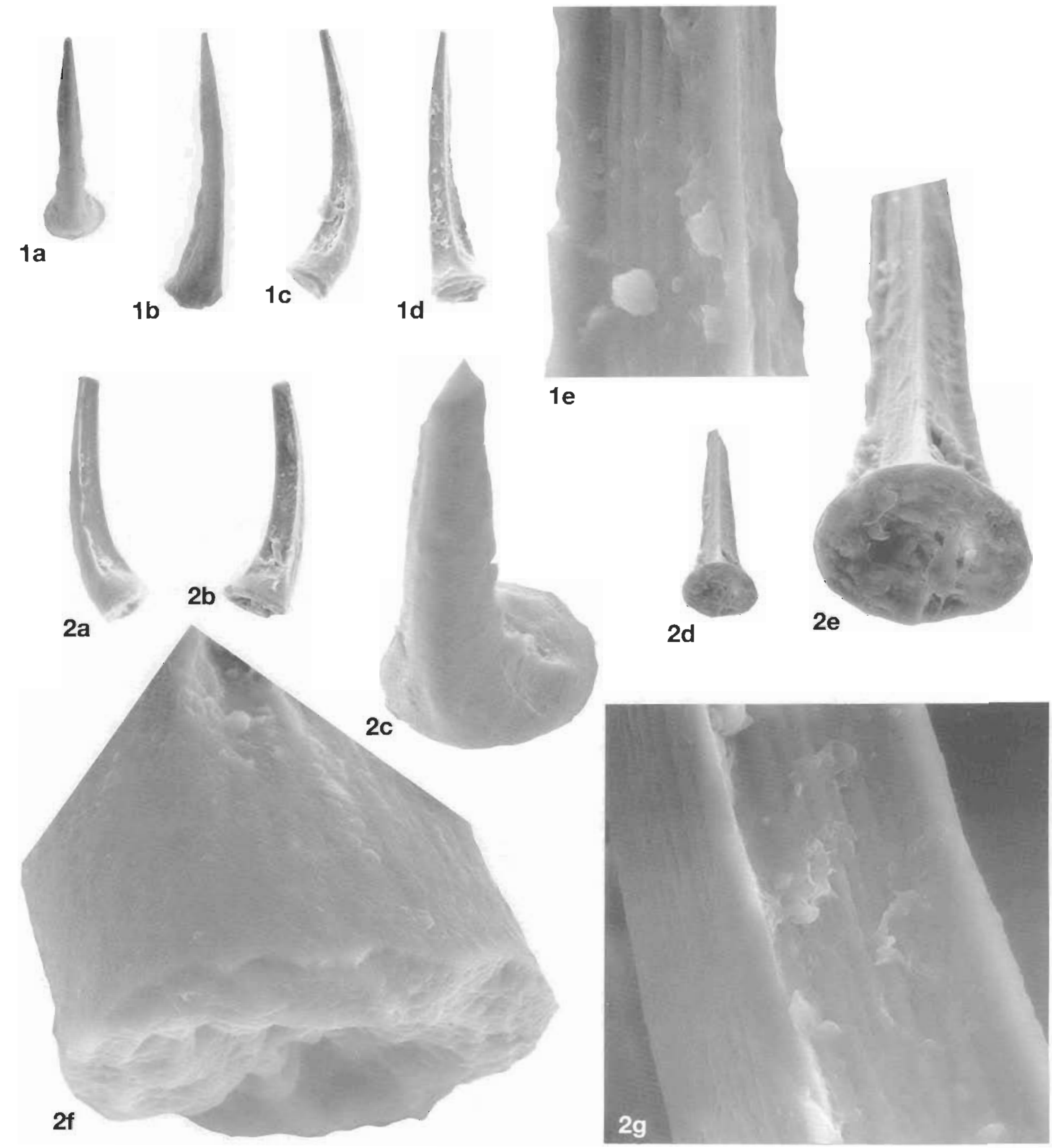


Figure 9. ***Jumudontus brevis*** **Sa element.**

All figures x 125, except as noted.

1. Symmetrical element (CPC 23295)|WCB 705/177A| **a,** anterior view; **b,** anterolateral view; **c,** lateral view; **d,** posterior view; **e,** x 975, enlargement of posterior side of cusp showing prominent keel and striae. **2. Symmetrical element** (CPC 23296)|WCB 705/177A| **a,** left lateral view; **b,** right lateral view; **c,** x 360, enlargement of anterior view showing well developed striae and both the major (posterior) and minor (anterior) lateral costae; **d,** posterior view; **e,** x 360, enlargement of posterior view; **f,** x 1100, enlargement of basal margin; **g,** x 1375, enlargement of lateral view of cusp showing striae development.

The Sb element is coniform with prominent costae and striations. This element is similar to the Sc element, except that both anterior and posterior margins have sharp flanges and the element is widest at about midlength.

The Sd element is a modified coniform type with a major posteriorly inclined and laterally compressed cusp. The anterior keel is bent inward and there is a small spur located near the basal margin on the outer anterolateral face. In larger specimens the posterior keel is extended and is morphologically similar in lateral view to the posterior blade of the Pb element. White matter is confined to the cusp, expanding from a narrow band above the basal cavity, to fill the entire cusp at about mid height. The basal cavity is very shallow.

Remarks. The basal flange and pustules are lacking on other species in these faunas; they help identify and associate the diverse elements that constitute this multielement species. The mixture of coniform, or modified coniform, and pectiniform elements in the apparatus structure of *Jumudontus gananda*

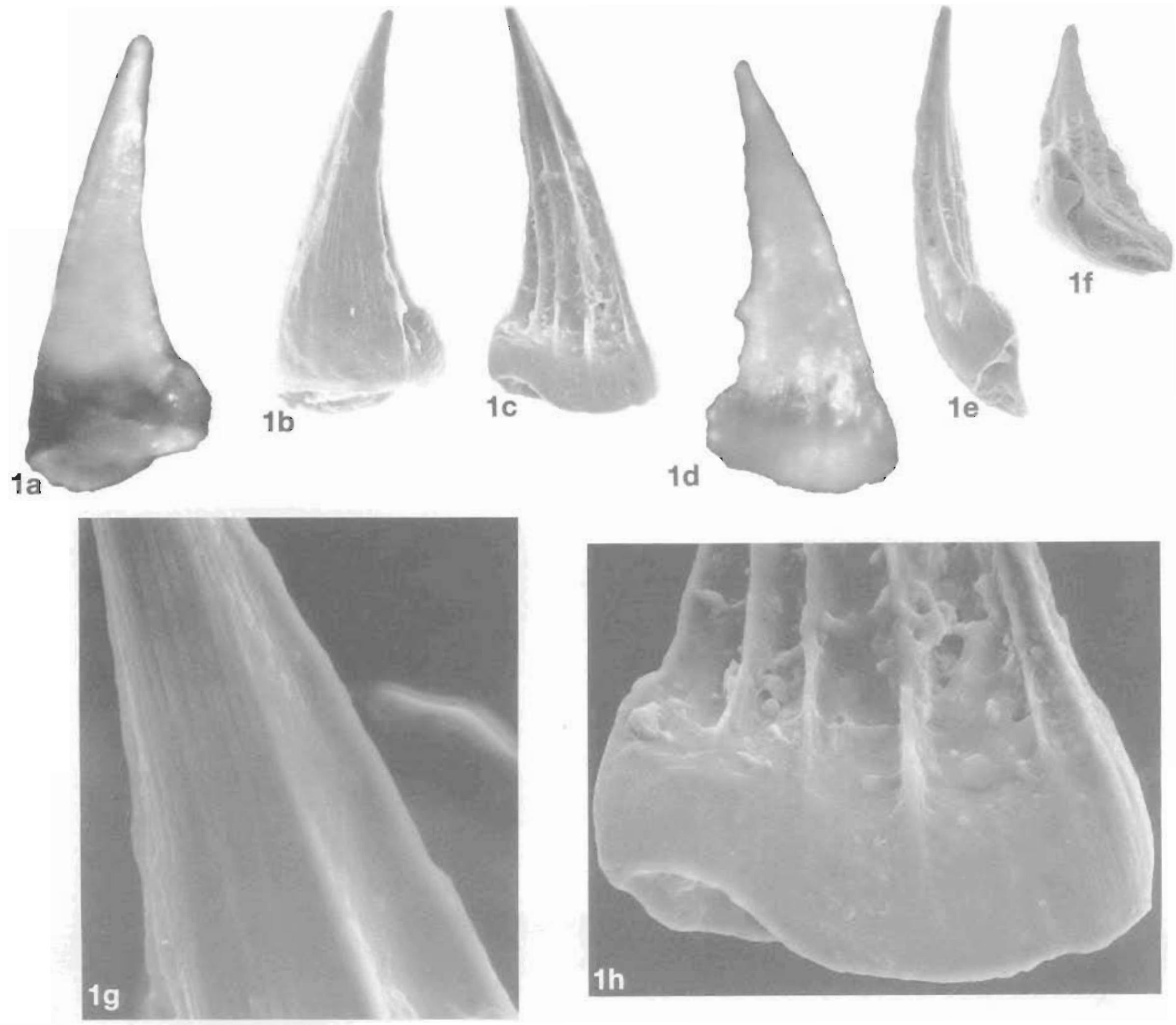


Figure 10. *Jumudontus brevis* Sb element.

All figures x 135, except as noted.

Left element (CPC 23297)[WCB 705/177A]. **a**, x 150, outer lateral view showing distribution of white matter; **b**, outer lateral view; **c**, inner lateral view; **d**, x 150, inner lateral view showing distribution of white matter; **e**, posterior view; **f**, basal view; **g**, x 750, enlargement of cusp showing striae; **h**, x 430, enlargement of inner lateral basal margin.

makes the apparatus similar in structure to that of *Icriodus*. The low abundance of the specimens reported in most studies, and the similarity to *Icriodus*, have made recognition of the apparatus structure less obvious.

Jumudontus brevis sp. nov.

Figs 9—13

Synonymy

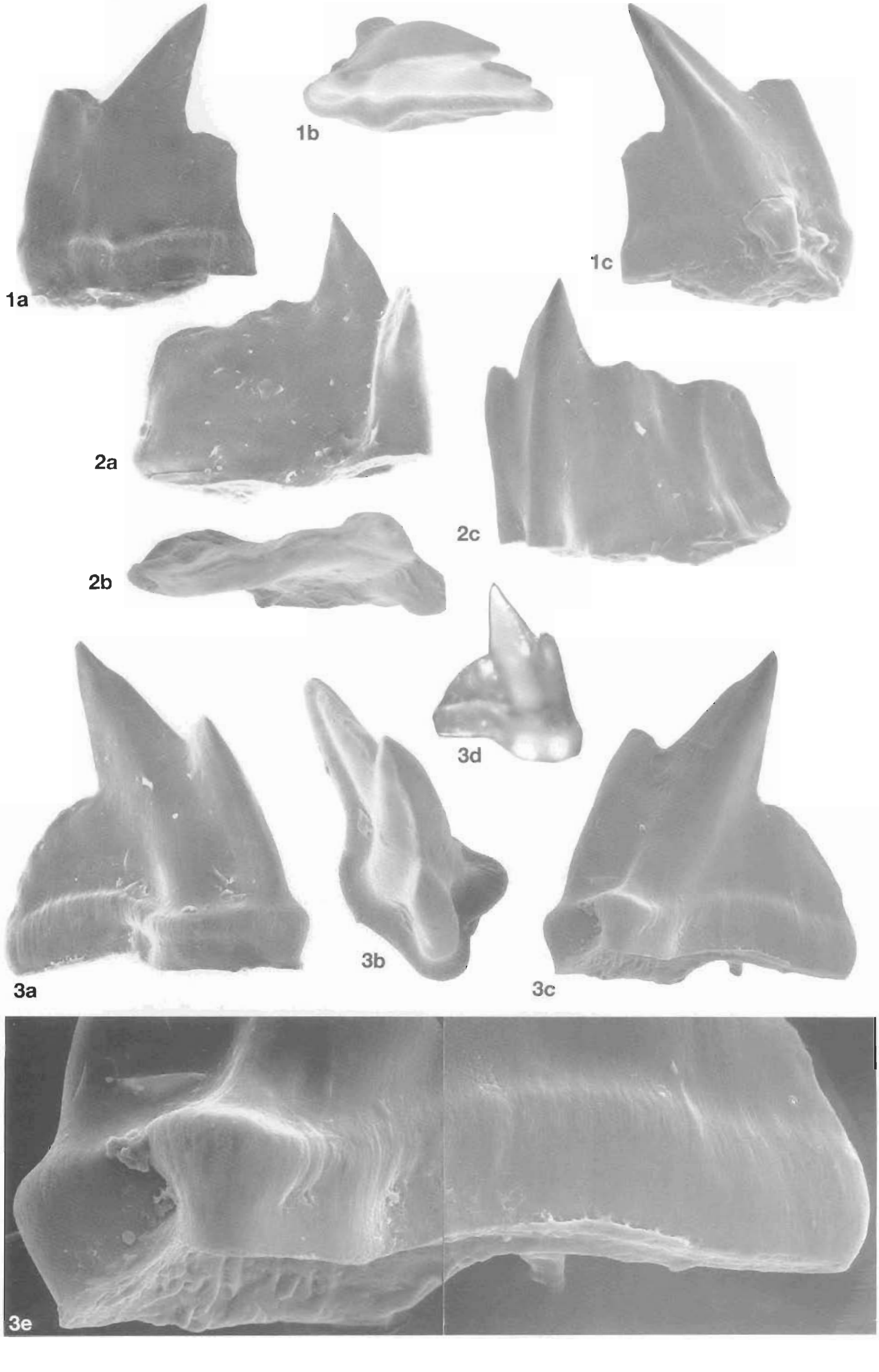
1964 ?*Rhipidognathus* sp., Ethington & Clark, pp. 695—698
1981 New Genus 2, Ethington & Clark, p. 117, pl. 13, figs 18—20, 24 [fig. 18 Pa element; 19, 20, 24 Pb elements]
1988 *Jumudontus* sp. Stouge & Bagnoli, p. 120, Pl. 3, fig. 17 [Pa element]
1988 *Jumudontus gananda* Cooper; Bergström, pl. 3, fig. 48 [Pa element]

Material studied. 12 elements: 5 Pa, 3 Pb, 2 Sa, 1 Sb. All from the Emanuel Formation, Canning Basin, Western Australia.

Diagnosis. Multimembrate coniform—pectiniform apparatus with coniform S elements and carminate Pb and Pa elements. The short anterior blades of the P elements may have denticles; the posterior blades lack denticles. The posterior blade of the Pb element is longer than the posterior blade of the Pa element. The lower part of the elements around the basal margin and cavity is hyaline but the upper part has white matter, either concentrated in random patches and denticles cores or diffused through a large part of the element. Element surfaces are striate.

Description. Only four of the probable seven elements of this apparatus have been identified. The P elements are robust and the S elements are comparatively larger than the S elements of *J. gananda*. The P elements have a narrow flange parallel to the basal margin, which has pustules developed on the surface. The surfaces of the elements has well developed striae.

The Pa element is carminate with a prominent cusp that is inclined slightly posteriorly and extends above general level of the oral margin of the blade. The truncated anterior blade may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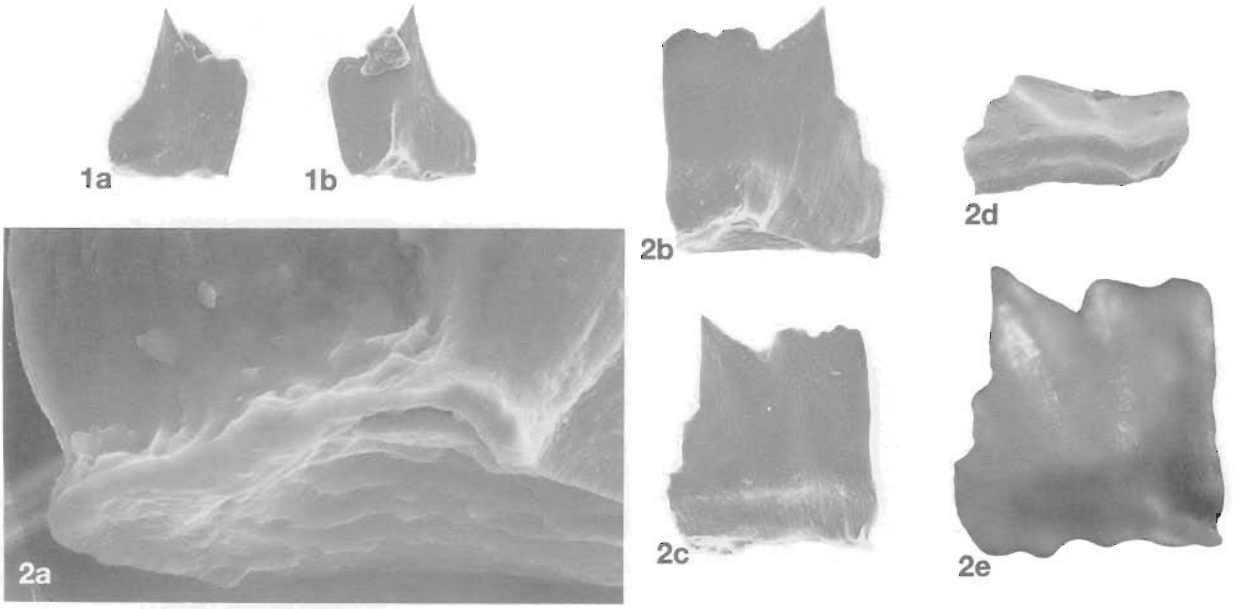


Figure 12. *Jumudontus brevis* early growth stages of Pa elements.

All figures x 100, except as noted.

1. Right element (CPC 23301)[WCB 705/212]. **a,** outer lateral view; **b,** inner lateral view. **2. Right element** (CPC 23302)[WCB 705/177A]. **a,** x 450, enlargement of inner lateral view showing the anterior part of the base of the crown; **b,** inner lateral view; **c,** outer lateral view; **d,** oral view showing outer lateral face; **e,** x 125, outer lateral view showing distribution of white matter.

Figure 11. *Jumudontus brevis* Pb element.

All figures x 100, except as noted.

1. Right element (CPC 23298)[WCB 705/175D]. **a,** inner lateral view; **b,** oral view; **c,** outer lateral view. **2. Left element** with broken anterior basal margin (CPC 23299)[WCB 705/141B]. **a,** inner lateral view; **b,** oral view; **c,** outer lateral view. **3. Left element** (CPC 23300)[WCB 705/212]. **a,** inner lateral view; **b,** oblique oral view; **c,** outer lateral view; **d,** x 50, inner lateral view showing distribution of white matter; **e,** x 270, enlargement of outer lateral crown base showing basal flange and anteriorly directed short process.

have one to three denticles, and a slightly longer posterior blade is without clearly defined denticles. The anterior margin of the blade is vertical, but the upper margin of the posterior blade slopes downward to the posterobasal corner. White matter is present in the upper part of the blade but is generally diffused rather than concentrated in denticles, except for the cusp which is albid. There is a short spur at the base of the cusp on the inner side of the element and the posterior blade is bent slightly outward. The anterior margin of the blade is rounded. The basal plate is large and flares downward and outward from the basal margin of the crown, except for the inner quadrant posterior of the spur where the basal plate is folded inward under the crown (see Figs 13.1D, 13.2D).

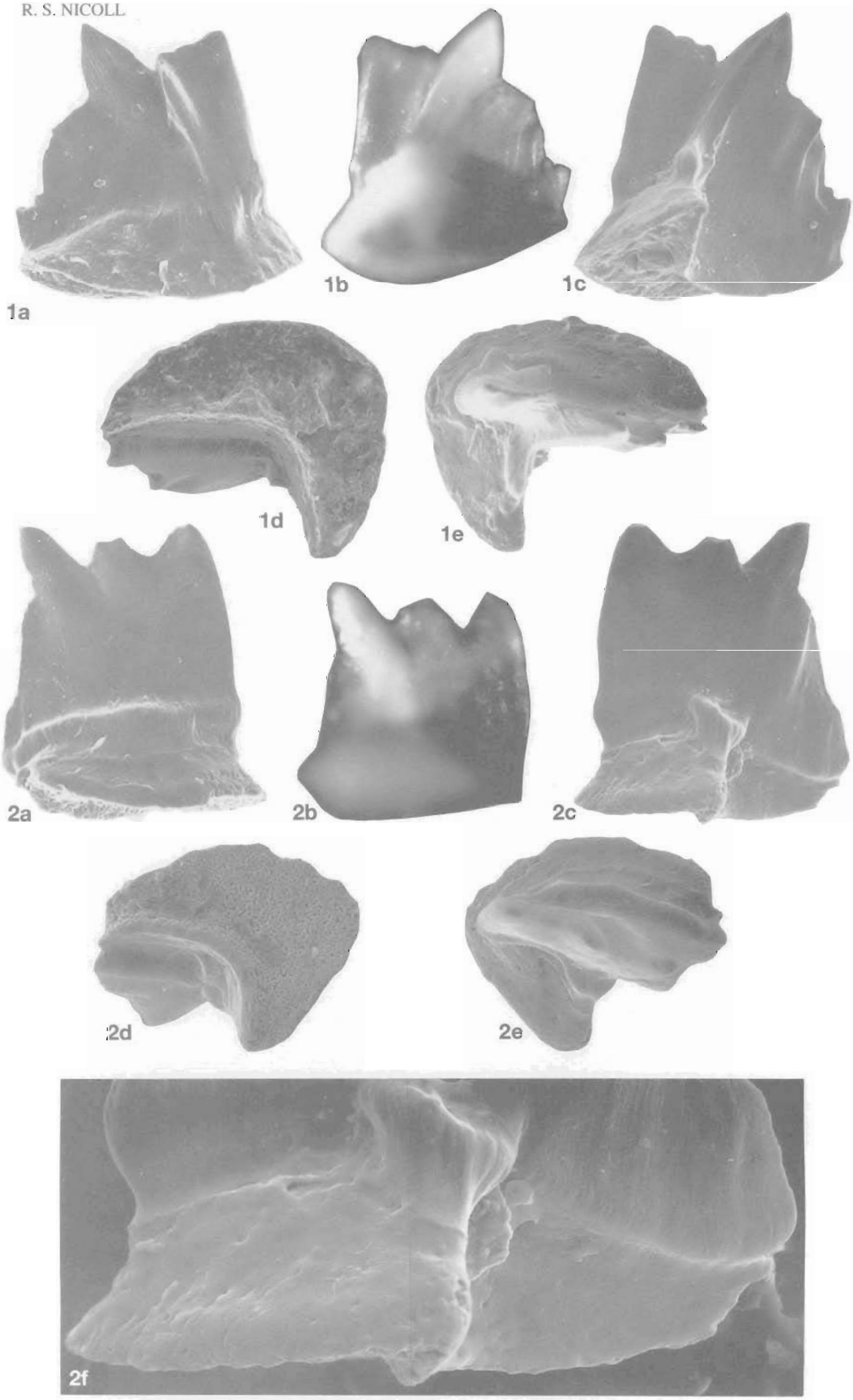
The Pb element is also carminate with a very short anterior blade, equivalent to only a single denticle, and a longer posterior blade that may be half of the length of the element. The anterior blade may be bent slightly inward. White matter distribution is similar to that found in the Pa elements, except that the only distinct denticle defined in the limited sample has been the cusp. There is an anteriorly directed spur at the base of the cusp on the outer side of the element. On the inner side of the element the flange is widest next to the cusp.

Three coniform S elements have been found that are part of the *J. brevis* apparatus. Two are symmetrical Sa elements and the third is an asymmetrical Sb element. The Sa elements are erect or slightly posteriorly recurved. The anterior margin is rounded and lacks a keel. There is a prominent posterior keel extending from the cusp tip to near the basal margin. There is a very small pair of anterior lateral costae and a much larger pair of posterior lateral costae that also extend from the cusp tip to near the basal margin. All surfaces have well developed striae.

The single asymmetrical coniform S element recovered is interpreted as an Sb element because it closely corresponds to the Sb element of *J. gananda*. The element is robust and slightly laterally compressed. It is bowed outward both in its height and length. The inner concave surface has several large costae and the outer surface lacks costa; both surfaces are striate. The basal cavity extends only a short distance into the base of the element. Next to the cavity the element is hyaline, but the rest of the cusp has disseminated white matter extending to the tip.

Remarks. *Jumudontus brevis* is very similar to *J. gananda* from which it can be differentiated by the much shorter anterior blade in both the Pa and Pb elements. The Sa elements have generally similar features, but the costae of *J. brevis* are less well developed. The Sb elements of both species are also very similar. Thus it is assumed that the M, Sc and Sd elements of *J. brevis* will also be similar to these elements in *J. gananda*. Both species have P elements that are robust when compared with other elements in the associated fauna.

The recovery of elements that can be assigned to *Jumudontus brevis* from Australia, Utah, Texas, Newfoundland and Baltoscandia indicate that this species probably has a similar worldwide distribution to that of *J. gananda*.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Appendix 1. Locality information

Material for this study is derived from an ongoing investigation of conodont faunas of the Horn Valley Siltstone in the Amadeus Basin and from the Emanuel Formation in the Canning Basin. Detailed locality information is given only for samples from which figured material has been obtained. Other locality information will be published in conjunction with the separate regional studies.

Amadeus Basin — Horn Valley Siltstone

85-2021/L. From measured section on the southern side of the Gardiner Range Anticline located 29 km northwest of Pattalindama Gap. The Horn Valley Siltstone is 130 m thick in this section and sample 2021/L is located 69.3 m stratigraphically above the base of the section.

Map reference: Mt Liebig 1:250 000 topographic sheet SF 52-16, latitude 23°55.3′S; longitude 131°54.9′E.

Figure 13. *Jumudontus brevis* Pa elements with complete and intact basal plates.

All figures x 100, except as noted.

1. Right element (CPC 23303)[WCB 705/141B]. **a**, outer lateral view; **b**, x 90, inner lateral view showing distribution of white matter; **c**, inner lateral view; **d**, basal view; **e**, oral view. **2. Right element** (CPC 23304)[WCB 705/212]. **a**, outer lateral view; **b**, x 95, outer lateral view showing distribution of white matter; **c**, inner lateral view; **d**, basal view; **e**, oral view; **f**, x 260, enlargement of inner lateral view showing detail of the lower part of the crown and the basal plate.

86-2031A. From spot sample collected from the middle part of the Horn Valley Siltstone, 8km west of Ellery Creek along the strike of the outcrop belt of the MacDonnell Ranges.

Map reference: Hermannsberg 1:250 000 topographic sheet SF 53-13, latitude 23°48.3′S; longitude 132°59.2′E.

Canning Basin — Emanuel Formation

WCB 705. Measured section along Emanuel Creek upstream from its junction with an unnamed tributary creek. Type section of the Emanuel Formation, previously measured by McTavish (1973) and Legg (1973). The Bureau of Mineral Resources measured section starts at the creek intersection (latitude 18°39.8′S; longitude 125°53.86′E) and extends over a distance of 2.1 km to a point (latitude 18°39.2′S; longitude 125°54.83′E) where exposure becomes very poor and discontinuous. Samples are located stratigraphically above the base of the measured section as follows: 141B - 211.5 m, 175D - 262.5 m, 177A - 265.5 m, 212 - 318 m.

Map reference: Bruten 1:100 000 topographic sheet 4060, Western Australia.

BMR Journal of Australian Geology & Geophysics, 13, 229 - 236

First record of Callovian ammonites from West Kalimantan (Middle Jurassic, Kalimantan Barat, Borneo, Indonesia)

G. Schairer[1] & A. Zeiss[2]

A small collection of ammonites of Callovian age is described from West Kalimantan. It includes *Hecticoceras* (*Lunuloceras*) *brightii* (Pratt), *H.* (*L.*) *lunuloides* (Kilian), *Hecticoceras* (*Putealiceras*) aff. *punctatum* (Stahl), *Reineckeia* s.l. sp., and *Indosphinctes* sp. New elements are *Hecticoceras* (*Lunuloceras*) nov. sp. A, *Kalimantanites nodosospinatus* nov. gen., nov. sp., *K. occultenodosus* nov. sp. and *Borneoceras sanggauense* nov. gen., nov. sp.

Introduction

The ammonite fauna studied comes from West Kalimantan (Kalimantan Barat, Borneo, Indonesia), 40 km northwest of Sanggau, on the road from Kembajan to Tangjung, 17 km south of Kembajan (map Sanggau, NA 49-14, East Indies, 1:250 000, Indonesia-Malaysia; 110° 23'E, 0° 25'N; Fig. 1). All the ammonite specimens were collected (at different times, and by several people, including inhabitants) from a 20 m section in a quarry excavated in gently dipping (5—10°) beds of the Brandung Formation. Little is known of this formation because it is confined to only two outcrops mappable at 1:250 000 scale in West Kalimantan. Its base is not exposed, but it underlies the Pedawan Formation, which contains a diverse marine fauna (foraminifers, radiolarians, echinoids, bivalves, and ammonites) and flora (pollen, algae, and fossil wood) indicating Early and Late Cretaceous age. A contact between these two formations has not been seen, so the precise relationship between them is not known.

The Brandung Formation is composed of calcareous shale, slaty shale, mudstone, siltstone, sandstone and muddy limestone. It is commonly carbonaceous. Apart from ammonites, it contains belemnites, bivalves, coral fragments and plant matter. It is a possible correlative of the Kedadom Formation (in Sarawak), in which bivalves have affinities with those from the Late Jurassic in Japan.

Because the Brandung Formation ammonite assemblage was collected by different people at different times, the relative stratigraphic position of each specimen is not known.

Many of the specimens are crushed or fragmentary; some are calcite-filled with recrystallised shells. The ammonites are embedded in blackish limestones and shales, which resemble, for example, the rocks of Spiti, Himalaya. The rocks are partially recrystallised micrites. In thin section (Plate 3, fig. 2), fossil debris and a few fossils are recognisable. These include foraminifers, radiolarians, sponge spicules, shell fragments of bivalves, gastropods, and ostracods, and fine plant debris. The rocks contain dispersed pyrite, partially as framboidal pyrite. Dinoflagellates, nannoconids and calpionellids could not be unequivocally identified. Burrows are recognisable on polished surfaces.

