



DISCONTINUOUSLY RISING LATE CAINOZOIC EUSTATIC SEA-LEVELS, WITH SPECIAL REFERENCE TO SUNDALAND, SOUTHEAST ASIA¹

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ABSTRACT

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A Late Cainozoic global eustatic sea-level rise, of greater magnitude and opposite trend to previous schemes, is indicated, with important consequences on climates, sedimentation, pedogenesis, oceanographic features and biological distributions, especially for Sundaland and other equatorial regions.

An abrupt sea-level depression during the late Middle Miocene to around 1000 m below present, is correlated with an emergent Sundaland continent. Increased land/sea area ratio resulted in more seasonal semi-arid climates facilitating savanna expansion and laterite development. A major Miocene discontinuity in Sundaland is paralleled worldwide by contemporaneous unconformities or facies changes on continental terraces, reduced oceanic sedimentation and truncation and pedogenesis on Pacific reefs. Sea levels have since risen discontinuously at around 10 cm/10³ a with maximum transgression in the late Quaternary. Sea-level curves are constructed assuming that eustasy is mainly due to superposition of glacio-eustatic fluctuations on a linear tectono-eustatic trend, adjusted to fit Sundaland data.

Before the Middle Pleistocene Sundaland coastlines changed very little. Once since then did seas rise above the shelf-break causing major coastline shifts, dramatically affecting sedimentation and climates. Extinctions of savanna-adapted mammals resulted from their geographical isolation and unsuitability of increasingly homogeneous rain-forest habitats. Intervening glacials temporarily restored former continental environments.

INTRODUCTION

Recent studies of late Cainozoic deposits in the Sundaland area have shown the inapplicability of schemes (ZEUNER, 1959; TANNER, 1968; FAIRBRIDGE, 1971) indicating a general lowering of global eustatic sea-levels during this period. Even those (e.g. CHAPPELL, 1974) which suggest that successive late Quaternary interglacial sea levels were similar to, or slightly higher than the present level, are not consistent with Sundaland data.

A number of workers, including TJIA ET AL. (1975) and STAUFFER (1973) consider the Sunda Platform (continental margins of Peninsular Malaysia, Indonesian Tin Islands, West Borneo and the Sunda Shelf excluding Tertiary basal areas) (Fig. 1) to have been a tectonically stable craton since the mid-Tertiary. Furthermore, unequivocal evidence for significant late Cainozoic downwarp, uplift or tilting is lacking, and lithostratigraphic correlation is possible between

areas over 1000 km apart (ALEVA ET AL., 1973; BATCHELOR, 1976, in press; RYALL ET AL., 1977). The dominantly continental Quaternary sediments are not known to exceed 250 m thickness, either on or off-shore. No earthquake epicentres have been reported from Sundaland for the period 1962-1969 (U.S. DEPT. COMMERCE, 1970), nor from Peninsular Malaysia in historical time (TJIA ET AL., 1975). KUENEN (1950) remarked that the normal gradients of the large submerged valleys on the Sunda Shelf are formidable evidence for the complete crustal stability of this area, at least since their formation during the Pleistocene. DICKERSON (1941) also believed stability to be characteristic of Sundaland during Plio-Pleistocene times.

HAILE (1971, 1975) has shown that there are no good evidences for the presence in Peninsular Malaysia of sea levels above 6 m and those in the littoral zone that have been dated are all Holocene (TJIA, 1977). Evidence provided for higher Quaternary sea levels in the Indonesian Tin Islands (TJIA, 1970-a, b) does not stand critical examination. Levels of the 18-25 m riverine 'high terrace' (of VAN OVEREEM, 1960) in Belitung, and breaks in stream gradients and surface slopes in Belitung and Bangka are not convincing evidence for high

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Fig. 1
Tectonic framework of the Sundaland area, Southeast Asia. Based on both published and unpublished (mainly oil company) data.

stillstands of the sea. The use of bauxite levels as a direct sea-level indicator has been challenged by WILFORD (1969). BROUWER (1925), WESTERVELD (1937), and KOESOEMADINATA & PULUNGONO (1972) appear to be in full agreement that the Sunda Platform represented a continuous land mass in late Tertiary time and was only inundated by the sea during the Pleistocene, so that present sea-levels are near their

maximum for the late Cainozoic.

STRATIGRAPHIC DATA FROM THE SUNDALAND TIN BELT

Recent studies of offshore drilling and shallow seismic data

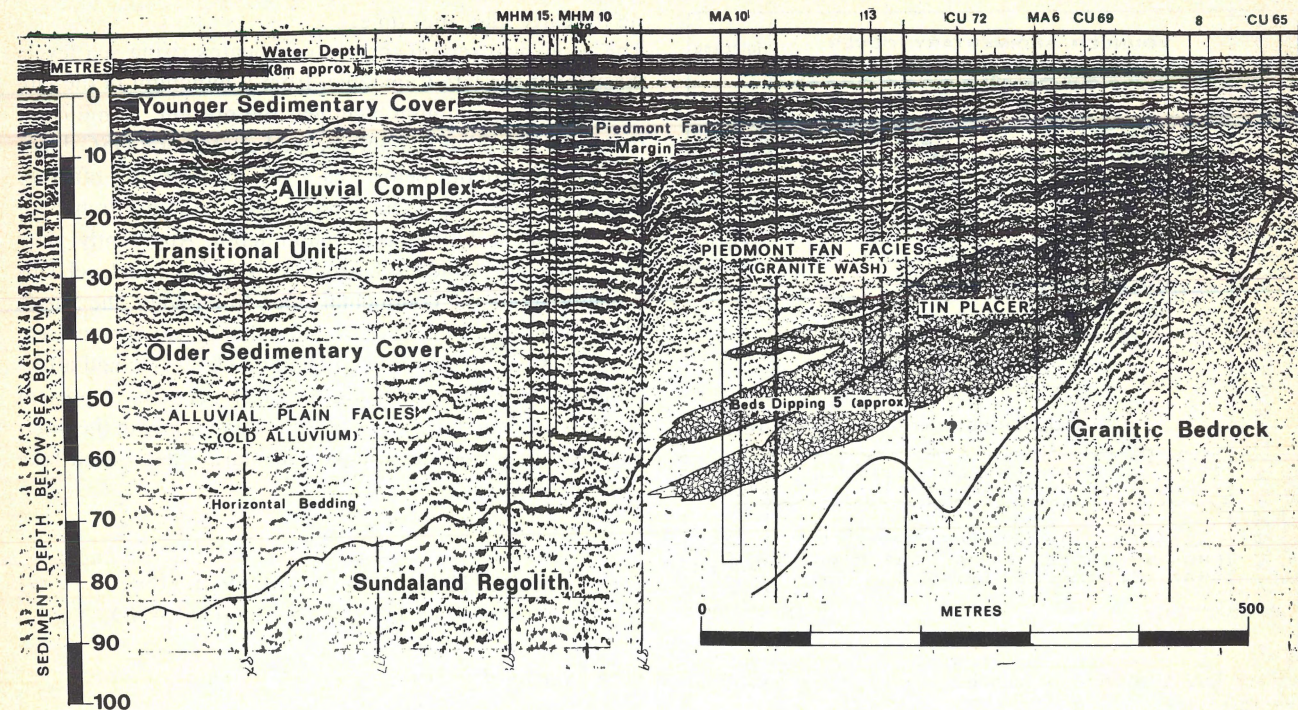


Fig. 2
Late Cainozoic stratigraphic/tin placer relationships with granitic bedrock in the Dindings nearshore area, Perak, Peninsular Malaysia (reproduction of EG & G High Resolution Boomer record; bore hole locations indicated).

from stable Sundaland provide confirmation of very low late Cainozoic sea-levels, and stratigraphic correlation has been established throughout the region. A typical seismic profile (Fig. 2) shows the relationships of the five regional units delineated (partly after ALEVA ET AL., 1973) to the underlying bedrock, in the Dindings nearshore area of Perak, Malaysia.

Younger Sedimentary Cover

This Holocene cover (YSC) is a superficial, blanket-like deposit of neritic muds and beach sands up to 30 m thick.

Alluvial Complex

Disconformably underlying the YSC is the Alluvial Complex (AC) consisting of meander channel and floodplain deposits with a 'Riss-Würmian' marine incursion below its base. Paralic deposits were, however, more restricted than at present. The regular occurrence of peats, and the repeated erosional phases and infilling of broad valleys incised to a 120 m depth maximum, indicates repeated climatic variations and changes in erosional base level caused by sea-level fluctuations younger than the 'Riss-Würm' interglacial. Observations in coastal placer mines allow correlation of these two units with the Young Alluvium (of WALKER, 1956 and STAUFFER, 1973) having a late Pleistocene-Holocene age.

