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Geological characteristics of certain coastal and offshore placers as essential guides for tin exploration in Sundaland, Southeast Asia

BRIAN C. BATCHELOR[1]*

"*A formation of very great importance in the consideration of the geology of Malaysia in its economic aspects is the alluvium... It seems evident, therefore, that a detailed study of the composition, the succession, and the time and method of formation, of the alluvial deposits of the country is as urgently required as any other form of geological research, for upon a correct understanding of the alluvium may depend the discovery of further deposits of tin-ore at present buried.*"

Sir Lewis Fennor, Report upon
the Mining Industry of Malaya
(1940, p. 18)

Abstract: Since over 95% of present tin output in Malaysia and Indonesia is mined from the "alluvium", and a considerable proportion of future production will derive from deeply buried coastal and submerged offshore placers where accurate target definition based on sound geological concepts is essential to reduce high exploration expenditures, greater emphasis need be given to integrated studies of the Late Cainozoic stratigraphy and the associated placers.

Offshore drilling and seismic data, and investigations of adjacent coastal mines, indicate that discontinuously rising Late Cainozoic eustatic sea levels and accompanying climatic changes have been the major controls on Sundaland sedimentation, facilitating regional lithostratigraphic correlation and subdivision into Sundaland Regolith (Late Miocene to Early Pliocene), Older Sedimentary Cover (Early Pliocene to Early Pleistocene), and Young Alluvium (Late Pleistocene to Holocene).

A tentative time framework for the depositional history and tin placer evolution appears as follows. The Sundaland Regolith, including lateritic soils and primitive eluvial/colluvial (*kulit*) placers, first developed under a semi-arid climate. Unconformably overlying Older Sedimentary Cover represents a piedmont fan facies (e.g. Boulder Beds) adjacent to bedrock scarps, demarcated downslope from a finer alluvial plain facies of Old Alluvium. Rich piedmont (*gugup*) placers are exemplified by the Western Boulder Clays in the Kinta Valley. Near the end of the Early Pleistocene, increased precipitation resulted in stream entrenchment forming residual-elutriational (*kaksa*=*karang*) and braided stream (*kaksa* and *mincan*=*karang gantong*) placers. Following a lateritisation phase, a second braided stream entrenchment resulted in further placer reworking and redeposition downstream as a younger mincan series within the Transitional Unit. Superficial reworking to form beach placers followed during two major transgressions across the Sunda Shelf, responsible for the "Older marine unit" and Younger Sedimentary Cover. Drop of sea level following the first transgression resulted in deep meander incision and placer destruction, and although subsequent fill was generally tin-barren, these young valleys have been deceptive targets for previous unsuccessful offshore exploration ventures.

The search for tin should take account of the fact that the major Southeast Asian sources are piedmont fan, braided stream and residual-elutriational placers formed on the emergent Sundaland continent within Older Sedimentary Cover (and Transitional Unit), and localised on the flanks of positive granite features and in adjacent shallow bedrock troughs. The Indonesian "Tertiary" series have a similarly high potential. Seismic interpretation of stratigraphic "pay horizons" should provide the main basis for future drill target definition and the delineation of offshore placer boundaries.

[1]Department of Geology, University of Malaya, Kuala Lumpur, Malaysia.
*alias Daud Abdul Fattah

INTRODUCTION

Exploration and mining trends strongly indicate that a considerable proportion of future tin production in Malaysia and Indonesia will derive from coastal and offshore placers. Classical inland mining will probably show a gradual production decline since, in Malaysia 80% of gravel-pump mines are operating on previously worked ground (Lim, 1977), and in Indonesia land reserves are rapidly diminishing (Sutedjo, 1974, 1977). In Malaysia during 1977, the three largest producers (Berjuntai Tin Dredging, Malayan Tin Dredging and Selangor Dredging) were operating almost entirely in coastal areas. Additionally, there have been significant placer discoveries at Kuala Langat on the Selangor coastal plain and in the Perak, Negri Sembilan and Malacca offshore areas. The Kuala Langat placer in particular, is believed to be "the biggest tin deposit area ever discovered in the world", with at least 300,000 tonnes of proven tin reserves (Hashim, 1978). Prospecting data provided by Singh (1978) gives considerable encouragement that many more deep coastal placers will be mined along the west coast in the foreseeable future. Fortunately, these are all dredging propositions. This mining method has been least affected by the inflationary cost spiral of recent years (fig. 1) and allows greater volumes of lower grade ground to be worked (fig. 2). In Indonesia, over 50% of the tin resource potential is now believed to lie in offshore areas (Simatupang, 1977). In contrast to onland mining, offshore dredging costs are significantly cheaper (Gocht, 1977, table 2), and average grades mined from the virginal deposits are much greater, and have dramatically doubled in the 1971–75 period (fig. 2).

For priority targets of deeply buried coastal and submerged offshore placers, surface indications are rarely found, and exploration expenditures are significantly higher than for the shallower inland targets. The discovery of these more elusive deposits will therefore require a more sophisticated geological approach with a better understanding of the Late Cainozoic regional stratigraphy and tin placer relationships, resulting from the application of seismic, drilling, sedimentology and stratigraphic techniques to the ore discovery problem.

The four offshore areas included in the present study are outlined in figure 3. These areas are spread along a considerable length of the Main Western Tin Belt which extends further north into Thailand and Burma, but apparently terminates to the south just below Bangka and Belitung Islands. From north to south the concessions are held by Pernas Mining, Malaysia Mining Corporation, the Billiton Company and P.T. Koba Tin.

My interpretations are based on offshore shallow seismic profiles and drilling data, as well as field samples collected from adjacent coastal open-cast tin mines. The similarity of seismic and lithological characteristics and general sedimentational environment, as well as the presence of major hiatuses allowing stratigraphic subdivision, facilitates lithostratigraphic correlation of Late Cainozoic sequences over 1000km apart (refer Ringis, 1976; Batchelor, 1976, 1977; Ryall and others, 1977). This is possible because the Sundaland craton (including Tin Belt areas) has been stable since the Miocene (Stauffer, 1973; Batchelor, in manuscript) and major sedimentational controls have been of a regional nature.

EUSTATIC SEA LEVEL CONTROL OF LATE CAINOZOIC SEDIMENTATION

Suggestions by Hosking (1969, 1971) that eustatic sea level fluctuations have been a major influence on the genesis of tin placers led me to undertake a major review

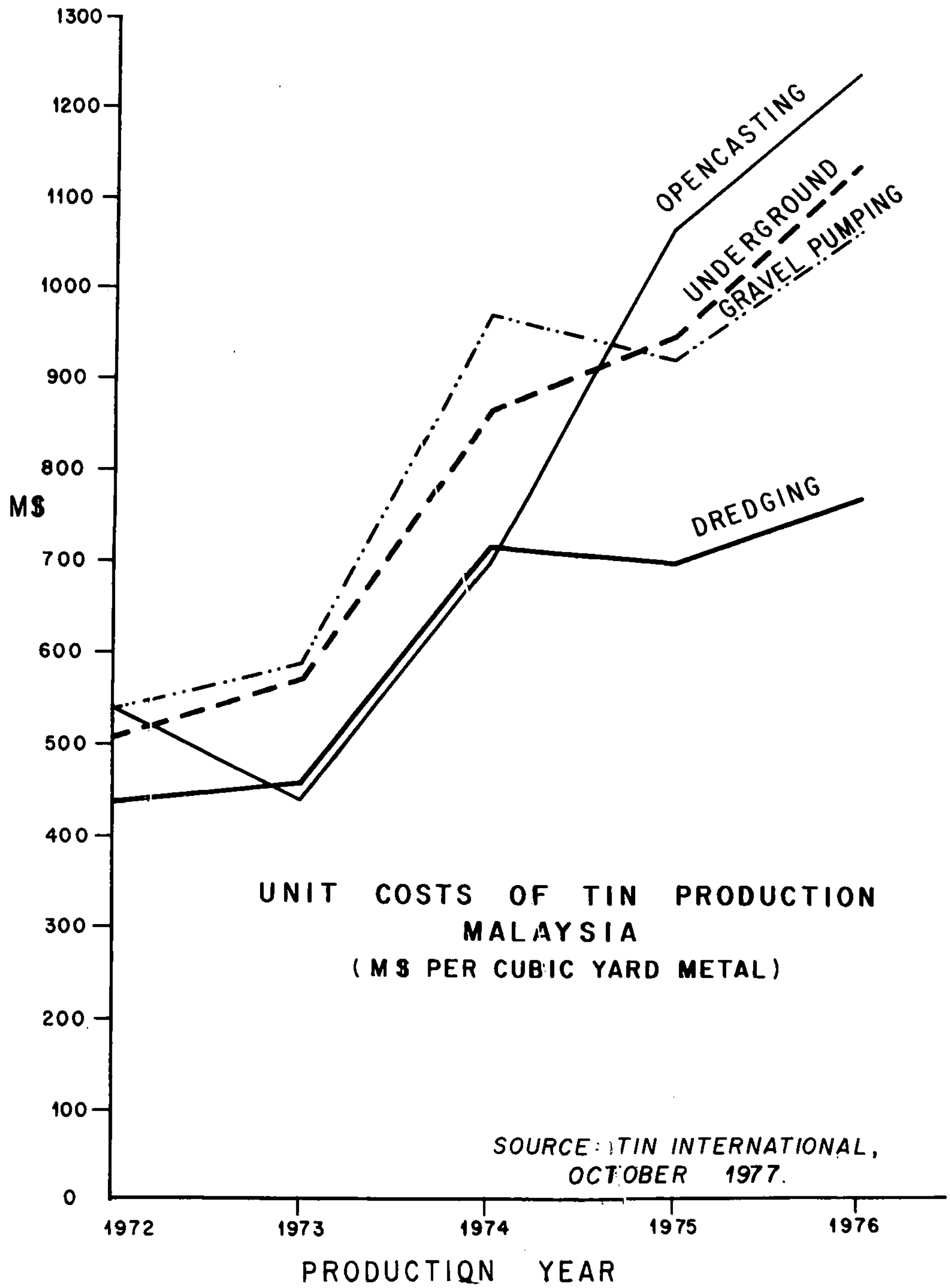

Fig. 1. Unit costs of tin production in Malaysia (1972–76), for various mining methods used.