Systematic description

Abbreviations

d diameter in mm
p primary ribs on a whole whorl
p/2 primary ribs on a half whorl
s ventral ribs for 10 primary ribs
uw umbilical width as a % of diameter
wh whorl height as a % of diameter

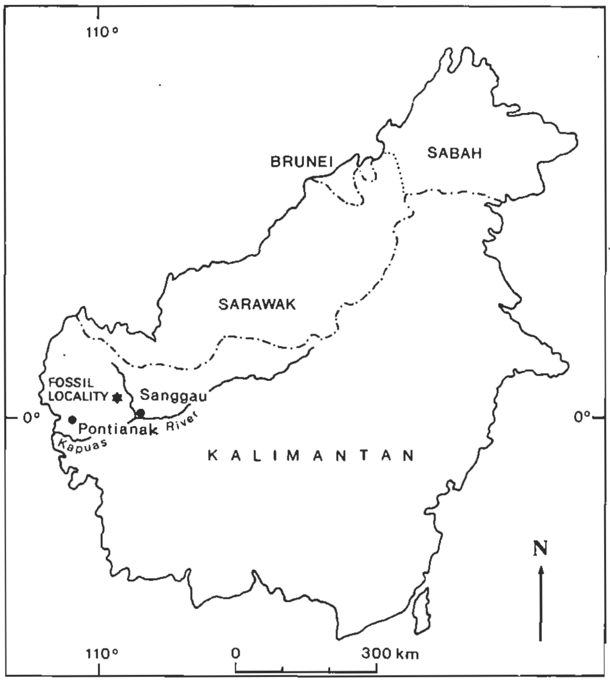

Figure 1. Sketch map of Borneo showing fossil locality (asterisk) from West Kalimantan.

Superfamily Haplocerataceae Zittel, 1884
Family Oppeliidae Douvillé, 1890
Subfamily Hecticoceratinae Hyatt, 1900
Genus *Hecticoceras* Bonarelli, 1893
Subgenus *Lunuloceras* Bonarelli, 1893

***Hecticoceras* (*Lunuloceras*)** nov. sp. A
Pl. 1, fig. 1

Material. 1 specimen (83 P 16 K).

Dimensions

d	uw	wh	p/2	s
40			10	22
30	17	50		

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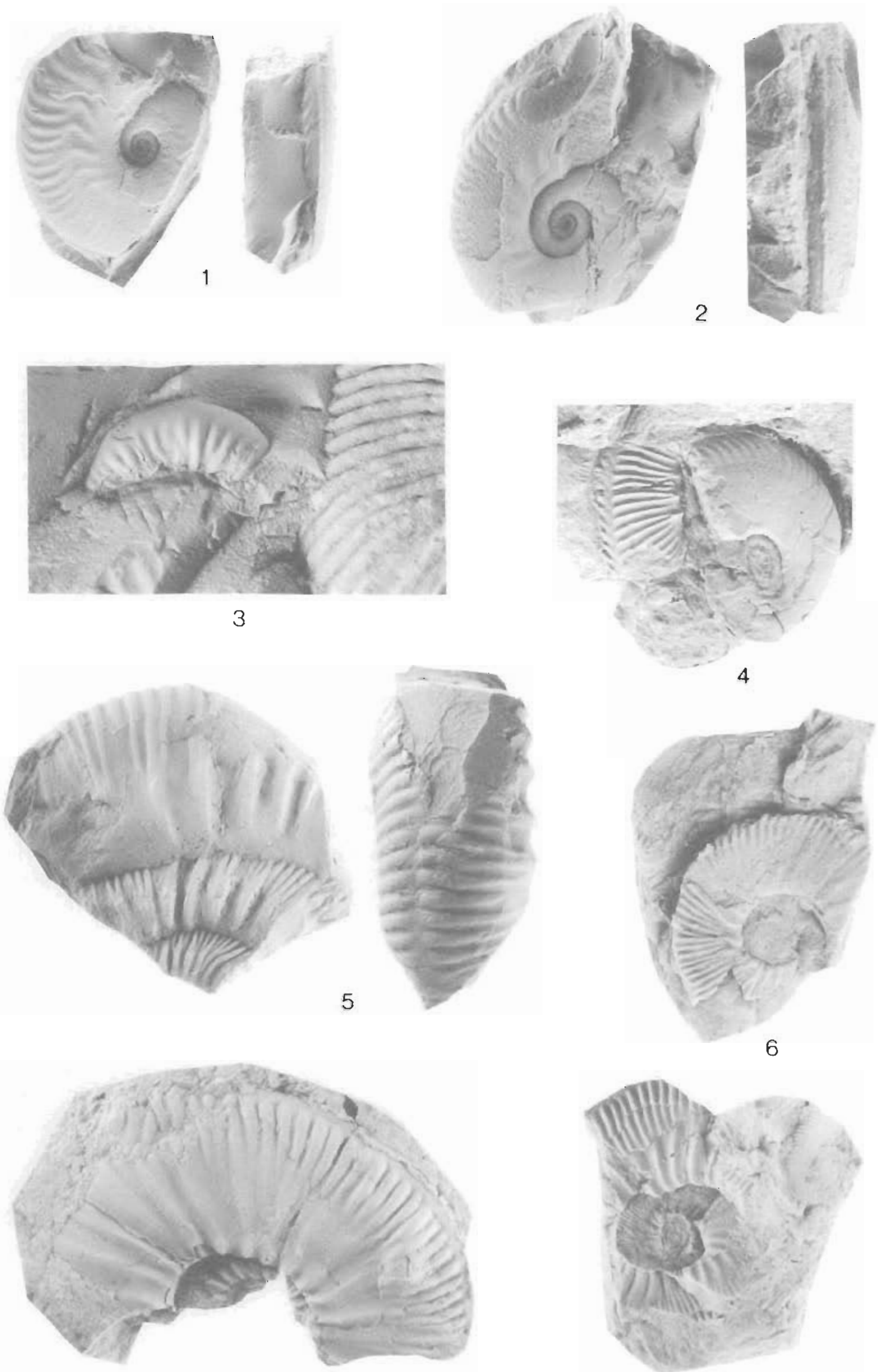


Plate 1.

All specimens from the Callovian from West Kalimantan. All specimens x1 unless otherwise indicated.
1, ***Hecticoceras* (*Lunuloceras*) nov. sp. A**, 83 P 16 K. **2,** ***Hecticoceras* (*Lunuloceras*) *brightii* (Pratt)**, 83 P 16 C/5, x2. **3,** ***Hecticoceras* (*Putealiceras*) aff. punctatum (Stahl)**, 83 P 16 C/12, x3. **4,** ***Hecticoceras* (*Lunuloceras*) *lunuloides* (Kilian)**, 83 P 16 O/1; **4, 5,** ***Reineckeia* s.l. sp.** 4, 83 P 16 O/2, x1.5. 5, 83 P 16 J. **6-8,** ***Kalimantanites occultenodosus* nov. gen, nov. sp.** 6, 83 P 16 R, paratype, x1.5. 7, 83 P 16 G, holotype. 8, 83 P 16 N, paratype.

Description. The involute specimen has a slender, somewhat shouldered and keeled whorl section. The umbilical wall is steep and high, with an umbilical edge.

Inner whorls appear to be smooth. Where the last whorl commences, fine falcate striae are recognisable. They transform into a falcate ribbing, and gradually strengthen toward the aperture. The ribs are biplicate, dividing at approximately the middle of the whorl side. Some intercalatory ribs exist. Primary ribs are concave, and prorsiradiate. They are very fine at the umbilical edge, and become more pronounced toward the middle of the whorl side, where they form a knee-like projection. The ventral ribs are concave, rursiradiate, and project at the ventral margin. They do not reach the keel.

Remarks. *Hecticoceras* (*Lunuloceras*) *subinvolutum* Bonarelli (Lahusen, 1883, pl. 11, fig. 16) of the Middle Callovian is comparable with regard to whorl section, umbilical width, and shape of the umbilical region, but has very weak ribbing.

The ribbing style has a certain similarity to *H.* (*L.*) *paulowi* Tsytovitch (1911, pl. 7, figs 8—12; stratum typicum: Middle Callovian; otherwise: Callovian; Zeiss, 1959: 44), and *H.* (*L.*) *pseudopunctatum lahuseni* Tsytovitch (1911, pl. 7, fig. 6; stratum typicum: Middle Callovian; otherwise: Middle and Upper Callovian; Zeiss, 1959, 49), but these species have a much wider umbilicus.

Hecticoceras* (*Lunuloceras*) *brightii (Pratt, 1841)
Pl. 1, fig. 2

1845 *Ammonites brightii* (Pratt.) Orbigny, 431, pl. 33, figs 11, 12
1959 *Hecticoceras* (*Lunuloceras*) *brightii brightii* (S. Pratt, 1841) Zeiss, 27

Material. 7 specimens (83 P 16 C/5 - 11).

Description. The primary ribs are strongly prorsiradiate, and most are well developed. The ribbing weakens at approximately the middle of the whorl side. Some specimens have a denser umbilical ribbing than the lectotype (Orbigny, 1845: pl. 33, figs. 11, 12). The ventral ribs are rursiradiate to rectiradiate, concave, and projected at the ventral margin. The umbilical wall is low and steep, the umbilical margin flat. The whorl section is slender, shouldered, and with a distinct keel.

Distribution. Mainly Middle and Upper Callovian (Zeiss, 1959, 29).

Hecticoceras* (*Lunuloceras*) *lunuloides (Kilian, 1899)
Pl. 1, fig. 4

1849 *Ammonites hecticus compressus* Quenstedt, 119, pl. 8, fig. 3
1889 *Harpoceras lunuloides*, Kilian; Kilian, p. 118
1959 *Hecticoceras* (*Lunuloceras*) *compressum compressum* (F.A. Quenstedt, 1849) Zeiss, pp. 30, 40, 141.

Material. 1 specimen (83 P 16 O/1).

Description. The crushed specimen (diameter 23 mm) is involute. On the ventral third of the whorl side fine, concave ventral ribs are developed. The umbilical part of the whorl side is smooth other than fine, irregular striae. In contrast to the holotype, the ventral ribs are present only on the ventral third of the whorl side. The specimen figured by Andal & others (1968, pl. 28, fig. 5) as *Hecticoceras* (*Lunuloceras*) cf. *lunula* (Reinecke) is very similar.

Distribution. Mainly Middle and Upper Callovian (Zeiss, 1959, 32).

Subgenus *Putealiceras* Buckman, 1922

Hecticoceras* (*Putealiceras*)** aff. ***punctatum (Stahl, 1824)
Pl. 1, fig. 3

aff. 1824 *Ammonites punctatus* Stahl; Stahl, 48, fig. 8 a—c
aff. 1959 *Hecticoceras* (*Putealiceras*) *punctatum punctatum* (C. F. Stahl, 1824) Zeiss, 63

Material. 1 specimen (83 P 16 C/12); fragment of an inner whorl.

Description. The whorl section appears to be circular. The domed ventral area has a faint keel, which is accompanied on both sides by a keel-like line.

The ribs are feebly flexuous, simple or biplicate, dividing somewhat inside the middle of the whorl side. The ventral ribs are slightly concave and reach the lateral keel-like line or cross the venter in a chevron-like, convex arc.

Distribution. Mostly Middle and Upper Callovian (Zeiss, 1959, 67).

Superfamily Perisphinctaceae Steinmann, 1890
Family Reineckeiidae Hyatt, 1900
Subfamily Reineckeiinae Hyatt, 1900
Genus *Reineckeia* Bayle, 1878 s.l.

Reineckeia s.l. sp.
Pl. 1, figs 4, 5

Material. 3 specimens (83 P 16 J, 83 P 16 O/2, 83 P 16 V).

Description. The specimens 83 P 16 O/2 (pl. 1, fig. 4) and 83 P 16 V are crushed inner whorls with biplicate and some triplicate ribs, and some intercalatory ribs. At the point of division, the ribs possess little tubercles. On the ventral side the ribs are interrupted and stand opposite.

The specimen 83 P 16 J (pl. 1, fig. 5) is a larger, somewhat crushed fragment with the remainders of three whorls. The inner whorl is comparable to the specimens 83 P 16 O/2 and 83 P 16 V. The middle whorl has points of division with pointed tubercles at the umbilical third of the whorl side. The ribs are mostly triplicate. Some constrictions are recognisable. The outer whorl has biplicate and triplicate ribs with some intercalatory ribs. The points of division at the umbilical third of the whorl side are slightly accentuated.

Remarks. Perhaps the specimens are representatives of the genus *Collotia*, ex gr. *C. oxyptycha* (Neumayr); cf. Cariou, 1984, pl. 43, fig. 1.

Genus *Kalimantanites* nov. gen.

Name. Named after the Indonesian part of Borneo, Kalimantan.

Type species. *Kalimantanites nodosospinatus* nov. sp.

Diagnosis. Moderately involute, *Reineckeia*-like. Inner whorls with biplicate and triplicate ribs, and intercalatory ribs. Points of division between the umbilical third and the middle of the whorl side with or ?without fine, pointed tubercles. Outer whorls with different types of ribs:

1) bundled, points of division with a spine near the umbilical margin.

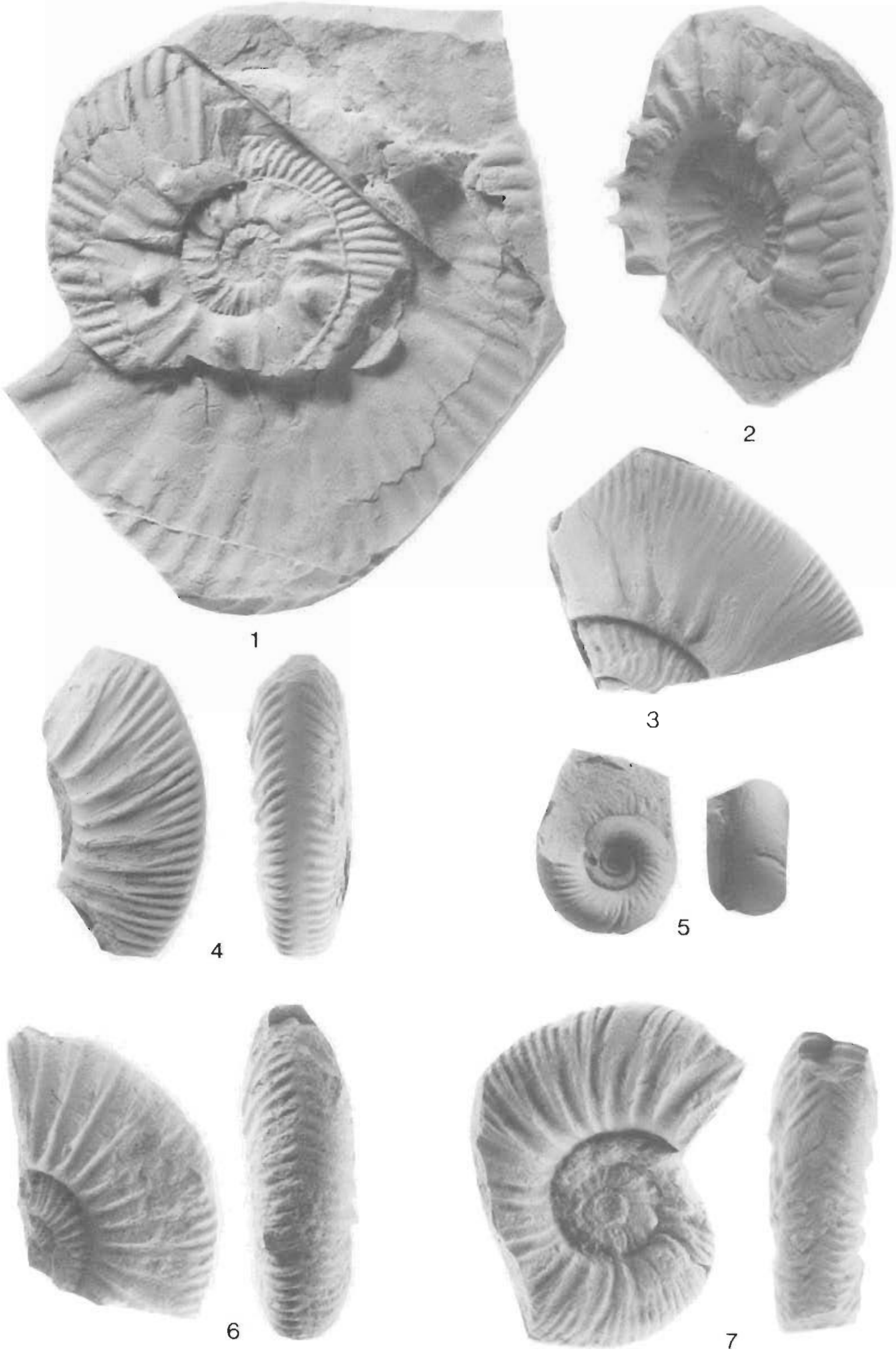


Plate 2.

Specimens 1—5: Callovian, West Kalimantan; specimens 6, 7: Callovian, Dalichai Formation, east Kuhe-Sharaf, E Semnan, Alborz, Iran. All specimens x1 unless otherwise indicated.

1, 2, *Kalimantanites nodosospinatus* nov. gen., nov. sp. 1, 83 P 16 A, holotype, latex. 2, 83 P 16 F, paratype, latex. **3, *Indosphinctes* sp.** 83 P 16 H. **4, 5, *Borneoceras sanggauense* nov. gen., nov. sp.** 4, 83 P 16 D, paratype. 5, 83 P 16 C/3, paratype, x3. **6, *Borneoceras* sp. 7, Reineckeiidae gen. et sp. indet.**

2) biplicate with intercalatory ribs; points of division near the umbilical margin or at the umbilical third of the whorl side; a little tubercle may exist near the umbilical margin.

3) ribbing more irregular with biplicate ribs and intercalatory ribs, rarely triplicate; points of division between the umbilical margin and the ventral third of the whorl side. Some ribs with a fine tubercle within the umbilical third of the whorl side.

On the venter, the ribs are interrupted by a smooth band and stand opposite. With or ?without constrictions on inner whorls, no parabolae.

Remarks. *Kalimantanites* is differentiated from other Reineckeiidae by its smaller umbilical width and the ornamentation of the outer whorls. The innermost whorls and the ventral side have distinct similarities to the other Reineckeiidae.

K. nodosospinatus shows some similarity with *Himalayites*, but in this genus the spines lie higher on the whorl side, the ventral ribs are not so numerous, the ventral interruption of ribs is not so pronounced, and the inner whorls have a rather perisphinctoid style of ribbing.

The outer whorl of *Spiticeras acutum* Gerth (1925, 63; pl. 3, fig. 1; text-fig. 2) with strong tubercles near the umbilical margin also shows some similarity with *K. nodosospinatus* but there are no intercalated ribs with or without fine tubercles, and a ventral interruption of ribbing is absent. The ornamentation of inner whorls is of rather perisphinctoid style.

Aulacosphinctids are differentiated by a more regular style of ribbing, and the absence of strong spines and ribs with or without fine tubercles.

Kalimantanites nodosospinatus nov. sp.
Pl. 2, figs 1, 2

Material. 3 specimens (83 P 16 A, 83 P 16 F, 83 P 16 L).

Holotype. Specimen 83 P 16 A (pl. 2, fig. 1).

Stratum typicum. Callovian.

Type locality. Fossil locality on the road from Kembajan to Tangjung, 17 km south of Kembajan.

Name. From the Latin *nodosus* noded, and *spinatus* spiny, named for the strong spines and fine tubercles on the ribs.

Diagnosis. A species of *Kalimantanites* with spines on some points of division in some stages of growth.

Dimensions. Holotype

d	uw	wh	p	p/2	s
90	32	41			40
63	30	40	16	9	34
40			18	9	42
25			21	11	30

Description. All specimens are crushed, septal suture and whorl section are not preserved. The ribbing of the innermost whorls (up to ~25 mm diameter) of the holotype (maximum diameter 105 mm) is relatively fine with prorsiradiate, biplicate and triplicate ribs, dividing at approximately the middle of the whorl side; some intercalatory ribs are present. At the point of division a fine, pointed tubercle exists. On the succeeding whorl, some of the ribs have strong spines at the umbilical margin. From the spines, 3 to 5 secondary ribs originate; some intercalatory ribs exist. Between these ribs are two concave, biplicate ribs with intercalatory ribs, dividing first at the level of the strong spines, then somewhat higher. On some of these ribs, fine tubercles exist in the level of the spines.

The ornamentation of the outer whorl — so far as it is recognisable — is similar to that of the preceding whorl, but blunter. On inner whorls, flat and broad constrictions exist.

Specimen 83 P 16 F (Pl. 2, fig. 2) differs from the holotype because the ribs between 30 mm and 45 mm diameter divide at about the middle of the whorl side, and some have a fine tubercle near the umbilical margin, but no spines. Then ribs with strong spines are present. At the end of the last whorl long, pointed spines are developed at the umbilical margin.

Specimen 83 P 16 L is poorly preserved, but shows some features of the species.

Kalimantanites occultenodosus nov. sp.
Pl. 1, figs 6—8

Material. 4 specimens, all fragmentary (83 P 16 G, 83 P 16 N, 83 P 16 R, 83 P 16 T).

Holotype. Specimen 83 P 16 G (Pl. 1, fig. 7).

Stratum typicum. Callovian.

Type locality. Fossil locality on the road from Kembajan to Tangjung, 17 km south of Kembajan.

Name. From the Latin *occultus* concealed, *nodosus* noded, after the fine, inconspicuous tubercles on some ribs within the umbilical third of the whorl side.

Diagnosis. A species of *Kalimantanites* with a perisphinctoid style of ribbing on the outer whorls, and fine tubercles on some ribs within the umbilical third of the whorl side.

Remarks. *Kalimantanites occultenodosus* differs from *K. nodosospinatus* by the absence of strong spines near the umbilical margin, and the more irregular, perisphinctoid ribbing of the outer whorls.

Description. The specimens are crushed and fragmentary. Septal suture and whorl section are not preserved. The innermost whorls (up to 20 mm diameter) show fasciculate ribs with 2—4 secondary ribs, and some intercalatory ribs. Tubercles are not recognisable. The points of dividing are located at the umbilical third of the whorl side. Toward the aperture, the points of dividing are mostly located at approximately the middle of the whorl side, some at the umbilical third of the whorl side. The ribs are biplicate with intercalatory ribs. On some ribs, little tubercles are recognisable within the umbilical third of the whorl side. On the outer whorl (holotype, ~75 mm diameter), the ribbing is irregular; ribs are mostly biplicate, rarely triplicate, with 1 or 2 intercalatory ribs. The points of dividing are located between the umbilical margin and the ventral third of the whorl side, mostly about the middle of the whorl side. On some ribs, a fine tubercle near the umbilical margin is recognisable. Constrictions and parabolae are not recognisable.

Family Perisphinctidae Steinmann, 1890

Subfamily ?Pseudoperisphinctinae Schindewolf, 1925

Genus *Borneoceras* nov. gen.

Type species. *Borneoceras sanggauense* nov. sp.

Name. Named after the island of Borneo.

Diagnosis. Moderately evolute perisphinctids with a slender, highly ovate whorl section. Ribbing somewhat irregular with prorsiradiate, mostly biplicate, sometimes triplicate or polygyrate or simple ribs, with intercalatory ribs. Points of dividing between the umbilical and ventral third of the whorl side, mostly somewhat ventral of the middle of the whorl side. Ribs interrupted on venter. Ventral ribs more prorsiradiate as primary ribs, standing opposite and forming an obtuse angle. Constrictions recognisable only on inner whorls, no parabolae.

Remarks. *Borneoceras* is grouped into the ?Pseudoperisphinctinae on account of the irregular ribbing without recognisable tubercles and the perisphinctoid inner whorls. However, there remain some doubts about this classification because of the character of the ventral side of the outer whorl, which is rather different from all other known Pseudoperisphinctinae.

An Iranian specimen, identified as Reineckeiidae gen. et sp. indet. (Pl. 2, fig. 7) shows some similarity in division of ribs on the outer whorl, but it has tubercles at the points of dividing.

Binatisphinctes, which shows some similarity in ribbing, has rursiradiate ventral ribs. *Epimorphoceras* has a more regular ribbing and no projected ventral ribs.

Certain Idoceratinae (Burckhardt, 1906, 1912; Ziegler, 1959, pl. 1, fig. 6) sometimes have similar ribbing, but the interruption of ribbing on the venter is not as clearly developed as in *Borneoceras*; some ribs are not interrupted, and some are only weakened; if the ribs are interrupted, they often alternate. Normally the Idoceratinae have constrictions in all stages of growth.

There are some similarities in ribbing with *Sivajiceras* and *Kinkeliniceras*, but the ventral ribs are not projected and interrupted.

Parkinsoniinae frequently have tubercules on the point of splitting in some or all stages of growth, and alternating ventral ribs. *Parkinsonia calloviensis* Loczy (1915, 379; pl. 16, fig. 11; pl. 18, fig. 11) should be mentioned because it shows some similarity with *Borneoceras sanggauense*. However, due to the indistinct figures, its systematic position is equivocal.

Borneoceras sanggauense nov. sp.

Pl. 2, figs 4, 5; Pl. 3, figs 1, 3

Material. 7 specimens (83 P 16 B, 83 P 16 C/1-4, 83 P 16 D, 83 P 16 M).

Holotype. Specimen 83 P 16 B (pl. 3, fig. 3).

Stratum typicum. Callovian. Sample 83 P 16 C is found with *H.* (*L.*) *brightii* (Pl. 1, fig. 2) and *H.* (*P.*) aff. *punctatum* (Pl. 1, fig. 3).

Type locality. On the road from Kembajan to Tangjung, 17 km south of Kembajan.

Name. Named after the village of Sanggau, West Kalimantan (Kalimantan Barat), 40 km southeast of the fossil locality.

Diagnosis. A species of *Borneoceras* with gently curved ribs, and a broad ventral band.

Dimensions.

	d	uw	wh	p	p/2	s
83 P 16 B	100	38	37	26	12	28
holotype	80			30	13	42
maximum diameter 105 mm						
83 P 16 C/1	80	38	34	32	17	
	65	37	35		19	30
	50				18	32
maximum diameter 80 mm						
83 P 16 C/2	45	36	38			
	37				17	24
	33				17	20
maximum diameter ~55 mm						

Description. The species is moderately evolute. The whorl section of inner whorls is circular, that of outer whorls highly ovate with convex whorl sides convergent towards the domed, narrow venter. The umbilical margin is rounded, the umbilical wall moderately steep.

The innermost whorls appear to be smooth. The next whorls are densely ribbed with simple and biplicate ribs. The number of biplicate ribs increases toward the aperture. Some intercalatory ribs are recognisable. The points of dividing lie at about the middle of the whorl side. Narrow and shallow constrictions are recognisable, but no parabolae.

The outer whorl contains straight to moderately concave, prorsiradiate primary ribs; their initiation on the umbilical wall is rursiradiate. The ribs are mostly biplicate, rarely simple, triplicate or polygyrate; there may be 1 or 2 intercalatory ribs. The points of dividing lie between the umbilical and ventral third of the whorl side, mostly at approximately the middle of the whorl side. The ventral ribs are more prorsiradiate as the primary ribs. Constrictions and parabolae are not recognisable.

On the venter, ribbing is interrupted by a broad band. The ventral ribs form an obtuse angle and stand opposite.

Remarks. The ribbing of the outer whorl is somewhat similar to some *Collotia*, but the tubercles of the Reineckeiidae are absent, and the ventral ribs are more projected.

A fragment of an ammonite of the upper Dalichai Formation (Callovian) east of Kuhe-Sharaf, E Semnan, Alborz, Iran (cf. Seyed-Emami & others, 1989) closely corresponds to the specimens from Kalimantan. However it differs by having stronger ribbing, more frequent polygyrate ribs, and a narrower ventral band (Pl. 2, fig. 6).

Subfamily Pseudoperisphinctinae Schindewolf, 1925

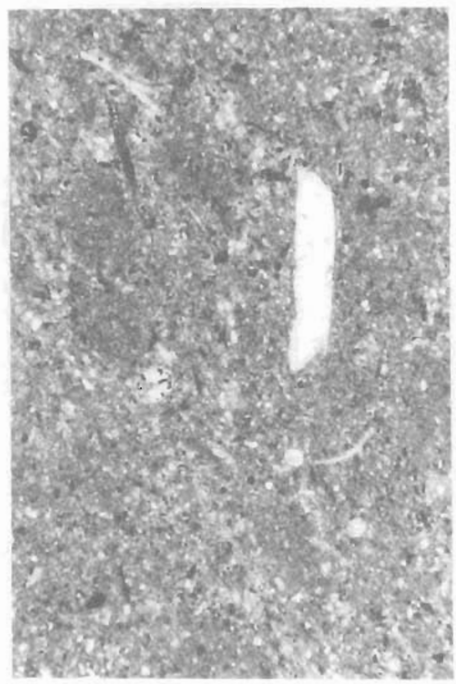
Indosphinctes sp.

Pl. 2, fig. 3

Material. 1 specimen (83 P 16 H), a fragment of two whorls.

Description. The specimen is somewhat crushed and has an irregular, slightly flexuous, mostly biplicate ribbing with intercalatory ribs. The points of dividing lie somewhat ventrally of the middle of the whorl side. The intercalatory ribs vary in length, and are simple or biplicate. A former peristome with fine, biconcave growth lines is recognisable at the beginning of the last whorl.

1



2

3

Plate 3.

All specimens from the Callovian from West Kalimantan. All specimens x1 unless otherwise indicated.

1-3, *Borneoceras sanggauense* nov. gen., nov. sp. 1, 83 P 16 C/2, paratype. 2, Thin section, 83 P 16 BB, x30. **3,** 83 P 16 B, holotype.

Distribution. The genus *Indosphinctes* is found from the Lower Callovian to the lower Middle Callovian (Mangold, 1970: 86; fig. 160; Cox, 1988: 22).

Conclusions

Finds of Triassic, Jurassic (Sinemurian, Toarcian, Tithonian) and Cretaceous ammonites are rare on Borneo (Sato, 1975; Sato & Ishibashi, 1984). Therefore, additional ammonite material is of particular interest. It is of great importance that the new ammonite material of West Kalimantan is of Middle Jurassic (Callovian) age. Although the material is not stratified, the occurrence of *Hecticoceras* (three species have an almost worldwide distribution; the new species has close affinities to European species), *Reineckeia* s.l. (a comparable form exists in Europe), and *Indosphinctes* sp. supports this age determination. There are two further lines of evidence:

1) A specimen from Mindoro, the Philippines, figured by Andal & others (1968: pl. 28, fig. 5) as *Hecticoceras (Lunuloceras)* cf. *lunula* (Reinecke), is very similar to *H. (L.) lunuloides* from West Kalimantan.