Older Sedimentary Cover

The Older Sedimentary Cover (OSC) generally lies disconformably below the AC and differs markedly from the overlying sediments. It comprises a proximal facies of subhorizontal, gravelly, poorly-sorted 'granite wash' close to bedrock in a piedmont-fan environment (cf. Boulder Beds of WALKER, 1956) distinguished abruptly from a distal facies in an alluvial-plain environment (cf. Old Alluvium of WALKER, 1956) in which horizontal bedding is more obvious and the alluvium is finer grained. Apart from lateral facies changes and minor diastems, this grey-bed sequence is quite massive indicating negligible effects from climatic or sea-level fluctuations. Morphogenetic development and sedimentation corresponds to that described by VERSTAPPEN (1975-a) for Pleistocene periods of low sea-level. Sedimentary structures, the lack of marine fossils, the occasional presence of peats and the dominance of kaolinitic clays indicate a totally continental origin in upland areas far from the sea coast. Whereas the AC is characterised by linear river incision (and fill) due to higher discharge rates prevailing at times of relatively high precipitation, the OSC is typified by fans and vertical aggradation of braided-stream deposits forming high terrace features as the result of more arid, seasonal climatic conditions when river discharges were not sufficient or prolonged enough to fully remove bed-load detritus. A Pliocene to

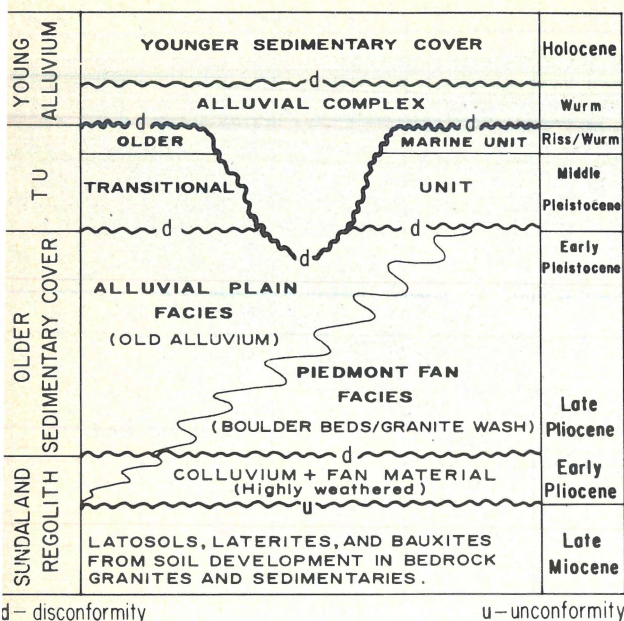


Fig. 3
Regional Late Cainozoic stratigraphic relationships in Sundaland, Southeast Asia.

early Pleistocene age for the OSC, as well as for the Old Alluvium (as earlier suggested by SCRIVENOR, 1928) is supported by determinations on pollen (ALEVA ET AL., 1973), fossil fruits (WARBURG, 1897) and vertebrates (STAUFFER, 1973) and the finding of Matuyama palaeomagnetic reversals at some localities (HAILE & WATKINS, 1974).

Transitional Unit

A poorly differentiated Transitional Unit of varied lithology (including peat and braided-stream alluvium, is occasionally found overlying partly lateritised Old Alluvium and separated by erosional disconformity from the Young Alluvium above (Fig. 3). The middle Pleistocene age indicated for this unit corresponds with finds of penecontemporaneous vertebrate remains from limestone caves (HOOIJER, 1962) and tectites (KROL, 1960; STAUFFER, 1973) from various Sundaland sites.

Sundaland Regolith

The Sundaland Regolith lying unconformably below the OSC represents deep soil development of red-yellow-brown latosols, laterites and bauxites within basement rocks, together with derived red-beds of colluvial and fan material. A number of workers (e.g. PATTERSON, 1967; STAUFFER, 1973; SCHELLMAN, 1977) have stressed the importance of tectonic stability and peneplanation for the development of laterites and bauxites, and further evidence suggests that this Sundaland pedogenesis took place under a seasonal savanna climate when sea levels were extremely low during late Mioce-

ne (to early Pliocene) time.

The geological record therefore indicates rising sea levels throughout the late Cainozoic, from a minimum in the late Miocene to a maximum high near the present. Admittedly, the deepest drilling has only proved continental OSC deposits to 120 m depth below sea level, in the Perak offshore area. However, their characteristic seismic appearance allows confident definition to 160 m depth. Apparently, only since the late Middle Pleistocene was the sea level sufficiently above the continental slope to inundate the Sunda Shelf over large areas (Fig. 4), such that glacio-eustatic sea-level fluctuations and related climatic changes could affect sedimentation patterns of the younger deposits in present coastal and nearshore areas of Sundaland. Only in the latter part of this period did widespread marine deposition take place here.

ADDITIONAL DATA SUPPORTING LOW SEA LEVELS IN SUNDALAND

Deep alluvial deposits

Probable equivalents of the OSC, represented by continental alluvium at considerable depths below present sea level, have been recorded by numerous authors from coastal margins of Peninsular Malaysia (Table I). Alluvium-filled valley features are known onshore from Perak, Selangor, Singapore and Kelantan, and in the nearshore areas of Perak and Pahang where they extend to depths of 200 m confirming the existence of extremely low Quaternary sea-levels.

Sunda shelf geomorphology

HILL (1968) described a series of elongate depressions in the Singapore Straits, the deepest of which is 217 m, in part of the shelf which is mostly less than 30 m deep. Although admitting the possibility of some downfaulting causing this deepening, Hill appeared to favour at least a 220 m sea-level lowering to explain stream erosion at this depth, as well as for the deeply buried Dindings Channel in Perak. The pattern of branching channels on the Sunda Shelf between Sumatra and Borneo is, according to KUENEN (1950), the finest example of a shelf channel system known. HAILE (1969, 1971) believed that the North Sunda Submarine Valley clearly indicates a sea level lower than - 110 m. The Proto-Lupar Channels which are mainly between 100 and 140 m deep (deepest 165 m), suggest even lower sea-levels, unless the shelf has subsided. It would appear also that shelf-break levels of the Sunda Shelf facing the Andaman Sea (128 m) and South China Sea (180 m) approximate late and earlier Pleistocene sea-levels, respectively. For the South China Sea, RIMM (1965) recorded sands from the shelf edge and slope at 135-360 m depth, thought by HAILE (1971) to have been deposited during a low Pleistocene sea-level phase.

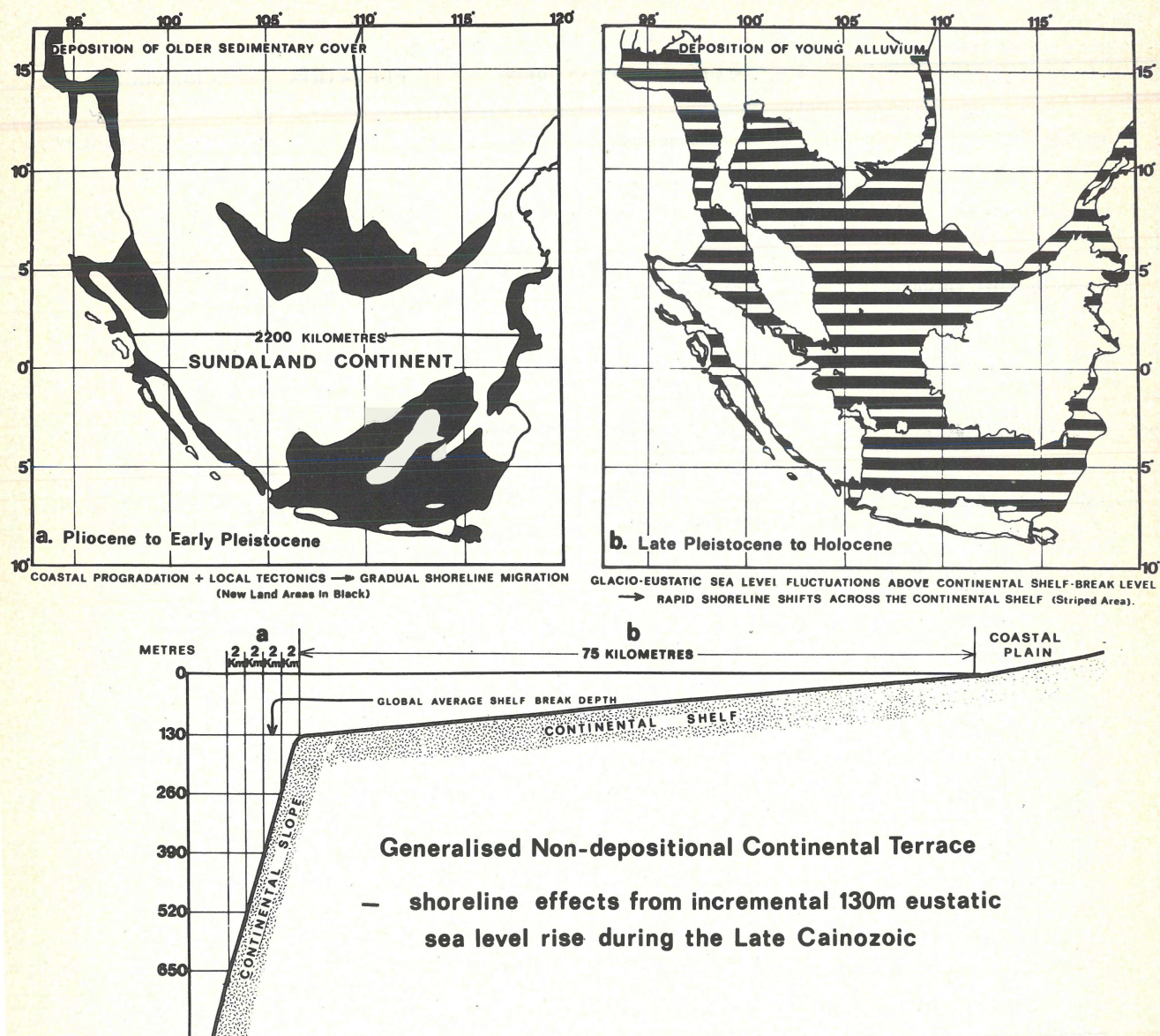


Fig. 4

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 (a) Pliocene-early Pleistocene, and (b) late Pleistocene-Holocene periods.