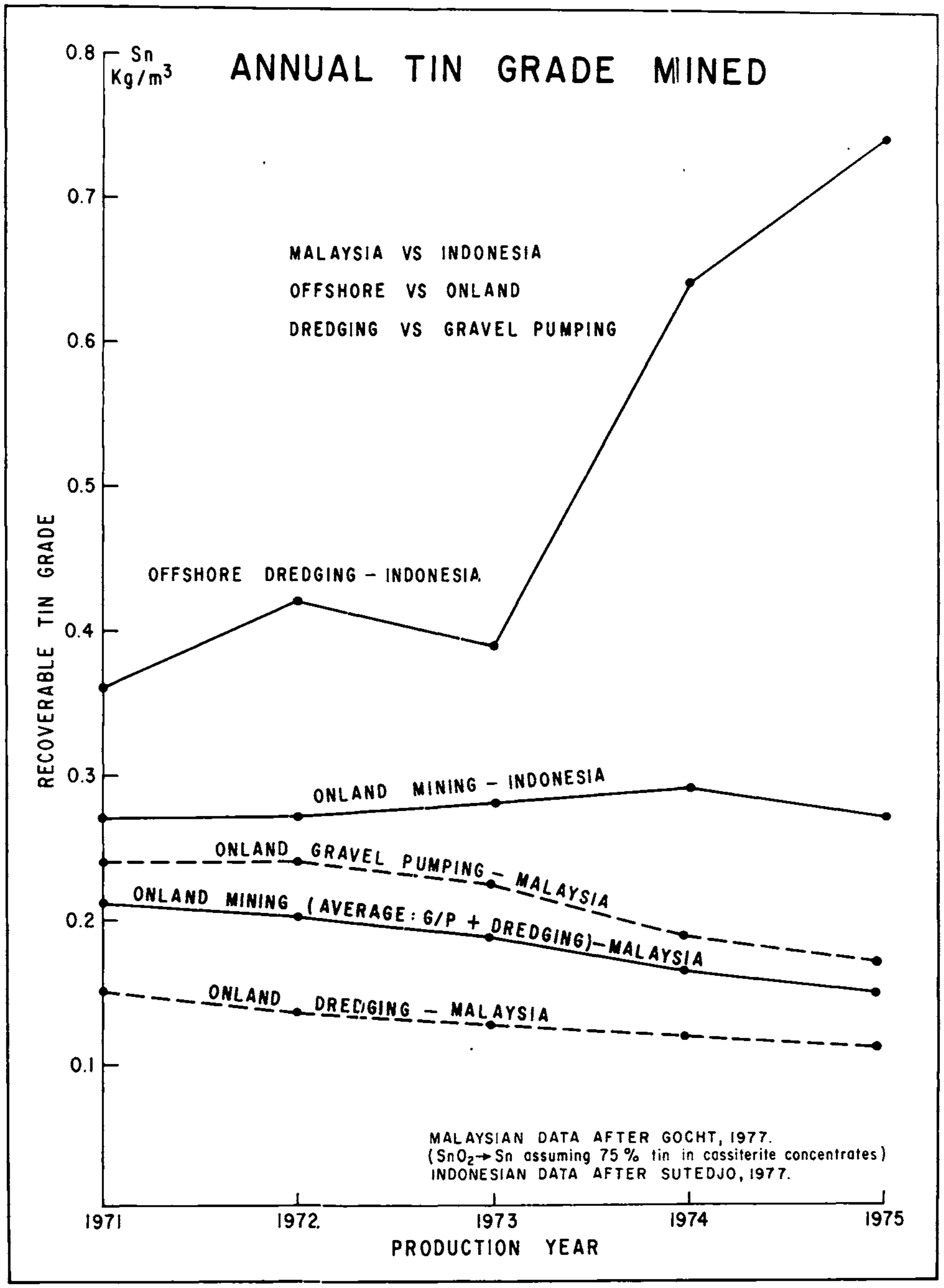

Fig. 2. Comparison of annual tin grade mined; Malaysia vs. Indonesia; offshore vs. onland; dredging vs. gravel pumping.

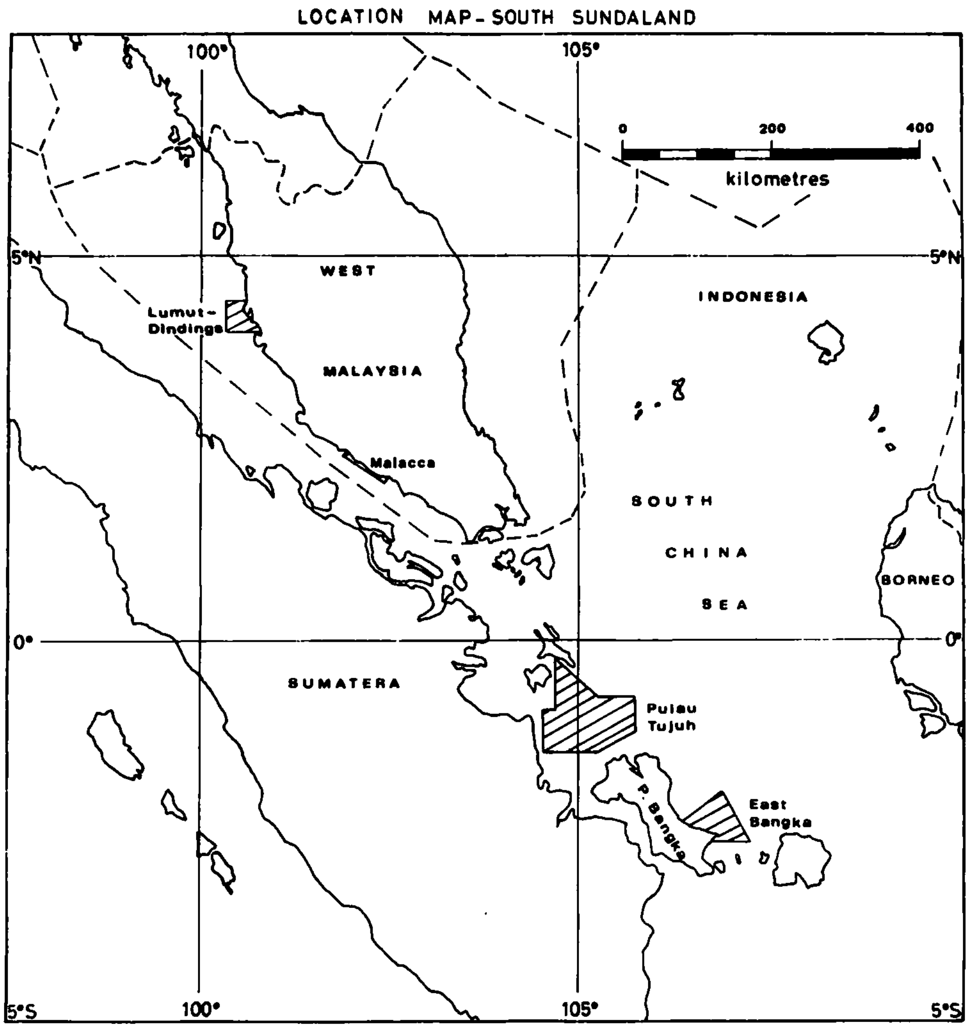

Fig. 3. Location map of south Sundaland, Southeast Asia, showing detail study areas.

of evidence worldwide (Batchelor, in manuscript). The resulting newly constructed global sea level curves (fig. 4), seriously challenge presently accepted views on sea levels and will I believe, have important repercussions to the earth sciences in general. These curves fully account for Sundaland evidence indicating Quaternary sea levels were as much as 130 to 230 metres below present, and the surprising fact that the deepest and also the bulk of offshore sediments are totally of continental origin, except for marine incursions near the top.

The curves represent the resultant of glacio-eustatic fluctuations superimposed on a general tectono-eustatic rise from very low sea levels 650 to 1000 m below present, represented worldwide by a major late Middle to Late Miocene unconformity (also refer Vail and others, 1977). The glacio-eustatic fluctuations are obtained by

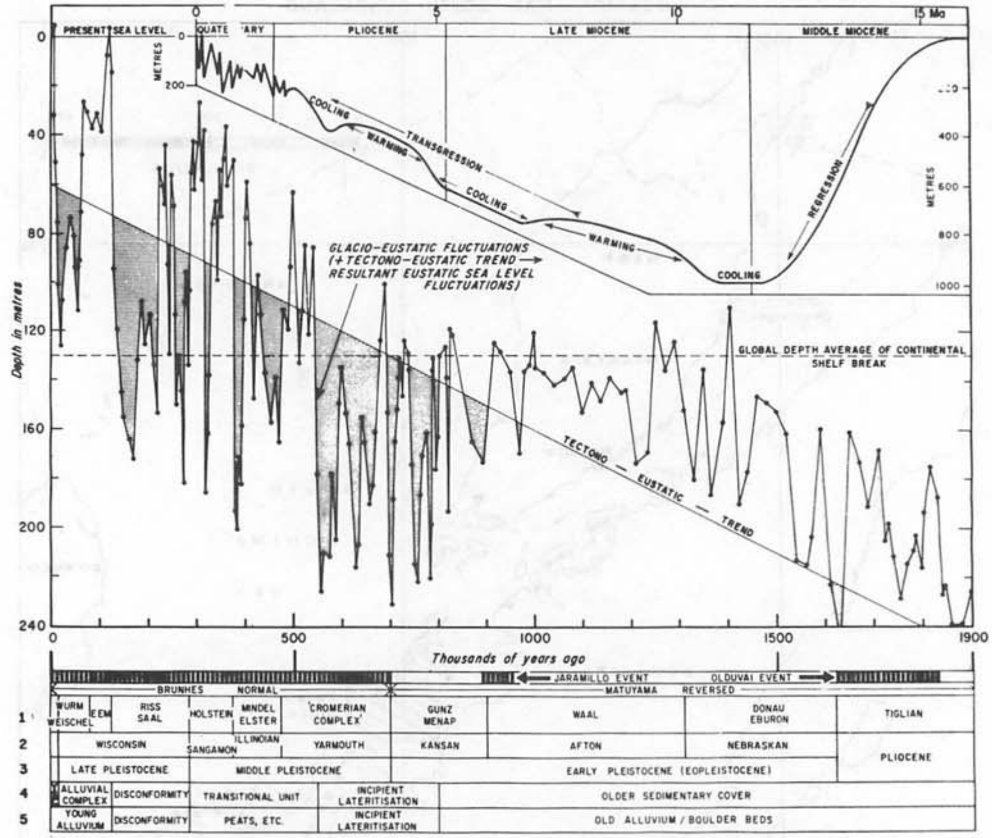

Fig. 4. Global eustatic sea level chart for the Late Cainozoic and Quaternary periods, and a tentative correlation of Sundaland stratigraphic sequences with the classical European and American palaeobioclimatologic stages (chronology based largely on van Eysinga, 1975 and other pertinent literature). Magnetic polarity chronology after La Brecque, *et al.* (1977).
1—Classical Alpine and north European Pleistocene subdivision;
2—Classical north American Pleistocene subdivision;
3—British Pleistocene subdivision (after West, 1968);
4—Sundaland Quaternary offshore lithostratigraphic subdivision;
5—Kinta Valley Quaternary lithostratigraphic subdivision (after Walker, 1954–55).

equating the oxygen isotope variation of foraminiferal shells from deep sea cores with changes in global ice volumes and hence sea levels. This is possible since we know that a 1.2 per mil isotopic variation over the last 17,000 years is equivalent to a 120m sea level rise for the same period (Shackleton and Opdyke, 1973). The glacio-eustatic null line representing the glacial/interglacial transition is then pivoted around the present projected null point (at —60m) until the resultant eustatic sea levels satisfy Quaternary low and high sea level control points.

The Late Cainozoic period can then be divided into three distinct environmental phases which affected Sundaland sedimentation. (1) *Late Miocene to Early Pliocene phase* of extremely low sea levels is correlated with a large emergent Sundaland continent (fig. 5), and semi-aridity with low, seasonal rainfalls since climates in equatorial regions are strongly controlled by land to sea area ratios (Verstappen, 1975a, b; Batchelor, in manuscript), especially on the Sunda Shelf representing the most extensive, coherent shelf on earth (Kuenen, 1950). Together with long-term tectonic stability, conditions were ideal for deep lateritisation and red-bed sedimentation, accompanying development of the "Sunda Peneplain" (of van Bemmelen, 1949). (2) *Late Pliocene to Early Pleistocene phase* of discontinuously rising sea levels up the continental slope with only minor shifts in shorelines due mainly to coastal progradation. Massive, thick, aggrading continental grey facies (piedmont fan and alluvial plain) sedimentation probably resulted from increasing and more regular rainfall causing increased denudation and sediment supply to rivers. (3) *Middle Pleistocene to Holocene phase* when sea levels finally rose above the shelf-break level to inundate large expanses of Sunda Shelf. Consequently, major lateral shifts in coastline (fig. 5b) due to rapid glacio-eustatic fluctuations dramatically affected both climates and erosional base levels resulting in highly variable sedimentation patterns. Sundaland data interpreted by Verstappen (1975a, b) and Batchelor (in manuscript) indicate that interglacial high sea levels and high rainfall (pluvial) climates (presently typical of the region),