2) A specimen from Kuhe-Sharaf, E Semnan, Alborz, Iran, identified as *Borneoceras* sp. (Pl. 2, fig. 6) is similar to *Borneoceras sanggauense*. This specimen was found together with an ammonite faunula of Middle to lower Upper Callovian age (cf. Seyed-Emami & others, 1989, fig. 3, no. 5). Preliminary determinations revealed the following species:

Sowerbyceras tietzei Till
Hecticoceras (Lunuloceras) aff. *lunuloides* (Kilian)
orbignyi Tsytovitch
(Brightia) aff. *solinophorum* (Bonarelli)
(Putealiceras) aff. *inaequifurcatum* Zeiss
(Putealiceras) aff. *lugeoni* Tsytovitch
Rehmannia (Loczyceras) aff. *discrepans* (Bourquin)
Reineckeia (Reineckeia) aff. *nodosa* Till
Reineckeiidae gen. et sp. indet. (Pl. 2, fig. 7)
Indosphinctes (Indosphinctes) aff. *pseudopatina* (Parona & Bonarelli)
Borneoceras sp. (Pl. 2, fig. 6)
Pseudopeltoceras sp. ex gr. *P. leckenbyi* Spath

This ammonite faunula is described by Schairer & others (1991).

Although a great part of the ammonite assemblage from West Kalimantan was unknown, this analysis appears to justify its inclusion in the Callovian. Based on the occurrence of *H. (L.) brightii*, *H. (L.) lunuloides*, *H. (P.)* aff. *punctatum*, and *Indosphinctes* sp., as well as comparison with the Iranian ammonite faunula, a Middle to lower Upper Callovian age is presumed.

Acknowledgements

Peter Pieters, AGSO, contributed to the location and geological setting of the Introduction. The material studied was shown to one of the authors (A. Zeiss) by T. Sato during the 3rd International Field Meeting of the Circumpacific Jurassic Research Group in Tsukuba, Japan. The offer to work on this material was accepted and a joint research project was planned with the co-author (G. Schairer). All material was lent to the authors. The strange looking fauna exhibits many endemic elements, which made work on this ammonite fauna very difficult and time consuming. Fortunately, K. Seyed-Emami, Tehran, Iran, placed a partly similar ammonite fauna of undisputed Callovian age at our disposal (Schairer & others, 1991), which negated any lingering doubts about the age of the fauna from West Kalimantan. This was also confirmed by considerable preparative work by one of the authors (G. Schairer), which resulted in a substantial additional collection of small but biostratigraphically diagnostic Callovian ammonites.

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BMR Journal of Australian Geology & Geophysics, 13, 237 – 250

Aspects of the structural histories of the tertiary sedimentary basins of East, Central and West Kalimantan and their margins

H.F. Doutch[1]

The Cainozoic structural history of west, central and east Kalimantan may have begun with formation of melange in the early Eocene, and a surrounding disturbed zone in which part of a mainly Cretaceous flysch trough and associated shelf deposits have been thrown into a confusion of dips and strikes. Uplift of the disturbed zone and adjacent southern outer shelf deposits of the trough was followed by sub-aerial extrusion of mid Eocene volcanics. Between early late Eocene and mid Oligocene times bursts of compression produced structural highs and a shifting pattern ofcomplementary flanking basin depocentres. Uplifted flysch-trough sediments became a northern provenance for the basins (and perhaps a southern provenance for more flysch deposition to the north) and may have been folded further in the process. In the south the Schwaner Batholith provided a bulwark to compression, although its northern margin was upwarped as a consequence. In the east deposits prograded southeastwards away from the northern provenance. As compression tailed off and basin downwarping and northern flysch provenance uplift consequently diminished, a peneplane may have begun to form on the flysch. This would have gradually decreased the amount of detritus available for filling the gradually shallowing basins. In the west downwarping and deposition probably ceased in the early Oligocene as a result of regional uplift. In the east renewed compression in the mid Oligocene caused uplift and folding, and interrupted prograding deposition. Penecontemporaneous intrusion of acid to intermediate stocks, plugs, dykes and sills occurred in both east and west. Prograding deposition recommenced in the east in the late Oligocene and has continued intermittently since; the northwestern provenance for the deposits has been uplifted from time to time, on occasion in conjunction with volcanism. The flysch fold belt that is central to the island of Borneo, on the evidence from the region analysed, was bent to its present shape in mid to late Tertiary times.

Introduction

This paper is based on Kalimantan Data Records completed by the Indonesia-Australia Geological Mapping Project (IAGMP), to some of which the author contributed, and the Geological map of the West, Central and East Kalimantan area (Pieters & Supriatna, 1990), which the author edited.

The IAGMP Data Records, which are Open File Reports of Indonesia's Geological Research and Development Centre (GRDC), accompany IAGMP's 1:250 000 scale preliminary geological maps. The Geological Map, at a scale of 1:1 000 000, differs in minor respects from the records; some of the differences are noted below. The area covered by the IAGMP map and records and this paper is shown on Figure 1. The generalised geology of the area is shown on Figure 2, and its structural domains in Figure 3. The paper concerns structural effects in the crust of the area, but deliberately essays few conclusions about tectonic causes.

The patterns of dips and strikes on the 1:250 000 scale IAGMP preliminary geological maps in the Data Records reflect difficult field conditions. Limited additional information can be got about deformed basin basement from imagery, which however supplies a great deal about basin bedding trends and dips, folding, and faulting. Basin dips are mostly shallow, occasionally horizontal or moderately steep, folds are open, and faults mainly normal.

General geology

Data Record and 1:1 000 000 map information show that the domains of the region are strung out in an arc that trends northwest in the west, west-northwest in the centre, and northeast in the east of the region (Figs 2, 3).

Cretaceous sediments occur throughout. Tightly folded and mildly metamorphosed probable deep-water flysch in the north is separated from less deformed and partly older outer shelf deposits in the south by a disturbed zone in which both occur in a confusion of strikes and dips, together with much undated melange. Some of the flysch deposits can be as young as early or mid Eocene. A few early and late Cretaceous granitoids intrude these rocks.

In the centre and east of the area there are sparse and scattered middle Eocene sub-aerial acid volcanics, and late Eocene to mid Oligocene sedimentary basins containing shallow marine and continental deposits, all overlying outer shelf and disturbed zone rocks. The volcanics and sedimentary basin sequences are only mildly deformed overall.

In mid to late Tertiary times most of the area was intruded by stocks, plugs, dykes and sills of granodiorite, diorite, dacite and andesite; in the northeast and northwest this igneous suite is overlapped in age and space by late Tertiary to Quaternary basaltic volcanics and much-dissected volcanoes.

A small cluster of Permo-Triassic inliers indicates a pre-flysch history of critical tectonic importance, but the structural implications of the occurrence of these basement(?) rocks as inliers are unclear.

Structural histories of the basins and their margins

The present-day basins that contain Late Eocene to Holocene deposits are structural basins that began as a shallow marine feature in the late Eocene. Later, they were separated by structural highs now represented by basement inliers.

Basins and their inliers are discussed below as elements of one domain. Adjoining domains consist mainly of pre-Eocene rocks with less clear Cainozoic histories, and these are accordingly given shorter shrift.

Domain of basins and inliers

The domain consists of the westerly trending Semitau High, the Juloi and Kembayan Inliers, the Busang-Murung Crescent, the Melawi, Ketungau, Mandai, West and Southeast Kutai Basins, and the Putussibau Depression. The Juloi Inlier is a term proposed here for a complex upwarp exposing Cretaceous outer shelf deposits between the Busang-Murung Crescent and the Schwaner Massif, and separating the Melawi and West Kutai Basins (see Figs 2 & 3).

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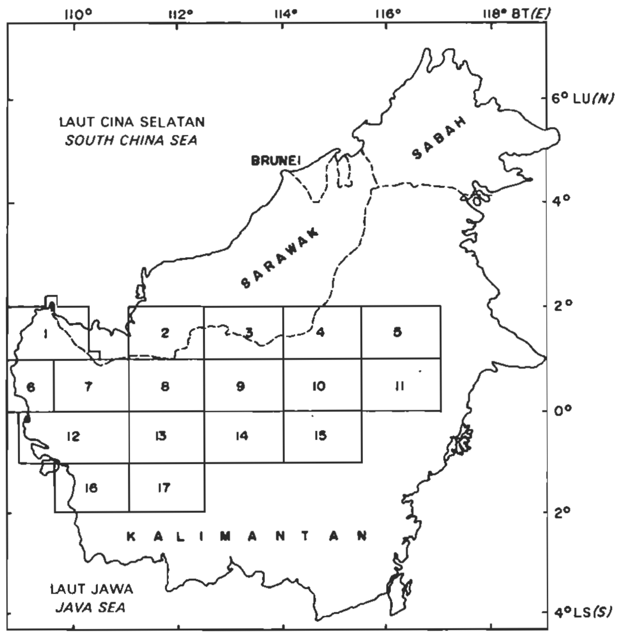
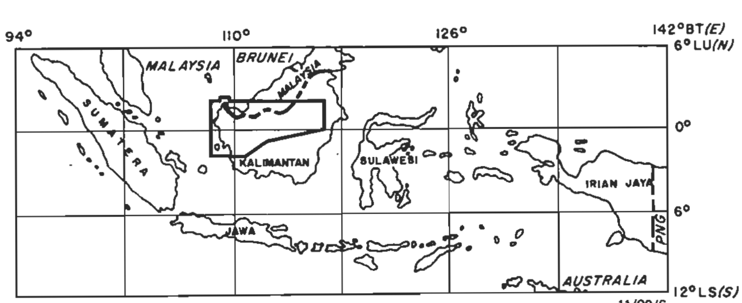


INDEKS LEMBAR PETA GEOLOGI SEKALA 1:250 000 YANG TERCAKUP DALAM PETA INI
INDEX OF GEOLOGICAL QUADRANGLES AT 1:250 000 SCALE COVERED BY MAP AREA

	Nama lembar *Quadrangles*	Penyusun *Authors*
1	Sambas & Siluas	E. Rusmana & P.E. Pieters (1989)
2	Nanga Obat	Y. Noya, P.E. Pieters & Surono (1989)
3	Peg. Kapuas	Surono, P.E. Pieters & Y. Noya (1989)
4	Long Nawan	Baharuddin, P.E. Pieters, D. Sudana & S.A. Mangga (1989)
5	Muara Wahau	S. Supriatna (in prep.)
6	Singkawang	N. Suwarna & R.P. Langford (1989)
7	Sanggau	S. Supriatna, U. Margono, P.E. Pieters, Sutrisno & R.P. Langford (1989)
8	Sintang	P.R. Williams & R. Heryanto (1985)
9	Putussibau	P.E. Pieters, Surono & Y. Noya (1988)
10	Long Pahangai	H.Z. Abidin, P.E. Pieters & D. Sudana (1989)
11	Muara Ancalung	S. Atmawinata & N. Ratman (in prep.)
12	Nangataman & Pontianak	P. Sanyoto & P.E. Pieters (1987)
13	Nangapinoh	Amiruddin & D.S. Trail (1987)
14	Tumbanghiram	T. Soejitno & T. Santosa (1986)
15	Muaratewe	A. Sudradjat & O. Koswanda (1977)
16	Ketapang	E. Rustandi & F. de Keyser (1988)
17	Tumbangmanjul	T. Soejitno & T. Santosa (1986)



LOKASI PETA/*MAP LOCATION*

Figure 1. Location of quadrangles and 1:1 000 000 scale geological map (after diagrams on 1:1 000 000 map).

The Melawi Basin is buttressed to its south by the Schwaner Batholith domain; to its north the basin has a folded relationship (the Silat Fold Belt of Williams & Heryanto, 1986) with the southern part of the Semitau High, perhaps the result of basin margin crumpling by High uplift.

The Ketungau Basin is downfaulted along most of its southern margin, essentially against melange of the disturbed zone in the northern part of the High. In the northeast this basin is faulted against early Eocene Lubok Antu Melange (Tan 1979, 1982), here treated as part of the disturbed zone, and to the north is flanked by alluvia (in Sarawak).

The Mandai Basin is probably an eastern continuation of the Ketungau Basin, being separated from it by the Quaternary Putussibau Depression. The Mandai is complexly faulted in the south against the Semitau High, but at the same time appears to be joined to the Melawi Basin. To the north and east, Mandai Basin strata rest unconformably on disturbed zone rocks of the Fold Belt domain.

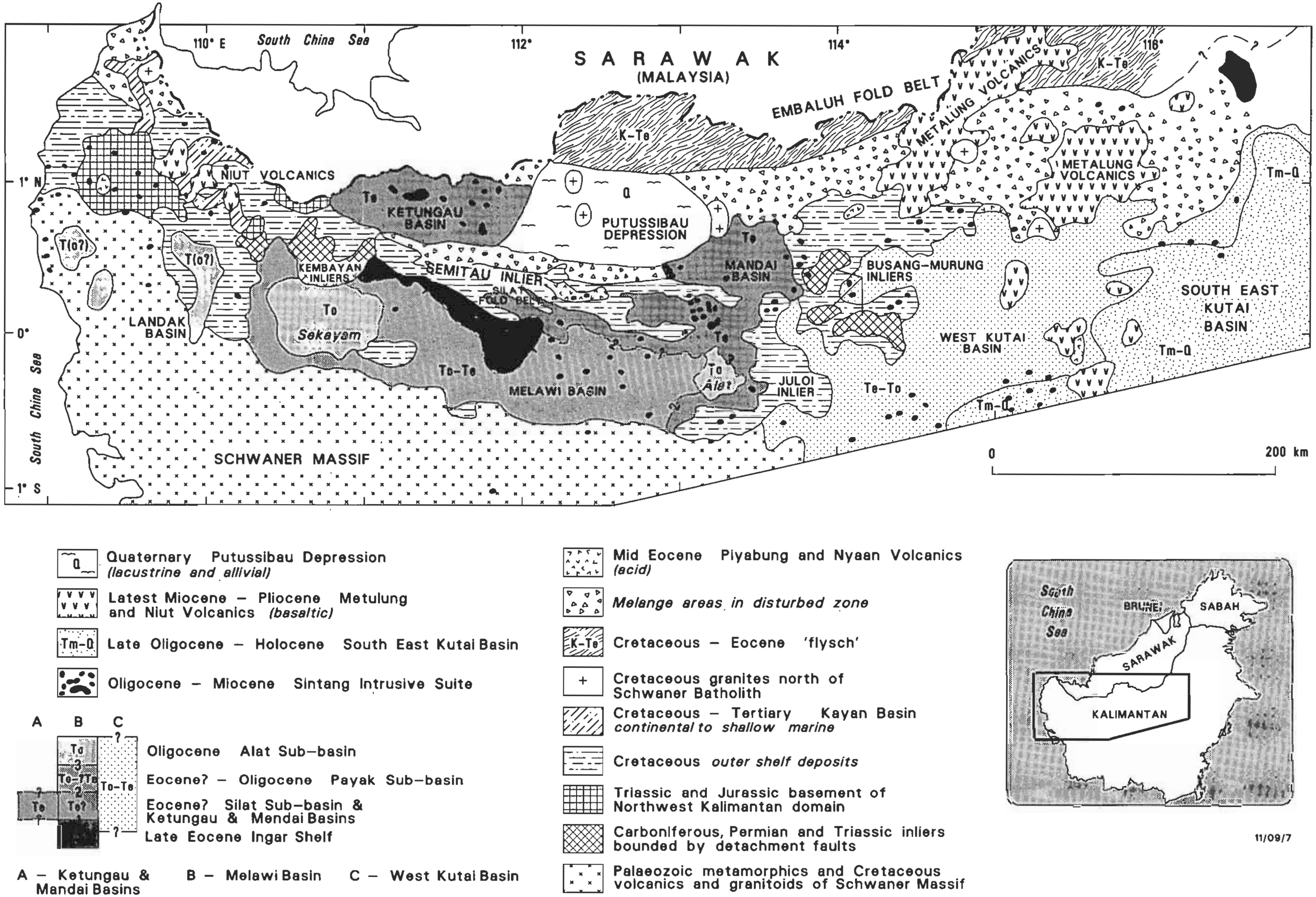


Figure 2. Generalised geology, IAGMP area, Kalimantan.

To the east of the High and its flanking basins, more particularly to the east of the Juloi High and the Busang-Murung Crescent, the West and South East Kutai Basins would seem to contain deposits derived from the Fold Belt domain; from their inception the deposits have been prograding seawards.

The Semitau High is given the appearance by its bounding structures and cover dips of a fault block tilted to the north. Outcrops of the High — which make up the Semitau Inlier — consist of large northwestern areas of disturbed zone melange faulted against southeastern areas of a deeper marine facies of the outer shelf Cretaceous sediments. Both formations are overlain in the east by radiometrically dated middle Eocene felsic to intermediate Piyabung Volcanics. To the north of the volcanics a few small bodies of fault-bounded Permo-Triassic rocks are surrounded by melange, of which they may be part.

The Semitau High terminates in the west against, or with, the Kembayan Inlier (Supriatna & others, 1989), a group of Carboniferous to Triassic inliers of similar area to those of the High's eastern terminator, the Busang-Murung Crescent. Carboniferous-Permian rocks of the Kembayan Inlier are cut by thrust faults. The Permo-Triassic components of both the Kembayan Inlier and the Busang-Murung Crescent are shown on the 1:1 000 000 map bounded by detachment faults (not mentioned in the Sanggau Data Record). Both types of fault are thought to be of late Tertiary age. There is a possibility that both the Kembayan and the Busang-Murung inliers are huge blocks within melange (D. Trail, AGSO, pers. comm. 1988).

The Sintang Intrusives Suite, superimposed in late Oligocene and Miocene times on all the structural basins and inliers, is referred to here as an igneous domain. The strings and groups of plugs and stocks have a rough alignment with the structural grain of the area, but give a stronger impression of structural control in the east.

Late Tertiary-Quaternary basalts of the Metulang Volcanics domain overlie the West and South East Kutai Basins, seemingly concordant with their structural trends; similar Niut Volcanics occur in the Northwest Kalimantan domain.

The Quaternary Putussibau Depression that separates the Mandai and Ketungau Basins contains lacustrine and alluvial deposits.

The east-southeasterly trends that dominate the Semitau High and Melawi Basins are said by Amiruddin & Trail (1989) to be controlled by pre-Cretaceous structure. Williams & Heryanto (1986) note the east-northeast faults that cut across this trend, affecting the youngest rocks of the Melawi Basin. Northeast trends dominate the West Kutai Basin.

Late Eocene to Early Oligocene basin formation

The deep sediment-filled depressions separated by the Semitau High are the present day structural Melawi, Mandai and Ketungau Basins. The most complex of them is the Melawi, with which correlation of the other two is a critical and fundamental matter. Published stratigraphic correlations depend on a few sparse fossil occurrences and perforce on lithological similarity — the Data Records and the 1:1 000 000 map Explanatory Notes are a good starting point for the details. This paper attempts to show *inter alia* that structural history can provide additional help with correlating, and that its constraints should be applied before resorting to lithological correlations. For this reason the structural history of the Semitau High is considered below in conjunction with that of the Melawi Basin before the other basins are examined.

Partial or comprehensive correlation proposals covering the Ketungau and Mandai Basins and the Melawi Basin succession include those of Williams & Heryanto (1986), Pieters & others (1987), Williams & others (1988), Pieters & Supriatna (1989) and Tate (1991). The unconformities of the Melawi Basin and the evolution of the Semitau High play minor parts, if any, in these proposals, and none of their correlations are wholly espoused here.

Unconformities and sub-basins

Unconformities can be regarded as surfaces bounding and in part defining sedimentary basins. Thus the mid Eocene to possibly early Oligocene surfaces south of the Semitau High could be said to separate and/or lead to the recognition of four basins. It is useful to see the four as sub-basins constituting the present day structural feature called the Melawi Basin; for example, the southwards migration of its depocentres can helpfully be related to sub-basin evolution. The present day structural Ketungau and Mandai Basins have no known internal unconformities, and so lack sub-basins of this kind. This paper's investigation of the histories of basin and sub-basin evolution and relationships leans towards this point of view.

This unconformity dominated concept has been touched on by Williams & Heryanto (1986) in defining their version of the Melawi Basin, which was the sequence between its second and third unconformities, their Melawi Group, a name retained by later workers (although revised by Pieters & Supriatna, 1989, 1990). The concept has been parallelled already in this paper in distinguishing between the West and South East Kutai Basins.

One might reasonably expect that the sequences between the unconformities should be regionally internally conformable and structurally homogeneous and that, for a best understanding of geological history, formal stratigraphic units will not transgress or include such basin-bounding and basin-defining surfaces. The 'Melawi Basin' of Williams & Heryanto (1986), and its sequence, conform to these criteria, but this is not always the case.

For example, in Pieters & Supriatna (1989), the formal stratigraphy of the present day Melawi structural Basin is completely covered by a basal Suwang Group (a term which they also apply to all the strata of the Mandai Basin) and an overlying Melawi Group. Both Groups contain an unconformity, neither of which is represented on their map. The structural and tectonic implications of the three unconformities and the four structurally contrasting sequences that they separate are thus somewhat obscured.

Melawi Basin Sub-basins

A history of the composite structural depression that is now called the Melawi Basin, which is confined between the Semitau High and the Schwaner Batholith domain, is presented below. Formation thickness figures are from Pieters & Supriatna (1989).

Ingar Shelf. The oldest of the Melawi's sub-basins is now represented by 1800—3000 m or more of fossiliferous upper Eocene shelf deposits (see Table 1), the Ingar Formation and its equivalent in the eastern part of the basin, the Mentemoi Formation (Pieters & others, 1987). Williams & Heryanto (1986) record boudinage, fracturing and cleavage in the Ingar Formation.

In Nangapinoh and Putussibau quadrangles Amiruddin & Trail (1989) and Surono & Noya (1989) have named an underlying unit the 'Haloq Sandstone' (see below). Examination of the IAGMP 1:250 000 scale preliminary maps suggests that this underlying unfossiliferous unit may not correlate with the West Kutai Basin

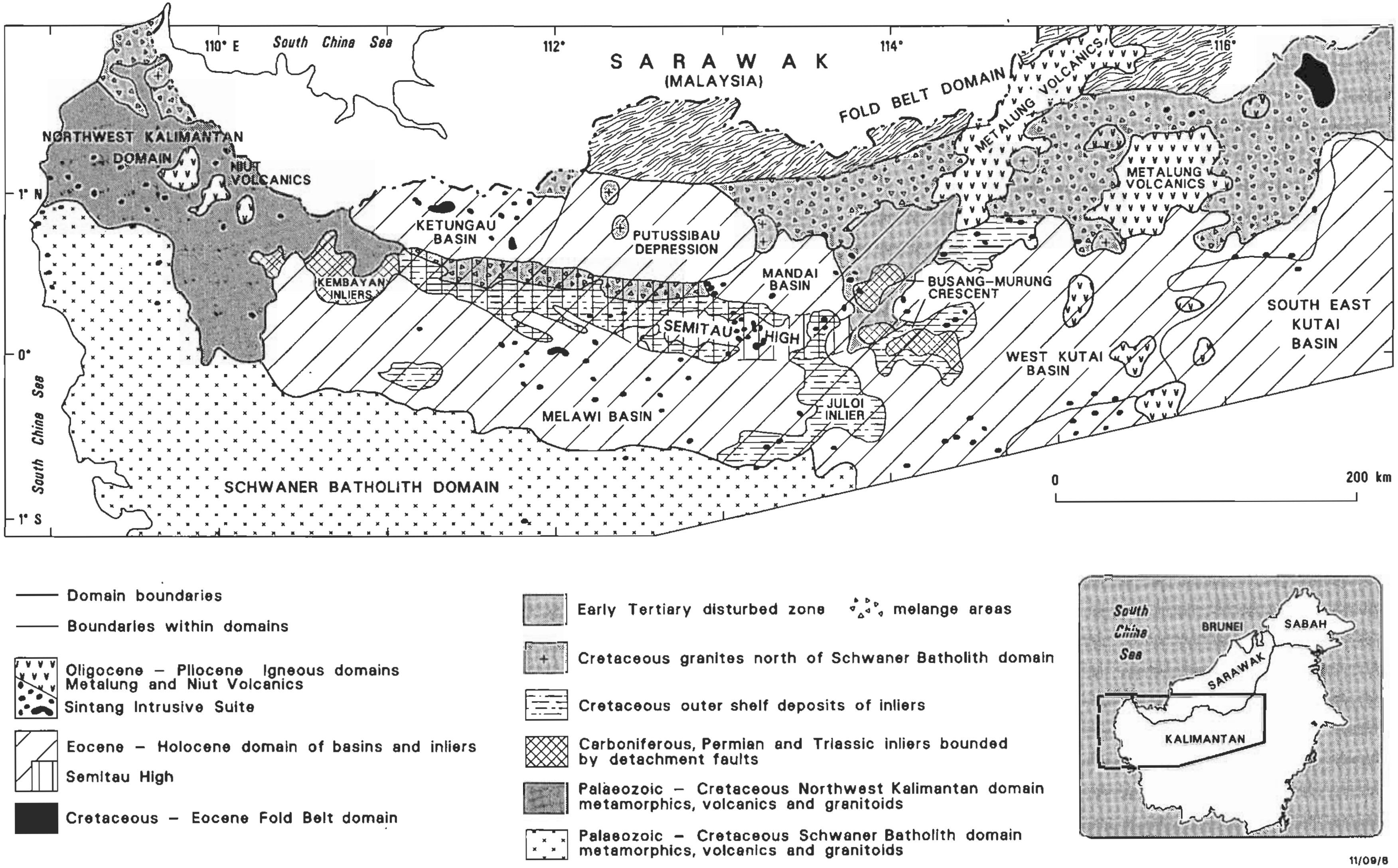


Figure 3. Structural domains, IAGMP area, Kalimantan.

fossiliferous upper Eocene Kiam Haloq Sandstone of Pieters & Supriatna (1989), and that its name could be misleading, at least in the context of a structural history analysis.

Further, Pieters & others (1987) mention a Mangan Sandstone underlying the Ingar in the Melawi Basin, and Pieters & Supriatna (1989) seem to place this at or near the base of their Suwang Group.

These units are truncated by an unconformity, and thus constitute a 'sub-basin', which is referred to in this paper as the Ingar Shelf (a possible misnomer — see later).

Silat Sub-basin. The Ingar Shelf was modified by the combination of rising of the Semitau High and downwarping to its south. In this new sub-basin at least 600 m of Dangkan Sandstone and 2000 m of Silat Shale accumulated conformably. Further uplift of the Semitau High probably caused formation of the Silat Fold Belt and ended deposition of the sequence. Williams & Heryanto (1986) noted slickensiding, shearing and large scale chevron folds in the Silat Shale. An unconformity later truncated the folded rocks and capped this second sub-basin. There is no evidence permitting direct dating of these events.

The Dangkan Sandstone and Silat Shale were combined as the Suwang Group by Williams & Heryanto (1986). It would seem appropriate, then, to speak of a Suwang Sub-basin, and Tate (1991, Table 1) shows this name on his correlation chart (albeit of Late Cretaceous age and related to a Melawi Basin of uncertain definition). However, Pieters & Supriatna (1989) included the Ingar Formation and Mangan Sandstone in the Suwang Group and applied the revised term to cover not only a Melawi Basin succession but also the complete Mandai Basin sequence. This renders erection of the name Suwang Sub-basin inadvisable, and in this paper the term Silat Sub-basin will be used.

Payak Sub-basin. The unconformity capping the Silat Sub-basin became the base of a third sub-basin as a result of downwarping. In it the Melawi Group of Williams & Heryanto (1986) was deposited. Up to 1200 m of Payak Formation and 800 m of Tebidah Formation are preserved, suggesting that compression was waning at this stage in the history of the Melawi Basin. It is uncertain whether an unconformity truncates the Tebidah — see Alat Sub-basin discussion below.

The Tebidah Formation may contain Early Oligocene nannoplankton (Dr G. Robinson, pers. comm., *in* Amiruddin & Trail, 1989).

Again, current usage of the term Melawi Basin, as well as the revision of the Melawi Group by Pieters & Supriatna (1989), precludes application of 'Melawi' as a name for the sub-basin, which is therefore referred to here as the Payak Sub-basin.

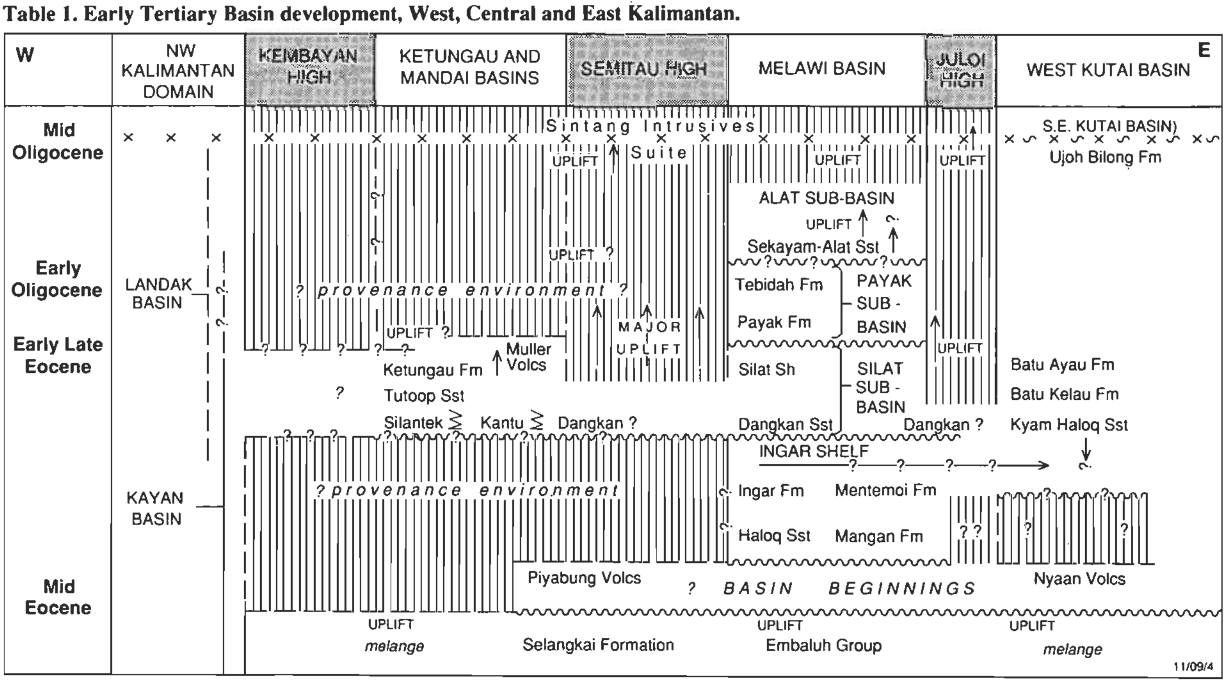
The 1:1 000 000 map shows an inlier of Jurassic—Cretaceous Kempari Sandstone (Pieters & Supriatna, 1990) in the south of the sub-basin; the inlier separates it into two lobes. It is not possible to choose between the alternatives of eastern and western depocentres and post-depositional uplift, although the latter seems unlikely.