Submarine geology of the Sunda Platform and adjacent margins

Studies by petroleum companies (e.g. KOESOMADINATA & PULUNGONO, 1972; TAMESIS ET AL., 1973; FLETCHER & SOEPARJADI, 1976; PALTRINIERI ET AL., 1976; WOOLLANDS & HAW, 1976), CCOP (UN) sponsored groups (PARKE ET AL., 1971; EMERY ET AL., 1972), and tin mining companies (ALEVA ET AL., 1973; BATCHELOR, in press) on the Sunda Platform and adjacent Tertiary basins of both shelfal (Malay-Thai and Sunda Basins) and continental margin (Northwest Palawan Shelf) geotectonic settings, indicate almost identical depositional histories and negligible tectonic deformation displayed

by sediments overlying the major region-wide mid-Miocene unconformity. This event represented major marine regression and emergence of the whole Sunda Platform and even parts of the deep marginal basins. It is probably at this time that the 'double planation' effect of VERSTAPPEN (1975-a) was at its maximum during final development of the 'Sunda Peneplain' (of VAN BEMMELN, 1949).

Except for tectonically-induced overprint in unstable areas (e.g. Sarawak), a strongly cyclic, almost synchronous depositional history is now well-documented for the late Cainozoic. Regional marine transgression and submergence reached a maximum in early Middle Miocene (planktonic zones N9 and N10) time (TAMESIS ET AL., 1973; MURPHY, 1975;

Table I
Evidence for Quaternary emergence in West Malaysia and adjacent parts of the Sunda Shelf

LOCALITY	NATURE OF FEATURE(S)	ELEVATION (m)	REFERENCES
1. Sunda Shelf, South China Sea . . .	Broad submarine valleys (North Sunda Submarine Valley System)	-110	<i>Kuenen, 1950; Haile 1971.</i>
2. Sitiawan, Perak . . .	Bore in alluvium; bottomed on bedrock	-111	<i>Richardson, 1947.</i>
3. Lumut-Dindings, Offshore Perak . . .	Max. depth of submerged Late Wisconsin river valleys	-118	<i>Batchelor, this paper.</i>
4. Bernam River, Selangor . . .	Bore in fluvial alluvium; bottomed on bedrock	-120	<i>Scrivenor, 1931.</i>
5. Kinta Valley, Perak . . .	Depth of river alluvium & bedrock valley gradient	-122	<i>Walker, 1956.</i>
6. Bedok Valley, Singapore . . .	P.U.B. test bore 3 in Old Alluvium; unbottomed	-122	<i>Pfeiffer, 1975.</i>
7. Sunda Shelf, Malacca Strait . . .	Continental shelf-break level (late Quaternary)	-128	<i>Batchelor, this paper.</i>
8. Butterworth, Province Wellesley . . .	Bore in alluvium, bottomed on bedrock	-137	<i>Courtier, 1974.</i>
9. Sunda Shelf, Peninsular East Coast (south) . . .	Broad infilled submarine valleys	-80 to -140	<i>Oele et al., in prep.</i>
10. Telok Anson, Perak . . .	Broad alluvium filled channels	-91 to -152	<i>Lenk-Chevitch, 1959.</i>
11. Lumut-Dindings, Offshore Perak . . .	Max. interpreted depth of Older Sedimentary Cover on seismic profiles	-160	<i>Batchelor, this paper.</i>
12. Sunda Shelf, South China Sea . . .	Open submarine channels (e.g. Proto-Lupar), north of Kuching	-165	<i>Haile, 1971.</i>
13. Kelantan River Basin, Kelantan . . .	Max. interpreted depth of 'Old Quaternary River Sediments'	-170	<i>Pfeiffer & Tiedemann, 1975.</i>
14. Sunda Shelf, Esso Concession . . .	Interpreted late Pleistocene sea levels from paleobathymetry data	-100 to -180 (?)	<i>Biswas, 1973, 1976; Batchelor, this paper.</i>
15. Sunda Shelf, South China Sea . . .	Continental shelf-break level (early Quaternary)	-180	<i>Batchelor, this paper.</i>
16. Sunda Shelf, Peninsular East Coast (north) . . .	Very broad infilled submarine valleys	-200	<i>Oele et al., in manuscript.</i>
17. Lumut-Dindings, Perak . . .	Dindings alluvium filled channel	-200	<i>Lenk-Chevitch, 1959; Koopmans, 1964.</i>
18. Sunda Shelf, Singapore Straits . . .	Singapore 'Deep's' (river valley remnants)	-217	<i>Hill, 1968; Haile 1969.</i>
19. Mt. Knabalu, Sqbah . . .	Interpreted pre-Würm snowline depression	-230	<i>Koopmans & Stauffer, 1968; Batchelor, this paper.</i>

PALTRINIERI ET AL., 1976) penecontemporaneously with large-scale rifting in the South China Sea and considerable tectonic deformation in marginal areas, evidenced in the Palawan Shelf, and Indonesia where this event is known (UMBROVE, 1949) as the 'Intra-Miocene' orogeny. Rapid regression which followed apparently resulted in maximum emergence during the time of N14 and N15 planktonic zones (late Middle Miocene), as suggested by their complete absence in the southern Malay Basin (ARMITAGE & VIOTTI, 1977) and Central Sumatra Basin (BAUMANN ET AL., 1973). The magnitude of this regression is indicated by the distinct regional change of facies and the enormous amount of coarse clastics deposited in the great petroliferous deltaic complexes which prograded over the proto-shelves and slopes (esp. east Kalimantan; cf. GERARD & OESTERLE, 1973; SCHWARTZ ET AL., 1973) in continental margin basins. Apparently in the Tembungo Field of Sabah, sea-level lowering allowed deposition of an inner neritic/fluviol-derived fan complex directly onto the abyssal plain, since the typically 'Bouma turbidite sequence' is not found in these massive, clean, well-sorted sands (WHITTLE & SHORT, 1977). The present gross morphology of the Sunda Shelf is mainly due to depositional activity at this time (i.e. Late Miocene to Early Pliocene).

In all stable areas, resurgence of the sea followed under conditions of discontinuous transgression throughout the late Cainozoic, with maximum marine incursion represented in the late Quaternary. In the Gulf of Thailand in western platform areas, continental fan and flood-plain deposits overlying the mid-Miocene unconformity are progressively followed by paralic, brackish marine sediments with a strong deltaic influence, and finally open marine deposition in the latter part of the Quaternary (WOOLLANDS & HAW, 1976). In the deeper Malay Basin, although penecontemporaneous continental deposition is minor, the same transgressive trend is represented (cf. also ARMITAGE & VIOTTI, 1977). On the Palawan Shelf, deformation of early Neogene sediments preceded total marine regression represented by the mid-Miocene unconformity. Shelfal transgression which recommenced in Late Miocene time, resulted first in deposition of fine-grained detrital carbonate and clastic sediments and finally of carbonate (partly reef) facies as open-marine conditions were established since early Pliocene time (TAMESIS ET AL., 1973). Sundaland foreland margins have been affected to varying degrees by the major Pliocene-Holocene orogeny, which tectonism (i.e. uplift) has caused local marine regressions (e.g. Java geanticline; refer PALTRINIERI ET AL., 1976), superimposed on the general Late Miocene to Holocene tectono-eustatic transgressional trend.

Beneath the Java Sea, EMERY ET AL. (1973) reported Pleistocene stream-cut channels filled with non-marine sediments. Their mention that only slight reworking by marine currents of the topmost layers has taken place, suggests that submergence of the shelf in this region was quite a recent event. Examination of BISWAS' (1973, 1976) data from the Malay Basin, in water depths less than 100 m, suggests that sea-le-

vel fluctuations recorded in punch-cores are probably of late Middle Pleistocene to Holocene age only. Calculations based on his estimates of palaeobathymetry suggest that sea-levels ranged from below 180 m (during R₄ time of his fourth regression) to just above present sea-level (at T₂ time of his second transgression in Seligi No. 1 well, and Tembungo well, Sabah), though for the latter level estimates vary. T₂ time probably corresponds to the maximum transgression during the 'Riss-Würm' interglacial, reported also by BROECKER & VAN DONK (1970) and CHAPPELL (1974).