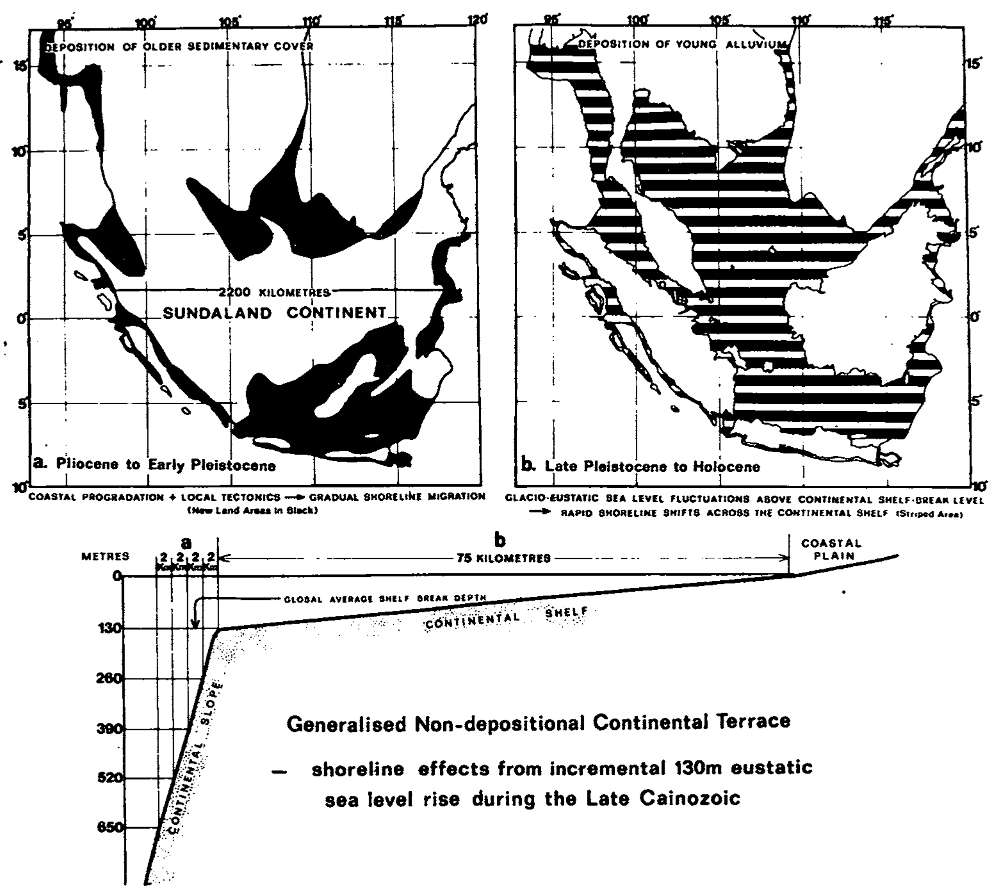

Fig. 5. Outline of the Sundaland Continent and its variable coastline positions, showing the areal extent of their coverage and relationship to the continental shelf-break level during the (a) Pliocene-early Pleistocene, and (b) late Pleistocene-Holocene.

correspond to widespread meander and flood plain development (and paralic sedimentation on the Sunda Shelf), whereas river incision characterised interglacial/glacial transitional periods (i.e. falling sea levels). Glacial low sea level periods correspond to interpluvials and incipient lateritisation, whereas aggrading braided streams and/or filling of incised channels took place during the transition from a glacial to interglacial period (i.e. rising sea levels).

LATE CAINOZOIC SUNDALAND STRATIGRAPHY

The three distinct environmental phases determined which are directly dependent on Late Cainozoic eustatic sea level relationships, provide the basis of my regional stratigraphic subdivision into basal Sundaland Regolith[1] (new name, this paper), Older Sedimentary Cover[1] (of Aleva, 1973; Aleva and others, 1973a), and the Young Alluvium[1] (of Walker, 1954–5; Stauffer, 1973). The standard offshore sequence first delineated by Aleva and others (1973a) from the Pulau Tujuh area, further subdivides the Young Alluvium into a marine Younger Sedimentary Cover and the Alluvial Complex. Onshore equivalents in Peninsular Malaysia have been described by Walker (1954–55) and Stauffer (1973), amongst others.

A typical seismic profile (fig. 6) shows the stratigraphy and granitic bedrock relationships in the Dindings nearshore area, Perak. The Holocene *Younger Sedimentary Cover* is a superficial, blanket-like deposit composed of neritic muds and beach sands up to 30m thick. Underlying this disconformably is the *Alluvial Complex* consisting mainly of meander channel and flood plain deposits with a "Riss-Wurmian" marine incursion below its base. Paralic deposits were however, more restricted than at present. Broad valleys are often incised in older deposits to depths of up to 120m below sea level. The regular occurrences of peat, and the repeated erosional phases and infilling of incised gullies, caused by eustatic sea level fluctuations younger than the "Riss-Wurm" interglacial, allow correlation with the Young Alluvium on land having a similar age (refer Sivam, 1969).

The *Older Sedimentary Cover* generally lies disconformably below the Alluvial Complex and differs markedly from all the overlying sediments. It comprises a proximal facies of subhorizontal, gravelly, poorly-sorted "granitic wash" close to bedrock in a piedmont fan environment, distinguished abruptly downslope from a distal facies in an alluvial plain environment in which horizontal bedding is generally more obvious and the alluvium is finer grained with improved sorting. The piedmont fan facies believed by me to be represented by Boulder Beds[1] in the Kinta Valley (refer Walker, 1954–55) and Batu Arang, Selangor (refer Roe, 1953), and alluvial plain facies or Old Alluvium[2] are partly diachronous with the Boulder Beds appearing somewhat earlier (refer Stauffer, 1973). Apart from lateral facies changes and a few

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[1]No type sections have as yet been formally designated by the respective authors of these informal stratigraphic units.

[2]Correlation of Aleva, *et al*'s Older Sedimentary Cover with stratigraphic horizons found in the Perak and Kedah offshore areas has been previously indicated by respectively, Ringis (1975) and Batchelor (1976), and Ryall, *et al*. (1977), on the basis of similar lithological and seismic characteristics and stratigraphic position. Furthermore, at Tk. Mengkudu, Perak in a coastal tin mine sequence, the equivalent onland horizon (offshore to onland correlation facilitated by excellent drill coverage in nearshore areas) was found (Batchelor, 1976) to be strongly comparable with Old Alluvium (and Boulder Beds) in the Kinta Valley, as described by Walker (1954–55) and Stauffer (1973). Correlation of Older Sedimentary Cover with the Old Alluvium in Singapore (where the type section has been formally designated by Anonymous, 1976) has also been argued by Batchelor (1977) and it is significant that according to Anonymous (1976, p. 52), "the general texture of the Old Alluvium as exposed in Singapore is consistent with that of an alluvial fan or piedmont plain type deposit".

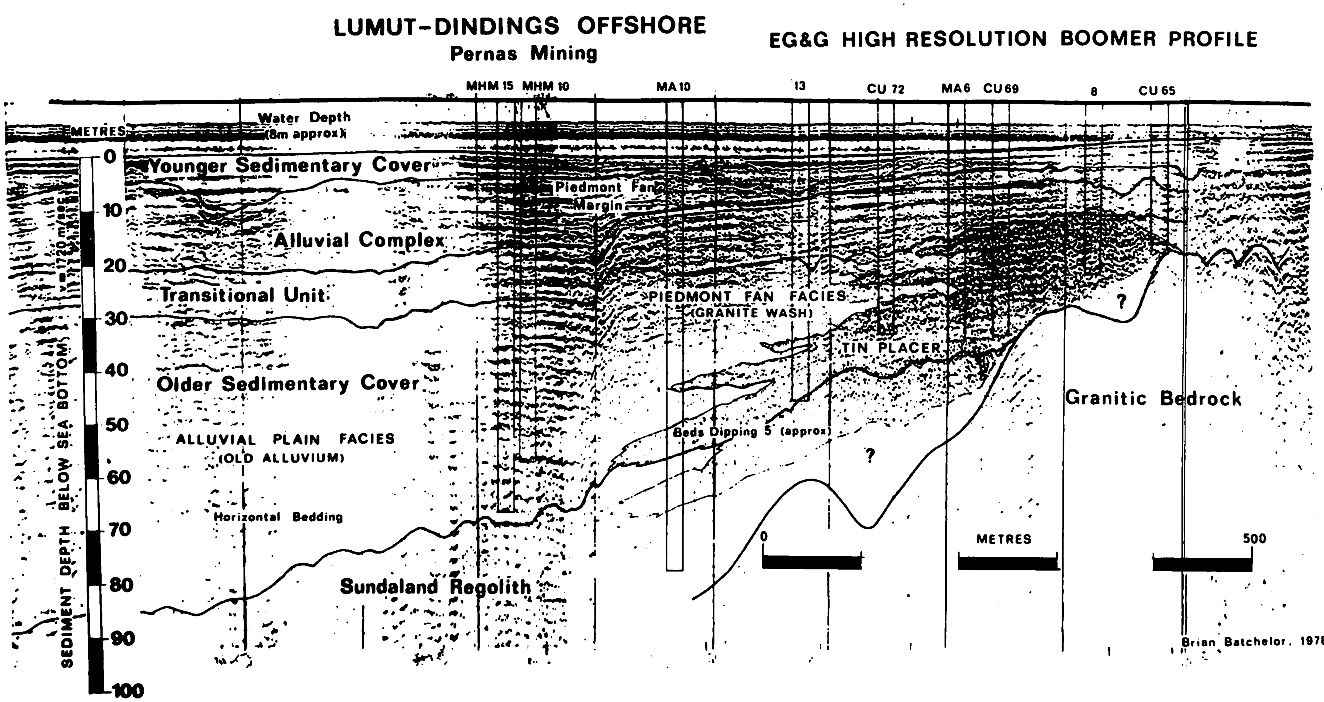

Fig. 6. Late Cainozoic stratigraphic/tin placer relationships with granitic bedrock in the Dindings nearshore area, Perak (reproduction of High Resolution Boomer record; interpretation partly after Ringis, 1976).

minor diastems, this grey-bed sequence is quite massive indicating negligible effects from climatic or sea-level fluctuations. In fact, the piedmont and braided stream deposits, sedimentary structures, the lack of marine fossils, the occasional presence of peats and dominance of kaolinitic clays, indicate a totally continental origin in upland areas far from the sea coast. The prevailing continental climate due to low eustatic sea levels resulted in low and intermittent river discharges so that resultant aggradation deposits formed high terrace features. In sharp contrast, the Young Alluvium is found in areas of low lying and flat relief, either as linear belts due to infilling of incised Late Pleistocene valleys often coincident with present streams, or as blanketing meander plain and paralic deposits in coastal and offshore areas.

A Pliocene to Early Pleistocene age for the Older Sedimentary Cover, as well as for the Old Alluvium (as earlier suggested by Scrivenor, 1928 and Burton, 1964) is supported by determination on pollen (Miocene or Pliocene: Aleva and others, 1973a; Late Pliocene or younger: Haile and Ayob, 1968), fossil fruits (Pliocene: Warburg, 1897) and vertebrates (Pleistocene: Hooijer in Stauffer, 1973), and the finding of Matuyama palaeomagnetic reversals at some localities (Haile and Watkins, 1974; Batchelor, 1976). A potentially important stratigraphic horizon characteristically found at the top of the Old Alluvium is a very stiff (tough), white or light greyish, massive clay, and rich tin placers are frequently found directly above or below it (e.g. refer fig. 8 and pp. 297, 302).

A *Transitional Unit* of varied lithology including peat and braided stream alluvium is occasionally found overlying partly lateritised Old Alluvium and separated by erosional disconformity (often deeply incised) from the Young Alluvium above (fig. 7). In offshore areas deposition of "Riss-Wurmian" marine sediments preceded the incision phase. Onland the Transitional Unit is best developed over limestone bedrock since this final phase of subterranean limestone solution caused major slumping of Old Alluvium, with lake and swamp development over resultant sags and steady accumulation of organic muds and peat (refer Scrivenor, 1913; Walker, 1954–55), and intraformational mudstone conglomerate (Plate 1(a)). The Middle Pleistocene age indicated for this unit corresponds with finds of penecontemporaneous vertebrate remains from limestone cave deposits (Hooijer, 1962) and tektites (Krol, 1960; Stauffer, 1973) from various Sundaland sites.

The *Sundaland Regolith* (fig. 6) lying unconformably below the Older Sedimentary Cover represents deep soil development of red/yellow latosols, laterites and bauxites within basement rocks of the "Sunda Peneplain", together with derived redbeds of colluvial and fan material. Laterites and bauxites are largely restricted to sedimentary bedrocks, whereas mottled sandy "kong" clay latosols characterise the granites (e.g. Plate 1(b)) where they may extend to considerable depth.