Ingar Shelf and Silat Sub-basin units do not crop out between the Payak Sub-basin and the Schwaner Batholith domain, suggesting that the Payak depocentre migrated southwards. This situation is reflected on the 1:1 000 000 map, on which the Melawi Group is shown overlapping both the Suwang Group and the Schwaner Batholith domain.

In finer detail, within the Payak Sub-basin the Payak Formation crops out in the north and the Tebidah in the south. The Tebidah transgresses over the Schwaner, and presumably also over the Payak and older formations (Amiruddin & Trail, 1989). Overall, the maximum thickness of the sub-basin is in the north. From the point of view of structural history, this configuration may have resulted in part from the progressive weakening of a southwards migrating downwarp between the rising Silat Fold Belt (and Semitau High) in the north and the Schwaner Massif in the south during an episode of southwards compression.

Alat Sub-basin. The fourth and last of the preserved sub-basins of the Melawi structural Basin is here referred to as the Alat Sub-basin, as it contains the undated Alat Sandstone. This formation

Table 1. Early Tertiary Basin development, West, Central and East Kalimantan.



occurs only in the east of the Melawi Basin. It cannot be differentiated from the Melawi Group on the 1:1 000 000 map.

The Alat Sandstone is considered to lie unconformably on the Dangkan Sandstone and on Semitau High rocks by Williams & Heryanto (1986), and is up to 250 m thick. Amiruddin & Trail (1989) did not observe an unconformity between the Alat and Tebidah in Nangapinoh quadrangle, but suspected the presence of one because of the abrupt change to coarser Alat lithology.

In the west of the Melawi Basin, west of the Kempari Sandstone inlier, the undated Sekayam Sandstone is 500 m thick and is lithologically similar to the Alat Sandstone. The Sanggau 1: 250 000 preliminary geological map (Supriatna & others, 1989) shows open shallow folding of the Sekayam.

The Sekayam Sandstone also overlies the Tebidah Formation, unconformably according to Williams & Heryanto (1986), who exclude it from their Melawi Group, and to Supriatna & others (1989), but conformably according to Pieters & others (1987). It cannot be differentiated from the Melawi Group on the 1: 1 000 000 map. The two formations are named on Figure 2.

The coarse lithology of the Sekayam Sandstone is said by Supriatna & others (1989) to indicate 'regional uplift', and that of the Alat by Amiruddin & Trail (1989) to suggest 'topographic rejuvenation'. The change to coarse lithologies, and the claims of local unconformities, suggest that recognition of an Alat Sub-basin is possible on stratotectonic grounds. Further, although there is uncertainty about widespread unconformity below the two sandstone units, it seems useful to separate them from preceding Melawi Basin history by a conceptual device such as sub-basin, and to exclude them from any past or future combination with older units in formal stratigraphic Groups.

The Alat and Sekayam Sandstones are the youngest strata preserved in the Melawi Basin succession. Still younger units may have accumulated, but the uplift event that the Alat and Sekayam seem to reflect could well have ended sedimentation in the Basin and initiated its erosion. The thinness and limited distribution of the units may indicate that uplift of the sub-basin began during their deposition, possibly Oligocene—Miocene uplift associated with emplacement of the Sintang Intrusives Suite.

The Alat episode appears to herald the end of compressive tectonics in the west of the region.

Generation of the Semitau High

On the 1:1 000 000 map the Semitau High has the appearance of a horst. It also shows up as a high on gravity maps in later Data Records. The youngest rocks affected by the faults that bound it are shown as upper Eocene on the map. However, unconformities and folding in the Melawi Basin south of the High permit closer analysis. Their implications for Semitau High generation further illuminate the history of the Melawi Basin and also provide information relevant to the formation of the Mandi and Ketungau Basins.

Beginnings. The truncation of the upper Eocene Ingar Formation is the first evidence that may point to the beginnings of the Semitau High. No rocks of the Ingar or underlying units appear to have been derived from the melange of the High (or any other area) or its middle Eocene Pyabung Volcanics, and the sedimentary sequence would appear to be a shelf deposit that could have overlain melange and volcanics before uplift of the High.

However, the Kiam Haloq Sandstone of the West Kutai Basin (Pieters & Supriatna, 1989) contains tuff clasts and, as already discussed, may have an equivalent below the Ingar in the Melawi Basin. The West Kutai unit may have derived its volcaniclastics from the nearby mid Eocene Nyaan Volcanics as a result of the uplift associated with the unconformity capping the Ingar. After truncation of the Ingar, a new downwarp received the deposits of the Dangkan Sandstone and Silat Shale. The Dangkan Sandstone appears to have been partly derived from nearby highlands with melange exposures (Williams & Heryanto, 1986). Faulting of the Ingar against the outer shelf Cretaceous of the High suggests that these highlands were in place before the Dangkan was deposited as this faulting does not affect the Dangkan in the Sintang quadrangle, although the possibility of its presence farther east is raised later.

The highlands may have been either the southern margin of an early version of the Fold Belt domain, or part of a Semitau Inlier of the times, an expression of the horst High which had been shaped (possibly as a stillstand feature) by the fault-margined downwarps of the Silat Sub-basin to its south and the Mandai and Ketungau Basins to its north.

The Dangkan Sandstone and Silat Shale are unfossiliferous. They might share a lower Oligocene age with the Tebidah Formation of the overlying Payak Sub-basin, which would mean that the uplift of the Semitau High that truncated the Ingar Formation was an Oligocene event. Much depends on preferred correlations for the upper Eocene Muller Volcanics of the Mandai Basin to the north of the High (see below).

Relation to Silat Sub-basin termination. The second unconformity in the Melawi Basin truncates one of the two long, simple, asymmetrical, easterly plunging synclines, each with a core of Silat Shale, that make up part of the present boundary between the High and the Basin. The synclines, unnamed on the 1:1 000 000 map, constitute the Silat Fold Belt (Fig. 2) of Williams & Heryanto (1986), who suggest that folding was a response of the sedimentary deposits to faulting below them. Increasing sand content towards the top of the Silat Shale may indicate uplift of the High; the later synclinal folding may mark continuation of this uplift.

Williams & others (1984) see the Fold Belt as one of the products of approximately 20 km of southerly thrusting. The high angle reverse faults that bound the Semitau High support the idea. If the faults between the High and the Ketungau and Mandai Basins were active at the time, then at least some of the downwarping and deposition in these basins could correlate with Silat Fold Belt rocks and their histories.

The unconformity is likely to have begun forming during the uplift and folding episode. Although the 1:1 000 000 map does not show unconformities with a specific symbol, the unconformity above the syncline is identical to the geological boundary on the map that separates the Groups subsuming its Eocene and proposed Oligocene sequences (cf Williams & Heryanto, 1986; Pieters & Supriatna, 1989). This boundary is not an unconformity in the West Kutai Basin, where it represents a conformable relationship between the Groups of that basin.

This is the unconformity at the base of the Payak sub-Basin, in which the Tebidah Formation is said to contain Oligocene fossils. But Williams & Heryanto (1986) report that the Payak Formation contains much volcanic debris. A possible source for this is the upper Eocene Muller Volcanics in the Mandai Basin, to the north on the other side of the High.

There may have been, therefore, a more or less continuous series of events beginning with the uplift reflected in the sands of the Silat Shale, continuing with the folding of the Silat and Dangkan and the truncation of the folds, and finishing with penecontemporaneous basin sinking and volcanism. The events, apparently in the late Eocene, would have constituted the most vigorous episode in the generation of the High.

Later history. Following development of the second unconformity, all subsequent deposits in the Melawi Basin including the youngest of them, the Alat Sandstone, appear to have been derived in part from a melange provenance (Williams & Heryanto, 1986). This was presumably to the north of the basin, and was most likely the melange of the Semitau High. It suggests the persistence of a northern structural high, in part at least as an early version of the Semitau Inlier shedding into the basin.

Uplift (in the Oligocene?) evidenced by deposition of the Alat and Sekayam Sandstones in the Alat Sub-basin may also have affected the Ketungau and Mandai Basin sequences, which could have provided some of the detritus deposited as the Alat on the High and as the sub-basin units. The uplift may have been associated with, and ceased after, emplacement of the Oligocene—Miocene Sintang Intrusive Suite.

The Semitau High is not just a palaeo-structure, although its existence as a modern high may be a result of late Cainozoic renewal. Before this, a considerable amount of the top of the High and its cover must have been removed from initial uplift times onwards until Sintang Intrusive Suite bodies were emplaced in what was left, and a good deal more of the High host rock must have been removed since. After the uplift causing the mid Oligocene unconformity which truncated the West Kutai Basin, further uplift may have been necessary to permit the unroofing of the intrusives. The modern outcrop component of the High, the Semitau Inlier, and the remnants of basin cover over its eastern end probably reflect its modification by such recent movements, particularly regional uplifts that changed drainage patterns or rejuvenated them, for example around the Busang-Murung Crescent.

It is difficult to envision the Busang-Murung and Kembayan Inlier rocks as solely the structural result of uplift of the High. Both masses could have preceded formation of the Semitau High as part of the melange event that affected the Cretaceous to early Eocene flysch trough and shelf, after which the masses could have been uplifted further as integral parts of the High.

The uplift episodes responsible for production of the Juloi Inlier could perhaps be linked with uplifts of the Busang-Murung body. The first of these, given the differences between the Melawi Basin and West Kutai Basin successions, probably occurred at the time of first uplift of the High. But the northeasterly trend component of the Juloi and Busang-Murung may indicate that their structural culmination took place after that of the Semitau High. Detachment faulting is thought by Pieters & Supriatna (1989) to have taken place in late Oligocene—Miocene times.

The Sintang Intrusive Suite, although showing much concordance with local structural trends, is quite discordant with them in a number of places, e.g. the line of plugs crossing the Semitau High west of the Busang-Murung Crescent. Overall the Suite gives the appearance of stitching together the basins and inliers.

Summary of Melawi Basin and Semitau High structural history

Deposition of upper Eocene Ingar Shelf strata was over a downwarped land surface of folded Cretaceous to lower Eocene rocks and perhaps sparse occurrences of mid Eocene sub-aerial acid volcanics. Ingar deposition was terminated by late Eocene uplift and downwarping, which resulted in the formation of an erosional unconformity truncating the Shelf succession.

Silat Sub-basin sedimentation followed, associated with uplift of a northern provenance taken to be the progenitor of the Semitau High. Continuation of this uplift caused deformation of the northern margin of the sub-basin, faulting it and beginning the formation of the Silat Fold Belt. As the Fold Belt evolved, penecontemporaneous erosion truncated it and the rest of the sub-basin, suggesting yet more uplift of the High, and the Payak Sub-basin began its southwards migration. Older sub-basin deposits have a volcanic component possibly derived from late Eocene volcanism just north of the present Semitau High and marking the end of its most vigorous episode of generation. Younger sub-basin deposits were probably derived in part from the High and may be of Oligocene age. Uplift of the High, taken together with formation of the Silat Fold Belt and southerly migration of the Payak Sub-basin, suggests an episode of north to south compression beginning in the late Eocene and dying out in the Oligocene.

An unconformity may have truncated the Payak Sub-basin before deposition of Alat Sub-basin strata, the composition of which suggests provenance uplift. This may have been a widespread phenomenon which affected not only the Semitau High — including production of the detachment faulting at either end of it — but also basin deposits north of it, and which eventually terminated deposition in the Melawi Basin. The uplift was probably associated with emplacement of stabilising Sintang Intrusive Suite bodies in late Oligocene and Miocene times. Further regional uplift led to the unroofing of the intrusives.

Melawi, Mandai and Ketungau Basins

Relationships. Correlating the Melawi, Mandai and Ketungau Basins can most easily begin by examining the implications of the continuity of strata between the Melawi and Mandai Basins as shown on the 1:1 000 000 map and the Putussibau 1:250 000 preliminary geological map. The lowermost strata in the southern part of the Mandai Basin continues unconformably over the eastern end of the Semitau High into the Melawi Basin, where these strata conformably underlie beds that disappear below the ?unconformity flooring the Payak Sub-basin.

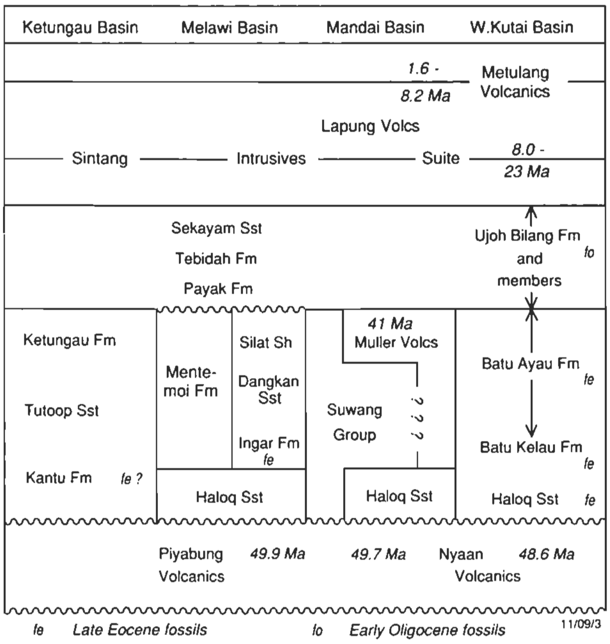
Melawi and Mandai Basins - 1:1 000 000 map correlations. On the 1:1 000 000 map the entire Mandai sequence is shown as Suwang Group, which extends into the Melawi Basin. In the terminology of this paper, the map correlates the Mandai Basin with the Ingar Shelf plus the Silat Sub-basin. Because there are no unconformities in the Mandai sequence and its timespan is uncertain, there have to be doubts about the correlation.

Inclusion of the Ingar Formation and Mangan Sandstone in the Suwang Group by Pieters & Supriatna (1989) raises the question of their possible equivalents in the Mandai. Unconformable overlap of Mandai strata on, as well as faulting of them against, the northern edge of the Semitau High is echoed by similar relationships between the Ingar and the southern edge of the High. The basal strata of the Ketungau Basin are also related to the High in this manner. However, this argument could be as easily applied to younger formations (see below).

Melawi and Mandai Basins - 1:250 000 preliminary map correlations. The Putussibau 1:250 000 preliminary map identifies the formation joining the two basins as the Haloq Sandstone (a name questioned above). Table 2, in part derived from this map, shows this 'Haloq' as the basal unit of yet another version of the Suwang Group, again covering the whole of the Mandai Basin sequence. Table 2 also shows the 'Haloq' beneath the Ingar Formation in the map area. Surono & Noya (1989) describe the two south of the Semitau High as part of a conformable sequence that continues upwards with the Dangkan Sandstone and Silat Shale.

This amounts to correlating the Mandai Basin with the Ingar Shelf plus Silat sub-Basin. If the Shelf and sub-basin prove conformable, then they would be invalid as defined, and should be replaced by a new sub-basin comprising their sum.

Table 2. Basin correlations, IAGMP Data Records (after Surono & Noya, 1989).



The 'basal sandstone' concept. These two map derivatives have their origins in the correlation paper by Pieters & others (1987). They assert that the Ketungau, Mandai and Melawi Basins share a common basal sandstone, and they lithologically equate the Ketungau and Mandai units that conformably overlie their shared basal sandstone with strata of this paper's Silat Sub-basin sequence. Their basal sandstone thus could be equated with the Dangkan strata of the Silat Sub-basin, or possibly with strata of theIngar Shelf. They do not consider the former alternative, which is explored further below.

Pieters & others (1987) assert that their basal sandstone unit is common to all four present day structural basins — Melawi, Mandai, Ketungau and West Kutai. Their unit contains all or parts of the Kiam Haloq Formation in the West Kutai Basin, the Mangan Sandstone in the Melawi Basin, the Behaba Sandstone in the Mandai Basin, and the Kantu and Silantek Formations in the Ketungau Basin. The Kiam Haloq and Silantek Formations yield upper Eocene fossils; beyond this there is little evidence for the assertion. Pieters & Supriatna (1990) use the term Kiam Haloq Sandstone for a unit of the Mahakam Group of the West Kutai Basin (see 1:1 000 000 map). They report that this unit subsumes the fossiliferous Kiam Haloq Formation of Pieters & others (1987), and the fossiliferous Haloq Sandstone of Abidin & Sudana (1989), both of which are West Kutai Basin units.

Contiguity of any of these West Kutai Basin units with the unfossiliferous 'Haloq Sandstone' of Putussibau and Nangapinoh quadrangles and with the Mangan Sandstone is a key issue. Map evidence does not clarify it, although contiguity with the Behaba Sandstone of the Mandai Basin seems possible.

The concept of a basal sandstone common to all four basins therefore seems to lack enough supporting data to use it as a starting point for correlating the oldest rocks of the Ketungau and Mandai Basins uniquely with particular strata of the Melawi and West Kutai Basins.

Melawi, Mandai and Ketungau Basins structural history — discussion and proposals

The absence of unconformities within the Ketungau and Mandai sequences can be used as a basis for proposing that their basal sandstones are younger than strata of the Ingar Shelf (Fig 2), perhaps correlating with the Dangkan Sandstone of the Silat Sub-basin.

The unconformity truncating the Silat Sub-basin probably did not form in the Ketungau and Mandai Basins, although it could have disappeared as a result of erosion. It might be equated with cessation of deposition in the two basins. The lower upper Eocene Muller Volcanics might mark the end of the Mandai as a depression.

The Dangkan Sandstone could well be the Semitau High cover that extends from the Melawi Basin into the Mandai Basin as part of the latter basin's basal strata. The Sintang quadrangle preliminary geological map suggests this, and raises questions about how the cover was recognised as being 'Haloq Sandstone' in the Putussibau quadrangle. If the cover is Dangkan, then the folding that it displays could be tied in neatly to that of the Silat Fold Belt. A Dangkan equivalent as basal strata for both the Mandai and Ketungau Basins would elegantly avoid uneasiness about the lack of unconformities in them. The age of the unconformity flooring both basins would be that of the unconformity between the Ingar Shelf and the Silat Sub-basin.

An episode of southwards compression first replaced the Ingar Shelf with the downwarps of the Silat Sub-basin and the Mandai-Ketungau Basin, then uplifted them and depressed the Payak Sub-basin along the southern flanks of the Semitau High which reacted with uplift, faulting and folding.

In the Mandai Basin open folds may reflect this episode, as may north-south bands therein of north-northwest and north-northeast trending imagery lineaments, which are probably conjugate sets of minor fractures.

Correlation is proposed, therefore, between the Dangkan Sandstone of the Silat Sub-basin with the Behaba Sandstone of the Mandai Basin and the Kantu Formation and fossiliferous upper Eocene Silantek Formation of the Ketungau Basin. It is also proposed that all these units are part of one continuous sheet which probably underlies the lower Upper Eocene Muller Volcanics of the Mandai Basin. The Ingar Shelf would then be the beginnings of only the Melawi Basin.

The Dangkan correlation implies exposure of basin basement rocks as a northern provenance for the Ingar Shelf. As mentioned above, there are no derivatives of melange or volcanics reported from the Ingar or Mentemoi Formations of the Melawi Basin, nor from its 'Haloq Sandstone'. 'Shelf' is possibly a misnomer. The feature may have been a shallow strait with a basement of melange, disturbed zone rocks and mid Eocene volcanics, with a northern shoreline south of a watershed that prevented it from acquiring detritus from the Lubok Antu Melange.

Post-Kantu (post-Dangkan) formations of the Ketungau Basin sequence may have had a melange provenance (Williams & Heryanto, 1986), perhaps the lower Eocene Lubok Antu Melange (Tan, 1979, 1982). If so, this may indicate a separate northern zone of uplift from that of the Semitau High. Such a northern uplift could have caused upwarping and deformation of flysch trough beds, initiating the Fold Belt domain. This domain then became a northern provenance for the Mandai and West Kutai Basins farther east, and for younger flysch deposits to the north in Sarawak. The beginnings of the West Kutai Basin may be no older than, or possibly equivalent to, Dangkan deposition.

Evidence for the Suwang or 'Haloq' based correlations include the fact that the Ketungau Basin sequence is approximately 7000 m thick (Pieters & Supriatna, 1989). Their Mandai and Melawi Basins Suwang Group totals 6000 m, suggesting a possible correlation in terms of the similar level of energy that went into the downwarping of all of them.

West Kutai Basin

The uplift/downwarp instability and associated east-southeast trends west of the Juloi High and Busang-Murung Crescent contrast markedly with the relative stability and northeast trends of the region to their east. Compare, for example, 8000 m of sediments in the intermontane Melawi structural Basin with 3500 m in the coastal-facing West Kutai Basin (thicknesses from Pieters & Supriatna, 1989).

The West Kutai Basin is apparently a southerly prograding sequence with no impeding distal high similar to the Schwaner Massif, and little provenance variation after uplift of its constituent disturbed zone rocks and adjacent flysch trough beds initiated the supply of sediments for the Basin. During deposition the West Kutai Basin downwarped more slowly than the western basins; sedimentation seems to have been continuous, with no unconformities forming in the late Eocene to early Oligocene sequence.

Quaquaversal folding of the conformable West Kutai Basin sequence may be solely the outcome of the late Oligocene deformational event that is reflected by the unconformity between this basin and the overlying late Oligocene to Holocene South East Kutai Basin. But while the northeasterly fold axes of the West Kutai could well have developed at this time, the north-northwesterly axes may be related to a mid Miocene or later event that produced northerly trending structures in the South East Kutai Basin (see below).

The Basin's characteristic northeast trends may reflect a concealed suture paralleling the Juloi High and the southeast margin of the Schwaner Batholith domain, and originally separating oceanic or Schwaner-like crust farther east from the Fold Belt domain flysch trough. Foss' gravity map of the region suggests that south of the Fold Belt domain in Long Pahangai quadrangle basement may be something like the Schwaner Massif (Abidin & Sudana, 1989). This may have provided a buttress against which the flysch trough was compressed and uplifted to become the provenance driving prograding sedimentation, possibly from Dangkan times until the onset of Sintang Intrusive Suite emplacement. These sediments now cover the buttress.

Late Oligocene to Holocene South East Kutai Basin

Achmad& Samuel (1984) attribute similar origins to the N.E. Kalimantan Basin and the Kutai Basin, describing five easterly prograding depositional cycles in both basins (Table 3). Where the cycles are separated by unconformities it is possible to consider each cycle as a sub-basin; however, persistence of onshore unconformities seawards is uncertain. The West Kutai Basin appears to be the oldest of the Kutai cycles and to conform onshore with the sub-basin criteria discussed above. The South East Kutai Basin does not, as it covers more than one of the younger cycles.

Pieters & Supriatna (1989, 1990) deal with only a small part of the South East Kutai. The 1:1 000 000 map shows the upper Oligocene tuffaceous Marah Formation, the Miocene tuffaceous Kelinjau Formation (the Anap of Abidin & Sudana, 1989), the Plio-Pleistocene Kampung Baru Formation, and Quaternary terrestrial and littoral deposits. The map also shows Sintang intrusive Suite bodies within the Kelinjau.

Achmed & Samuel (1984) present a Neogene correlation chart, incorporated in Table 3, which suggests that the Kelinjau may be part of their second or third cycle, the Kampung Baru (a Group on their chart) fourth cycle, and the Quaternary deposits (part of their Mahakam Group; cf Pieters & Supriatna, 1989) fifth cycle. The Marah (not shown by Achmed & Samuel) is second cycle by default and elimination and its unconformable relation with the West Kutai (Sub-)Basin.

In general the cycles reflect occasional northwest provenance uplifts— including that associated with the Metulang Volcanics domain episode which terminated cycle three and accompanied cycle four — and renewal of downwarping, mainly offshore to the east. The source of the volcanism during cycles two and three is unknown; some of it may have been produced during the last years of the Sintang Intrusive Suite domain episode.

On the 1:1 000 000 map the northeasterly trends characteristic of the West Kutai are less striking in the younger cycle sub-basins than the northerly trends, for example the northerly folds and thrust faults that deform the Late Oligocene and Miocene units, with which might also be included the cross folding in the West Kutai Basin. The north-south structures suggest an east-west compressive episode possibly of Metulang Volcanics age (the volcanics domain certainly has a dominant northeasterly trend, most probably inherited from mid Oligocene structures, but a northerly cross trend can be discerned).

The timing is supported by the probable culmination during cycle three of the northeasterly trending Samarinda Anticlinorium to the southeast of the map. Ott (1987) suggested that this feature resulted from southeastwards gravity sliding of basin deposits precipitated by provenance uplift in the late Oligocene to early Miocene.

The northerly trends parallel the northern part of the Fold Belt domain, to the north in Borneo, and the fold belt may have been bent to its present shape during Oligocene and Mio-Pleistocene east-west compression.

Notwithstanding this, cycle five is still active, and paired provenance uplift and depocentre deepening doubtless still in progress.

Quaternary Putussibau Depression

Quaternary sediments, mainly lacustrine, have been and are being deposited in the large oval Putussibau Depression, probably as a result of downwarping and fault damming. The Depression has formed mainly over the disturbed zone, but also overlaps the Fold Belt domain. The major axis of the Depression trends westerly. Foss (*in* Surono & Noya, 1989) explains the feature as an area of subsidence caused by isostatic forces acting on a large dense underlying body interpreted from his gravity anomaly map, those forces being consequent on the relaxation of the compressive tectonic forces associated with its emplacement.

Igneous domains

Mid Oligocene to Miocene Sintang Intrusive Suite domain

Mid Oligocene to Miocene igneous intrusive rocks have been generalised as the Sintang Intrusive Suite. The domain of intrusive bodies covers all other domains to a greater or lesser extent (Figs 2, 3). It comprises strings of small plugs and stocks. Emplacement of these took place after, or possibly during, the time that the West Kutai Basin was folded; the intrusives themselves do not seem to be deformed in any way. In many instances plugs locally domed up country rocks and instigated radial drainage. Lines of intrusions commonly occur along structural highs, for which their emplacement may be responsible. This is particularly the case in Long Pahangai Quadrangle, where the northeasterly trends of the highs and intrusives parallel the major structural grain, including the West Kutai Basin's structural margins. In Putussibau Quadrangle the intrusives have a less obvious westerly alignment.

The two trends cross where the Busang-Murung Crescent rocks crop out. The few Sintang Intrusive Suite radiometric dates (Bladon & others, 1989) suggest that the northeastern intrusions are younger than the western, and that the northeasterly trend may be superimposed on the westerly. The two intersecting trends are tangents to the arcuate Fold Belt domain.

The Suite may also be responsible for introducing or mobilising gold mineralisation in many places (Pieters, 1988).

Williams & Heryanto (1986) suggest that the Sintang Intrusive Suite was generated by crustal melting as a result of sedimentary basin downwarping combined with a rise in geothermal temperatures.

Miocene to Pliocene Metulang Volcanics domain

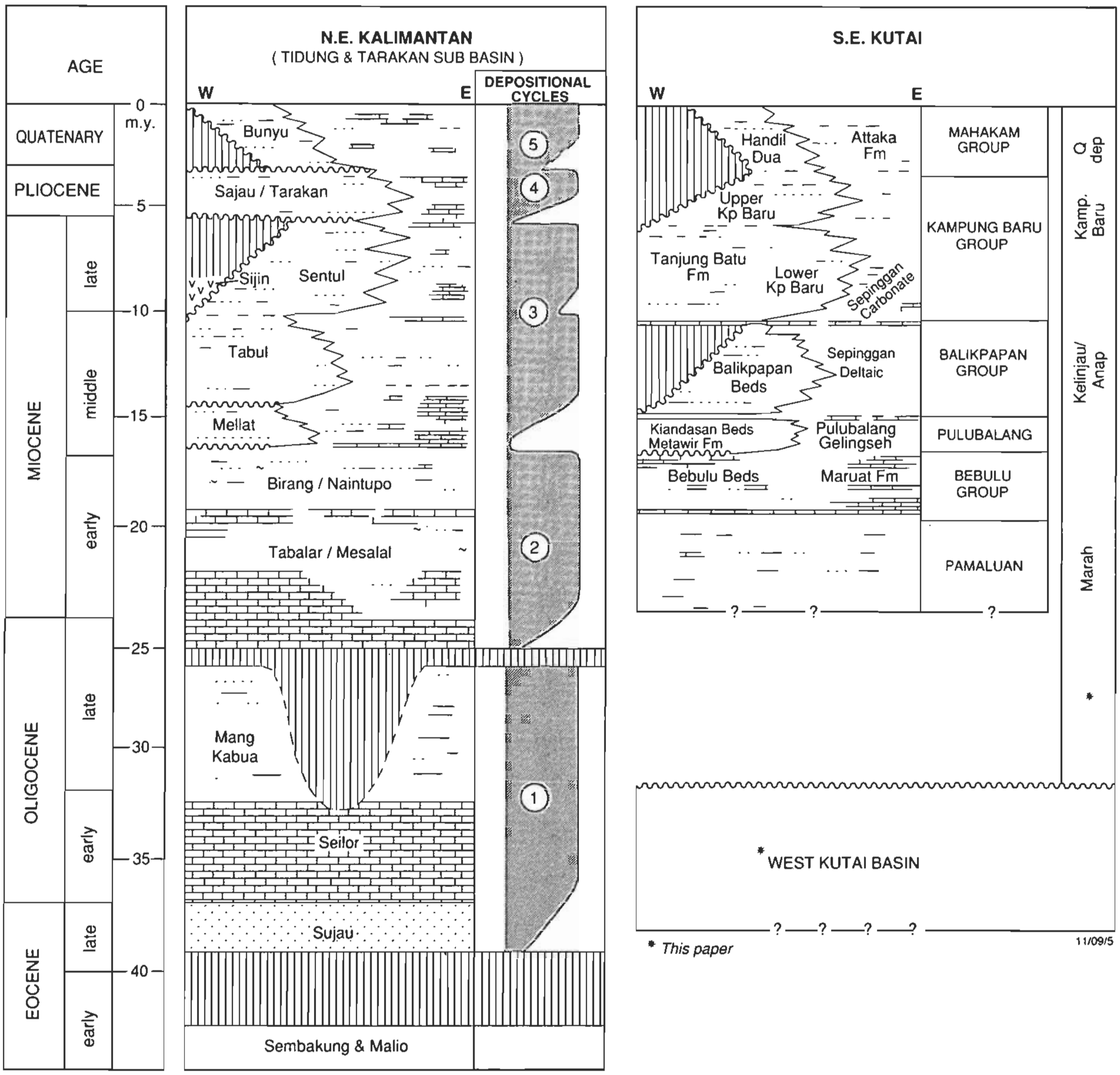
Before intrusion of the Suite ceased, basic lavas of the Miocene to Pliocene Metulang Volcanics domain began to be extruded in the northeast of the area, in Long Pahangai and Long Nawan Quadrangles (Abidin & Sudana, 1989; Baharuddin & Andimangga, 1989). This domain's general northeasterly trend is contiguous with that of the West Kutai Basin and the eastern part of the Sintang Intrusive Suite domain, and it overlaps both.