That the Late Miocene to Holocene transgression represents a eustatic sea-level rise is supported by the unlikelihood of vertical tectonics, isostatic adjustments, or variation in sedimentary accumulation rates, being the major controlling factors. Major post-Middle Miocene tectonic deformation is absent from the Sundaland craton. Differential Cainozoic isostatic adjustments would be expected if consideration is taken of the vast bedrock thicknesses denuded from previously emergent Sundaland and deposited in adjacent Tertiary shelfal basins, where sedimentary fill exceeding 10,000 m is reported (MURPHY, 1975). Shelf areas with thin sedimentary cover might expect to be uplifted in contrast to basinal areas suffering subsidence. However, sediments in both environments show a synchronous trend of late Cainozoic transgression (e.g. WOOLLANDS & HAW, 1976, Fig. 2), indicating that these factors were relatively unimportant. Neither can the transgression be explained as due to sinking of the whole Sundaland region, as envisaged by FAIRBRIDGE (1966). In fact, TJIA'S (1977) Sundaland post-glacial sea-level curve supports FAIRBRIDGE'S (1961) curve which FAIRBRIDGE (1971) assumed to be characteristic of stable coasts. The tentative Quaternary eustatic sea-level curve for Sundaland (Fig. 5) requires a tectono-eustatic rise of 10 cm/10³a for this period. Assumed subsidence rates for other 'cratonic' shelves where the thickness of the Tertiary cover is considerable, are much less. The subsidence rates off Cape Hatteras (U.S.A.) and on the NW African Shelf are 2 cm/10³a and 2.4 cm/10³a respectively, since the Late Jurassic (RONA, 1973-a). UCHUPI & EMERY (1967) calculated a lower Cainozoic rate of 1 cm/10³a for the Atlantic margin of the United States. The Sunda Platform, however, from where most of my evidence (Table 1) for low sea-levels is derived, has only a thin Cainozoic cover, so subsidence is assumed to have been negligible, and the late Cainozoic transgression represents, in fact, a eustatic event. The Middle Miocene-Holocene eustatic sea-level cycle established from Sundaland data is identical to that reported by QUILTY (1977) from the passive continental margin of west Australia, also believed by him to reflect global events.

Equatorial snow lines and alpine floras

KOOPMANS & STAUFFER (1968) believed that the snowline on Mt. Kinabalu (Sabah) was reduced between 760 and 1070 m during the Pleistocene. Noting "the absence of large ac-

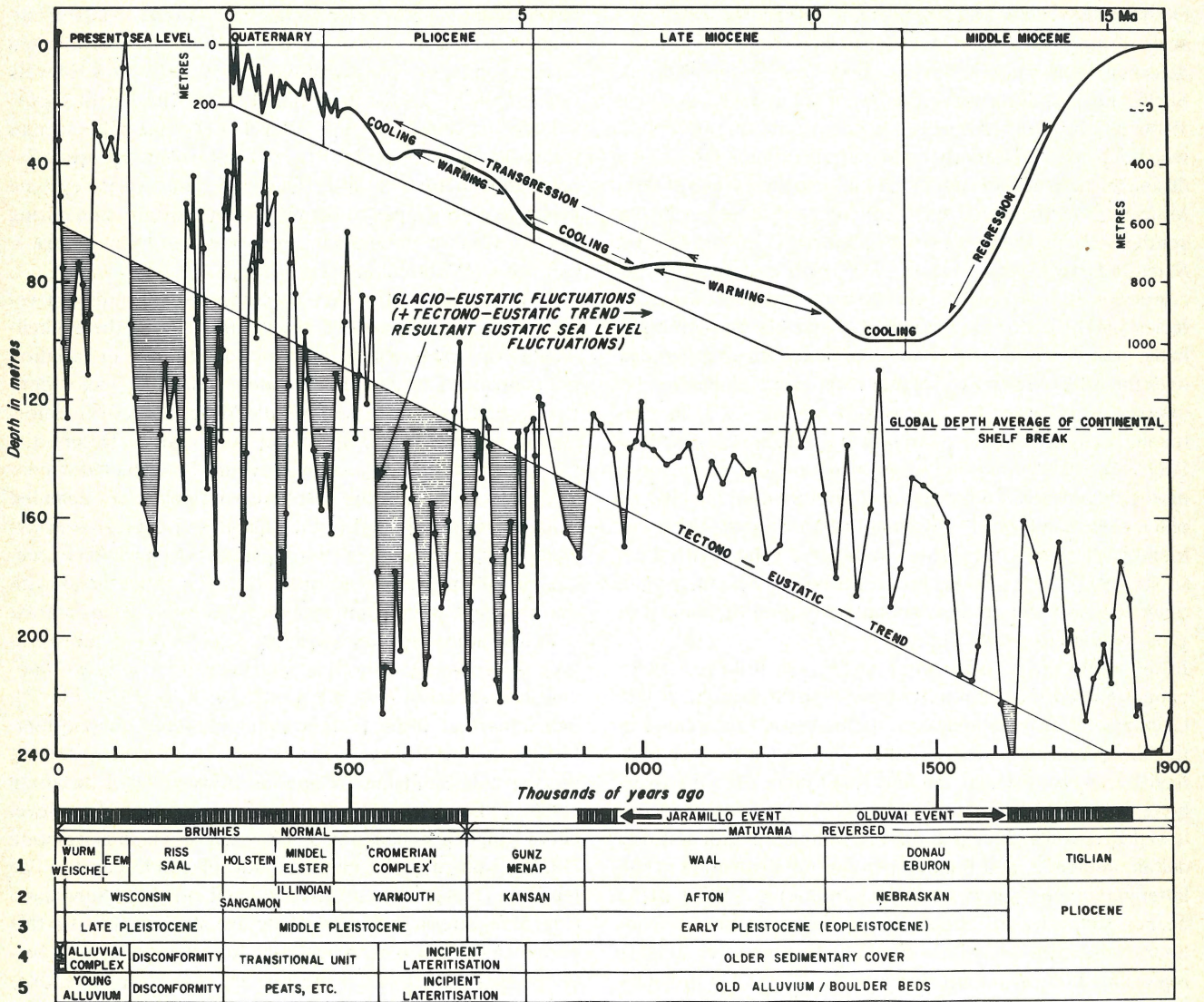


Fig. 5 Global eustatic sea-level chart for the Late Cainozoic and Quaternary periods, and a tentative correlation of Sundaland stratigraphic sequences with the classical European and American palaeobioclimatologic stages (chronology based largely on Van Eysinga, 1975, and other pertinent literature). Magnetic polarity chronology after LaBrecque 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, 1956).

cumulations of morainic material which must have formed from erosion of the summit area", Stauffer suggested that most glacial erosion occurred during the Riss of earlier glacial periods, and that the time since has allowed removal of most of this debris by stream erosion and mass movement. Geomorphological evidence from New Guinea mountains suggests a snowline lowering there of 950-1200 m (REINER, 1960; VERSTAPPEN, 1964; LOFFLER, 1972). Although the snowline position is a complex matter, dependent also on local climatic conditions, it does appear that a general snowline

lowering of 1000 m did take place in these areas. If, as has been suggested by COLLENETTE (1964), Kinabalu was uplifted in the mid-Pleistocene, then the actual snowline lowering there may have been even greater.

Probably the most reliable evidence for the amplitude of Pleistocene temperature changes in this region comes from palaeotemperatures determined from oxygen-isotope ratios of Foraminifera in deep-sea cores from equatorial and tropical oceans (e.g. EMILIANI, 1966, 1972; IMBRIE ET AL., 1973; SHACKLETON & OPDYKE, 1973; CLINE & HAYS, 1976). Estimates

for the maximum depression in oceanic ice-age temperatures as compared to the present, range from 2-6 °C, though most authors would accept a depression of 2-4 °C for the equatorial Pacific. If it can be assumed that temperatures of coastal plains would approximate those of ocean waters with perhaps a slightly higher diurnal variation due to greater dryness during glacial periods, then 5 °C is probably the maximum average temperature depression acceptable for coastal Sundaland. A similar figure has also been suggested by VERSTAPPEN (1975-b) and HAMMOND (1976) for Asian monsoon regions. Assuming the lapse rate of around 0.65 °C/100 m, measured for Malaysian highland areas (BURGESS, 1969) was also applicable in general under Pleistocene glacial conditions, then a 5 °C temperature depression could explain a snowline lowering of about 770 m. It would seem reasonable to assign the remaining depression of 230 m (or more) to a pre-Würm Pleistocene glacial eustatic sea-level lowering, drawing altitudinal temperature zones down with it.

MULLER (1972) mentioned that the present montane vegetation on Kinabalu includes the conifers *Phyllocladus* and *Podocarpus* which are well-established only above 1000 m altitude. *Podocarpus* first appeared there in the Upper Pliocene, and *Phyllocladus* at the Plio-Pleistocene transition, both having migrated all the way from New Guinea. Both geologists and botanists find difficulty in explaining this alpine migration across great expanses of present lowland and sea areas, especially since Muller considered that a connecting mountainous land bridge was a necessity. A geomorphological setting of such type would have developed in part during glacial periods of very low sea-levels. If a low glacial sea-level of at least -230 m occurred in the Pleistocene, then on the basis of previous calculations, a depression of this conifer zone by 1000 m to the present sea-level could have taken place. Also, if subsequent denudation is considered, parts of the landscape would have been higher by hundreds of metres, especially since Pliocene uplift preceded the conifer migration into Borneo (JACOBSON, 1970), so low altitude barriers at that time would have been narrower. These factors, together with the considerable dispersive ability of montane pollen in general could effectively explain this enigmatic migration. Alternatively, if glacial agencies are discounted as being unimportant in the Late Pliocene, migration could still have been facilitated by a significantly lower sea-level, due mainly to tectono-eustatic factors.