The majority of Sundaland soils of this type are believed to be fossil (e.g. Voort, 1950; Law and Leamy, 1966; Eyles, 1970), having formed during long-term tectonic stability under a semi-arid, seasonal, savanna climate when sea levels were extremely low and a marked rain shadow was created east of the Sumatran Barisan (refer Ashton, 1972), uplifted during the Middle Miocene (Verstappen, 1975b). Mohr and van Baren (1954) cite evidence of old lateritic soils formed on Miocene and Pliocene strata in Indonesia, and Pendleton and Shanasuvana (1946) attributed most lateritisation in Thailand to the Mio-Pliocene, in agreement with the Late Miocene to early Pliocene age suggested for the Sundaland Regolith, thereby relating its formation to major marine regression and the resultant global discontinuity discussed earlier (page 287).

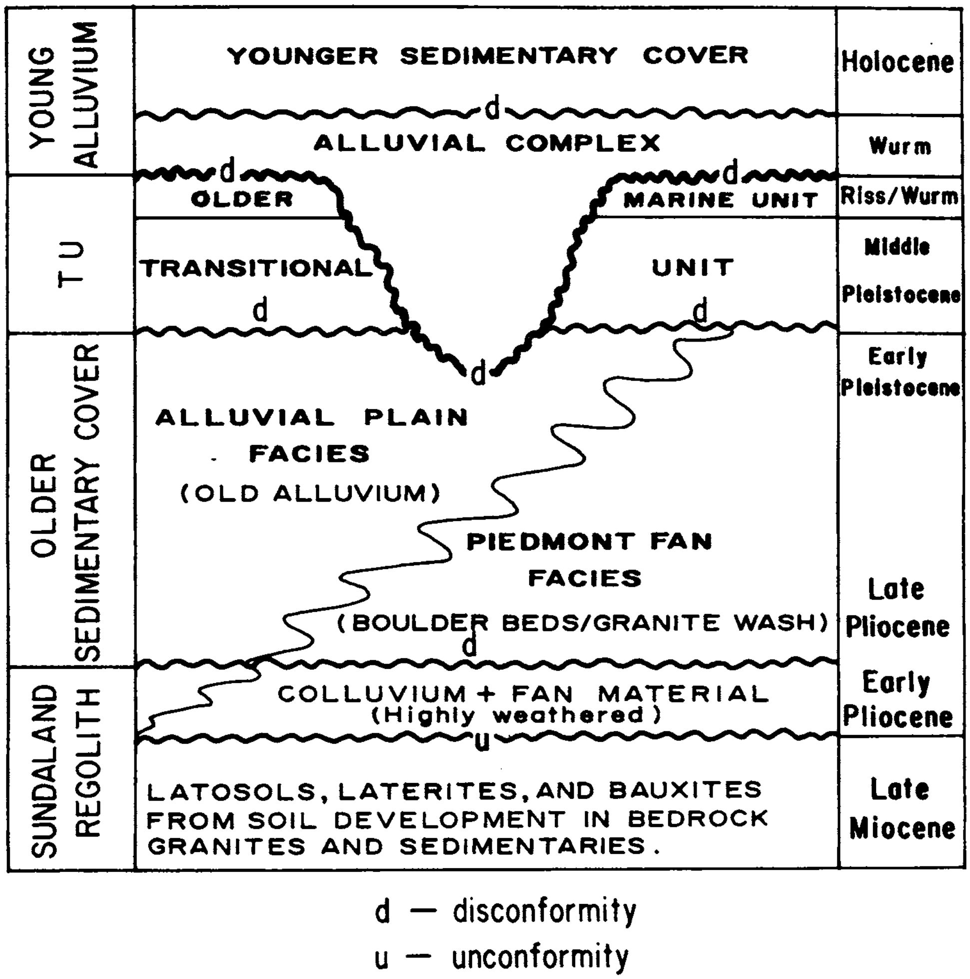

Fig. 7. Regional Late Cainozoic stratigraphic relationships in Sundaland, Southeast Asia.

SUNDALAND TIN PLACER EVOLUTION

A tentative time framework can now be applied to the evolution of tin placers which did not just appear suddenly but had a lengthy development since the Middle Miocene when primary mineralisation was first exposed on a grand scale. Greisen-bordered vein swarms along Permo-Triassic granite margins have been the main contributors of cassiterite to placers of the Western Tin Belt (Hosking, 1977), generally lying within or straddling the granite boundaries.

Placer formation generally requires first a deep lateritic weathering of primary sources, producing in granite a sectile mass of quartz and resistates such as cassiterite in a kaolin matrix. Consequent volume decrease of the mother rock assisted by erosion, and the sinking of freed cassiterite grains in the soil to a position marking toughening of the bedrock, sometimes allowed sufficient concentration to form workable *eluvial placers*. Soft mineralised eluvium and talus from mechanical weathering was then transported down the gentle peneplain slopes by creep, assisted by sheet floods from violent seasonal cloudbursts which, because of the sparse savanna cover, were effective in removing much barren material. This transport allowed further enrichment of cassiterite to form *colluvial placers*, generally found as a superficial cover on stream divides, less than a few hundred metres from their source. These placers are termed "*kulit*" in Indonesia. Together with tin-bearing iron-cemented conglomerates (Plate 2(a); also refer Scrivenor, 1928, p. 194), their genesis mainly took place within the Sundaland Regolith during the Late Miocene to Early Pliocene phase of semi-aridity.

Mass-wasting eventually allowed accumulation of stanniferous colluvium at the base of hillslopes. Faults and contact zones were often weak spots which, especially if augmented by hydrothermal alteration became preferentially eroded. With a continued rise in sea level and precipitation, mountain scarps were initiated by gullying at these loci. Rainfall although intermittent was often intense, and because of the dominant clayey matrix, debris flows of sodden stanniferous regolith including core boulders and talus became the major agents forming *piedmont fan placers* in an oxidising environment. It is not surprising that Scrivenor (1928, p. 195) termed these "torrential deposits", known locally as "*gugup*", and the poorly-sorted "granite wash" of Willbourn (1936) can also be included. These are found as massive wedges in discontinuous strips along the valley sides, thickening and dipping away from bedrock scarps at angles of 5° to 30°. Piedmont placers have great economic importance as exemplified by the Western Boulder Clays (of Scrivenor, 1918) in the Kinta Valley which lie adjacent to granite contacts at the foot of the Kledang Range, and off the Lumut-Dindings coast (fig. 6), also in Perak. Although extremely rich, these placers are generally patchy and lie less than 1km from their primary source. As with eluvial and colluvial placers, the plus 48 mesh cassiterite fraction is often large and angular.

Braided streams beginning to extend across the coalescing fans resulted in enrichment of piedmont placers by removal of barren clay and sand which accumulated downslope in broad basement troughs. Since discharge energies of ephemeral streams were still low and reduced further on reaching the adjacent flood plain, major aggradation of (initially tin-poor) Old Alluvium took place. Near the end of the Early Pleistocene when high sea levels approached the shelf-break level, increased regular precipitation resulted in the entrenchment of perennial braided streams into their alluvium and headward erosion of bedrock which, in some cases, released fresh sulphides (e.g. galena and chalcopyrite), and further cassiterite to the placers when hypogene ore zones were penetrated (refer Hosking, 1972). Coarser material became transportable and many piedmont placers suffered major reworking. During downcutting, the stanniferous gravels remained *in situ* as sieve deposits allowing additional concentration by elutriation to form the exceedingly rich *Indonesian kaksa and Malaysian karang placers* which lie as a thin layer on bedrock pediment (refer Aleva, 1973; Aleva and others, 1973b). These are comparable with primitive placers in the angularity and coarseness of their cassiterite. However, where pre-existing placers were not gravelly, this concentration mechanism was less effective allowing streams to transport cassiterite in hydraulic equivalence with their bed-load. Transport of these placers

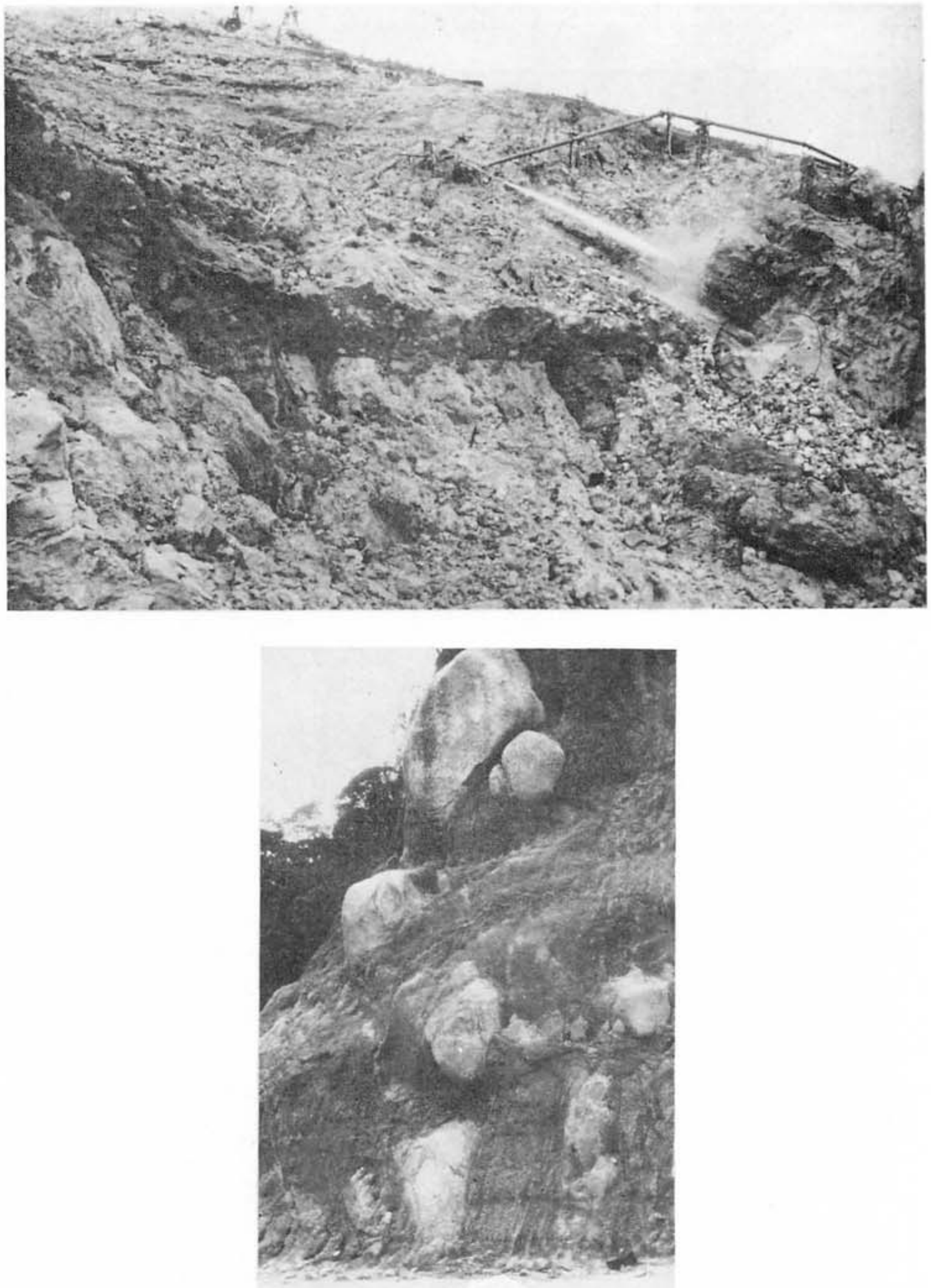

Plate 1 (a) Disturbed sequence of intraformational mudstone conglomerate (of Transitional Unit) unconformably overlying Old Alluvium slumped between marble bedrock pinnacles. Bylco-Azira Mine, Puchong, Selangor. (Photo: W.S. Yim)

(b) Reddish-brown latosol (probably fossil cf. Sundaland Regolith) with unaltered core-stones developed over granitic bedrock. Genting Highlands Casino, Selangor.