The volcanics seem to have been extruded on an old land surface, possibly a peneplane, to have been accompanied by uplift, and to be associated with structural highs. Uplift is reflected in river nick points; above these, the erosion suffered by the volcanoes does not seem to have been enough to unroof most of the intrusive bodies of the Sintang Intrusive Suite Domain, and the radiometric age overlap of the two domains needs looking into.

Tate (1991) suggests that the Metulang Volcanics represent 'the final stages of post-magmatic activity'.

The similar Niut Volcanics are dealt with in the next section.

Table 3. Comparison of depositional cycles, North East Kalimantan and South East Kutai Basins (after Achmad & Samuel, 1984).



Northwest Kalimantan domain

West of the Semitau High and its flanking basins, and to some extent overlapped by them, lies the Northwest Kalimantan domain of mainly Palaeozoic and Mesozoic rocks (Fig. 2 and 1:1 000 000 map). Younger Mesozoic rocks include western representatives of the outer shelf Cretaceous succession and unconformably overlying locally synclinal Kayan 'Basin' sandstones of Upper Cretaceous to Lower Tertiary age (Supriatna & others, 1989). Tate (1991) includes the Kayan in the Ketungau Basin and cites Tan (1986) as asserting that its deposition ceased in the late Eocene, at the time of Silat Fold Belt truncation.

Much of the gentle synclinal folding of the Kayan strata may be of the same age as that of the tight folding of the Embaluh Group flysch trough beds of the Fold Belt domain to their northeast. The milder structural scenario continued with limited Eocene or Oligocene Landak 'Basin' downwarping and sedimentation. This feature was possibly the western end of the Melawi Basin before being separated from it by basement uplift reminiscent of the Juloi High; the gravity map in Supriatna & others (1989) supports this idea. The relatively stable structural setting of the Kayan and Landak sequences lies south of the disturbed zone, whereas the Fold Belt domain is to its north.

The Oligocene and Miocene Sintang Intrusive Suite domain also occurs within the Northwest Kalimantan domain. Radial drainage commonly developed later, and the synclinal dips and possible bounding faults of the Kayan 'Basin' outliers may owe something to doming between the outliers by intrusive bodies not yet unroofed. However, substantial erosion must have taken place to expose those intrusives presently outcropping.

Northwest-southeast trends dominate in the Northwest Kalimantan domain. Sintang Intrusive Suite bodies trend southeast in places, a trend most noticeable in Singkawang quadrangle. The southeast-trending Pliocene basaltic Niut Volcanics extruded over the domain are a diminished mirror image of the northeasterly-trending Metulang Volcanics domain of the eastern quadrangles. And in a broad way there is something of a regional southeast plunging synclinorial aspect to the distribution of the older rocks of the Northwest Kalimantan domain.

Amiruddin & Trail (1989) comment on the dominance of the northwesterly trend in the Nangataman Quadrangle to the west of Nangapinoh, and its continuance through Singkawang quadrangle towards Natuna Island. This trend possibly originated during the Jurassic (Supriatna & others, 1989).

Schwaner Batholith domain

South of the Melawi Basin, and overlapped by it, is the Schwaner Batholith domain. It was originally coastal to the outer shelf Cretaceous rocks to its north; except at its present eastern end, in the Juloi Inlier, the contact is now hidden beneath the Melawi Basin succession.

On the 1:1 000 000 map the regional contact between the Melawi Basin and the Batholith domain is a fairly straight east-southeasterly line, although a few basin sediment outliers occur to the south of it. Overall the contact has the appearance of a monoclinal hinge which is parallel to the axis of the Melawi Basin, a warp that once controlled the Cretaceous shoreline, and which developed further as the basin deepened, perhaps. Amiruddin & Trail (1989) remarked that the presence of sedimentary breccia at the contact of the Tebidah Formation and Batholith domain rocks suggested that the southern margin of the Melawi Basin was considerably steeper than the present day northern slope of the Schwaner Highlands.

East-southeasterly trends also feature within the Batholith domain. Amiruddin and Trail (1989) reported this to be the trend of the schistosity within a metamorphic belt that lies close and parallel to the domain's boundary with the Melawi Basin, and suggest that it had pre-Early Cretaceous origins. The belt is better preserved in the east than in the west, reflecting perhaps a weak easterly component of plunge of the northern part of the domain, possibly acquired at the time of basin flank uplift in the early Tertiary.

Occurrence of an uplift is supported by the fact that the whole of the northern part of the Schwaner Batholith domain consists of eastsouth-easterly trending belts of rock that are older than those in the southern part. This may be the result of differential upwarping associated with downwarping of the Melawi Basin, and consequent erosion. Looking at this from a slightly different angle, Amiruddin & Trail (1989) suggest that the absence in the north of the domain of volcanics and of high-level phases marked by tonalite outcrops indicates deeper erosion than in the south, where pegmatites and volcanics occur. They also note the presence of easily eroded sandstone in the north at altitudes which suggest that some of the uplift of that part of the domain may be comparatively young.

While east-southeasterly trends are probably the most important in the domain, on the 1:1 000 000 map northwesterly and northerly trending structures are more obvious in some areas. Amiruddin & Trail (1989) remark that such regional differences exist, and that west of Nangapinoh quadrangle northwesterly trends replace the east-southeasterly trends.

In the southern part of the domain, belts of volcanics between granite highs trend northeast. This trend also shows up to a minor extent in the preservation of the northern metamorphics, and in the alignment of some of the few Sintang Intrusive Suite plugs that occur in the domain. The trend continues northeastwards beyond the domain as Sintang Intrusive Suite domain trends at the eastern end of the Semitau High. Farther northeast lies the northeast-trending Metulang Volcanics domain. This trend direction is also that of the southeastern margin of the Schwaner Batholith domain and of the regional strike of the deposits of the West Kutai Basin. The prograding deposits of the South East Kutai Basin dip southeasterly away from and normal to its northeast-trending West Kutai hinterland, so in this area the trend seems to have matured in Oligocene-Miocene times.

It appears that while the Schwaner Batholith domain may have played a buttressing role during Cainozoic compression episodes it did not escape internal modification by them (much constrained by pre-Cretaceous structure).

Fold Belt domain

The Fold Belt domain is the northern margin of the study area; the greater part of it is in Sarawak. Strictly speaking the domain should probably be restricted to the zone of strike ridges of Cretaceous to early Eocene flysch and exclude the disturbed zone and melanges. The strike ridge zone, mainly of Embaluh Group strata in Kalimantan, was named the Embaluh Fold Belt by the author (*in* Surono & Noya, 1989).

In Long Nawan quadrangle disturbed zone rocks and melanges are included in the Embaluh Group; in Long Pahangai and Putussibau quadrangles they are part of the Selangkai Formation. While the disturbed zone concept was developed by this author mainly to emphasise structural complexities, the zone could also be a useful informal stratigraphic unit. It would be characterised in part by melanges, and in part by younger outer shelf and older flysch trough strata (given northerly younging of the outer shelf deposits (Williams & Heryanto, 1986), and probably also of flysch trough deposits). If deformed zone rocks are excluded from the flysch Embaluh Group and the outer shelf Selangkai Formation, in which they are included by Pieters & Supriatna (1989, 1990) and the authors of relevant Data Records, this would enable a clearer appreciation of the disturbed zone, and cleaner-cut definitions for the outer shelf and flysch trough units.

The nature of deformation of the flysch deposits has not been studied systematically. In general it is flysch bedding strikes that indicate the regional arcuate trend (best seen on imagery and the 1:250000 preliminary maps), westerly in the west and northeasterly to north in the east. Dips are southerly to southeasterly and steep, with some overturning. Some of the steepness and the arc of trend may well have been acquired after the mid Oligocene, on the basis of some South East Kutai Basin structures.

Air photographs and Landsat and radar imagery yield very little information about structures in the outer shelf deposits or disturbed zone. In strong contrast the flysch beds stand out as belts of strike ridges, in which isoclinal folding is recognised with difficulty in a few places — but it is tempting to assume it to be ubiquitous. Pieters (pers. comm. *in* Williams & others, 1988) asserts tectonically juxtaposed Cretaceous and Tertiary rocks in a zonally alternating outcrop pattern. Faults sub-parallel to bedding strikes are common; these and fold steepening probably increased progressively in conjunction with Eocene—Oligocene sedimentary basin downwarping and later events.

Local details of structures in the flysch are recorded in Surono & Noya (1989, field photo captions). Photographs taken by IAGMP geologist Peter Williams in 1985 show the following features, some or all of which could be Tertiary:

— D3 folding on a decollement;
— transposed bedding parallel to cleavage;
— transposed bedding on both sides of an intrafolial fold;
— a D2 fold, with rotated cleavage in the core.

The arc of strike ridges trends from east-southeast in the west to northeast and north in the east. It is paralleled by elements of the domain of basins and inliers. In the west, the interdependence of all of these features during late Eocene to early Oligocene basin evolution indicates some crustal shortening as compression pushed everything southwards towards the Schwaner Massif. In the east, the same east-southeasterly trends could have persisted during West Kutai Basin deposition, although the northeast trending mid Oligocene fold axes in that basin, and the similar trend of lines of Sintang Intrusive Suite plugs within the basin and nearby, suggest that the northeast trend either was established in the adjoining part of the Fold Belt domain by then, or was impressed on it at the time of folding and intrusive activity.

The development of a peneplane on the strike ridge zone constrains this timing. The peneplane is most obvious as an old land surface on which Metulang Volcanics have been extruded in Long Nawan quadrangle (Baharuddin & Andimangga, 1989). In a few places there has been relief inversion by erosion since lavas flowed down valleys of the old surface. More generally, maps and imagery show that, allowing for displacement by faulting, summit concordance of the strike ridges is widespread. How this surface relates to the Sintang Intrusive Suite is unclear, but it does not seem to have been produced during unroofing of the intrusions.

It is possible that the peneplane had its origins in the dying out of uplift and folding of flysch trough strata north of the disturbed zone in the early Oligocene, as already postulated, northeast bedding trends being set by then. Provenance uplifts during South East Kutai Basin deposition could have resulted in erosional etching of strike valleys and ridges in the peneplane, but possibly could point to the likelihood of much younger planation.

Summary of Cainozoic structural history, West, Central and East Kalimantan

On present evidence, the Cainozoic structural history of this area began with the formation of the lower Eocene Lubok Antu Melange. It is possible that formation of the melange signalled the end of flysch trough deposition and was penecontemporaneous with disturbed zone derangement, uplift of the Cretaceous outer shelf deposits and extrusion of the middle Eocene volcanics on them, and early deformation of the flysch trough farther north as the beginnings of the Fold Belt domain — all of this resulting from the one episode of compression.

Between early late Eocene and mid Oligocene times bursts of compression produced a number of structural highs separating shifting sedimentary basin depocentres. In the south the Schwaner Batholith domain provided a buttress to this compression, although its northern margin was upwarped as a consequence.

Basin history began with deposition on the Ingar Shelf. The basement of these deposits in central Kalimantan consists of disturbed zone rocks, Cretaceous outer shelf strata, and mid Eocene volcanics. Basement downwarping may indicate continuation of the southwards compression that caused its previous uplift.

Late Eocene to early Oligocene compressional uplifts of the Semitau, Juloi and other Highs modified the Ingar Shelf into the Silat, Payak and Alat Sub-basins of the Melawi Basin, embraced the Silat Sub-basin-equivalent Ketungau and Mandai Basins, and separated the West Kutai Basin from the Melawi Basin; uplifts also separated the Melawi and Ketungau Basins from their ?outliers sitting on the Palaeozoic and Mesozoic complexes of the Northwest Kalimantan domain. The uplifts were associated with mild deformation of the older basin sequences and rare volcanism.

To the north there were probably contemporaneous uplifts of the Fold Belt domain flysch, but as compression weakened and basin downwarping diminished a peneplane may have begun to form in the northern provenance, lessening the amount of detritus available for depositing in the shallowing basins.

The Kembayan Inlier and the Busang-Murung Crescent owe much to these uplifts, and may represent reaction of 'continental crust' margin (to which the Schwaner Batholith Domain was hinterland) with north-south compression episodes (but see Tate, 1991). Farther east, the West Kutai Basin may conceal a more stable oceanic or Schwaner-like crustal bulwark.

Renewed compression in the mid Oligocene caused folding of the West Kutai Basin. The detachment faults of the Kembayan Inlier and the Busang-Murung Crescent may also be attributable to this event. Penecontemporaneous emplacement of the Sintang Intrusive Suite is less clearly related to structural highs in the west than in the east; their younger northeasterly alignments may indicate a bending of the Fold Belt domain in this direction at the time.

South East Kutai Basin deposition unconformably followed the West Kutai sequence with four more prograding cycles, the youngest still accumulating. Each was triggered by provenance uplift; the second-last uplift was associated with extrusion of the Metulang Volcanics and northerly bending of the fold belt. The northwesterly trend of the Niut Volcanics of the same age seems to be simply a matter of long established structural controls in the Northwest Kalimantan domain.

Recent development of the Putussibau Depression (and a similar feature adjacent to the Samarinda Anticlinorium in the South East Kutai Basin) are ascribed to isostatic readjustment. No older examples are known.

A simplistic approach to structural genetics that takes into account the predominance of northwest trends in the west, east-southeast trends in the south, and northeast trends in the east is postulation of compression of crust and cover southwards. The northern margin of the Schwaner Batholith domain bulwark was upwarped at the same time as the east-southeast trending basins deepened against it. The northwest and northeast trends are taken to reflect similar warps in resistant crust already shaped by pre-Cretaceous structures. The occasional extrusion of volcanics may indicate relaxation, even rebound, between episodic bursts of compression. The Sintang Intrusive Suite may have been generated by extreme downwarping leading to melting, the Metulang and Niut Volcanics being a last expression of this process.

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History of geoscientific investigations in West Kalimantan, Indonesia

F. de Keyser[1] & Johanna Noya-Sinay[2]

The first reliable geological data from journeys by Europeans into the interior of Kalimantan between 1816 and 1850 came from Schwaner. Dedicated geological investigations started in 1850 with the establishment of a Mines Department (Mijnwezen), which sent the geologist Everwijn on eight trips (1853—1857) to check reported mineral occurrences and prepare geological maps and reports. Results were discouraging. In 1879, a 20 year period of mineral investigations and geological mapping was initiated by van Schelle and continued by Wing Easton. It covered the south Sambas, Singkawang, and western Sanggau Quadrangles. Posewitz in 1892 published an English translation of his review of work done since 1826. In 1883-1884, the eastern region of West Kalimantan was for the first time geologically reconnoitred by a private expedition led by Molengraaff. After Wing Easton's departure in about 1900, there was a hiatus in field work, though several consolidating reviews were published. From 1923 to 1932, another systematic mapping project covered most of West Kalimantan, resulting in reports on the eastern and western regions. Geological and mining activities were reduced during and after World War II. New legislation in 1967 promoted foreign investment, leading to regional searches for various minerals and increased geological research. Since 1972 several countries including Australia have undertaken mapping projects jointly with Indonesian government departments, using a wide range of survey methods.

Introduction

A joint venture between the Department of Mines and Energy of Indonesia and the Australian International Development Assistance Bureau (AIDAB) undertook systematic regional mapping of West Kalimantan in the 1980s. This work, the Indonesia-Australia Geological Mapping Project (IAGMP), was carried out by the Geological Research and Development Centre, Indonesia (GRDC) in cooperation with the Australian Geological Survey Organisation (AGSO, then the Bureau of Mineral Resources), from 1983 to the end of 1989. The results have been prolific: more than fifty published and unpublished records, reports, maps, explanatory notes, and journal papers have been produced (Bladon & De Keyser, 1989). The present paper is a somewhat different kind of contribution to the knowledge of West Kalimantan.

In a country like Indonesia, where most pre-World War II literature is in Dutch (and some in German and French), access to information is denied to most English-speaking workers, and even to the younger Indonesian geologists. This paper therefore provides an overview of the history of geoscientific investigations in West Kalimantan, especially the pre-World War II investigations (Figs 1,2), to redress access and language problems with the older literature. Mineral occurrences are not reviewed here, but they are dealt with in individual IAGMP Data Records.

Some highlights of our research for this paper include the rediscovery of the original thin-section collections examined by Gisolf and van Bemmelen (1939), van Bemmelen's large scale sampling locality maps, and details of a forgotten multi-level underground mine.

History to 1816

Gold was known to occur in West Kalimantan as early as the Hindu period, from about the eighth century AD. Princely envoys from the Sambas/Landak states, dressed in clothes woven of gold wire, apparently carried gifts of gold to the Emperor of China in 977 AD and 1406 AD (Posewitz, 1892). After the 13th century, the first Chinese began to enter West Kalimantan, but it was not until the 18th century that, attracted by diamonds and gold, they began to immigrate in great numbers from southern China, settling in the Sambas and Landak regions. They were not given official mining rights until 1760 AD when the Prince of Mempawah allowed his goldfields to be worked by the Chinese. Soon afterwards they seem also to have taken over the gold workings and surrounding territory of the Sultan of Sambas, which led to clashes with the Dayaks and coastal Malay inhabitants. The first large Chinese settlements were at Montrado and Larah; between 1775 and 1780 the Chinese expanded their activities to the Mandor area. They introduced systematic alluvial working practices, and also began working vein deposits to limited depth. Since diamonds were an even more important export product, much sought after by the Dutch East Indies Trading Company, the Chinese worked the alluvial diamond fields of Landak from the early 1800s to the early 1820s, after which production declined.

The first European contact with West Kalimantan was made by the Dutch East Indies Trading Company, formed in 1602, which started trading along the shores of Borneo in 1606, establishing trading posts in Landak and at Sukadana. Although the company charted the island's coast line, they jealously guarded their trading sources and secrets, and actively discouraged exploration of the unknown inland regions by banning travel into the interior and treating the preparation of maps and charts as a criminal offence. This barren period lasted until the company's dissolution in 1789.

European reconnaissance

During the Napoleonic wars, the Indonesian territories were occupied by the British government under Governor Sir Stamford Raffles from 1811 to about 1816, after which the Dutch started to regain their influence in Kalimantan. The Dutch government then began efforts to improve the general knowledge of the Indonesian Archipelago, including its geography, ethnography, biology, and geology. A 'Commission of Natural Sciences' was established. From 1816 to 1850, scientists of various nationalities came to Indonesia on a wave of idealism and enthusiasm. The earliest expeditions were to Kalimantan, because of its rumoured mineral wealth and potential.

Results of these expeditions were mixed. Many of the young investigators succumbed to tropical illnesses, or died in accidents or in armed attacks. Indonesia was then still largely covered by dense tropical rainforest, and the lack of local knowledge, and difficulties of access, communications and transport, all severely hampered the explorers.

At about the same time, the country was reconnoitred and traversed by many administrative officers. Although these did not contribute much to geological knowledge, they accumulated a wealth of data and prepared topographical maps and sketches.

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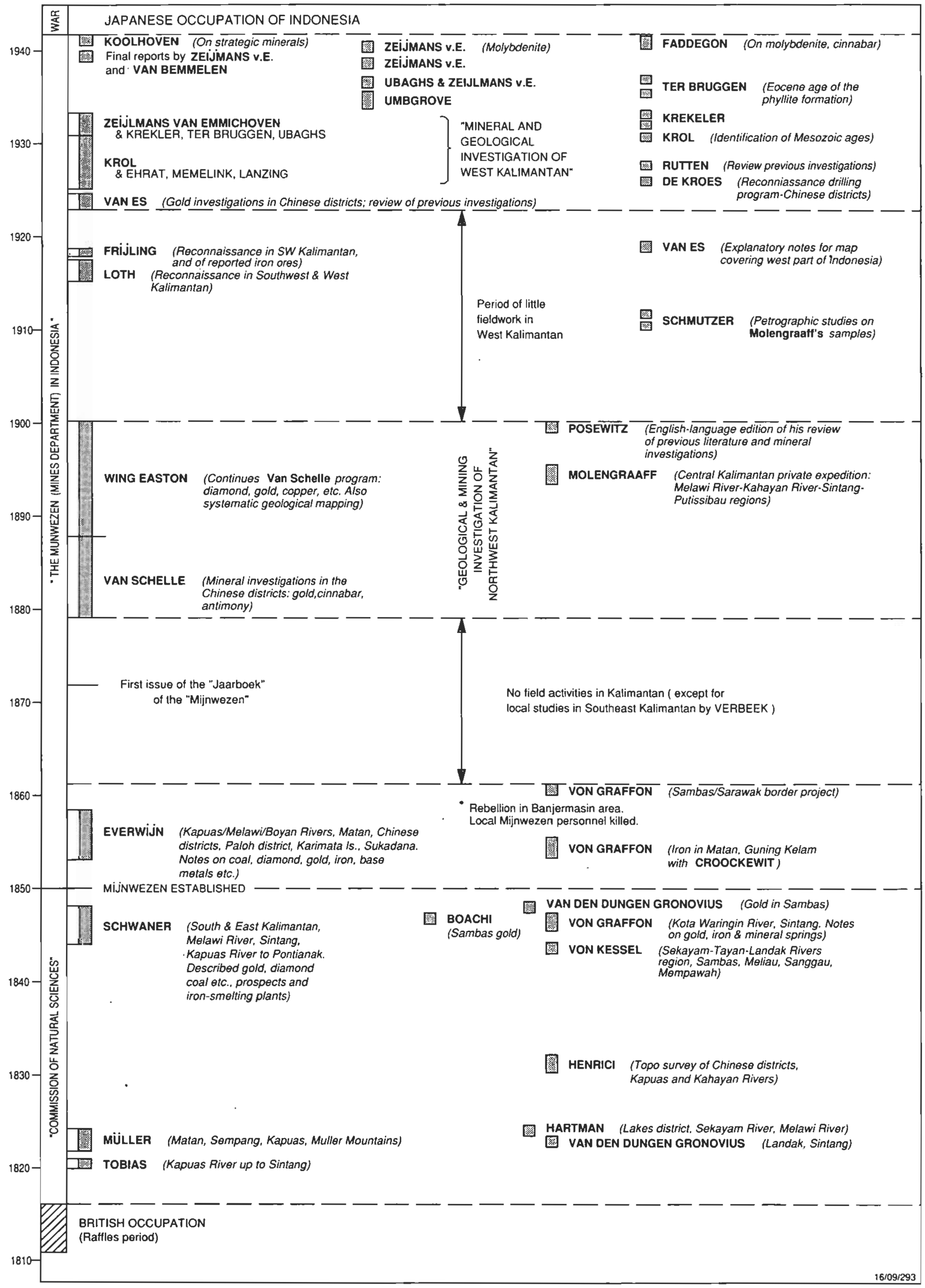

Figure 1. Chronology of pre-World War II investigations in West Kalimantan.

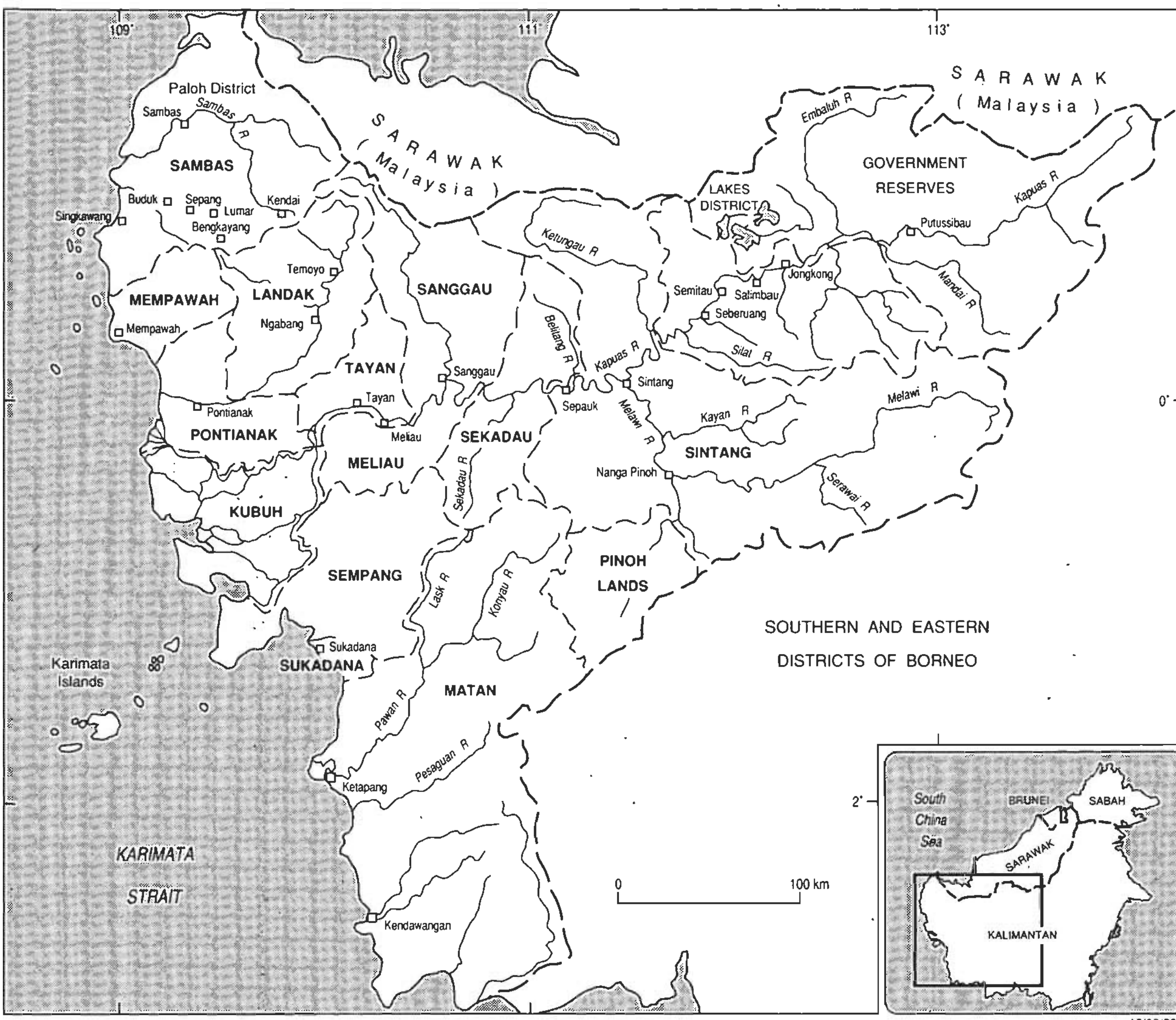

Figure 2. Pre-World War II administrative districts of West Kalimantan.

Commission of Natural Sciences

The most important explorer at that time was Dr. C.H. Schwaner, a German member of the Commission of Natural Sciences, and one of the few with a geological background. Between 1844 and 1847 his travels took in the Martapura River (where he discovered coal deposits), the south coast of Kalimantan, the Barito River, and the crossing of the watershed between the Barito and Mahakam Rivers. He travelled up the Kahayan and Katingan Rivers, crossed the divide between South and West Kalimantan (old Dutch divisions), and via the Melawi River arrived at Sintang, whence he continued down the Kapuas River to Pontianak. He died in 1851 from tropical fevers.

His geological work included the discovery of many Tertiary coal deposits, the description of gold and diamond panning activities and of iron-smelting works by the dayaks, and the recognition of extensive Tertiary formation as well as a very large granite batholith in the Katingan area. Fortunately, his valuable reports were saved and posthumously published (Schwaner, 1853, 1854).

Another member of the Commission of Natural Sciences, the German H. von Gaffron, initially accompanied Schwaner as a draftsman. Though Schwaner is usually credited as the first European traveller to cross from South to West Kalimantan, von Gaffron had already done so via Kotawaringin, the Lamandau River to its origin, and then by the Pinoh and Melawi rivers to Sintang.

In 1846 von Gaffron was commissioned to explore the unknown western part of South Kalimantan for coal. This work brought him also to the old district of Matan, which covers most of the KETAPANG Sheet area. Here he prepared a map of all 'known' and suspected mineral occurrences. Von Gaffron (1853) was the first to report on 'extensive' iron ore in the Kotawaringin district of TUMBANG MANJUL[3].

In 1854 he was appointed 'Assistent Resident' based in Sintang, and made several journeys on the Kapuas River and some of its tributaries. His last job in Kalimantan, in 1859, was a secret mission mapping the boundary between SAMBAS and Sarawak. Von Gaffron had a long and adventurous career. However, he was not much of a geologist, and published a note on a 'famous giant diamond' in Matan which was later found to be just a piece of a large quartz crystal.

[3] Capitalised area names refer to 1 : 250 000 Quadrangle areas.

Trips by Administrative officers: Tobias, Hartman, Müller, von Kessel, Henrici, van den Dungen Gronovius

The first European to travel up the Kapuas River was J. H. Tobias, who reached Sintang in 1820, making a map on the way. In 1822, D. J. van den Dungen Gronovius made a topographical sketch map of the Landak region, and also reached Sintang. In 1823 Hartmann, too, journeyed up the Kapuas River as far as the Lakes district and the Jongkong tributary. On a second trip he reached Merenkiang (Mengkiang) on the Sekayam River, and travelled up the Melawi River to its junction with the Kayan River.