Late Cainozoic palaeogeography, soils, climate and vegetation

Certain characteristics of Sundaland soils and vegetation support the concept of very low eustatic sea-levels during the late Cainozoic. A sea-level drop of around 230 m would fully expose the Sundaland continent, which would form a considerable extension to the main Asian landmass (Fig. 4). The minimum dimension of Sundaland would then exceed 1000 km, and the greatest distance of the central core from

the sea would be about 800 km. Additionally, if we accept that Late Miocene to Middle Pleistocene sea-levels never rose much above the continental slope, then the outline of Sundaland during this period would have changed very little, since beyond the shelf-break bathymetric contours are closely spaced. The sea-level at this time would have fluctuated up and down the continental slope with only minor lateral shifts. Presumably, only during the late Quaternary, when sea levels rose considerably above the shelf break with consequent major lateral shifts in coastlines across the Sunda Shelf, did sea-level fluctuations have such a drastic effect on sedimentation patterns and biological distributions.

VERSTAPPEN (1975-a) stated, in regard to Pleistocene glacial climates in Sundaland, that a considerable reduction in rainfall would have occurred, probably equalling or exceeding that in most other equatorial regions. Increased continentality represented by increased aridity and a more pronounced dry season was largely ascribed by him to a positional shift of the Intertropical Convergence Zone, the decreased influence of 'thermally inert' ocean waters, the greater extent of land areas and the global drop in temperatures. The first two factors, however, are largely dependent on the conversion of large warm shallow seas to land areas, which would have more than doubled. Regarding the glacial temperature-drop, EMILIANI & SHACKLETON (1974) found that average temperatures were depressed less in the equatorial Pacific than in the equatorial Atlantic and Caribbean. Additionally, lowered sea-levels would themselves directly affect climate by depressing altitudinal temperature zones. Eustatic sea-level variation would therefore appear to be at least as important as global temperature depression in affecting Sundaland glacial climates. Marked global cooling, probably accompanied by worldwide sea-level lowering, has also been established for the Late Miocene, Mio-Pliocene and late Pliocene. Together with an apparent maximum eustatic sea-level lowering and expanse of Sundaland in the Late Miocene, and the presence of a rain-shadow east of the Sumatran Barisan following strong mid-Miocene uplift (ASHTON, 1972), the late Tertiary (particularly Late Miocene) would be expected to show maximum continentality, greater even than the succeeding Pleistocene glacial periods. A major arid phase in Australia was also initiated in the Late Miocene (BOWLER, 1976).

It would seem significant therefore, that laterites and bauxites generally lie at the base of late Cainozoic sequences in tin-belt areas and are more abundant in a belt stretching from south Borneo, Bangka and Belitung through Riouw to Johore and Malacca, which would have represented the Sundaland core. Although the genesis of such deposits is still the subject of much discussion, I wish to stress certain features which have apparently been understated by many agronomists. The majority of laterites (and bauxites) are now considered to be fossil soils in Thailand (PENDLETON & SHANASUVANA, 1946), Peninsular Malaysia (LAW & LEAMY, 1966; EYLES, 1970) and Indonesia (VAN DER VOORT, 1950; MOHR & VAN BAREN,

1954). ASHTON (1972) noted the lack of laterite-pan formation under present humid rain-forest conditions in west Malesia. GRUBB (1963) stated that secondary kaolinisation of bauxite (plus silicification) is evident throughout the Johore deposits and believed that the optimum bauxitisation period had now passed. WOLFENDEN (1965) also noted that secondary alteration of bauxite was taking place under present-day swamp conditions in Sarawak. Lateritic soils thought to be forming under present wet monsoonal conditions in West Malaysia, may actually include reworked lateritic material (LAW & LEAMY, 1966; GRUBB, 1966). Long reaction times are prerequisites for both strong bauxitisation (PATERSON, 1967; SCHELLMAN, 1977) and lateritisation (MOHR & VAN BAREN, 1954) indicating the requirement also of penecontemporaneous peneplanation during a long period of geomorphological stability. It is obvious, therefore, that the present climate is not necessarily characteristic of such pedogenesis, and indeed the strong landscape dissection and extent of present alluviation (EYLES, 1969), and the considerable mass movement of soil material under present wet monsoonal conditions, are detrimental to its formation (refer LAW & LEAMY, 1966).

MOHR & VAN BAREN (1954) cited evidence of old lateritic soils formed on Miocene and early Pliocene strata in Indonesia, and PENDLETON & SHANASUVANA (1946) attributed most lateritisation in Thailand to the Mio-Pliocene, in agreement with the late Miocene-early Pliocene age of the Sundaland Regolith in tin belt areas. Requirements generally given for such pedogenesis are a low water-table with the periodic upward movement and concentration of soluble iron and aluminium salts in combination with sufficiently dry aerobic conditions in the profile for oxidation and deposition to occur seasonally. The simplest chemico-physical environment to explain formation, and one favoured by the majority of workers, is a warm, rather semi-arid tropical climate with a marked alteration of wet and dry seasons (e.g. SIVARAJASINGHAM ET AL., 1962), characteristic of savanna plainlands (FAIRBRIDGE, 1968). It is not surprising therefore, that WING-EASTON (1937) invoked such conditions for the genesis of ferruginous eluvial and residual-elutriational tin placers (as well as laterites and bauxites) in the late Neogene during very low sea-level stands in the Indonesian Tin Belt, and this concept is partly supported by BON (1977). These deposits are best developed in the Sundaland core regions where continentality would have been especially enhanced by extremely low late Tertiary sea-levels.

VERSTAPPEN (1975-a) argued that the exchange of 'drought plants' between the Australian and Asiatic continents via Sundaland, must have taken place when a tropical climate with a more pronounced dry season was more wide-spread than at present. Absence of the Asian savanna tree flora, at least at species level from east Malesia, suggested to ASHTON (1972) that savanna migration probably took place in late Tertiary time, and certainly before the late Pleistocene. MORLEY (1977) noted the migration into north Borneo in late Miocene-Pliocene time of the mangrove taxa *Aegialites* and

Camptostemon, which are presently restricted to areas exhibiting marked seasonality. These views also support the concept of maximum continentality in the late Tertiary due mainly to drastic sea-level lowering. In favour of a general late Cainozoic sea-level rise to the present maximum is the evolutionary history of the Sundaland Dipterocarpaceae flora, according to ASHTON (1972). An initial immigration of all major existing genera in the late Tertiary was followed by rapid dispersal while continental conditions prevailed. As early Pleistocene conditions became moister, early diversification led to the evolution of large groups of inland species. Towards the end of this period, diversification took place into extensive lowland hills, shortly to be submerged for the first time under the South China Sea. The late Middle Pleistocene and later times, characterised by high sea-levels, witnessed a much reduced rate of diversification.

Late Cainozoic land mammal (and fish) distribution

The world faunal characteristics of the Pliocene to Middle Pleistocene period represent evolutionary progression with the appearance and invasive spread of new taxa. In contrast, the main differences between faunas of the Middle and Late Pleistocene consist of extinction without replacement, though the loss of mammals in Sundaland was apparently less catastrophic than elsewhere. It would appear from MEDWAY'S (1972) excellent account that, in addition to climatic changes affecting vegetation, the presence and subsequent disappearance of land bridges, was a major factor affecting the dispersion, evolution and extinction of Sundaland mammals in late Cainozoic times.

GROVES (1975) believed that the first arrival of land mammals into Sundaland did not predate the Pliocene. The major influx of the Indian Siwalikian fauna took place in the early Lower Pleistocene and the Javan herbivores were then adapted to riverine, forest-edge or forest habitats (MEDWAY, 1972). Even at that time, a forest barrier prevented the introduction of savanna-dwelling Siwalikian animals. From the earlier discussion it is apparent that, if a savanna grassland corridor existed between the Asian mainland and Sundaland, its occurrence was more likely in Mio-Pliocene time before the Siwalikian fauna had even appeared in India. With continued sea-level rise and denudation of Sundaland mountains, the Sundaland climate in the lowermost Pleistocene could already have shown decreased continentality reducing the extent of savanna vegetation.

During the Middle Pleistocene, many forest-dwelling species invaded the western area and it is evident (MEDWAY, 1972) that forest animals could move freely across Sundaland. However, some animals were clearly adapted to browsing and grazing, their diet being rich in bamboo, grass, and in the case of *Manis palaeojavanica* (an extinct pangolin), tall termitaries which are presently restricted mainly to savanna country outside of Sundaland. Grazing ungulates which reached Java are particularly dependent on large tracts of grassland, and

this supports Medway's contention that a savanna belt straddled the Equator across Sundaland at least temporarily, during periods of greater continentality. Because the land bridges were always open (with the Sunda Platform completely emergent), the Sundaland Middle Pleistocene mammal faunas became essentially homogeneous with only minor local differences in composition (MEDWAY, 1972). Differences in land faunas at this time across Sundaland, can be largely accounted for as suggested by GROVES (1975), by the fact that the Sunda river system (of KUENEN, 1950) was sufficiently large then, that the rivers represented barriers to migration in their lower courses, and the narrowness of the bottleneck at their headwaters would also strongly restrict contact. ASHTON (1972) also believed that the present Lupar Valley represented a marked phytogeographical barrier. High sea-levels and consequent island isolation therefore are not necessary to explain Sundaland faunal differences prior to the Late Pleistocene.