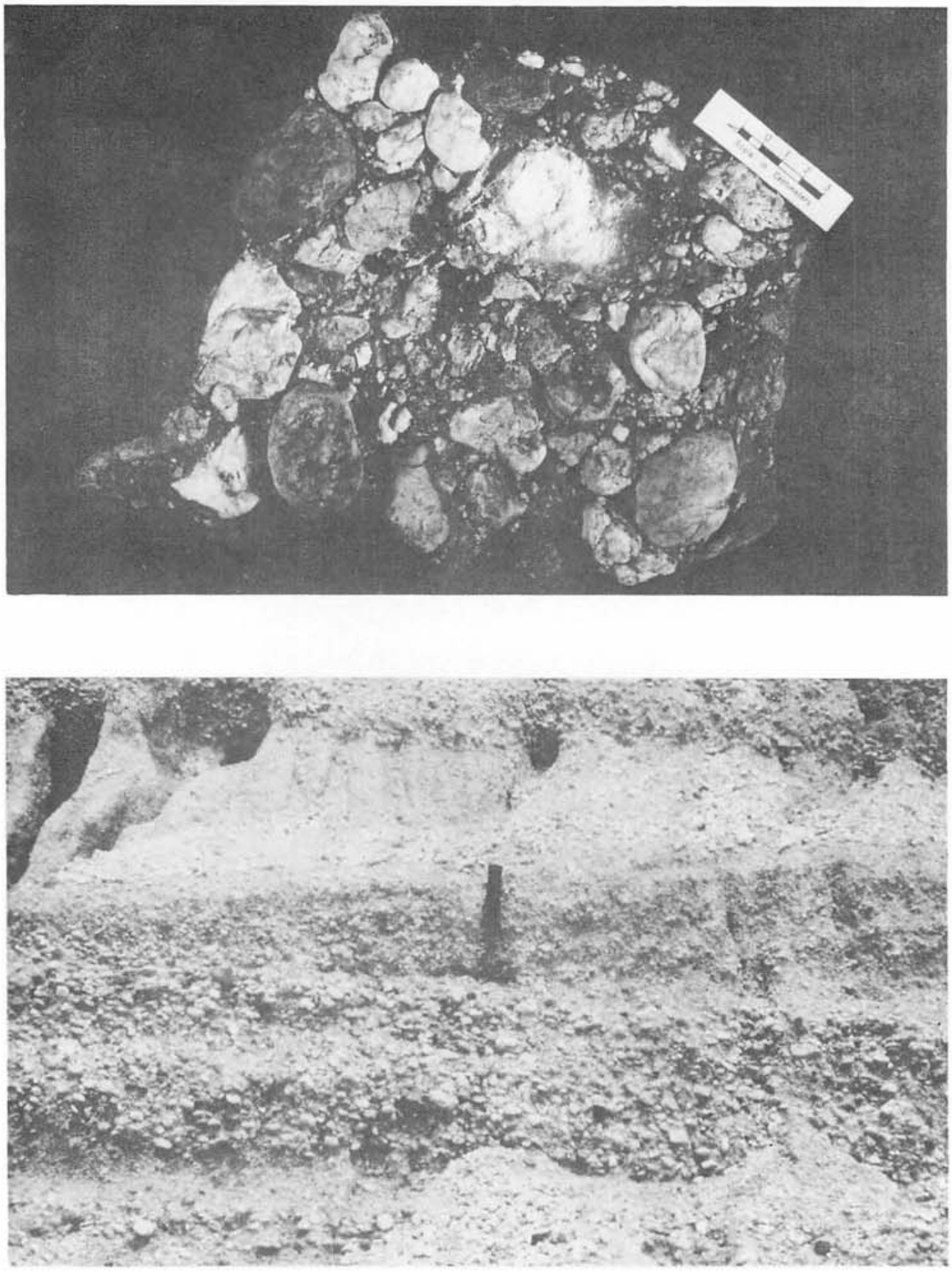

Plate 2 (a) Tin-bearing iron-cemented pebble conglomerate found overlying a thin, loose, yellow ish-brown fluviatile sand horizon (both of Sundaland Regolith) above bedrock schists. Safety No. 3 Mine, Subang, Selangor.

(b) Crude horizontal and low angle tabular cross-stratification in poorly sorted stanniferous clayey sands and imbricated gravels (i.e. braided stream alluvium) of Old Alluvium. Safety No. 4 Mine, Subang, Selangor. (Photo: W.S. Yim) was also dependent on the initial grades and volumes of pre-existing placers, stream gradients, and bottom irregularities. Gradients exceeding 1 in 150 resulted in total bed-load transport and cassiterite dispersion whereas gradients around 1 in 300 allowed concentration (refer also Bateman, 1959, p. 234; van Overeem, 1960, p. 452). by selective fluviatile transportation to form *braided stream placers*. Transportation of up to 5km from their source was possible, especially on smooth clay bottoms These placers often extended across the alluvial plain forming hanging placers, known in Indonesia as *mincan*, or *karang gantong* in Malaysia. Braided stream placers (Plate 2(b)) generally show a marked decrease in cassiterite grade and grain size downstream but this is countered by their greater thickness and wider, more uniform distribution.

Figure 8 shows cross-sections of two separate mining areas in East Bangka, Indonesia. In Area A a rich kaksa lies directly on granite which is locally mineralised. The cassiterite is much patchier than the main placer in Area B—a hanging mincan of equivalent age which overlies alluvial plain detritus on sedimentary bedrock. The older placers in Area B are of poorer grade because at that time most cassiterite was localised in piedmont fans adjacent to granite contact scarps, 2km upstream. The tough clay marker (refer p. 292) overlying rich placers in both areas, often forms a thick blanket covering lowland stream divides in many tin fields.

Following planation and lateritisation of the Old Alluvium, late Middle Pleistocene sea levels rose for the first time above the continental shelf-break forming great expanses of warm, shallow seas across the Sunda Shelf. Also because of the generally higher interglacial oceanic temperatures (refer e.g. Emiliani, 1955) facilitating greater evaporation over littoral seas, the resultant increased precipitation on adjacent lands provided rivers with higher discharge volumes and erosive capacities, thus causing a second major phase of braided stream entrenchment. This exposed earlier *kaksa* in headwater regions resulting in re-concentration and further additions of cassiterite (and primary sulphides) from valley slopes. Downstream these placers overrode the tough clay blanket forming another *mincan* series, well illustrated by Osberger (1968a, fig. 3; 1968b, figs. 6,7) showing transverse and longitudinal stream profiles in the upper, middle and lower reaches (also refer fig. 9). The large Kuala Langat placer (refer p. 284) is probably of this type since it partly overlies Old Alluvium. The Indonesian *Padang placers* (of Osberger, 1968a) lying in similar stratigraphic position are of gigantic width and extend up to 10km from primary sources. *Mincan* placers resulting from a number of reconcentration cycles differ from other types in the fineness of cassiterite which may be brought into concentration zones by rivers, as well as forming anomalous trains away from tin sources. Also during this incision phase, slumping of older placers took place over limestone terrains and underground streams deposited *cave placers* in Perlis and Kinta, locally including *calcite-cemented alluvium* (refer Scrivenor, 1928, p. 194).

Some superficial reworking and destruction of placers then followed during two major marine transgressions across the Sunda Shelf, limited to about 6m above present sea level. The first was around 120,000 years BP and the second since 10,000 years ago (refer fig. 4). Some placers were enriched through elutriation by waves and tides, and longshore currents redistributed them. Rich *beach placers* formed along relatively stationary strand lines are generally thin, though may be widespread since considerable transport was often possible. Placers formed where abrasion platforms intersected tin-bearing bedrock regolith are differentiated from those formed from placers intercalated in an alluvial sequence. Where the original plus 48 mesh cassiterite was do-

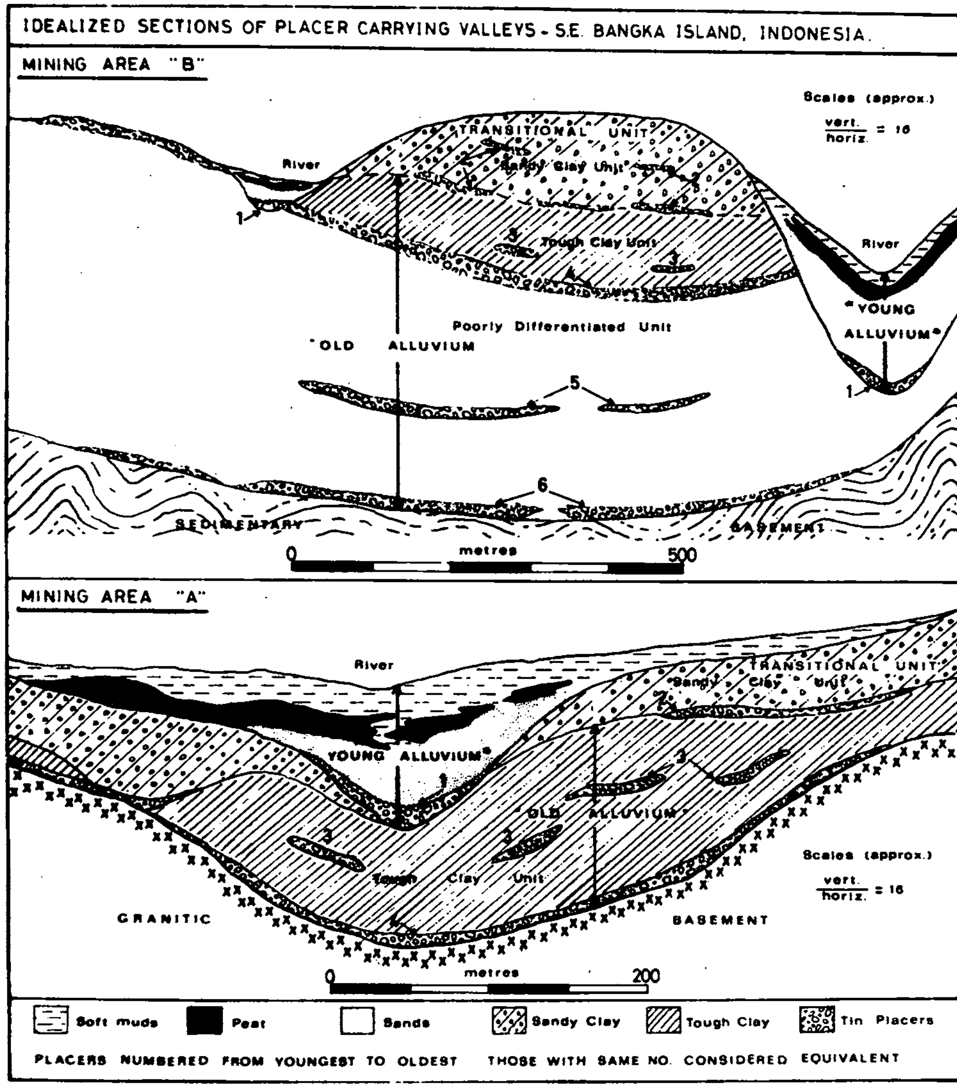

Fig. 8. Idealised sections of placer carrying valleys, S.E. Bangka Is., Indonesia.

minant, the strength of marine reworking is indicated by the increase in finer fractions which may lead to placer destruction.