In 1822 G. Müller became Inspector of the Interior Provinces, and undertook a number of topographical surveys, starting in the districts of Sempang (Simpang), Matan and Sukadana. He apparently reported the possible presence of tin in the region. (This error was perpetuated by von Gaffron in 1845 in his map of known or suspected mineral occurrences). In 1823 Müller mapped the west coast from Sambas up to Cape Datuh (Datu) and the Rajang (Redjang) River in Sarawak, where the hostile attitude of the locals induced him to return to Sambas. He then travelled up the Kapuas River, making topographical sketch maps on the way. He mapped the Lakes district, and reached the Sibau River. In 1824 he attempted to cross Kalimantan from east to west, and was the first European to cross the boundary between East and West Kalimantan. He was murdered on the Bungan River by Punan dayaks (Rutten, 1927), and his notes were lost.

From 1830 to 1831, A. H. Henrici made a topographical survey of the gold-rich Chinese Districts, which extended from southern SAMBAS to SINGKAWANG, the Landak region, and the northwestern corner of NANGATAMAN. He also prepared a large, 16 sheet topographic map of West Kalimantan (Posewitz, 1892).

In 1843, O. von Kessel journeyed from the Kapuas River north to the Sarawak border, through the districts of Landak, Tayan, Meliau, and Sanggau, mapping at 1: 250 000 scale (Posewitz, 1892). His unpublished map was later used in making 'Versteeg's Atlas' (no further details known). Von Kessel (1850) described the hydrological features of the country, and was the first to report gold and diamonds in the region. Van den Dungen Gronovius (1847) reported on gold diggings in the Sambas district.

This ended a period of *ad hoc* investigations and travelling expeditions by administration officers and enthusiastic members of the Commission of Natural Sciences, few of whom (with the exception of Schwaner) knew much about geology or mineralisation. Most of the work was cartographic, and much information also became available on the geography, ethnography, botany, and zoology of Kalimantan. However, in many cases reports and samples were lost, mainly because of canoe accidents, hostilities, or disorganised means of transport.

The first professionals 1850-1879

Establishment of the Mijnwezen

The establishment in 1850 of a department of Mines, or Mining office, heralded the beginning of systematic scientific investigations of the mineral deposits and geology of West Kalimantan. The Mijnwezen in Nederlandsch Oost-Indië, initially headquartered in Bogor (Buitenzorg), was later transferred to Jakarta (Batavia), and finally settled in Bandung. Its aim was the investigation of the country's mineral potential.

The scientific staff of the 'Mijnwezen' consisted solely of mining engineers until 1909, as professional geologists were not produced by the Dutch universities until then. The first three geologists were recruited in 1909, and occupied temporary positions. In 1928—1929 the first few palaeontologists (Umbgrove, Gerth, Tan Sin Hok) and one petrologist were taken on. Up to 1904, the official strength of scientific staff was 15 mining engineers, but this number was not often maintained during the earlier years because of illness, death, or extended sick leave. After 1904, additional mining engineers were recruited as temporary officers, bringing the total up to a maximum of 79 earth scientists in 1930, including 8 geologists, two palaeontologists, and one petrologist. Between 1930 and World War II the number fell back to fewer than 40 positions.

Initially, rock and fossil collections were sent to specialists of international standing for further study, until Mijnwezen's own experts could take over. In its first two decades, the Mijnwezen published its reports in a general periodical covering all the natural sciences in Indonesia: the *Natuurkundig Tijdschrift voor Nederlandsch-Indië*. In 1872 the first issue of the Jaarboek (annual report) of the Mijnwezen was published.

During the first few years of the Mijnwezen, there were still a few non-Mijnwezen explorers in West Kalimantan. Von Gaffron was active in the upper Kapuas River region and along the SAMBAS/Sarawak border. In 1854 J. H. Croockewit, a 'chemicomineralogist', visited Gunung Kelam (Klam), 20 km east of Sintang, in the company of von Gaffron, and described the mountain as being composed of argillaceous sandstone (Croockewit, 1856). G. A. F. Molengraaff later identified the rock correctly as a porphyritic microgranodiorite. Croockewit also reported on the salt water springs near the Spauk (Sepauk) River, and described the Paloh district in SAMBAS (Croockewit, 1855). In 1855 he was engaged by the government to examine the occurrence on the Kapuas and Melawi Rivers of coal, used to fuel steamships on the Kapuas.

At the time the Mijnwezen was established, the Chinese Districts were in turmoil. Trouble had arisen when the Chinese miners and traders organised themselves into 'kongsis', gradually becoming more powerful and suppressive, and thus coming into conflict with the indigenous population. The Sultan of Sambas requested assistance from the Dutch, who could do little initially as their only garrison, at Sukadana, consisted of some 15 soldiers. Monterado was occupied in 1854, and the kongsis dissolved.

Everwijn's travels

Towards the end of this period of unrest, the Mijnwezen organised its first official geological and mineralogical expedition in West Kalimantan. Mining engineer Everwijn made a series of long journeys, to check the reported mineral occurrences, make geological observations, and prepare maps of the country traversed.

Everwijn made 8 trips (Fig. 3) between 1853 and 1857, three along the Kapuas River and its main tributaries (in 1853, 1856, and 1857), the others involving investigations in the SINGKAWANG, KETAPANG/KENDAWANGAN, SAMBAS, SANGGAU, and part of TUMBANG MANJUL areas. The resulting map (Everwijn, 1879) represented the first true geological sketch map of parts of West Kalimantan. Unfortunately, Everwijn's work was carried out during, and just after, the last few months of the troubles in the Chinese Districts, and was impeded by the still uncooperative attitude of the native population.

Everwijn's three Kapuas River journeys. Everwijn's first Kapuas River voyage was a preliminary investigation of reported coal occurrences in the Salimbau, Jonkong (Djonkong), and Bunut (Boenoet or Boenot) regions. In the Salimbau region (between Suhait and Jongkong), outcrops of coal beds 30 cm and 90 cm thick were found in two localities, with some coal rubble

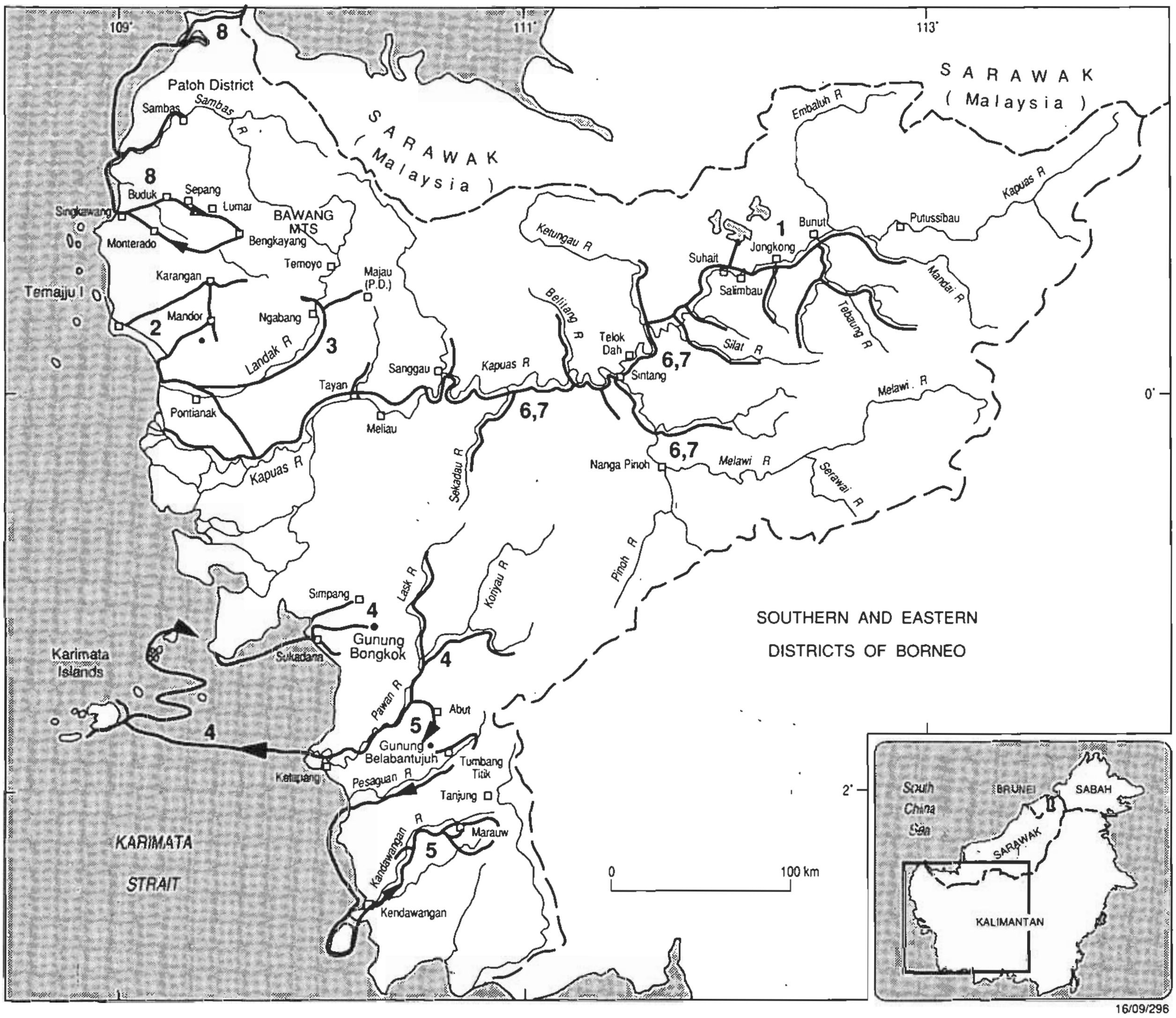

Figure 3. Traverses by Everwijn (1879).

at a third site, all of good to very good quality. Locally the overlying sands were auriferous. Along the Embau River 17 km south of Jongkong, fragments of coal of excellent quality were found, but no outcrops. In places along this river, coarse sands and gravels contained some gold and locally also a few diamonds. About 18 km upstream of the Boyan (Bojan) River (a tributary of the Bunut), fairly good quality coal 30 cm and 60 cm thick was exposed in several places. Half an hour up the Tebaung River, and one hour up the Mentibah River, coal beds 40 cm and 1 m thick were found, of indifferent quality. Overlying sands in the latter river again contained some gold.

On his second and third trips along the Kapuas River, Everwijn continued his search for coal, this time downstream from Salimbau. A few kilometres up the Seberuang River he discovered marly limestone beds with numerous 'nummulites'. This locality became a well known site, and the so called 'nummulites' were reidentified first as *Patellina scutum* or *P.trochus* by von Fritsch (1875), then as *Orbitolina concava* (Martin, 1898), *Orbitolina scutum-trochus* (Yabe & Hanzawa, 1931), and most recently as *Orbitolina lenticularis* by Hashimoto & Matsumaru (1974).

Everwijn lacked the opportunity to visit high quality coal beds and some alluvial gold reported from the upper reaches of the Silat River, and a 30 cm thick high-grade coal layer at TalokDah (a little upstream of Sintang) reported by Croockewit. He went partly up the Ketungau, Melawi, and Pinoh Rivers, finding only traces of coal and coaly shale in the latter two. At Sintang, he found alluvial gold at the confluence of the Melawi and Kapuas Rivers, and some gold workings not far from Sintang, about 1.5 km inland from the Melawi. He noted Chinese-owned alluvial gold workings north and south of the river banks upstream and downstream from Sanggau, straddling the boundary between SANGGAU and NANGATAMAN. Diamonds were found in the auriferous gravels south and southeast of Sanggau village, probably just within NANGATAMAN. Everwijn concluded that downstream from Salimbau no exploitable coal seams existed, and that those found were more properly classified as brown coal.

Just downstream from Tayan, Everwijn found gold being won from high level alluvials along the north bank of the Kapuas, and was shown brown coal samples from near Cempedeh (or Tiang-Kandang) Mountain.

Mandor-Mempawah-Karangan area visit. Early in 1854, Everwijn travelled to the Mandor-Mampawa region within SINGKAWANG to check on the gold mining activities reported by Boachi (1846). His first target was Gunung Tampi (now Gunung Segiangan), where copper ore was supposed to have been discovered around 1850 by an English naturalist working in Sarawak, who accidently strayed across the border into Kalimantan. As Gunung Tampi lies more than 100 km from the Sarawak border, Everwijn rejected the story and concluded that it was a Dutch army captain who had first visited Gunung Tampi in 1851 and had found native copper there. However, many years later Krol (1929c) discovered another Gunung Tampe, on the Sarawak/SAMBAS border; the reported rich copper ore had come from a small copper-silver-gold deposit a dozen kilometres west of this mountain, on the Bayur (Bajoer) river on the southeastern flank of Gunung Asuansang. Everwijn had visited the wrong mountain, but his error remained undetected in the literature as Krol's report was never published.

From Gunung Tampi, Everwijn travelled to the Mandor-Karangan area, where he described the gold workings at Gunung Snaman (Senaman, now Semubueh) which spread out along the base of the mountain, on the slopes, and along the crest. The gold is derived from impregnations and veinlets of finely disseminated gold-bearing pyrite on the crest. On his return to Pontianak Everwijn also recorded granite cut by dioritic veins on the islands of Penibungan and Temaju, but found no trace of mineralisation.

Visit to Landak River region. In March 1854, Everwijn travelled to the middle reaches of the Landak River, where he located small alluvial diamond workings. Thinking that the diamonds were derived from micaceous and siliceous slates and phyllites, he expressed surprise that such rocks had not yet been exploited. From near Ngabang, he walked northeast more or less along the Belintian River to 'Majau' (not found on any available maps, but possibly in the vicinity of Bunan and Sungaitaras, 25 to 30 km east from Ngabang), where he visited the Chinese-owned alluvial and lode gold workings. On the way he noted sandstones which probably correlate with the 'post-Triassic' sandstones later described by Wing Easton from the Singkawang region, and which were thought to be late Cretaceous or perhaps even early Tertiary sandstones. The Chinese miners at Majau had dug eight trenches, and were digging another one which they planned to sink down to about 17 m, the maximum depth their primitive methods enabled them to reach. The mineralisation appeared to be associated with a pyritiferous quartz vein, and Everwijn speculated that the ore grade would increase in depth, seeing the efforts made by the miners to deepen the trench.

Sukadana-Sempang-Matan region. From May to August 1854, Everwijn visited the Sukadana-Simpang-Matan region in KETAPANG and the southeastern part of NANGATAMAN, to check the tin mineralisation previously reported by Müller and von Gaffron. Everwijn recorded syenites in the Sukadana district, and granite at the Palong Mountains (Gunung Bongkok), but found no trace of tin. Going up the Pawan and Biya rivers, he described granites and syenites, as well as sandy and shaly sediments which locally had been contact-metamorphosed to slates and hornfels. Strangely enough he did not recognise the widespread volcanics as such but, judging from his map, mistook them for hornfelsed sediments. Going north along the Laur River, he discovered some old high level alluvial gold workings at the NANGATAMAN border which appear to have been small or of low grade as they had already been deserted by the Chinese miners.

Finally, Everwijn visited many of the Karimata Islands, found to consist mainly of granites, intruding some altered claystones and ferruginous claystones. Again, no trace of tin could be found.

Southern Matan district. In 1855 Everwijn visited the southern part of the Matan district, including south KETAPANG, the northwestern corner of TUMBANG MANJUL, and the northeastern corner of KENDAWANGAN, completing his trip by travelling down the Kendawangan River to the coast.

His main intention was to check the tin potential of the region, following the identification of cassiterite in one of a series of samples collected in 1852 by an army officer. Everwijn first visited the Abut (Aboet) locality on the north side of Mount Belabantujuh (then known as Gunung Malajoe, or Malayu in modern spelling[4]) in south KETAPANG, where the tin-bearing sample had been collected. He was told that in about 1845 Chinese miners had been working alluvial deposits west of Abut, but that profits had been so meagre that the place was soon abandoned. Walking south, past the granitic Gunung Malayu, he found old gold diggings on the south side of the mountain, which according to the locals had been mined in 1825 (some of these pits were relocated by members of the IAGM Project in 1984). Again, however, there was no trace of tin ore. Next, Everwijn sailed to the mouth of the Kandawangan River and continued upstream to the northeastern quadrant of KENDAWANGAN, whence he traversed on foot to the northwestern corner of TUMBANG MANJUL, making geological observations on the way. He came to some weakly auriferous sands, but found no trace of tin.

Paloh region and Chinese districts. In 1857, Everwijn visited the Paloh region in northern SAMBAS to check the area for iron, copper, and tin occurrences. According to legend, iron ore had been mined and smelted by the Chinese and Dayaks long before Everwijn's days, and he indeed discovered remnants of two smelting furnaces and a few occurrences of very low-grade and inferior iron ore, though there was no sign of large, rich deposits. Nor was there any trace of the expected copper and tin. He then walked the coastal track to Cape Datuh (Datu) and into Sarawak, describing the geology but not finding any minerals.

A month later Everwijn visited the Buduk (Boedoek) area on the SINGKAWANG/SAMBAS border, where native copper was reportedly being won from alluvial sands. He was shown rich alluvial gold placers and some small lode-gold deposits in pyritiferous quartz veins cutting variegated slates. This gold was very fine and contained appreciable amounts of what was said to be the gold-telluride sylvanite and locally some bismuth. Everwijn did not find any platinum, although Boachi (1846) had written that much platinum was found in association with the gold at Buduk, but that the miners considered it to be a useless mineral. Boachi added that in earlier years the platinum had indeed been sold, but that because of low profits the practice had been stopped.

Everwijn returned to Singkawang via the villages of Sepang, Lumar, Bengkayang, and Montrado in the Chinese Districts, a distance of 135 km. On the way he noted grey, bluish, and variegated slates and shales, in places alternating with argillaceous sandstone beds, whereas the Bawang Mountains and the mountains near Singkawang were granite. Everywhere he found Chinese-owned alluvial gold workings in both recent and terrace alluvium. The purest gold seemed to be that of Sepang. Near Bengkayang and Monterado some lode gold occurred, as at the Hang-mooi-sang (also Han-Muy-San, Hang-oei-san, Hamisan) mine about 10 km north of Monterado. A vein 2 m thick, with a 75 cm core of quartz and gold-bearing(?) pyrite, was being worked to a depth of about 15 m, the practical limit.

In 1871, high grade lead and zinc ore was found by locals near Marouw on the Kandawangan River, about 14 km south of the

[4] See Appendix 1 for spelling variations between pre-War War II and post-World War II Bahasa Indonesia.

KETAPANG border at Tanjung. In 1876 about 43 tonnes of this ore were sold in Singapore by a Chinese miner. The exact location cannot be pinpointed as the topographic names mentioned in the reports are not shown on the available maps. The ore consisted of sphalerite and galena with associated pyrite. Cretier (1879) published a chemical analysis, and later LeRoy & Croes (1880) prospected the area, finding ore at two isolated sites, but nowhere in situ as a lode or vein. Everwijn wrote two small reports on the occurrence.

Everwijn's final report. In a final review, Everwijn (1879) presented his somewhat surprising opinions on the geology of West Kalimantan. He thought that all the 'neptunic' slaty/shaly deposits in the areas visited were of the same 'very old' age; that there were no Mesozoic rocks in West Kalimantan; and that there was no evidence of volcanic activity either recently or in the past, since he had not come across any volcanic rocks, nor had he seen any mountains that remotely resembled a volcano. As mentioned earlier, he had indeed travelled over volcanic deposits but had thought them to be contact-metamorphic rocks.

Everwijn's report was generally negative about the mineral potential of West Kalimantan. Tin, the main mineral sought, was conspicuous by its absence. The only coal worth considering, in the Salimbau area, was too remote. The diamond deposits were largely mined out, and no large scale mining seemed possible, nor were the copper, lead, and iron occurrences of much interest. As for gold, alluvial deposits were largely exhausted, but there appeared to be some potential in lode-gold mining: Everwijn argued that the Chinese miners had no technical experience in working underground veins or in the mechanical and chemical extraction of gold from the ores, nor did they have the proper tools to go deeper than 15 m. Hence he suggested that an experimental shaft should be sunk to 40–50 metres on a selected prospect. He compared the gold-telluride-bismuth-pyrite veins at Buduk with similar lodes in Colorado, drawing attention to the fact that the latter became rich only at depths of 33 to 50 m below the surface.

During a rebellion in the Banjermasin district in southeastern Kalimantan in 1881, all Mijnwezen personnel in the area were killed. This, combined with the disheartening effect of Everwijn's report, led to a 20 year period during which fewer expeditions were undertaken.

First systematic geological and mining investigations 1879-1900

Van Schelle

In 1879, 25 years after Everwijn's travels, a new period of activities by the Mijnwezen set in when C.J. van Schelle began a 6-year program of investigations of minerals and coal in West Kalimantan (the 'Geological and Mining Investigations in Northwest Borneo'), mainly in the Chinese Districts, the Landak region, and the upper Kapuas River. At the same time, a start was made with the systematic topographic mapping of the western region by a qualified surveyor's team.

Van Schelle's numerous reports include an informative historical summary of the rise and fall of the Chinese kongsis; detailed descriptions of the methods of gold winning; descriptions of alluvial and vein-gold workings around the Monterado (1883b, 1887b) and Bengkayang (1883a, 1887a) centres, and in the Seminis and Sepang areas and the Sekadau mountains in Sambas (1884b); the first gold production statistics (1882); visits to small copper and lead occurrences around Monterado; the gold veins near Melassan in the southwestern corner of SILAS; search for mercury and antimony near Lumar, Uduk, and in the upper Sekayam River and Jambu (Djamboe) River (an old name for one of the upper branches of the Landak River); investigations of iron ore at Pajilu (Padjiloe) near Monterado, and of hematitic iron ore in the upper reaches of the Sambas River; a study of the good quality coals near Napan at the Boyan River in the Bunut region (1883c), used to fuel steamships on the Kapuas; and a report on the cinnabar occurrences of West Kalimantan (1887c).

He reported rumours that the Kendai region (northwest area of SANGGAU) and the upper reaches of the Darit or Menyukai River still contained rich unexploited gold placers. He also concluded that, contrary to Boachi (1846), there was no platinum in the Sambas district. He produced (van Schelle, 1884a) a 1: 500 000 scale map of all mineral localities within the area bounded by the Sambas and Landak Rivers.

In 1879 van Schelle became the first geologist to visit the region between the Lakes district and the Embaluh River, near the Sarawak border. The trip was made under protection of an army escort because of the hostile attitude of the Batang Lupar dayaks. He found the border mountains to consist of 'old slate' with quartz veins, and collected many rocks and fossils, which were unfortunately lost in a canoe mishap on the Kapuas.

In the Chinese Districts, van Schelle recognised an east–west trending, strongly folded formation of siliceous slate, sandstone, and conglomerate, intruded by granite and volcanics, and unconformably overlain by Tertiary sandstones. He was the first to apply the term 'Oude Lei Formatie' ('old slate formation') to all the folded slaty/shaly beds in West Kalimantan, to which he attributed a Devonian age. He did not explain his reasoning for this, but Wing Easton (1914) stated that van Schelle equated the slates with similar rocks of supposedly Devonian age in Sumatra).

In the northwestern corner of SANGGAU van Schelle discovered the small volcanic cone of Gunung Melabu (van Schelle, 1886), composed of flows and pyroclastics of hornblende andesite. He also found extensive sheet basalts in the Ledo area and thought that their origin was in the Bawang Mountains. Near the township of Siluas he found massive beds of limestone which he suggested could be reefal deposits of unknown age. He further distinguished Senonian sediments, Tertiary sandstones with coal layers and shaly beds (Eocene?) and younger argillaceous sandstone, shale, and mudstone. Fossils found by van Schelle in the Seberuang River, and originally thought to be 'nummulites' by Everwijn, were identified as the possibly Cretaceous foraminifer *Patellina* by K. von Fritsch (1879).

Van Schelle also collected fossils from shale near Sepang (SAMBAS), which were dated by Martin (1898) as Mesozoic, possibly Cretaceous. This was disputed by Wing Easton (1899b) who found ammonite imprints at Sepang and near Lumar which were identified by Krause as *Harpoceras radians* of Liassic age. Age determination from fossils was more problematic then, and the rocks at the different fossil locations belonged to different stratigraphic horizons. Everwijn's statement 20 years earlier, that Mesozoic deposits did not exist in West Kalimantan, was therefore invalidated.

Review in English of investigations in Kalimantan

By the 1880s a significant amount of data on Kalimantan had been compiled. Almost all reports were in Dutch, and to most people Borneo still remained an unknown and mysterious island. As late as 1886 an Austrian journal (*In* Posewitz, 1982)stated that in Borneo 'no one has yet succeeded in navigating the larger rivers for any distance from the mouth'. At least 60 years earlier, the first European travellers had gone up the Kapuas River all the way to the Lakes district!

In 1889 the Hungarian Theodor Posewitz, who had served as an Officer of Health in Kalimantan, published a detailed summary in German of all previous investigations and mining reports. An

English translation followed (Posewitz, 1892). His work, notwithstanding geological shortcomings, was a most valuable contribution which made Dutch sources accessible to German and English speaking scientists.

Regional mapping by Wing Easton, 1885– ~1900

In 1885, N. Wing Easton joined van Schelle's team as second mining engineer, and took over the leadership when van Schelle was transferred in 1887. A five year lull in field activities followed, during which the fossil collections of van Schelle were described and identified by Prof. K. Martin of Leiden University who established the presence of Mesozoic strata in areas where van Schelle had expected a Devonian age for his 'old slate' formation.

Geological investigations were resumed by Wing Easton and his assistant Koperberg in 1893, after the completion of a new topographic map which was of a very high standard even by today's criteria. Wing Easton regretted the heavy stress on economic geology that had characterised van Schelle's work. He therefore undertook a more systematic regional geological mapping program to support exploration efforts. In contrast to van Schelle, Wing Easton paid much attention to geological syntheses and to the genesis of mineralisation. In line with Martin's recommendations, he tried to bring more clarity in the geological relationships between Mesozoic and supposed Palaeozoic formations.

Investigations involved the region covered by SINGKAWANG, western SANGGAU, and southern SAMBAS and SILUAS up to 01°15' N latitude. The results were published in a voluminous work in German, with 10 geological maps at 1: 100 000 scale (Wing Easton, 1904) (Fig. 4).

Wing Easton (1889) found two alleged volcanic cones (Sitong and Pando) in northwestern SANGGAU; discussed the diamond deposits along the Landak and upper Sekayam Rivers (Wing Easton, 1894); reported the discovery by his assistant Koperberg of ammonites in a limestone bed near Temoyoh on the Landak River; reported on the geology along the Kapuas River (Wing Easton, 1899a) and on the copper occurrences around Mandor (Wing Easton, 1899b); and gave a geological overview of West Kalimantan (Wing Easton, 1914).

In his reports (one of which included a very useful locality map) on the Landak diamonds, Wing Easton (1894, 1895) suggested that the diamonds were derived from basic igneous rocks. This followed an earlier reference by Posewitz (1889) reporting a statement by a Professor Lewis in the USA that the usual host rocks of diamonds are serpentines (altered peridotites). From 1925 onwards Wing Easton adopted this belief. Everwijn (1879) had thought that the Landak diamonds were derived from veins in the basement slates, and the theory current in Wing Easton's days was that diamonds were produced in acid igneous rocks.

By visiting at least 27 copper-bearing localities within a radius of 5 km of Mandor, Wing Easton and Koperberg confirmed Everwijn's and van Schelle's conclusions that there were no good copper and lead prospects in the region.

On his trip to the Kapuas River area, Wing Easton (1899a) collected many fossils from a large number of localities, including the Silat River and some of its tributaries, the Seberuang, Melawi and Kayan Rivers. They were described by Martin (1898), increasing the knowledge of Mesozoic and Tertiary deposits in the region.

The ammonite fauna collected by Koperberg at Temoyoh on the Landak River was described by Krause (1904) and dated simply as Cretaceous. Wing Easton believed the fauna was Cenomanian. The problem of determining the age of Mesozoic strata in West Kalimantan and Sarawak recurred for later investigators such as Icke & Martin (1905), Vogel (1902), Krause (1911), Yabe & Hanzawah (1931), von Koenigswald (*in* Zeijlmans van Emmichoven, 1939), Hashimoto & Matsumaru (1974) and JICA (1982). Ages were sometimes updated more than once, when fossils were found to have been misidentified, or when the age range of certain species had to be expanded. The latest age given for the Seberuang locality is now early Aptian to earliest Albian. In the Chinese Districts van Schelle's 'Devonian old slate formation' has been split into Triassic, Jurassic, and Cretaceous units, as a result of later investigations (e.g. JICA, 1982).

Wing Easton subdivided the 'old slates' into a lower phyllite section and an upper, slightly sandy shale or slate section which also contained 'diabase porphyrites'. He guessed that their ages ranged from 'possible Palaeozoic or Lower Triassic' to 'Upper Triassic, perhaps even Lower Jurassic'. The Triassic age was based on the identification of *Monotis salinaria*, a fossil given to him by a prospector, the precise sampling location of which unfortunately could not be retraced.

Fossils collected later by Wing Easton indicated that more and more areas of 'Devonian old slate' were Lower Jurassic and Cretaceous. He subdivided his Jurassic succession tentatively into four conformable units of locally calcareous shales and thin sandstone (Upper Lias; Lower, Middle, and Upper Dogger) based on lithological and palaeontological differences. This succession is underlain by Upper Triassic or Lower Jurassic 'transitional beds' which he equated with Molengraaff's 'Danau Formation'. It is overlain by thick-bedded sandstones which Wing Easton guessed to be Malm or Lower Cretaceous. The unconformably overlying 'Plateau Sandstone' of Molengraaff (1900, 1902) from the SINTANG/PUTUSSIBAU area, was considered by Wing Easton to be Upper Miocene. Earlier, Wing Easton had cautiously spoken of post-Triassic sandstone, which also included Upper Cretaceous sandstones. He mapped two suites of volcanics younger than the 'Plateau Sandstone', and thought they were Pliocene to Quaternary: a hornblende-andesite and dacite suite, and a younger sheet basalt.

Wing Easton's final report and conclusions

Wing Easton's final report (1904) is largely a description of his traverses. He was proud of his work, stating that, although many areas were only reconnoitred, at least the geology of those localities that he had mapped 'in detail' had been resolved 'with great accuracy'. The report is not easily digestible, and suffers from an awkward rock nomenclature and from unusual concepts that he believed to be undeniable facts.