MEDWAY (1972) stated that there has been no new immigration of a large mammal into Sundaland since the Middle Pleistocene, and by the close of the Late Pleistocene few grazing mammals survived. The ecological specialisations of mammals which failed to survive into the Late Pleistocene indicate a drastic reduction in open jungle and savanna areas due to a markedly decreased continentality near the Middle-Late Pleistocene transition. The zoological evidence therefore strongly indicates that Pliocene to Middle Pleistocene sea-levels, though rising discontinuously, never lay much higher than the continental shelf break. However, marine invasions of the Sunda Shelf since the Middle Pleistocene resulted in the extinction or size diminution of many mammal groups due to a reduction in readily available food following their geographical isolation and the unsuitability of the increasingly more homogeneous, dense rain-forest environment, typical of the tropical monsoon climate presently prevailing in much of Sundaland.

Studies on the Palawan fresh-water fish in the Philippines showed that, although the genera are Bornean, only one is specifically identical. DICKERSON (1941) believed that this indicated a connection with Borneo via his 'Molengraaf River' in the early Pleistocene but not during the late Pleistocene. He also stated that the 200 m isobath probably indicates many connections in Sundaland during glacial phases of the early Pleistocene, and the 100 m isobath during the last glacial phase.

WORLDWIDE OCEANOGRAPHIC DATA SUPPORTING LOW EUSTATIC SEA-LEVELS

Further confirmation of global late Cainozoic low sea-levels must necessarily be sought in the shelf-break region of stable continental margins, as well as deeper oceanographic features which in their morphology or depositional history may show eustatic sea-level control.

The depth of non-glaciated continental shelves worldwide is relatively uniform with the shelf-break lying between 125 m and 180 m. The average depth of 132 m (SHEPARD, 1948) is considered characteristic of stable margins, since this level is believed to approximate the Late Pleistocene sea-level stands (e.g. DIETZ, 1952; CURRAY & MOORE, 1964), the latest being at 120-125 m depth, 17,000 to 20,000 B.P. (e.g. CURRAY, 1965). According to LEWIS (1974), a shelf-break at more than 120 m depth is probably older than 20,000 B.P. I therefore believe that shelf-break levels of the Sunda Shelf, facing the Andaman Sea (128 m) and South China Sea (180 m) approximate Late Pleistocene and earlier Pleistocene sea-levels, respectively. A brief literature review suggests that late Cainozoic sedimentational histories in shelf-break areas are best shown on relatively wide, non-glaciated shelves with a moderate rate of sediment supply. The predominant nature of such shelves is a 'depositional terrace' (CURRAY & MOORE, 1964) where considerable paralic (particularly deltaic) sedimentation is found (e.g. U.S. Atlantic and Gulf coasts: UCHUPI & EMERY, 1967, 1968; Bering Sea: HOPKINS ET AL., 1969). In these cases, the influence of basement relief on present sea-floor morphology is often masked by the overlying sediments and the shelf break is a function of late Cainozoic sea-levels and their fluctuations, rather than a reflection of the basement surface.

In many parts of the world, the time when development of the modern continental terrace was initiated, followed the major marine regression in the late Middle to Late Miocene represented by either a marked unconformity (or peneplanation surface), decreased sedimentation rates, or evidence of regressive sedimentary facies (e.g. Australia: JONES ET AL., 1975; HOCKING, 1976; QUILTY, 1977; Philippines: TAMESIS ET AL., 1973; South Africa: DINGLE, 1971; U.S. Gulf coast: JORDAN ET AL., 1964; EMERY & ZARUDZKI, 1967; U.S. Atlantic coast: MURRAY, 1961; RONA, 1970; SHIDELER & SWIFT, 1972; Bering Shelf: HOPKINS ET AL., 1969). This regressive period corresponds to that previously determined for Sundaland strongly supporting the idea of a global eustatic sea-level lowering far below the present continental shelf break. Since younger discontinuities are generally less widespread and more variable in their time of formation, it would appear that the "worldwide contemporary hiatus in late Cenozoic sediments on depositional shelves", originally postulated by GALLOWAY (1970), is probably represented by this event of late Middle to Late Miocene age. Divergences in time of initiation in some areas can certainly be accounted for by local tectonic and depositional factors, palaeogeographic location, or uncertainties in palaeontologic dating of the event.

The accumulating evidence on low late Cainozoic sea-levels, together with the mass of data originally provided by SHEPARD (1948, 1949) supporting the largely subaerial nature of submarine canyons down to at least 1000 m depth, suggests that they were mainly formed subaerially during the extreme Cainozoic marine regression in the Oligocene (refer VAIL ET AL., 1977) when canyon formation is known on the

southeast Australian shelf (CONOLLY, 1968; HOCKING, 1976), off southern France (BOURCART, 1950) and central California (TRAVERS, 1972). The global variation in depths of canyon termini (c.f. SHEPARD & DILL, 1966, p. 25, appendix) approximates a normal gaussian distribution with a mean for well-developed terminations of 1816 m, which I believe may be related to this maximum sea-level lowering. However, during the late Miocene regression these canyons were probably strongly rejuvenated and further deepened by subaerial agencies. The late Miocene regression is also believed responsible for the complete drying out of the Mediterranean Sea and extensive evaporite formation (cf. HSU ET AL., 1973) when, according to FLEMMING & ROBERTS (1973), eustatic sea-levels may have been 800-1000 m lower.

Studies on the Eniwetok and Bikini atolls in the western Pacific (SCHLANGER, 1963) disclose that during their history of shallow submergence they were synchronously affected by two or three emergences (e.g. during the Oligocene and late Miocene) during which the reefs were totally truncated by subaerial erosion and red 'terra rossa' soils developed. The late Miocene 'solution unconformity' at 335 m depth on both atolls, is underlain by a zone of solution channels and recrystallised calcite to a depth of more than 550 m, suggesting a eustatic sea-level fall of similar amount since FAIRBRIDGE (1976) believed that such emergences could not be explained by either crustal cooling or isostasy. Furthermore, the subsequent continuous build-up of shallow-water limestones (save for Pleistocene unconformities) requires a steady rise to the present sea-level. KUENEN (1950) drew attention to the remarkable fact that guyots of less than 940 m depth appear to be very scarce. From previous evidence it would seem that the last major sea-level fall (i.e. late Miocene) failed to expose deeper guyots, whereas those above this level allowed the build-up by coral reefs to form atolls. The fact that the bulk of seamounts appear to be older than 30 million years indicates (cf. FAIRBRIDGE, 1976) that subsidence due to crustal cooling is unlikely, so the 940 m level may prove to be the closest estimate of the late Miocene sea-level depression.

Commonly overlying the major late Miocene discontinuity in continental shelf-break areas are a series of deltaic sediments interspersed with strata of other paralic and open-shelf facies and interrupted by as many as 4 or 5 disconformities (e.g. U.S. east coast: UCHUPI & EMERY, 1967, 1968; KNOTT & HOSKINS, 1968; GARRISON, 1970; Gulf of California: CURRAY & MOORE, 1964; West African coasts: MCMASTER & LA CHANCE, 1968; MCMASTER ET AL., 1970; DINGLE, 1973) which represent mainly Pleistocene eustatic sea-level fluctuations. It is quite apparent from studies made off the U.S. Atlantic coast (KNOTT & HOSKINS, 1968; GARRISON, 1970) that Pleistocene sea-levels were often below the shelf-break, at which times rivers caused extensive erosion of the outer shelf region, to the south of glacial limits near Georges Bank. Since the aerial extent of each successive erosional surface is less widespread than its predecessor, a general Pleistocene sea-level rise is suggested, with the glacio-eustatic events superim-

posed. In many areas worldwide, rapid progradation on the continental slope and outer shelf during low sea-levels was followed during interglacial sea-level rise by paralic (particularly deltaic) upbuilding, tending to stabilise the level of the shelf margin with reference to contemporary sea-levels, in order to maintain a marine profile of equilibrium. Continuous paralic deposition must also have been facilitated in areas with high accumulation rates by compensatory down-warp of the continental margin. However, the effect of isostatic and tectonic factors in causing subsidence of outer shelf areas (i.e. continental flexure) in late Cainozoic time, appears to have been often overemphasised (LEWIS, 1974, p. 53). GALLOWAY (1970) stated that while downwarping had occurred on some shelves, the depression rate is too slow to account for the present depth of many late Cainozoic erosional features. CURRAY & MOORE (1964) and UCHUPI & EMERY (1967) reported from the Gulf of California and U.S. Atlantic coasts, the presence of a series of untilted and undeformed paralic deposits which would suggest negligible subsidence, but a general rise of Quaternary sea-levels to the modern shelf-break position.