Figure 10 profile shows in longitudinal section the elongated beach placers parallel to the Dindings coastline, Perak and their relationship to continental placers further offshore, in a section perpendicular to it. The oldest placers of colluvium and derived piedmont fans at the foot of scarps, underlie braided stream placers of lower grade and finer cassiterite. The latter have suffered greater transportation and are often found extending up to 1200m with continual grade decrease offshore from small coastal valleys. However, the two beach placers are richest. The upper shows a hyperbolic

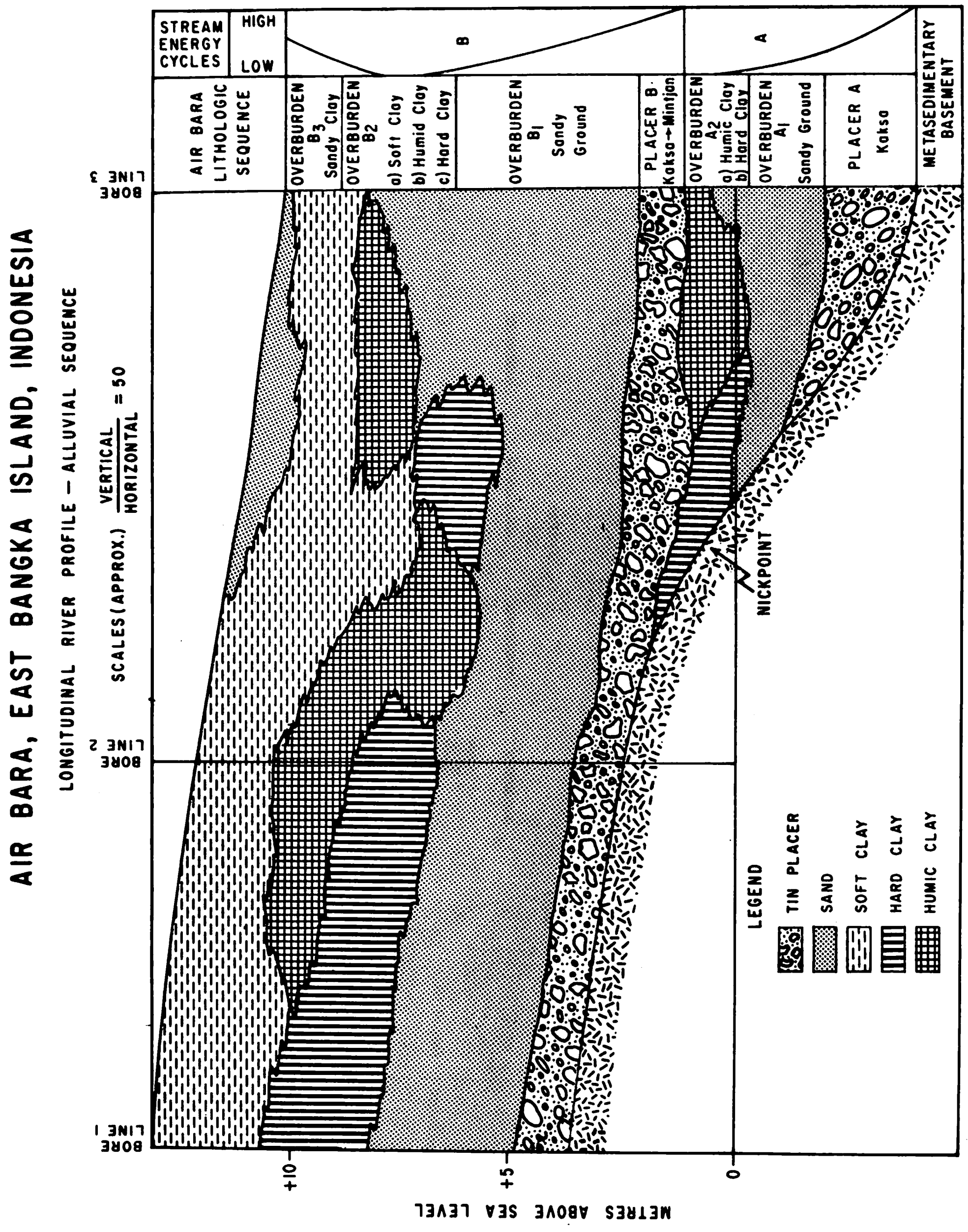

Fig. 9. Longitudinal river profile and alluvial sequence, Air Bara, East Bangka Is., Indonesia.

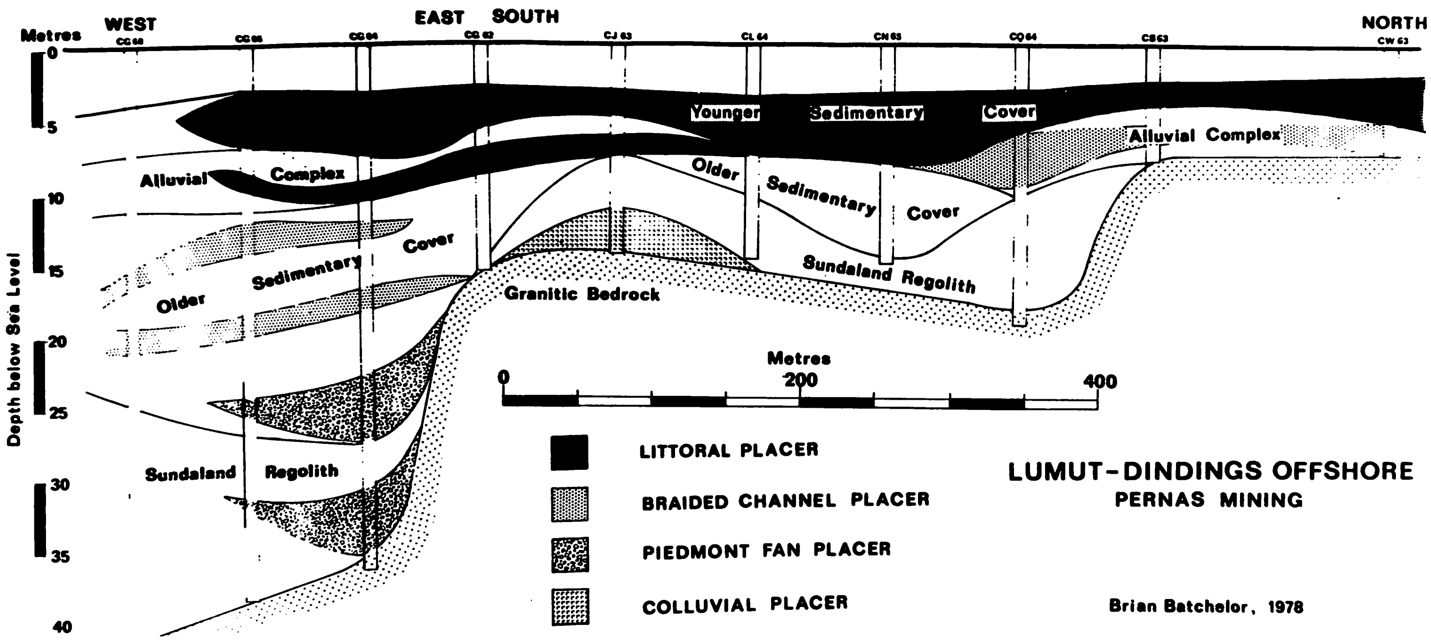

Fig. 10 Dindings nearshore area, Perak. Longitudinal section section of beach placers parallel (north-south) to the coastline and a section (east-west) perpendicular to it, showing the relationships between colluvial, piedmont fan and braided stream placers.

depth decrease in cassiterite grade (refer Arman, 1976) suggesting its recent formation by removal of the tin-bearing regolith from adjacent coastal granite hills, now largely devoid of soil.

Following the first marine transgression coinciding with pluvial conditions and meandering streams, sea levels fell to 120m depth and rejuvenation resulted in deep V or U-shaped valley incisions in the soft underlying alluvium. Because of their high discharge volumes, their finer texturally mature sediment load, their steep gradients and smooth bottoms, stream transportive capacity increased dramatically allowing them to clean their bottoms completely, resulting in the destruction of many placers (refer fig. 14). Economic *meander stream placers* in Young Alluvium are extremely rare, apart from Bangka (e.g. refer fig. 8). They could only form from erosion of rich pre-existing placers and deposition dependend on gradient irregularities forming channel deposits, or point bar deposits on the insides of meanders, especially after minimum sea level was reached 17,000 years ago. These low grade placers are generally irregularly distributed sometimes at considerable distance from their source, and form the base of a graduated series of sands, peat and muds. The rapid accumulation of sediments in a then sluggish drainage system in which swamps developed, created a locally reducing environment, especially in organic-rich horizons, facilitating *in situ* diagenetic sulphide (esp. marcasite and pyrite) development (refer Hosking, 1972; Hosking and Yeap, 1977a, b). Valley extensions offshore were filled with barren lacustrine and deltaic muds as sea levels rose to the present. Obviously these young valleys are of little economic interest. In the Peninsula, such areas are represented by deep estuarine fill off major deltas including the Bernam and Kelang.

EXPLORATION APPLICATIONS: A DISCUSSION

The major Southeast Asian tin sources are braided stream, piedmont fan and residual-elutriational placers. Together with eluvial and colluvial placers, these are spatially restricted mainly to the flanks of positive granite features and contact zones, and adjacent shallow bedrock troughs. These are priority exploration targets, especially offshore where deposits deeper than 60m commonly have thick clay overburdens and cannot presently be dredged. It is surprising this simple philosophy was not consistently applied initially by a number of companies involved in offshore tin exploration.

Osberger (1965) stated that "Of four near-shore placers discovered after 1958 (off Belitung Is.), only a small one could be said to have been found in an area where it was thought to occur: the others were found where they were not supposed to occur according to the hypothesis". During the unsuccessful first phase of the Billiton Company's Pulau Tujuh exploration, valley targets were priorities resulting in *only* one hole proved with good tin values from a total of 53 drilled (Bon, 1977). Aleva (1973) reported that "The exploration, thought to be a straight forward logistic exercise, developed into a geological study. It took several years of investigation in a variety of geological disciplines to arrive at a new exploration concept" which ultimately proved successful.

Many previous failures including much wasteful drilling, were partly due to the so-called "*valley hunting*" *principle* which was based on two major fallacies. Firstly, well-defined Young Alluvium valleys offshore were expected to contain extensions of rich onshore placers. This was incorrect since such placers are generally older than these incised valleys (refer pp. 295–301). Secondly, offshore sources were considered virtually non-existent so that offshore placers must be due to extensive valley transportation from coastal mineralisation sites.

The generally unsuccessful exploration program off the East Bangka concession (fig. 3) was largely based on valley hunting concepts. The supervising geologist reported (Kajuara Mining Corporation, 1975, unpublished report) that "The generally low cassiterite grades encountered in the offshore drill holes proved to be a constant source of puzzlement throughout the drilling programme, particularly in the downstream offshore portions of known placer-bearing valleys". Figure 11 section includes the only 'economic' hole (OSB3) drilled out of a total of 117. This discovery was largely accidental since these holes were drilled to test young valleys but fortunately were extended below into the Older Sedimentary Cover. The valleys were filled with barren dark swamp and estuarine muds overlying a pale grey alluvial plain facies with *mincan* placers. Many unnecessary holes were drilled in young valleys (as shown for instance in fig. 12) which are totally unprospective having been filled during a deltaic phase, in areas without shallow granitic subcrop in sight. These features probably connect up with the major Molengraaf Valleys draining submerged Sundaland (refer Kuenen, 1950, fig. 203) which are also non-prospective for offshore placers.

Intelligent seismic interpretation is the closest we can get to a remote detection technique for submerged placers. The Billiton Company's great success at Pulau Tujuh lies partly in the fact that stanniferous gravel targets could almost immediately be outlined from seismic profiles and relatively few drillholes were then needed to substantiate proven reserves (refer Bon, 1977).

In the Malacca nearshore area being prospected by the Malaysia Mining Corporation (fig. 13), this approach appears to be eminently feasible. Rich beach sands had early in this century been worked along a 20km strip of coastline south of the Linggi River, and up to 1km offshore (refer Warnford-Lock, 1907). On Pulau Besar a gravel-pump mine was operating until 1958. Seabottom grab sampling and coring in 1976 during a joint Malaysian-German survey under UNDP/CCOP auspices, located a number of extremely anomalous cassiterite areas (Fed. Inst. Geosci. Natur. Resourc., Federal Republic of Germany, 1976, Map 5) which are restricted to offshore granites and their mineralised contact zones, delineated by me from company drilling and seismic data. Figure 14 profile, which lies perpendicular to the coast in the richest area drilled to date (i.e. 20/3/78), shows a *kaksa* placer stratigraphically restricted to the base of the Old Alluvium. Its rather dense, coarse, speckled seismic character indicates the presence of gravelly sands (refer e.g. Ringis, 1976). The identification of this horizon on adjacent profiles allows my confident prediction of placer extensions into areas which have not as yet been drilled. Strong sub-horizontal reflections higher up indicate the typical presence of overlying tough clays (refer p. 292), which is confirmed by drilling. The Late Pleistocene valley incision which partly destroyed the placer, is filled by estuarine and marine muds, indicated by their good stratification and lighter, finely-textured seismic character.