Wing Easton's unit of 'Quartz Porphyries' is rather contrived. It encompasses a large number of unrelated rock types of different origin, including rocks in which quartz is rare, rocks that are not porphyritic, and even sedimentary quartzitic rocks which he mistook for extremely acid end members of a magma series ('eruptive quartzite', 'quartzitic quartz porphyry').

He considered that the 'Quartz Porphyries' were the cause of all mineralisation in the region, and were the formation from which the 'Plateau Sandstone' arenites had been derived by weathering and disintegration. He was so convinced of this that he predicted excellent gold potential in the 'Plateau Sandstone', and assumed that each large body of this formation had to have a 'quartz porphyry' core. He therefore occasionally drew outcrops of 'quartz porphyry' within large bodies of the sandstone formation on his maps where they had not been observed in the field, but where he predicted they should be. When he was later transferred to Sumatra, he convinced headquarters to restrict a planned gold exploration program exclusively to areas of rhyolitic deposits. These guide lines were subsequently ignored by the field geologist.

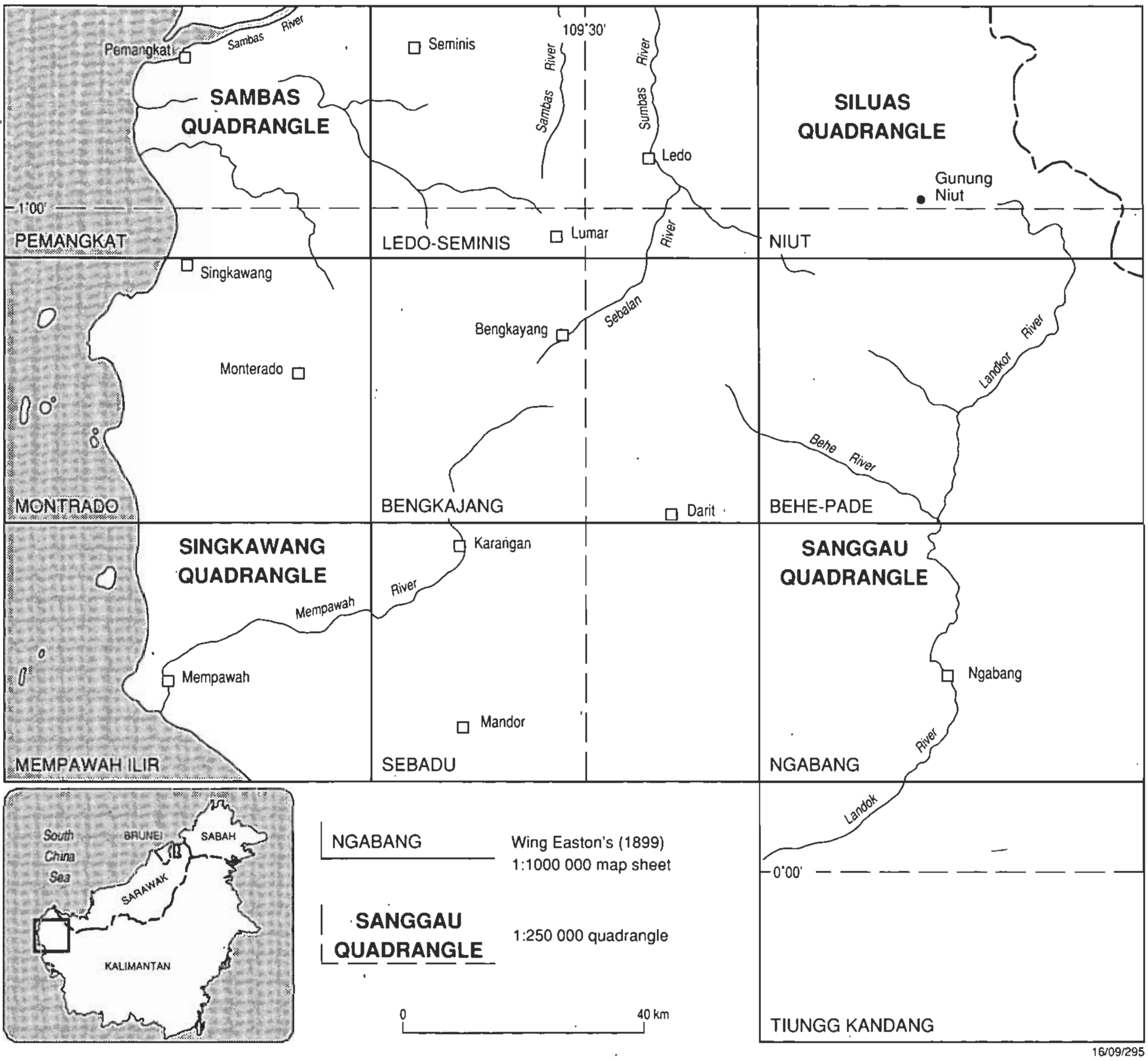

Figure 4. Area covered by Wing Easton's (1904) map sheets.

Wing Easton believed that the granites in West Kalimantan were the oldest 'primeval' rocks of early Proterozoic or even Archaean age. Ignoring previous reports of contact-metamorphic effects, he maintained there were none. Later (Wing Easton, 1914) he admitted that some rare granites might be younger.

The departure of Wing Easton ended 20 years of steady, systematic geological mapping in the Chinese Districts and some traverses in the Kapuas River drainage area, which had led to the recognition of large tracts of Jurassic and Cretaceous and probably also Triassic deposits at the expense of the 'Devonian' old slates, and the realisation of new problems that needed further work. Although he left West Kalimantan in about 1900, he retained his interest in the region and occasionally published papers on the 'Plateau Sandstone', the genesis of diamonds, and the origin of the Indonesian Archipelago (see below).

Molengraaff, 1893–1894: central east Kalimantan travels

While Wing Easton was working in the western part of West Kalimantan, Molengraaff began the first professional geological investigations in the central-eastern part of West Kalimantan (Molengraaff, 1900, 1902). Molengraaff led a privately financed and organised expedition in 1893-1894 which covered parts of PUTUSSIBAU, PEGUNUNGAN KAPUAS, SINTANG, and TUMBANG HIRAM. His fossil collections were described by Newton & Holland (1899), Hinde (1900), Krause (1897) and others, and parts of his rock specimens were studied by Schmutzer (1909, 1910). In his clear, well written report, Molengraaff summarised the main points of the geology of west and east Kalimantan, updating his ideas in later papers (e.g. 1914).

Molengraaff found regions of amphibolites, amphibole-chlorite-quartz schists, and glaucophane schist, and regarded them as of Archaean age, though he later added that some of them could possibly be metamorphosed parts of the 'Danau Formation', a view reinforced by Schmutzer (1909).

IAGMP workers recently included these rocks in their Busang Complex (Surono & Noya, 1989), for which a Triassic age was obtained by K/Ar dating. Molengraaff also described spectacular domes and peaks of dacitic and rhyolitic volcanics, currently known as Sintang Intrusives. Schmutzer (1910) described garnet-bearing amphibole andesites from the Sungai Embau drainage area, 20-45 km south of Jongkong, SINTANG. Garnet in one sample occurred as an alteration product of amphibole, together with aggregates of chlorite, iron oxides, pyroxene, and calcite. In another sample the garnet was in feldspar phenocrysts which it replaced, and was not an older inclusion.

Molengraaff's 'Danau Formation' consisted of a complex of siliceous sediments (including quartzites, cherty slates, and radiolarites) and basic volcanics (including dolerite, basalt, tuff, agglomerate, and spilite). The formation is rich in radiolaria, for which Molengraaff accepted Hinde's (1900) date of post-Palaeozoic, possibly Jurassic. Molengraaff had found 'Danau Formation' outcrops overlain by Lower(?) Cretaceous sediments. Wing Easton correlated his Triassic to Lower Jurassic 'transitional beds' in the Chinese Districts with the 'Danau Formation'.

Later authors tended to consider them Triassic (e.g. van Es, 1918; Umbgrove, 1935; Krekeler, 1933; ter Bruggen, 1935), and Krol (1930) distinguished between a Lower Cretaceous clastic subdivision and a pre-Norian (Upper Triassic) subvolcanic unit. Zeijlmans van Emmichoven (1938) even placed the formation in the Permo-Carboniferous to Upper Triassic.

Molengraaff gave the name 'Plateau Sandstone' to the thick-bedded sandstone complexes which unconformably overlie the Cretaceous and older formations, and occur as mesas and plateaus (commonly blockfaulted) from SAMBAS in the west to perhaps as far east (Rutten, 1927) as the upper and middle Mahakam River region. The name was adopted by Wing Easton and others. Although Molengraaff at first considered the possibility that the 'Plateau Sandstone' might be older than the Melawi deposits, foraminifera from similar rocks in the Mahakam area to the east showed a late Miocene age (*in* Rutten, 1927, who expressed doubt as to whether the sampled rocks were 'Plateau Sandstone'). Since Molengraaff's work, the 'Plateau Sandstones' have been studied by many investigators in Kalimantan and Sarawak. They have been split into a number of separate units with different names and with ages ranging from Senonian to Oligocene and possibly Miocene. The name 'Plateau Sandstone' is no longer used.

European attempts at mining and prospecting

European mining concerns from 1889 tried to enter the gold prospecting and mining business which for so long had been a monopoly of the Chinese. The Goudexploratie Maatschappij 'Bengkayang' prospect at the western foot of the Bawang Mountains was at a site teeming with Chinese alluvial miners (Goudexploratie Maatschappij 'Bengkayang', 1898, 1899, 1900), and the company expected to find a good source of gold in the area.

The first mining engineer and manager reported two 'rich gold-bearing quartz lodes', one of which was running 2 oz of free gold per ton. He was succeeded by another engineer who downgraded the prospect somewhat, recommended sinking in depth on the lodes, and taking up alluvial grounds. An experienced consultant then recommended further expenditure on alluvial gold instead of the lodes. The second engineer was sacked for incompetence, and his replacement reported that the area of good alluvial gold was greatly exaggerated. By then finance, as well as the patience of the Directors, had run out and the venture was disbanded. This appears to have been a common pattern among European companies attempting to get into gold mining, which failed because of undercapitalisation, mismanagement, lack of experience, and underestimation of access and transport problems.

Various dredging ventures met similar fates. They encountered problems such as rough river beds with obstructing sandstone bars; thick beds of sticky clay; concentration of gold in thin basal gravel layers often at near-unmanageable depth, and resting on irregular, stony bedrock; abundant decaying masses of tree trunks; and a lack of gold placers suitable for dredging. These problems endure. Recent Australian ventures in Kalimantan have failed because of undercapitalisation. Australian dredging companies in the Monterado region have experienced similar difficulties.

1900-1923, a period of review

Between 1900 and 1920, the only field work in Kalimantan was done by J. E. Loth in 1916-1917, and H. Frijling in 1917. Fossil samples collected by Molengraaff and Wing Easton were described by Krause (1897, 1904, 1911) and Icke & Martin (1905), and rock samples of Molengraaff were examined by Schmutzer (1909, 1910). Several papers and reviews were published, by Wing Easton (1904, 1914, 1917, 1921), van Es (1918, 1919, 1923), Hövig (1913, 1917), 't Hoen (1917), van Lier (1918) and Grondijs (1917).

Wing Easton's papers

Following Wing Easton's Final Report (1904), he reviewed (1914) the geology of West Kalimantan, maintaining his intrusive 'Quartz Porphyry' group, denying the existence of contact-metamorphic phenomena, and dating the granites as Precambrian. He conceded that the 'Plateau Sandstone' may have been deposited during a large transgression, as Molengraaff (1914) had suggested. Later, ignoring the presence of coal beds in the formation, he speculated (Wing Easton, 1917b) that the associated red mudstone of the 'Plateau Sandstone' might indicate formation in a desert environment. In spite of criticism by van Es (1921) and others, the desert environment model seems to have had some support for similar arenites in Sumatra (see Wing Easton, 1917b).

Wing Easton (1921) was the first geologist to apply Wegener's theory of continental drift, published in 1920, to the origin of the Indonesian Archipelago. He concluded that Indonesia and Malaya had no genetic connection with Southeast Asia, and noted many geological, morphological, and faunal differences between the eastern and western parts of Indonesia. These observations could be accommodated by assuming that east and west Indonesia had originally formed part of a protoantarctic continent, with west Indonesia on the western side of Wilkesland, east Indonesia on the eastern side. The west Indonesian part probably started to drift during the Triassic, while Australia began to move during the Eocene, preceded by the eastern Indonesian part. The western Indonesian part would have arrived at its present site before the Ice Age, while the eastern part settled as late as the Quaternary. Wing Easton's ideas foreshadowed modern plate tectonic theories, which became popular about half a century after Wing Easton's publication!

Loth's travels

J. E. Loth (1918), a mining engineer with the Mijnwezen travelled through parts of TUMBANG MANJUL, KETAPANG, SANGGAU, SINTANG, and perhaps other Quadrangle areas, but the route is not described in his report. He briefly discussed various known formations such as the 'Danau Formation', Melawi beds, Bukit Alat sandstone and Ketungau beds, and mentioned Cenomanian deposits along the Kembayan River, at Beduai, and in other places. He noted that the *Orbitolina*-bearing Cenomanian sediments along the Kembayan River transgressively overlie the granite that had intruded 'Danau Formation' deposits, as the basal conglomerate contained pebbles and boulders of the granite. Consequently this granite had to be Upper Mesozoic but pre-Cenomanian. He concluded that the Bukit Alat sandstone was Eocene, because it resembled Eocene sandstone deposits elsewhere in Indonesia, and because of the chemical composition of the coal layer in the sandstone.

In Loth's view, the Bukit Alat sandstone unconformably overlies the Melawi beds (named by Martin), and he concluded therefore that the latter were most likely to be Upper Cretaceous ('Senonian'), in spite of the Lower Tertiary age determined by Krause and by Martin on fossil evidence. Later, Rutten (1927), a Dutch palaeontologist, criticised Loth's conclusion: the unconformity was by no means accepted fact, and in his opinion there was either no unconformity or at most a very slight disconformity. Rutten suggested that Loth had discarded Martin's fossil determinations without sufficient proof that they were wrong.

Frijling's (1920) visits to the Kotawaringin, Matan, and Pinoh regions

Mining engineer H. Frijling (1920) was sent out in 1917 by the Mijnwezen to evaluate iron ore deposits mentioned by von Gaffron (1853) in the regions of Sampit and Kotawaringin in southwestern Kalimantan, and part of KETAPANG (Matan) and the Pinoh Lands in West Kalimantan. Frijling's geological observations were limited. He found a predominance of granitic rocks, covered in part by 'effusive products of the granitic magma'. More mafic granitoids noted in a few localities were considered to belong to the marginal facies of the main granite bodies. He divided the sedimentary rocks into two groups:

- moderately dipping quartzites with tuffaceous shales, sandstones, greywackes, marly limestones, and limestone, commonly showing contact-metamorphic effects (especially the limestones) where close to granite;
- gently dipping sandstones, argillaceous sandstones, and sandy shales, in which no contact effects were observed; of probable Tertiary age.

Frijling confirmed the existence of von Gaffron's iron ores, and found additional occurrences in southeastern KETAPANG. The deposits are described in an anonymous report (Anon, 1921) probably by Frijling. Two distinct classes of iron ore were recognised: the magnetite–hematite ores and the limonitic ores, the former being regarded as the result of 'pneumatolytic contact-metasomatism' by adjoining post-Triassic granitoids. The report suggested that the limonitic ores represented gossans over base metal deposits. Frijling's original maps (stored in the GRDC archives) showed some iron ore localities in the Semuhar-Ayerdoea area ('Riam Danau') and south of Ayerdua in the northeastern border zone of KENDAWANGAN.

Van Es review of West Kalimantan geology

L. J. C. Van Es (1921, 1923), a geologist and mining engineer of the Mijnwezen, published reviews of geology in West Kalimantan. He concluded that many of Wing Easton's 'Quartz Porphyries' were actually hornfelsed sediments; that the granites, far from being the oldest primeval rocks, must be younger than the Triassic formations because of the observed contact metamorphic effects, and were probably younger than Jurassic. He alone considered the 'phyllitic old slates' to be contact-metamorphosed Triassic beds. He said that some steeply dipping sandstones which both Molengraaff (1902) and Wing Easton (1904) had included in the 'Plateau Sandstone' were somewhat older strata of the Cretaceous 'platy sandstones'. He criticised Wing Easton's habit of drawing outcrops of 'Quartz Porphyries' within 'Plateau Sandstone' where none had been observed, and his ideas about the 'Quartz Porphyries' bringing mineralisation in the region.

Van Es pointed out that mineralisation was around the margins of granites, often within contact aureoles, and Wing Easton's 'Quartz Porphyries' were commonly hornfelsed rocks. The presence of mineralisation in those 'porphyries' was therefore not surprising. Van Es studied Frijling's rock samples, and concluded that many of Frijling's 'Quartz Porphyries' were hornfelsed sediments, which Everwijn 100 years before had correctly mapped as metamorphic shales.

Van Es also suggested that the Eocene Melawi, Ketungau and Belitang Basins once formed one large entity, which became split into three parts by erosion.

A few other published and unpublished reports appeared between 1900 and 1923, including notes on the Sinturu gold mineralisation north of Bengkayang (Hövig, 1913), a summary of contact-metamorphic iron ores in Indonesia (Hövig, 1917) and of ore occurrences of Indonesia by 't Hoen (1917), an overview of the mining industry in Indonesia (van Lier, 1918), and of mercury ores in Indonesia (Grondijs, 1917). They are of little significance.

Systematic mapping of West Kalimantan, 1923-1932

From about 1923 to 1925, van Es was involved in gold investigations in the Chinese Districts, and this work grew into the 'Mineral and Geological Investigation of West Borneo' program (West Borneo Program), led by Krol from 1925 to 1931. When Krol retired in 1931, the leadership was transferred to Zeijlmans van Emmichoven who stayed in that function from 1931 to the end of the Program in 1932.

The West Borneo Program undertook exploration in the following areas (see Fig. 2 for locations):

1925 Reconnaissance of the Paloh District, northern Sambas, by Krol and his assistant Ehrat.

1926 Reconnaissance of the Tayan District and Sarawak, by Krol, Ehrat, and Memelink (Ehrat 1926).

1927 Tayan, Meliau, South Matan and Sarawak, by Krol and Lanzing.

1928 North Matan, Sempang, Pinoh Lands, Kubu, and Sanggau, by Krol, and Lanzing in part.

1929 Sanggau and South Sekadau, by Krol.

1930 Mostly the eastern part of West Kalimantan, with a traverse to the Rajang (Redjang) River in Sarawak, by Krol assisted by ter Bruggen and later also Krekeler.

1931 Krol returned to The Netherlands on sick leave. Field work continued in eastern West Kalimantan and adjoining Sarawak, by Zeijlmans van Emmichoven, Krekeler, and the engineer Ubaghs.

1932 Continuation of field work to mid-1932, by Zeijlmans, Krekeler, and Ubaghs. End of Program.

The region previously mapped by van Schelle and by Wing Easton was excluded from the program, as their work was considered to be satisfactory.

The West Borneo Program, unlike previous surveys, concentrated on the regional geology of a very extensive area instead of focusing on scattered ore and mineral occurrences. The two reports published in 1939 by van Bemmelen and Zeijlmans contain much information, although interpretation of the stratigraphy in West Kalimantan and adjoining Sarawak shows a number of errors which have become clear from later investigations (e.g. see Haile, 1955b). Several thousand thin-sections were described, and 33 chemical rock analyses were made from the western area alone. Because of the paucity of field data and the lack of index fossils, the geological maps were far from reliable, and the geological boundaries sketchy (van Bemmelen). The same applied to the eastern area, which extended from the Sekayam River east to the border with East Kalimantan.

Zeijlmans van Emmichoven's report on the eastern part of West Kalimantan was published in 1939. Krol's illness prevented him from producing a report on the western part. After Krol's death in 1933, the task of compiling a report from his notes fell to van Bemmelen, who had never worked in Kalimantan. He had to rely mostly on the thin-section descriptions by Gisolf (undated) and Esenwijn in 1928, and on Krol's unpublished reports (1929a—d) and field notes, for his report (van Bemmelen, 1939).

The reports of Zeijlmans van Emmichoven (1939) and van Bemmelen (1939) were extensively used by the IAGMP geologists, who revised many of the ideas and stratigraphical opinions expressed in them, redefined old formations and created new ones, brought clarity to some of the problems, and introduced new data on geological ages and large-scale structural elements. The work of Zeijlmans and van Bemmelen has been compiled in the Data Records for the various Quadrangles (unpublished), and in many separate publications. The unpublished reports of their co-workers on which these volumes are based deserve some attention.

Krol (1929?a) confirmed that copper ore had been found near Mount Tampi in the Paloh District in 1846 by a straying English naturalist from Sarawak, and noted that Everwijn had been directed to the wrong mountain of similar name in the Mandor area. The ore sampled by Krol's party assayed 3.8 g/t Au, 8.8 g/t Ag, and 8% Cu (not 8 g/t Cu as printed in van Bemmelen, 1939, 309).

Krol wrote explanatory notes (Figs 5—7) on various Quadrangles including DATO & KUCHING (Krol, 1929?b) and the Paloh region (Krol, 1929?c), and a detailed report on the ore vein systems at Gunung Selakean east of Bengkayang (Krol, 1928?), where he mapped five ore veins containing gold, silver, lead, copper, zinc, arsenic, and traces of bismuth. The thickness of the veins ranged from 30 cm to over 2.3 m, over lengths from 30 m to 650 m. The mineralisation was described as closely related to andesite-induced processes.

Krol (1930a) suggested that Triassic, Jurassic, and Cretaceous strata could be identified and mapped on the basis of their different strike directions, but this attracted little support (Krekeler, 1932b)

The geologist Krekeler worked for the Mijnwezen mainly in the Sekayam/upper Landak River and the Ketungau and Belitang Rivers areas, and also made traverses in Sarawak and along the upper Melawi River. His unpublished reports (1933b, c, 1934) contained detailed observations along well described routes that can be easily retraced. He collected numerous fossils, tried hard to deduce the ages of various formations, and included sketches and locality maps, and descriptions of thin-sections. His work was thorough and conscientious, and he probably deserved much greater credit than he seems to have received.

Other separate publications on the Program's work were by Krekeler (1932a, 1933a) on a new occurrence of Permo-Carboniferous and Triassic rocks and fossils in Sarawak; and by Esenwein (1932) on corundum and diaspore pebbles ('lebur' stones) in the diamond fields of West and Southeast Kalimantan. Ubaghs and Zeijlmans van Emmichoven published a joint paper (1936) on the Palaeogene of Borneo.

Zeijlmans van Emmichoven also published a paper on the Eocene south of the Keriau River (1935), a summary of the geology of Central Kalimantan (1938), and a paper on the Tertiary west of the Lakes district (Zeijlmans van Emmichoven & ter Bruggen, 1935). Ter Bruggen published an article on the lower Tertiary in phyllitic facies in West Kalimantan (1932), and a thesis on the Eocene age of the phyllite formation in Central Borneo (1935). This led to a spirited public debate with Zeijlmans, who was firmly convinced of a Cretaceous age (Zeijlmans van Emmichoven & Ubaghs, 1936 a–c; ter Bruggen, 1936). Later work supported ter Bruggen's opinion, though some of the phyllites are indeed Cretaceous.

Other activities, 1923 to World War II

Working independently of the West Borneo Program, De Kroes (1926) from 1922 to 1925 carried out government auger and Bangka drilling programs for gold in selected areas of the Chinese Districts (Fig. 8), as well as a reconnaissance auger drilling traverse from Bengkayang to the Landak River, panning numerous alluvial and soil samples on the way. The results were generally disappointing.

In 1927, Rutten reviewed the geology of Indonesia, up to the end of van Es's work. He noted with satisfaction that geologically, the Indonesian part of Borneo was better known at his time than the Malaysian part. He was inclined to believe van Es's conclusion that many of the 'Quartz Porphyries' of Wing Easton were hornfelsed rocks, but criticised van Es for not having provided hard evidence in the form of thin-section descriptions and photographs, pointing out that Wing Easton's work had been the result of 'years of untiring field work and laboratory studies' and therefore warranted a more convincing presentation of counter arguments. Rutten also took a midway position between the two mutually opposed opinions of Wing Easton and van Es regarding the age of the granites. He was the first to suggest that there were two main ages, with the younger granites distributed in a northern belt, and the older granites in the Schwaner Mountains and the southwestern part of Kalimantan. Lastly, Rutten rejected van Es's idea that the phyllitic 'old slates' were contact-metamorphic sediments, stating that they were 'typical products of regional metamorphism'.

Rutten was not convinced that the three small volcanoes described by van Schelle (1886) and Wing Easton (1889) from northwestern SANGGAU were indeed volcanoes, and he disclaimed van Schelle's assertion that the Gunung Melabu volcanics contained nepheline[5]. Rutten (1927) summarised the work of Krause, Vogel, and other palaeontologists on the collections gathered by van Schelle, Koperberg, and Wing Easton. These collections indicated that significant parts of the so-called Triassic 'old slates' were Jurassic and Cretaceous, although finds of *Monotis salinaria* indicated that some of the 'old slates' were indeed Triassic.

Wing Easton (1925) had proposed that diamonds were derived from altered peridotites (sensu lato). He had a published debate in 1930-1931 with the Mijnwezen mining engineer P. Hövig on diamond genesis (Wing Easton, 1933), Hövig maintaining that diamonds were produced in acid igneous rocks. An excursion to south Kalimantan, led by W.C.B. Koolhoven, resolved the question when some small diamonds were found in a 'weathered ultrabasic rock' which resembled the 'blue ground' of the South African diamond fields (Wing Easton, 1933). Hövig (in a postscript to Wing Easton, 1933) gracefully acknowledged defeat. Much later (Bergman & others, 1987) it was found that the 'intrusive ultrabasic breccia' is more likely to be of sedimentary origin.

An independent engineer, H. Witkamp (1932 a, b), carried out field investigations of diamond concessions in the Sekayam River area for a private concern. His detailed report contained a locality map and described his six terrace levels and their relation to the diamond occurrences. According to Witkamp the diamonds had been transported over very long distances from their area of origin.

[5] This is still possible as leucite basalt has been described by H.A. Brouwer (*in* Rutten, 1927) from the source area of the Kayan River in LONG NAWAN, showing that alkali basalts do exist in Kalimantan.

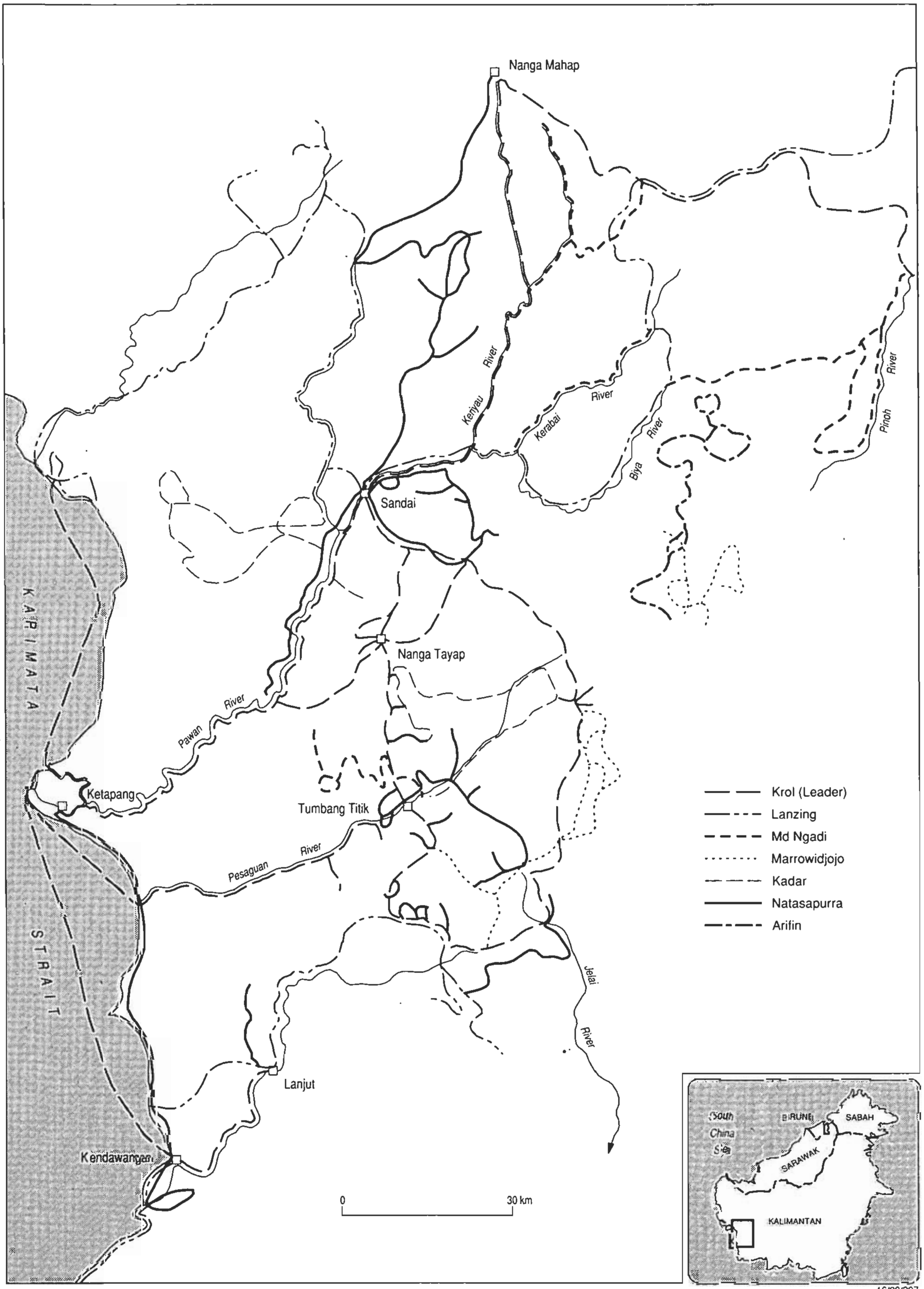

Figure 5. Traverses by Krol's parties in southwestern West Kalimantan.