Accumulating evidence from submerged wave-cut platforms and associated erosional features on continental terraces, also supports the concept of Pleistocene sea-levels lower than previously considered. Soundings by DILL (1969) and PRATT & DILL (1974) on tectonically stable continental margins of the Bering Shelf and Australia, show strong evidence for continuous terraces at 146, 165, 200 and 240 m depth. Pleistocene eustatic sea-level lowering forming the 240 m terrace was also supported by deep submersible observations of terraces and gravel deposits off California, subaerial erosion features on carbonate banks and survey data from shallow seamounts. SCHWARTZ (1972) proposed that shelf breaks on Cobb and Bowie Seamounts in the Pacific represent Pleistocene sea-level lowering of 220-256 m. JONGSMA (1970) found terraces in the Arafura Sea, off northern Australia at depths of 130, (150), 170-175, and at about 200 m with littoral reef material from the latter dating older than 170,000 B.P. Well developed, undeformed terraces off the east Australian coast are known at depths of 160 m (JONES ET AL., 1975), 180-220 m (CONOLLY, 1969; THOM ET AL., 1972), and the regular extension of the Port Jackson stream profile cut to 140 m depth on the outer continental shelf, represents sea-level lowering below this depth (THOM ET AL., 1972).

Numerous authors (e.g. HEEZEN ET AL., 1959; DONN ET AL., 1962; KNOTT & HOSKINS, 1968) have described a distinct horizontal wave-cut terrace between 142 and 154 m depth, reaching a maximum discernible width of 6 miles, extending along the U.S. Atlantic continental margin for over 100 miles with occurrences of sand, pebbles and shallow-water shells (Ewing et al.: see DONN ET AL., 1962). Shell material is dated older than 30,000 B.P. and represents sediment infilling of an older erosional surface at 165 m depth. These and other benches at a similar level in the West Indies are probably Pleistocene (HEEZEN ET AL., 1959). RONA (1970) reported a

probable surf-cut bench in the Cape Hatteras region at 195 m depth and suggested correlation with benches at around 175 m off Virginia. These may also correspond to the wave-cut bench near the Hudson Canyon considered by KNOTT & HOSKINS (1968) to have been cut by a lowered Illinoian sea-level. However, this data (and the 124 m last glacial sea-level position) may be compromised by findings of DILLON & OLDALE (1978) that the continental terrace has probably been tilted north of an inflection zone running through New Jersey. BOURCART (1949) found 3 'terraces' along the U.S. Atlantic border and assumed the deepest (500-1000 m) to be Mio-Pliocene, one between 200 and 500 m Upper Pliocene and the 'terrace' from 0 to 200 m to date from late Wisconsin to Holocene. A well-defined 280 m terrace and 240 m escarpment on the Walvis Shelf off Southwest Africa may represent late Pleistocene sea-level positions (VAN ANDEL & CALVERT, 1971).

Drowned valleys well below present sea-level occur on most coasts and extend across continental shelves to depths of 100-200 m. Buried channels recorded by EWING ET AL. (1963) and KNOTT & HOSKINS (1968) off the north U.S. Atlantic coast at 150, 156, and 202-260 m depth, though partly of glacial origin, are related to low Plio-Pleistocene sea levels. MCMASTER & ASHRAF (1973) reported a buried valley system extending off New England to 150-200 m depth, and considered it to be of 'pre-glacial' age. Investigations on the French continental shelf (VERGER, 1970) provided evidence of several old shorelines, the deepest of probable karstic origin standing below 200 m, together with coarse subaerial deposits. The shelf off east India carries oolitic sands with abundant shallow-water Foraminifera even at 180 m depth, suggesting low sea-level deposition and non-deposition since the sea rose (SHEPARD, 1973). Steplike topography of the Australian Sahul Shelf closely resembles a system of late Cainozoic erosional surfaces on the adjacent land (VAN ANDEL & VEEVERS, 1965). Though the shelf was exposed during most of the late Cainozoic it has only been submerged recently.

The findings documented above lend considerable support to GALLOWAY'S (1970) contention that drowned valleys, cliffs and erosional features of continental shelves required a prolonged period of low sea level (below the shelf margin) followed by a period of gradually rising sea-level.

QUATERNARY EUSTATIC SEA-LEVEL CURVE

The suggested maximum Quaternary eustatic sea-level lowering for Sundaland of around 230 m, indicates that glacio-eustasy is an insufficient mechanism, since most authors (e.g. DONN ET AL., 1962) believe it can only explain up to 159 m sea-level depression. In agreement with a large and increasing body of opinion (e.g. RONA & WISE, 1974) that tectono-eustatic factors have made important contributions to Phanerozoic sea-level fluctuations, I also believe this was the major factor during the late Cainozoic. MORNER (1976) in a con-

troversial paper, refutes the probability of synchronous global eustatic changes though his views have not yet been subject to rigorous testing by other workers. It is still to be ascertained whether suggested vertical changes in the geoid (up to 185 m) affect sufficiently the primary trend of global glacial + tectono-eustasy on the time scales considered here. The general contemporaneous nature of major Phanerozoic transgressions and regressions (e.g. RONA, 1973-a; VAIL ET AL., 1977) suggests the geoidal-eustasy factor may have been overestimated. The Quaternary (and late Cainozoic) sea-level curve (Fig. 5) is therefore tentatively considered to be the sum of glacial and tectono-eustatic events, though the possibility of contributions from other factors cannot be dismissed.

The glacio-eustatic component

Many authors (e.g. IMBRIE ET AL., 1973; SHACKLETON & OPDYKE, 1973; VAN DONK, 1976) agree that O^{18} -curves based on isotope analysis of Foraminifera from deep sea cores primarily represent global ice-volume curves and hence glacio-eustatic sea-level fluctuations. I have therefore used those curves of SHACKLETON & OPDYKE (1973) and VAN DONK (1976) from the equatorial Pacific and Atlantic, to approximate the Quaternary glacio-eustatic effect. For the interval 0-825,000 B.P., the Shackleton-Opdyke curve would seem a better estimate since it is largely substantiated by independent evidence (e.g. late Wisconsin glacial maximum at 18,000 B.P.: CLINE & HAYS, 1976; ages of Barbados interstadial terraces: BROECKER & VAN DONK, 1970). However, because of age adjustments in certain faunal levels on which chronology of the Shackleton-Opdyke curve is based, I have used the corrected (V28-238) curve as given by VAN DONK (1976, Fig. 4), together with the V16-205 curve of Van Donk for the remaining 1 Ma Quaternary interval. In both cases the glacial/interglacial transition or 'null line' is taken as the midpoint of the isotopic variation (around 1.2‰) between the late Wisconsin glacial maximum and the present day. This variation is then equated to the 124 m eustatic sea-level fluctuation suggested for the same period (CURRAY, 1965) providing a scale for determining the magnitude of Quaternary glacio-eustatic fluctuations around the 'null line', presently equivalent to a -60 m (approx.) sea level. A similar approach was used by SHACKLETON & OPDYKE (1973, Fig. 7) to construct their glacio-eustatic sea-level curve for the past 130,000 years.

The tectono-eustatic component

Because of the limited relevant data available from Sundaland, it is necessary to assume a linear Quaternary tectono-eustatic trend for the sea-level curve. This would seem acceptable since FLEMMING & ROBERTS (1973) believed the duration of the tectono-eustatic cycle is around 10 Ma. The trend gradient can then be determined approximately by the necessity that the resultant (i.e. glacial + tectono-eustatic) sea-

level curve satisfies the following control data:

(1) sea-levels rose discontinuously from a late Miocene low to present levels, and only in late Middle Pleistocene time did they first rise significantly above the -130 m continental shelf break;

(2) apart from high sea-levels over the past 6000 years, and around 125,000 B.P. (well documented worldwide at between +2 and +10 m; cf. BROECKER & VAN DONK, 1970 and CHAPPELL, 1974) as suggested by Biswas' data, sea levels have never risen above present levels since the mid-Miocene transgressive event;

(3) buried river channels require relatively prolonged periods of low sea-level of at least 130 to 220 m depth;

(4) the Mount Kinabalu snowline depression suggests sea-level lowering of around 230 m during the Riss or an earlier glacial period;

(5) certain transgressive/regressive sea-level cycles are indicated for the Middle Pleistocene to Holocene period, from marine seismic and drilling studies off the Perak coast and from calculations based on BISWAS' (1973, 1976) palaeobathymetry data;

(6) shelf-break levels of the Sunda Shelf facing the Andaman Sea (128 m) and South China Sea (180 m) approximate late Pleistocene and earlier Pleistocene sea-levels, respectively.

The resultant combined glacial/tectono-eustatic sea-level curve indicates a gradient for the tectono-eustatic trend of 10 cm/10³a rise throughout the Quaternary.

EUSTASY AND LATE CAINOZOIC SEA-LEVEL CHANGE

Synchronous worldwide transgressions other than glacio-eustatic are probably controlled by eustatic sea-level rise resulting from a decrease in the combined volumetric capacity of world ocean basins (RONA, 1973-a), WISE (1972) and QUILTY (1977) favoured a constant freeboard earth model, and believed that the present sea-level is close to the normal maximum for the Cainozoic. Using a hypsographic curve model, FLEMMING & ROBERTS (1973) estimated that a tectono-eustatic sea-level depression of 800-1000 m is possible through size increase of the ocean basins. A significant contributive factor would be a volume decrease of the world-oceanic ridge system which can explain as much as a 300-650 m sea-level change (MENARD, 1964; VALENTINE & MOORES, 1970; FLEMMING & ROBERTS, 1973; Pitman & Hays: see RONA & WISE, 1974). HAYS & PITMAN (1973) demonstrated that the global mid to upper Cretaceous transgression was probably caused by a contemporaneous pulse of rapid sea-floor spreading at most of the mid-oceanic ridges causing them to expand, accompanied by increased subduction and island arc orogenesis. Subsequent continental emergence resulted from a reduction in sea-floor spreading rates. It is significant therefore, that FLEMMING & ROBERTS (1973) reported a global acceleration in spreading rates at 10 Ma, coinciding with the

initiation of the worldwide Late Miocene transgression. HAYS ET AL. (1972) believed that a new regime of underthrusting so initiated resulted in a major Late Cainozoic phase of volcanism. This view is confirmed by findings of KENNETT & THUNELL (1975) that global explosive volcanicity increased from a low in the late Middle Miocene (zones N13 to N14) to a present maximum (increasing markedly from mid-Pliocene). Another volcanicity peak occurred in the early Middle Miocene (zones N9 to N12).