By far the majority of economic placers formed before the Late Pleistocene when the Sundaland continent (refer fig. 5a) was fully emergent. Subsequent marine transgressions generally resulted only in superficial reworking. This knowledge allows extension of our present search to shallow mineralised bedrock areas throughout the Sunda Shelf where rich offshore placers perhaps lie hundreds of kilometres from present tin fields. One such example is tiny Berhala Island, lying in the Malacca Straits 100km east-northeast of Medan, with an extensive surrounding area of less than 30

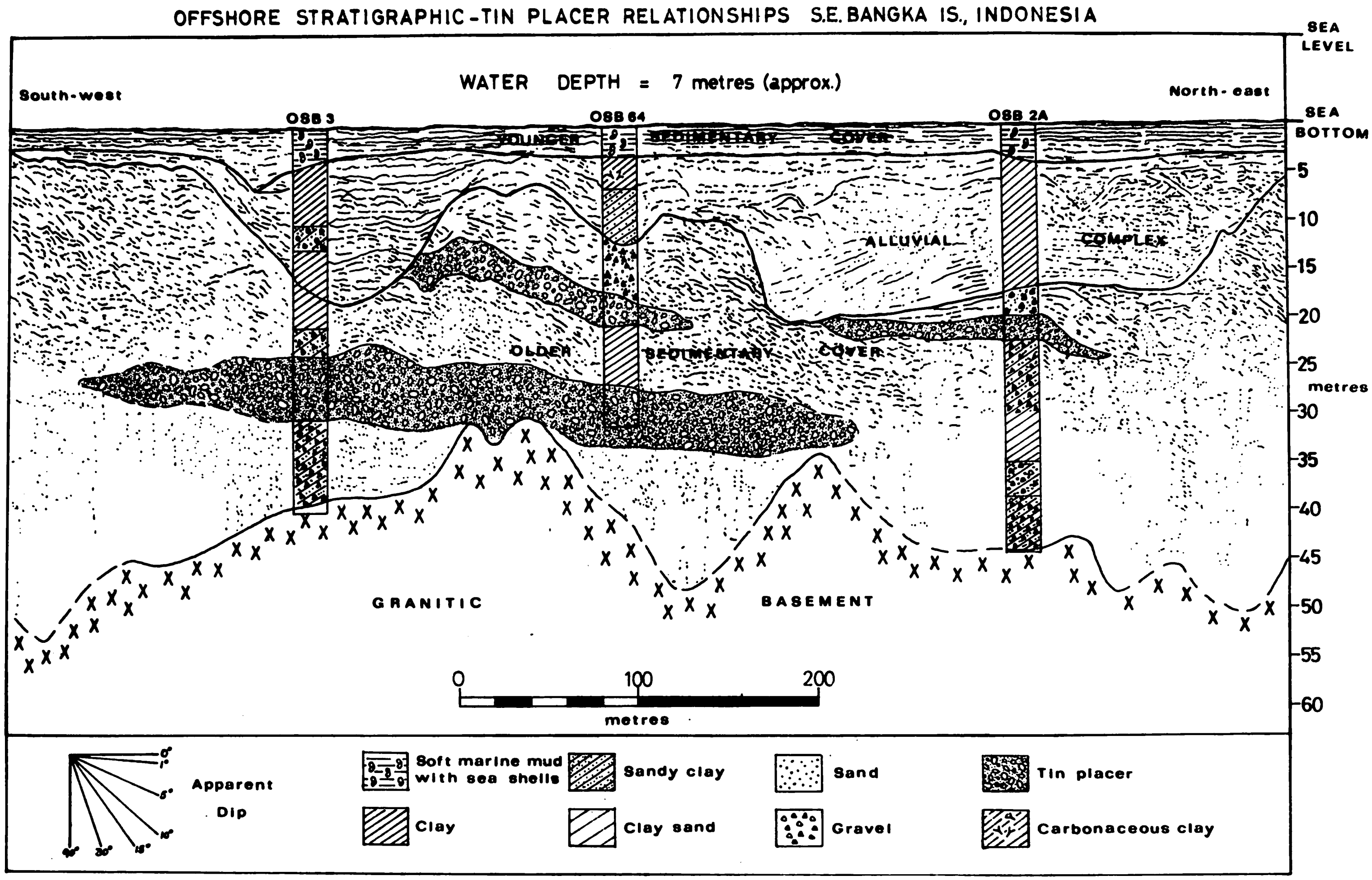

Fig. 11. Late Cainozoic stratigraphic/tin placer relationships in a nearshore area off East Bangka Island, Indonesia (tracing of High Resolution Boomer record).

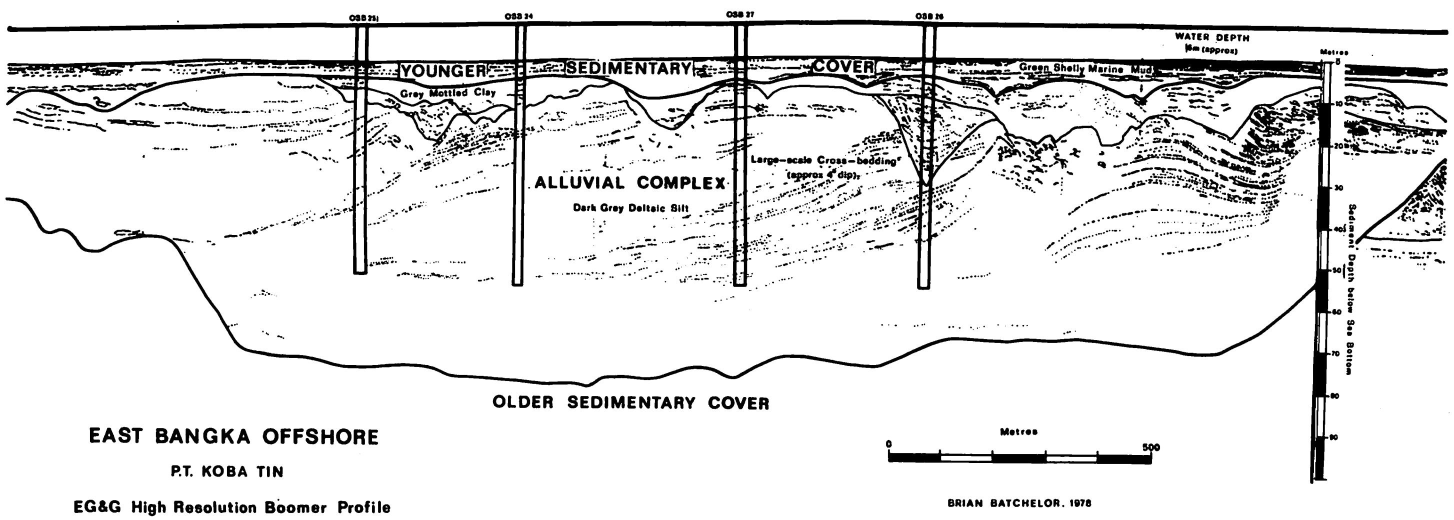

Fig. 12. Young fluviatile valley filled with barren deltaic and marine muds of Young Alluvium, East Bangka Is., Indonesia (tracing of High Resolution Boomer record).

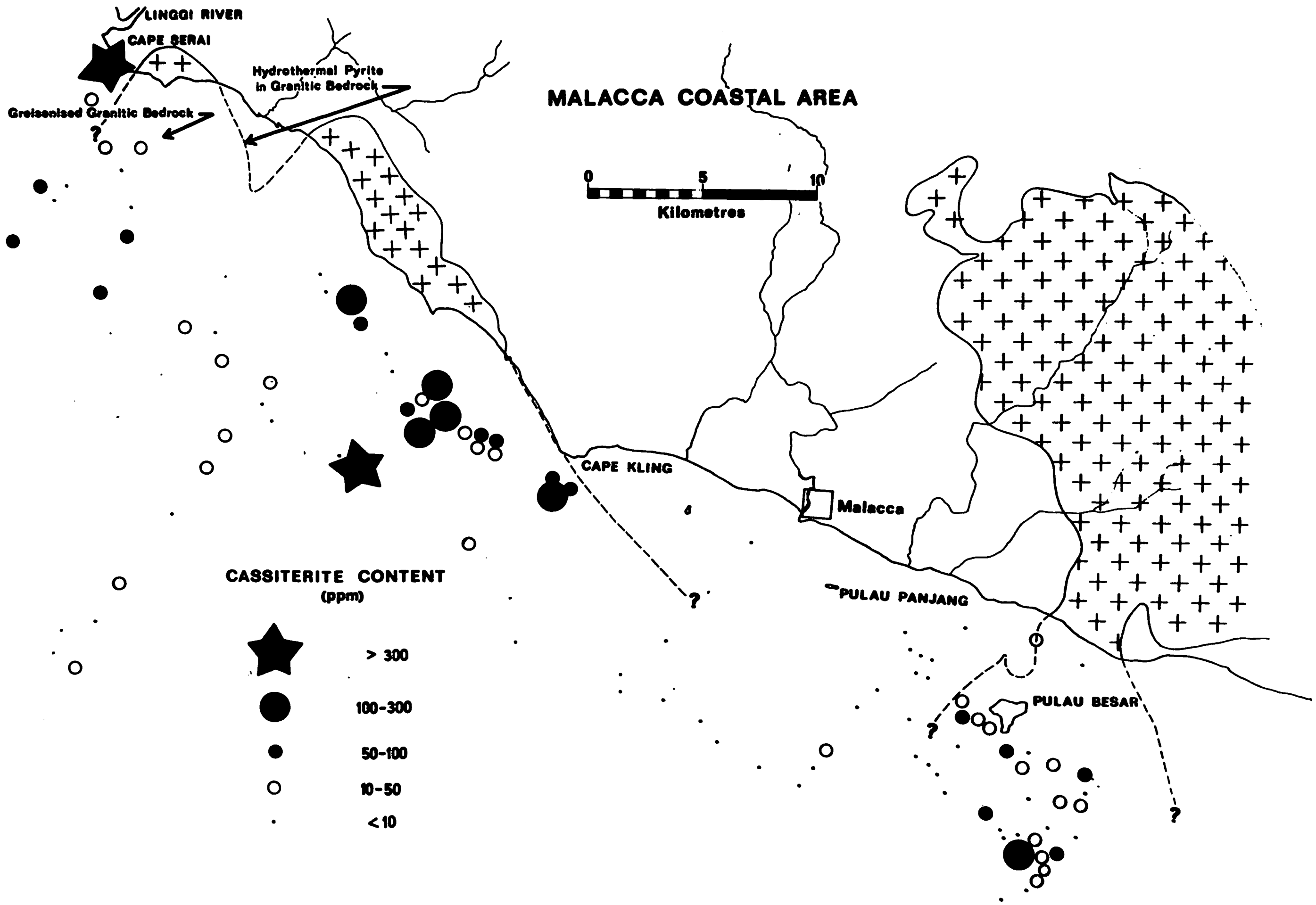

Fig. 13. Malacca coastal area. Granite/sedimentary bedrock contact zones (onland from Geol. Surv. Malaysia Dwg. no. 63/182; offshore interpreted from MMC drilling and seismic data) and seabottom cassiterite distribution (from Fed. Inst. Geosci. Natur. Resource; Fed. Republ. Germany 1976).

fathoms (55m) depth (fig. 15). The island is composed of monazite-bearing granites, dumortierite-aplites and pegmatites with stanniferous beach sands, also with tourmaline and accessory minerals characteristic of mineralised Tin Belt granites (van Bemmelen, 1949). As far as I know, this area has never been prospected for offshore placers and certainly warrants further investigation.

Around the Indonesian Tin Islands, the deepest sediments overlying bedrock (the "Tertiary" series) exhibit strong subhorizontal seismic reflections and were assumed to be marine (e.g. van Overeem, 1971; Ronojudo, 1973). Sutedjo (1977) termed these beds "old marine sedimentary layers" and considered them to have no stanniferous potential, even though (he said) they had never been penetrated by drilling. The constituent sedimentary units which have been considered in this context are of partly dissimilar character and will be discussed separately.