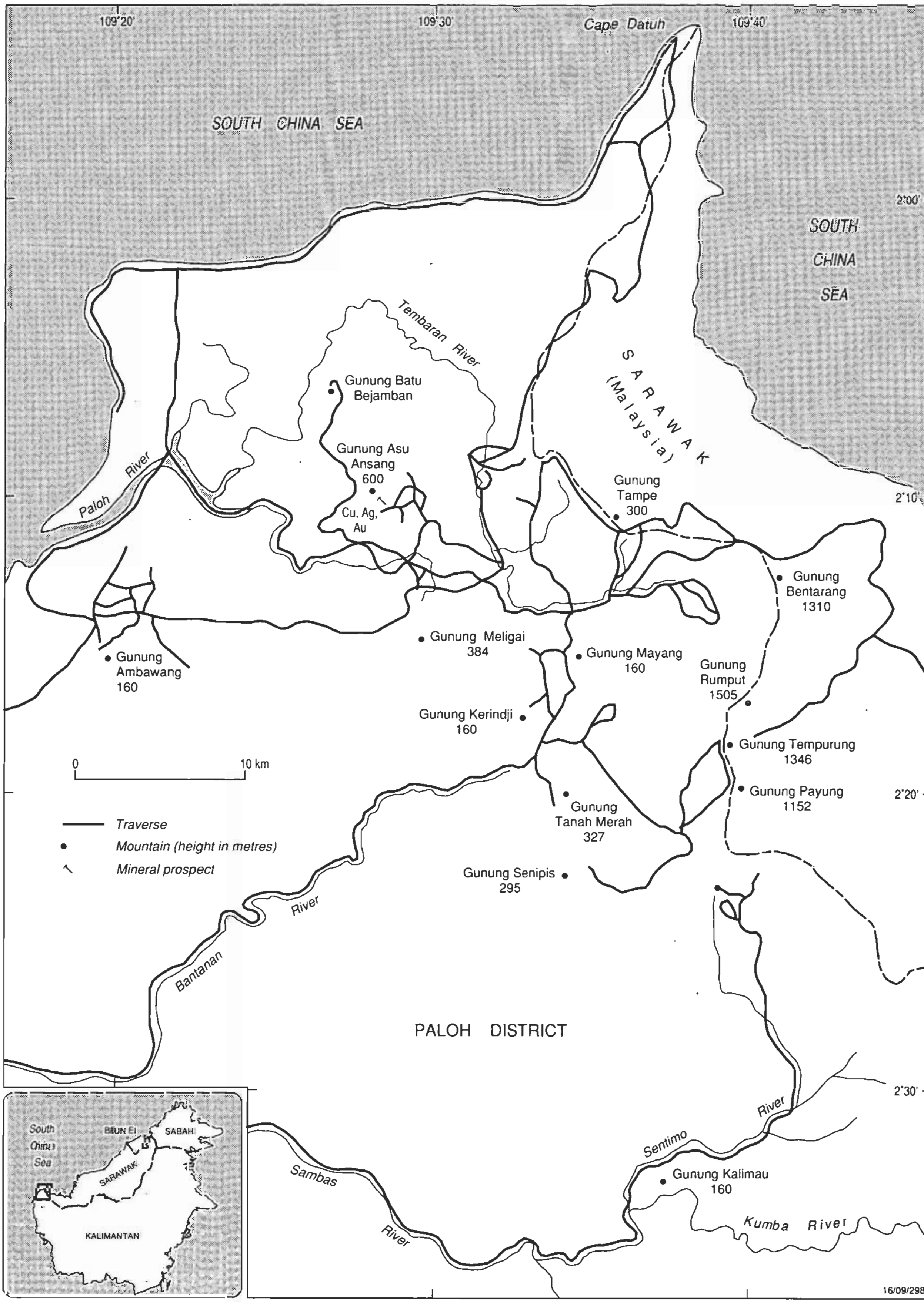

Figure 6. Krol's traverses in the Paloh district, northern SAMBAS.

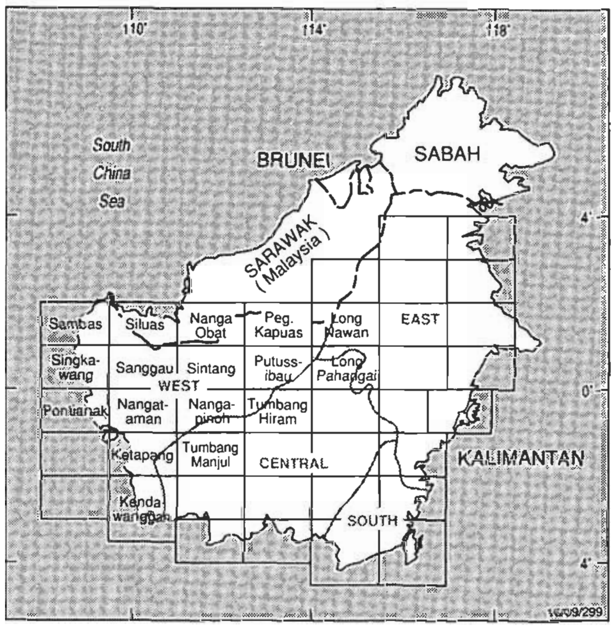

Figure 7. Location of 1: 250 000 Quadrangles covering West Kalimantan.

Umbgrove (1934, 1935a) rejected Wing Easton's 13 year old theory of continental drift solution, and the Dutch geomorphologist G. L. Smit Sibinga (1935) responded in defense of Wing Easton.

Schlaich (1939) reconnoitred the Melawi Basin in 1939 for the BPM/Shell oil exploration company. He noted many contradictions in the older literature. Although Zeijlmans van Emmichoven (1938) considered the 'Plateau Sandstone' to be an upper sandy facies of the Palaeogene 'Melawi Series', with the Silat Shale representing a lens within the 'Plateau Sandstone', Schlaich concluded that the 'Plateau Sandstone' was Eocene, and disconformably or unconformably overlies the 'Melawi Series' (also Eocene). Despite a few oil indications in a limnic facies lens of the Silat Shale, Schlaich concluded that the stratigraphic conditions were not favourable for the formation of economic oil reserves. However, he did recommend a closer investigation of one or two anticlinal structures.

At the completion of the West Borneo Program in 1932, systematic geological field work ceased, and activities were confined to studies of mineral occurrences and the writing of reviews. Much of this work remained unpublished because of the sudden interruption of World War II, with Japanese forces occupying the country in February 1942.

J. G. H. Ubaghs (1940), a Mijnwezen geologist, reviewed various copper, lead and zinc occurrences, the Selakian veins, the Chinese district copper shows, and the Kendawangan lead-zinc pods in West Kalimantan, but did not contribute anything new. From his discussion of the Tampi copper locality it is clear that he had not read Krol's report and was still unaware that Everwijn had investigated the wrong mountain. In his review of diamonds in Kalimantan (1941), he noted that both Wing Easton (1904) and Krol (1920) had recorded three diamondiferous areas in West Kalimantan: Landak, Sekayam River, and the Kapuas River near Semerangkai. Van Es had recorded many more locations, including the Menyukai (Menjoekai) River which according to Wing Easton (1904) did not contain diamonds. Van Es probably confused Darit village on the Menyukai River with the locality Nanga Darit in the Upper Sekayam basin, where diamonds had been recorded. Everwijn (1879) had mentioned two additional sites on the Kapuas River, within 20 km upstream and downstream of Sanggau.

Zeijlmans van Emmichoven (1939b), too, reviewed the mining industry in Kalimantan and its economic future. He stated that since 1889 several European managed gold mining companies were established, which had generally been short-lived and unproductive. Two mines opened in 1935 and 1936 had had some success, though output in one (Serantak) had strongly declined in the 4 years of its existence. Production in the other mine (Pandan) had shown a healthy increase. Despite this, Zeijlmans remained very pessimistic about the future of the gold mining industry and the potential of the known occurrences of base metals, diamonds, mercury, molybdenum and other ores.

However, in 1941 Zeijlmans van Emmichoven (1941a, b) adopted Everwijn's view that ore grades might increase with depth, and agreed that the Chinese miners could not delve deeper than 15 m. He drew attention to large discrepancies between field and laboratory gold assays of finely disseminated sulphidic ore. In one case, the field determination was 0.055 g/t Au, and the laboratory chemical assay result was 17 g/t Au. In another case, the results were 0.4 g/t Au (in the field) and 4.0 g/t Au (laboratory). Similarly, gold values from the Hang-Moei-San mine obtained by the laboratory were about 300 times higher than those obtained in the field. Zeijlmans therefore concluded that the potential of sulphidic vein gold deposits could not be written off, because efficient extraction of very fine-grained gold from sulphides should be feasible by modern technology. He also recommended that future exploration include testing in depth, as suggested by Everwijn many years before. The underground Pandan mine was used to demonstrate increasing richness in silver content with depth, and smaller increases in gold. According to an analytical result slip Zeijlmans found at the mine, a channel sample of the main vein in depth contained 8.16% Cu, 170 g/t Au, and 156.4 g/t Ag.

At the instigation of Zeijlmans van Emmichoven, the small molybdenite shows first reported by Wing Easton from the headwater region of the Ledo River, 10 to 13 km northwest of Bengkayang, were investigated in detail by Faddegon (1941b), who located eight outcrops of molybdenite-quartz veins in granite. The molybdenite was commonly coarsely crystalline (in books up to 1 cm across), but also occurred finely disseminated in impregnation zones. Accompanying minerals included pyrite, some chalcopyrite, scheelite, and sparse magnetite and hematite. 'Casserite', mentioned in his report, could not be found by JICA (1982) geologists who suspected that Faddegon had mistaken some sphalerite for cassiterite in his thin-sections. Faddegon concluded that the molybdenite deposits had no economic potential.

Zeijlmans van Emmichoven (1940a) investigated another molybdenite prospect at Mount Benaul, 20 km southwest of Ngabang, where the mineral had first been found in about 1900. He found a little molybdenite in only one of the four pits dug, and considered the prospect to have little potential.

In 1941, Faddegon (1941a) visited the cinnabar prospect at Sekireh, near Lumar. Although generally thought that cinnabar was derived from the hydrothermally altered basic volcanics at the prospect (Van Schelle, 1884a, 1887c), Faddegon concluded that the mineral was genetically associated with a silicified quartz keratophyre in the locality.

The Mijnwezen geologist M. A. Koolhoven (1941) advised the Dutch East Indies government on a proposal to reserve two areas (in central Sumatra and West Kalimantan) that contained prospects of strategic minerals. His report contained two appendices: one by Faddegon on Sumatra, the other by Zeijlmans van Emmichoven (1941b) on various metals in West Kalimantan.

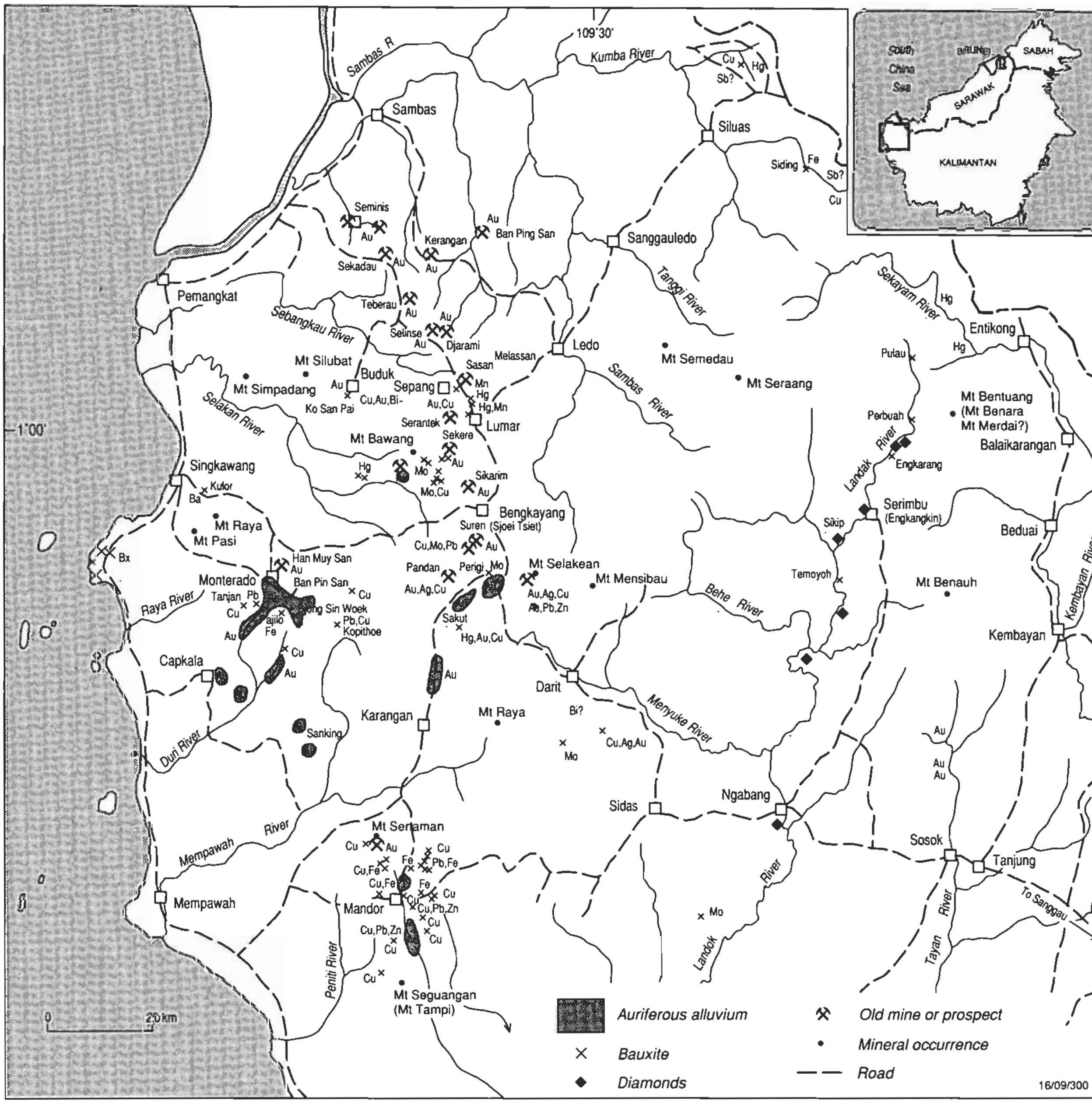

Figure 8. The Chinese districts.

1942-1966: the dead years of World War II and its aftermath

During the War, geological investigations were scarce or remained unreported. The Japanese did carry out some small-scale mining of manganese from three localities in the Lumar area (Hirata, 1944; Tarring & Bellows, 1952) and mercury from the Tebaung (Nambah) River in PUTUSSIBAU (Surono & Noya, 1989). Small-scale geological surveys probably accompanied those activities.

After the War, times remained turbulent during the Indonesian struggle for independence. There was a marked decline in mining because rehabilitation and modernisation of existing mines was hampered by lack of capital, and private investment was not encouraged (Sigit, 1973). A few papers were written abroad, including the following:

Beltz (1944) reviewed sedimentary basins in Indonesia and their potential for oil deposits. In West Kalimantan this included the Melawi River Basin, which he described as a lower Tertiary embayment of thick terrestrial deposits and volcanics interbedded with some brackish water deposits, perhaps with some marine incursions. An oil seep was reported from the eastern end of the basin in shales of presumed Eocene age.

Zeijlmans van Emmichoven (1946) reviewed the cinnabar occurrences around Lumar, originally discussed by van Schelle (1884a, 1887c) and later investigated by Faddegon (1941a). According to Zeijlmans, the quartz keratophyre contained irregular pipe like cavities filled with clay very rich in coarse cinnabar, which also impregnated the cavity walls in finely disseminated form.

De Roever (1946) summarised Zeijlmans 1946 report, adding that 'most mercury deposits in the world are associated with great tectonic lines ... and many are genetically related to young igneous rocks'. He noted that the mercury deposits in the Boyan River region, too, were associated with such zones of tectonic disturbance, and occurred in Cretaceous sedimentary regions, which in West Kalimantan often have some bituminous content.

The most important contribution was a compilation and synthesis of the geology and mineralisation of Indonesia by van Bemmelen (1949, reprinted 1970), commissioned by the Dutch government. Van Bemmelen lost his original manuscript during the War, and took three years to rewrite it.

In 1952, Tarring & Bellows made a quick reconnaissance of mineral deposits in the Chinese Districts, including a gold vein at Gunung Serantek west of Lumar, the manganese prospects northwest of Lumar, cinnabar at Sekere, bauxite at Roban on the Bengkayang road 3 km from Singkawang, and kaolinite in a swamp 5 km southeast of Singkawang. They also mentioned the existence of a stockpile of manganese ore at Sentete on the Sambas River, left there by the Japanese.

Westerveld (1952) published a tectonic scheme of Indonesia in which four orogens in ever widening zones spread themselves towards the Indian Ocean, each orogen characterised by a specific mineralisation pattern, composition, and age. In his view, West Kalimantan belonged to the Late Jurassic Malayan Orogen which also included the Malay Peninsula and the Indonesian tin islands. Katili (1974) found numerous discrepancies in this scheme and concluded that it could not be used as a basis for mineral exploration.

In 1954, Westerveld compared the radioactivity and chemistry of the granites of West Kalimantan with those of the tin islands, and concluded that the chances of discovering tin deposits in West Kalimantan were slim.

In 1960, the IMCO, C.Itoh, & Meiji Mining companies investigated low-grade bauxite deposits discovered after the War along the coast 15-20 km southwest of Singkawang township. A second report was produced a year later (Meiji Mining, C.Itoh, & Kishimoto Schoten). The four bauxite bodies overlie granodioritic rocks.

When the Geological Survey Department of British Borneo was established in 1949, and started their own systematic geological surveys, the Dutch literature became of growing interest to their geologists. A selection of 10 Dutch written papers was therefore translated into English (see Haile, 1955a), including papers by Krekeler, Krol, ter Bruggen, and Zeijlmans van Emmichoven & Ubaghs. There were a number of points on which the Sarawak geologists disagreed with the old Dutch ideas; they are summarised by Haile (1955b) and include the age and relationships of the 'Danau Formation', the phyllite formation, the fault system west of the Lakes district, and the Kantu and Engkilili Beds.

1967-1990: from slow recovery to accelerating development

Government policy after 1965 strongly favoured mineral exploration and development. In 1967, the Foreign Capital Investment Law was introduced, together with the New Mining Law, and competitive bids were invited from private companies for the exploration of 53 separate units of potential mineral-bearing land, averaging 9000–10000 km² (Sigit, 1973). Geological investigations started to concentrate on age determinations, palaeomagnetics, and regional structural and tectonic syntheses culminating in plate tectonic theories. Later, Indonesian government agencies undertook joint projects in partnership with overseas governments and institutions. The Indonesia-Australia Geological Mapping Project was one of the latest and most comprehensive examples of such joint projects.

Exploration for oil, gold, uranium, tin, diamonds, bauxite

One of the first companies to enter Indonesia on the basis of the New Mining Law was ALCOA, whose Indonesian offshoot Alcoa Minerals of Indonesia (PT Alcomin) from 1967 to 1971 prospected for bauxite in large parts of the country, including West Kalimantan, where large tonnages of low grade bauxite were outlined in the Sandai region, KETAPANG. However, economic feasibility was marginal, and exploration ceased when prices slumped on the world market. The Billiton Maatschappij included the coastal zone of southwest Kalimantan in an exploration program for offshore tin deposits between the Karimata Islands and the Kalimantan coast. Between 1969 and 1979 a joint BATAN/CÉA (Badan Tenaga Atom Nasional/Commissariat à l'Énergie Atomique of France) search for uranium in a huge part of Kalimantan resulted in the discovery of a mineable deposit in the Ela Ilir (or Kalang) region, NANGAPINOH. Its geology and mineralisation are described in several papers (in International Atomic Energy Agency, 1988).

Over the years a number of oil and mineral companies have prospected and explored in West Kalimantan, but their amassed data have remained largely confidential. Among the oil companies have been the BPM (Bataafse Petroleum Maatschappij, i.e. the Shell exploration branch) (Schlaich, 1939), BP Petroleum Development Ltd. (Buchan, 1973), Union Oil Company of California (Wories, 1974) and Total and Elf-Aquitaine of France, following a reconnaissance by Pertamina. All of these companies showed interest in the Melawi and/or Ketungau Basins. Some of the mineral exploration companies and semi-government agencies that have looked into West Kalimantan are Anaconda (including diamonds), BP Minerals International, the French Commissariat à l' Énergie Atomique (CÉA) in joint venture with BATAN, and Esso Minerals. Most attention has focused on gold and diamonds, but the BATAN/CÉA Joint Venture was specifically searching for radioactive minerals.

The last 5 years have seen a remarkable boom in gold exploration, after an improved 'fourth generation' Contract of Work (COW) made entry more attractive to foreign interests. In West Kalimantan these have included BP Minerals, Pelsart, Duval, Jimberlana Minerals, Rio Tinto Indonesia, Jason Mining, Dominion Mining and Reniso Goldfields. Successful finds have been made in East and Central Kalimantan, but not yet in West Kalimantan, where Rio Tinto Indonesia has had problems with its gold dredging operations at Mandor (opened up in late 1988), and development work appears to be continuing on the Monterado alluvials. As in the old days, many companies have proved to be small and undercapitalised and, when hit by the October 1987 share market crash, tried to sell off their interest to more powerful concerns.

The history of mineral exploration by foreign companies in Indonesia 1967-1991 has recently been reviewed in a very useful paper by van Leeuwen (1991), who discussed various technical aspects, certain geological features of the more important new discoveries, and the evolution of the Contract of Work system.

Geological investigations

Geological investigations after 1967 started to concentrate on age determinations and regional structural and tectonic syntheses, later followed by a long list of plate tectonic papers which reached the most contrasting and varied range of conclusions imaginable. In neighbouring West Sarawak, systematic geologic mapping programs since the end of World War II have added greatly to understanding of the geology there. Those related to the geology of the border zone with West Kalimantan include Haile (1954, 1957), Wilford (1955, 1965), Wolfenden & Haile (1963), Wilford & Kho (1965) and Tan (1979, 1982).

Muller (1968) dated the microflora in 'Plateau Sandstone' samples from the Kayan and Penrissen areas in Sarawak as Senonian-Eocene. Haile (1972) preferred the (post-)Eocene ages suggested by larger foraminifera, saying that 'dating by pollen is not well established in Southeast Asia' so that the microflora age could be unreliable. Pollen from a shale specimen collected by Haile

(1973) from an outcrop mapped as Triassic(?) 'Ketapang Complex' on the Pawan River, Ketapang Sheet, was determined to be Cretaceous by H.J.Barten of Brunei Shell Petroleum Company, which led Haile to suggest that most of the formation might be Upper Cretaceous.

A palaeomagnetic investigation including radiometric dating on igneous samples was made in the NANGATAMAN, KETAPANG, and KANDAWANGAN areas (Haile & others,1977), and further radiometric dating from the Tambelan and Bunguran Islands (Haile & Bignell, 1971) established mostly Cretaceous ages. Other radiometric dates were obtained by the French during their joint BATAN/CÉA uranium exploration (Guéniot 1976). The latest radiometric ages of granites and volcanics have been obtained during the IAGMP.

Hashimoto & others (1975) reviewed Cretaceous palaeontology and ages in Southeast Asia, including Borneo, and Hashimoto & Matsumaru (1974) redefined the *Orbitolina* fauna from the Seberuang Cretaceous.

The Cretaceous and Tertiary stratigraphy of Borneo and its equivalent in West Kalimantan was discussed in considerable detail in an interesting unpublished work by Buchan (1973), who used invalid formation names unknown in the published literature.

Controversy still exists about the age, correlation, and palaeoenvironment of the various rock units on either side of the border. For example, estimates of the age of the phyllitic unit ('old slate formation', 'phyllite formation', 'Sembakung Formation', etc.) have ranged from Devonian to Eocene! Structural complications commonly obscure normal boundary contacts. Molengraaff, for example, had already recognised the existence of a 250 km long, east-west running fault zone which separates the phyllitic formation in the north from the 'Danau Formation' to the south. According to Haile (1957), the 'Danau Formation' interfingers with the flysch sediments of the Lupar Formation in Sarawak. Buchan (1973) bundled together the 'Danau Formation', the Lupar Formation (in West Sarawak), and the Bunguran Beds (on the Natuna Islands), creating a 'Danau Group' which, together with the Ujut Group and another group, is part of his 'Rajang Supergroup'. On fossil evidence, Haile attached a Late Cretaceous age to the 'Danau Formation' in Sarawak.

Buchan further described the Ujut Group as a thick flysh sequence which included his 'Sembakung Formation'. In northeastern West Kalimantan this sequence had been called the 'phyllite formation' by ter Bruggen (1932, 1935), and 'old slate formation' by Molengraaff. The latter was uncertain of the age of the 'old slates' (which he regarded as a continuation of the 'old slates' of the Chinese Districts), suggesting at one stage that the unit was older than the Danau Formation, and on other occasions that it might be Tertiary.

Buchan's (1973) age for the 'Sembakung Formation' in Sarawak is Late Cretaceous to Middle and Late Eocene, which agrees with the age estimates of both ter Bruggen (1935, 1936) (Eocene) and Zeijlmans van Emmichoven (Zeijlmans van Emmichoven & Ubaghs, 1936a, b) (Late Cretaceous). The equivalent formation in West Kalimantan has been renamed the Embaluh Group by the geological team of the IAGMP, and is thought to be Eocene.

Tan (1982) found Early Eocene nannofossils in the sheared pelitic matrix in his Lubok Antu Melange in the Lupar Valley, West Sarawak. The melange consists of blocks of Lower Cretaceous radiolarian chert; Upper Cretaceous greywacke and slate; ?Cretaceous and Eocene limestone; mudstone, sandstone, hornfels, basalt, spilite, gabbro, and serpentinite. He postulated that the melange was caused by early Tertiary southeast subduction of oceanic crust.

Pulunggono (1985) reviewed the history of geological investigations and theories in the general region of Sundaland, concentrating on Sumatra, and barely touching on West Kalimantan.

The global structural setting and development of Borneo have been discussed by many authors. The earliest (Wing Easton, 1921) used Wegener's continental drift theory (see above). Some 40-50 years later, the structural setting of Borneo was described in terms of the geosynclinal concept (e.g. Haile, 1969, 1972; Klompé & others, 1961). With the renaissance of a revamped continental drift theory in the form of plate tectonics, a spate of papers has been published since 1972 on the origin of the global features in the Southeast Asian and western Pacific region (e.g. Hamilton, 1972, 1973, 1979; Haile, 1973a, b, 1979, 1981; Katili, 1973, 1974, 1975; Pupilli, 1973; Ben-Avraham & Uyeda, 1973; Hamilton, 1976; Ben-Avraham, 1978; Shield, 1979; Ridd, 1980; Taylor, 1980, 1983; Audley-Charles & others, 1981; Stauffer, 1983; Hutchison, 1984; Sengör & Hsü, 1984; Sengör, 1985, 1986; KeRu & Pigott, 1986). In these speculations, Borneo was variously thought to have been derived from Southeast China, Indochina, the Antarctic (Wing Easton, 1921), a cluster nestled in between North and South America, Southeast Asia, and Australia before the opening of the Pacific Ocean (Shields,1979), or as an agglomerate of microcontinents derived from southeast China and Western Australia

Joint Indonesian/foreign agency projects

After 1970, several countries undertook joint projects with Indonesian government agencies. Following Indonesian/American reconnaissance geochemical sampling in the region from 1970 to 1973, a joint Indonesian/Belgian geochemical survey (Viaene & others, 1981) carried out detailed geochemical sampling in the Gunung Pasi/Gunung Rajah area between Singkawang and Monterado, with accompanying geological mapping to correct Wing Easton's (1921) old map and to assist in interpretation of geochemical results.

A detailed Indonesian/Japanese joint venture program of geological, geophysical, and geochemical investigations was undertaken over a three-year period from 1979 to 1982 (JICA, 1982), encompassing an area of roughly 1500 km^2 straddling the border between SINGKAWANG and SANGGAU. Survey methods included airphoto interpretation, mapping, geochemical and geophysical surveys, petrographical and palaeontological studies, chemical analyses, radiometric dating and mineral studies. Results included recognition of granites of two different age groups; a subdivision of the Upper Triassic/Jurassic stratigraphy; and clarification of the types and distribution of mineralisation.

The program concluded that:

- the 'Matan Complex' in the KETAPANG area may be correlated with the Jurassic sediments in the JICA survey area;
- two ranges of granite ages exist: 124-95 Ma and 27-20 Ma. The granitoids belong to the calc-alkaline series and are of the 'magnetite-type';
- West Kalimantan appears to form part of the Cretaceous magmatic arc that extends from South China through the southern part of Indochina to West and Central Kalimantan;
- about six types of mineralisation can be recognised, involving gold, base metals, molybdenite and manganese. They are genetically associated mostly with the Late Cretaceous to Miocene plutonic and subvolcanic events;
- stream sediment sampling and geological mapping can together outline mineralised zones on a regional scale;

- soil geochemistry and geophysics along with detailed geological surveying are very effective in estimating the distribution range and grade of mineralised zones in detail.

In view of the detailed character of the JICA survey, it is somewhat surprising that the long-lost Pandan mine was not rediscovered.

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Appendix 1. Spelling of Bahasa Indonesia

Pre-World War II written Bahasa Indonesia used spelling rules based on Dutch phonetics. Since Indonesia obtained its independence, spelling conventions have changed. This might cause some confusion when reading pre-War reports, and the following explanation of the main differences is therefore provided:

Old	*New*	*Pronunciation*	*Examples*
oe	u	as in broom, doom	boekit → bukit goenoeng → gunung batoe → batu
tj	c	'tj' as written Almost, but not quite, as 'c' in church	tjap = cap Tjitaroem → Citarum
j	y	'y' as in yellow	Japen → Yapen Soerabaja → Surabaya
dj	j	'j' as in jovial	djalam → jalan djam → jam
c	s	before the vowel 'e' a normal 's' sound	Ceram → Seram

Thus, 'Tjiandjoer' has become 'Cianjur', 'Tjioedjoeng' is 'Ciujung', 'tjatjing' is now 'cacing', 'tandjoeng' is 'tanjung', etc. The unstressed 'a' is usually written 'e' in the Dutch custom, as in 'Melajoe' for Malayu, where the stress falls on the second 'a'. Note that the pronunciation remains the same. Many Indonesians preferred to retain the old spelling of their names, others conformed to the new spelling. Therefore we may find, side by side, Suharto and Soeharto, Sukarno and Soekarno, Yanus and Janus, Priharjo and Prihardjo, etc.

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