The *Ranggam Beds* (Osberger, 1965; 1967a, b; 1968 a, b) along Bangka's west coast, comprise dark brownish-grey, pink or grey "tough" clays with thin intercalations of carbonaceous and sandy layers. At Ranggam, the lowermost beds include lenses of pebble conglomerate and sands (which in Mine TK6 I found to be stanniferous) while the upper 6m are varve-like. Dr. R.J. Morley (written communication, 28/2/77) reported a rich assemblance of swamp and lowland forest pollen from it, as well as mangrove taxa suggesting restricted estuarine deposition, probably in consequence of its position on the border of the South Sumatra Basin—a former penetrating seaway. Osberger (1965, p. 116) believed the Ranggam Beds to be probable equivalents of the (mainly paralic) Pliocene Palembang beds, and Morley thought the contained pollen were either Pliocene or Pleistocene. Faulting and gentle folding of the Ranggam Beds (Harsono, 1975) are therefore probably related to the Plio-Pleistocene tectonic event evident throughout the South Sumatra Basin. Osberger (1965, pp. 96–97) believed the fossil-less *Old Series* of Singkep Island to be equivalents, and lower pebble beds on washing were found to contain some cassiterite. The Pliocene (?) *Raya Beds* (Osberger, 1958; 1967a, b; 1968a, b; CITRA, 1966) between Bangka and Belitung Islands, comprise grey, plastic, compact clay and sand. They were previously considered to be marine, based on a suspect environmental interpretation by N.V. CESCO (Coastal Engineering Survey Consultants) geophysicists (vide Overeem, 1971) and a mistaken report (Hartono vide Untung, 1968) of Pleistocene foraminifera in the beds, previously sampled by CITRA (Compagnie Industrielle de Travaux-Enterprise Schnieder). Foraminifera had been reported by CITRA (1966, p. 12) only from shelly sand layers *above* the Raya Beds but not from the Raya Beds themselves. Open-cast mine exposures of Raya Beds near Air Mesu, Bangka Island, pointed out to me by Sdr. Bismark Sahagian of P.T. Timah, showed the typical continental aspect of Older Sedimentary Cover, with stanniferous gravels underlying a tough clay member (refer p. 292).

On the basis of lithology, stratigraphic position and seismic character I believe the Raya Beds are probable equivalents of the alluvial plain facies of the Older Sedimentary Cover (i.e. Old Alluvium). The Ranggam Beds are perhaps also time equivalents of the Older Sedimentary Cover (as is suggested by Tjia, 1977) though because of their proximity to the South Sumatra Basin, they show a markedly different paralic aspect. Contrary to previous suggestions (Osberger, 1967a, b; 1968a, b; 1971; Simatupang, et al., 1974) these "Tertiary" series are often highly stanniferous (e.g. Sutedjo, 1973, p. 145; 1977, fig. 2, "Old Alluvial") and should be thoroughly investigated for *kaksa* and piedmont placers where they wedge-out against basement (particularly granite) culminations, as well as *mincan* channel placers lying just below the upper tough clay horizons.

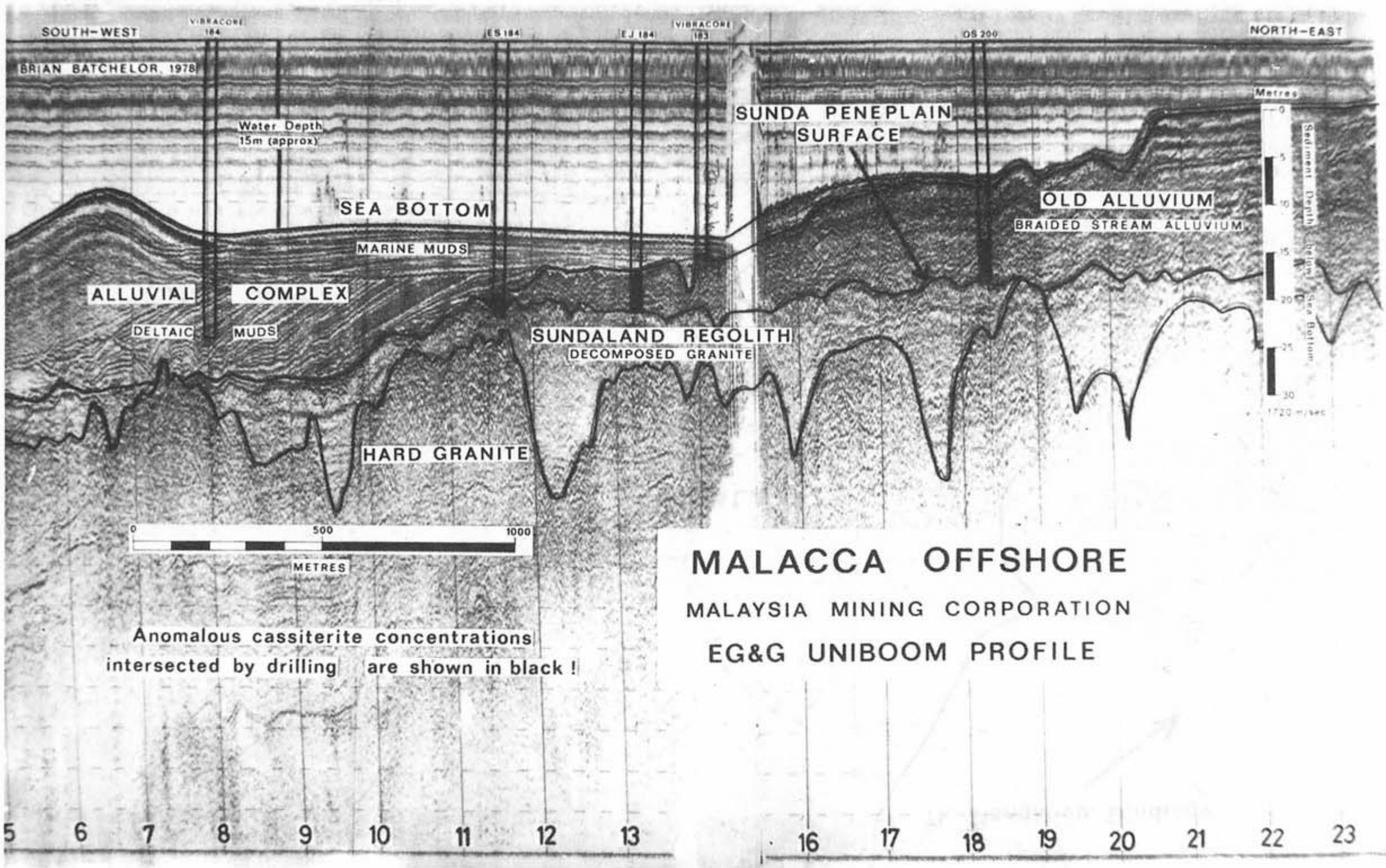

Fig. 14. Late Cainozoic stratigraphic/tin placer relationships in the Malacca nearshore area (reproduction of Uniboom record).

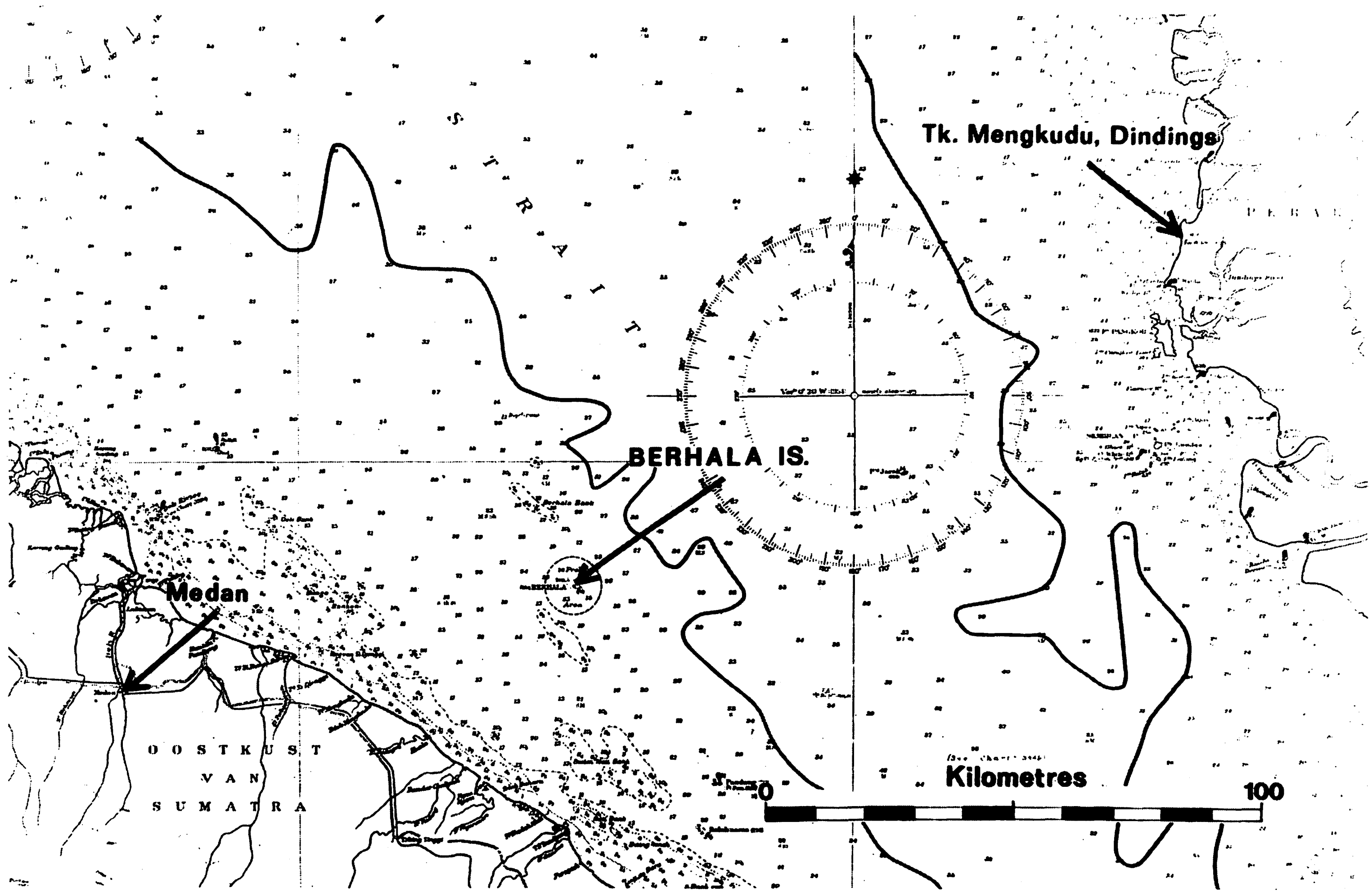

Fig. 15. Central part of the Malacca Straits showing position of Berhala Island with respect to Medan, Sumatra and Tk. Mengkudu, Perak. 30 fathoms isobath shown in bold outline. (Taken from British Admiralty Chart, 1952, Diamond Point to One Fathom Bank, Scale 1:500,000. Hydrographic Office, London).

Similarly in Malaysia, a Canadian-Malaysian Colombo Plan mapping project in the Mersing area (Chong and others, 1970, fig. 13), outlined an extensive exposure of Old Alluvium bordering the northern margin of the Lenggor granitoid which is known to carry placers along its eastern border (refer Mineral Distribution Map of Peninsular Malaysia, 1976). However, this area of Old Alluvium has not subsequently been considered as potential mining land, even though prospecting of it would appear to be warranted.

Since the Older Sedimentary Cover is the most economic mineral producer both in Malaysia and Indonesia, it is recommended that national geological surveys, universities and mining companies give high priority to its regional mapping both onland and offshore. Professor Stauffer (1966/67) stated over a decade ago that "The Quaternary sediments (in Peninsular Malaysia) are regarded ... as an inconvenience obscuring the real geology, and are ignored wherever possible". In light of the fact that more than 95% of Malaysia and Indonesia's total tin production derives from the "alluvium", it is encouraging to find this anomalous situation is now being speedily rectified, allowing geologists to play a fuller role in developing the region's tin industry.

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A study of this nature was only possible through the willing co-operation of many tin mining companies operating in the region. In particular, I wish to thank executives of Pernas Charter Management Sdn. Berhad, Pernas Mining Sdn. Berhad, Malaysia Mining Corporation Berhad, P.T. Koba Tin and Billiton Exploratie Maatschappij Indonesia B.V. for their generous assistance and permission to publish initial results from my studies on their seismic and drilling data, and the UNDP/CCOP for providing training on seismic interpretative techniques under Dr. John Ringis, Senior Marine Geologist.

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