The Sundaland chronology of late Cainozoic eustatic cycles and orogenesis closely follows previous concepts. Mid-Miocene transgression (maximum: zones N9 to N10, or 15 to 16 Ma, cf. BERGGREN & VAN COUVERING, 1974) contemporaneous with regional tectonism in marginal basins, was followed by major eustatic regression in the late Middle Miocene (maximum: zones N14 to N15, or ca. 10.5 to 13 Ma). Sea levels then rose discontinuously to the present, accompanied in marginal areas by major orogenesis from Pliocene time onwards. Comparable late Cainozoic eustatic cycles found off west Australia (QUILTY, 1977) and indicated by similar sea-level histories previously determined for a number of continental margins worldwide attest to the general global synchronicity of these events. VAIL ET AL.'S (1977, Fig. 3) sea-level curve, which is taken as a worldwide compilation, also shows general agreement, especially in the major fall (and unconformity) of pre-late Miocene (10.8 Ma) age and the preceding Middle Miocene high sea-level. On this basis, a global tectono-eustatic sea-level curve (Fig. 5) is constructed, assuming that the Sundaland rate of Quaternary tectono-eustatic rise can be projected back into the late Neogene to give a maximum sea-level lowering (below present level) of around 1000 m, which can effectively explain deep contemporaneous sub-aerial features of continental shelves, coral atolls and submarine canyons.

Since major development of the Antarctic ice cap around 10-12 Ma (VAN ANDEL ET AL., 1975; KENNETT, 1977) marked by global cooling and regression (e.g. WOLFE & HOPKINS, 1967; MERCER, 1973), it has remained a semi-permanent feature with relatively small volume changes. However, global cooling resultant from its expansion is evident for the Mio-Pliocene (around 5 Ma; KENNETT, 1977) and late Pliocene (2.3-3 Ma; HAYS & OPDYKE, 1967; KENNETT ET AL., 1971), separated by a period of marked ice regression and eustatic sea-level rise (HAYS ET AL., 1973). These fluctuating ice phases are confirmed by the bipolar latitudinal expansion and retreat of cold water isotherms detected by Late Miocene to Holocene planktonic Foraminifera (BANDY, 1968). Believing that the resultant sea-level fluctuations were of an order of magnitude similar to those in the Pleistocene (i.e. around 100 m), BANDY (1968) constructed a global glacio-eustatic sea-level chart which I have superimposed on the Sundaland tectono-eustatic trend to give the resultant late Cainozoic global eustatic sea-level chart (Fig. 5).

GENERAL IMPLICATIONS AND CONCLUSIONS

Eustatic sea-levels

A global Late Miocene to Holocene tectono-eustatic sea-level rise at a probable rate of $10 \text{ cm}/10^3 \text{ a}$ was apparently consequent upon increasing oceanic ridge volume and faster spreading rates with resultant major orogenesis and volcanicity in continental margin and island arc regions since the Pliocene. This mechanism is also believed responsible for high Middle Miocene (15-16 Ma) sea levels accompanied by regional, and presumably (net) global orogenesis. The successive late Middle to Late Miocene (10.5-13 Ma) minimum sea-level of around -1000 m would be mainly consequent on net global tectonic quiescence and decreased oceanic ridge volume. The regression rate appears to have been roughly 3 times faster than that of transgression. VAIL ET AL. (1977) also found major global sea-level rises to be gradual though the falls were generally abrupt. Superimposed glacio-eustatic fluctuations were important from about 12 Ma ago following the Antarctic ice sheet development. Although geoidal-eustasy may result in significant local divergences from the Quaternary sea-level curve, its restricted magnitude is not expected to affect the general trend of the major late Cainozoic transgression.

Climatic variation

In equatorial areas (especially Sundaland) the late Cainozoic sea-level fluctuation was the major climatic control. In general, high sea-levels during early Middle Miocene and parts of late Quaternary time, correlate with relatively uniform, pluvial, monsoonal climates, moderated by an increase in ratio of oceanic to continental area, resulting in climax tropical rain-forest. Late Middle Miocene to Early Pliocene low sea-levels correspond to a period of restricted oceanic circulation and increased continentality with marked thermal gradients and seasonal contrast resulting in a more severe, semi-arid climate. Peneplanation and lateritisation was then dominant in oxidising inland environments. It is significant that closely related red-beds are best developed during the Devonian and Triassic at times of marked global regression, continental emergence (cf. WISE, 1972, Fig. 2) and semi-aridity (e.g. LAMING, 1973; HUBERT, 1977). Rising sea-levels with increased precipitation result firstly in aggradation deposits (i.e. piedmonts and alluvial plains of braided streams) and finally in meander plains, lakes and swamps with improved maturity of river valleys and sediment composition. Middle Pleistocene to Holocene glacio-eustatic sea-level fluctuations and associated temperature variation resulted in more rapid climatic effects.

Marine sedimentation rates and hiatuses

Maximum sediment accumulation rates during the late Pha-

nerozoic correlate with worldwide epicontinental marine transgression or the reversal between a transgression and regression, while minimums correspond to regression or the reversal between a regression and transgression (RONA, 1973-a). The late Cainozoic eustatic sea-level cycle therefore requires high rates of sediment accumulation for the early Middle Miocene and late Quaternary (increasing to the present), whereas lower rates and even hiatuses would apply for late Middle Miocene to early Pliocene time. DSDP data from the world's oceans entirely confirms this situation, and the globally synchronous nature of the fluctuations (RONA, 1973-b; VAN ANDEL ET AL., 1975; DAVIES ET AL., 1977). The most widespread erosional event of the late Cainozoic reached a maximum about 12 Ma B.P. in the equatorial Pacific. Although VAN ANDEL ET AL. (1975) attributed this to enhanced bottom-water flow resulting from major development of Antarctic glaciation, I believe this hiatus and contemporary low sediment accumulation rates worldwide can only be effectively explained by accepting evidence for the increased aridity of continents at that time, lower discharge volumes of rivers and consequent decreased sediment supply (both chemical and detrital; cf. present-day desert Australia) to the oceans. This situation reversed once pluvial conditions were generally re-established by the late Cainozoic sea-level rise. Sediment peaks and hiatuses contemporary with those discussed here are also documented by QUILTY (1977) from the west Australian margin and are directly correlatable with regression and transgression in the manner of RONA (1973-a).

Oceanographic features

Because of minimum sea-levels in late Middle to Late Miocene time, continental shelves (and epeiric seas) hardly existed and deltaic sediments and flysch (also 'turbidites') were dumped directly onto continental slopes and even abyssal plain margins forming great fan complexes, sometimes at the termination of submarine valleys. These deposits often have excellent oil potential (e.g. Borneo - Kutei and Tarakan Basins: FLETCHER & SOEPARJADI, 1976; California: SULLWOLD, 1961). Although the majority of submarine canyons probably formed during maximum Cainozoic regression in the Oligocene, late Middle to Late Miocene low sea-levels probably resulted in their strong rejuvenation and subaerial deepening. Increased sediment accumulation rates in the Quaternary, and glacial sea-level lowering to and below the shelf-break level (evidenced by deeply submerged wave-cut terraces and unconformities) facilitated turbidity current action and mass movements on unconsolidated sediments (cf. KUENEN, 1950, p. 503) thus modifying canyon profiles. Also during the late Miocene low sea-level, shallow seamounts were eroded, and exposed coral formations were partly dissolved and recrystallised. With the succeeding sea-level rise, atolls were formed where coral growth kept pace with the rate of sea-level change.

According to MOORE (1954, 1955) and NEWELL (1963), the most dramatic episodes of mass extinction in the fossil record took place during major marine regressions, often associated with regional unconformities and crustal quiescence. Rates of global regression (and accompanying environmental changes) were greater than those of transgression (VAIL ET AL., 1977), so evolutionary changes in many organisms could not keep pace. During regressive periods, the marked alteration of oceanic circulation and thermal regime (VALENTINE & MOORES, 1970; HAYS & PITMAN, 1973), and the diminution of epicontinental seas, together with increased thermal gradients, seasonality and aridity on continents would produce considerable ecological stress resulting in extinctions in both marine and terrestrial faunas. However, the formation of extensive land bridges then allowed development of newly-evolving cosmopolitan land faunas. Evidence suggests that the late Miocene regression was of lesser magnitude than those of the post-Cretaceous and Oligocene, and consequent extinctions were less evident.

However, this regression led to one of the most important developments in primate evolution. The well-established trend in most equatorial regions during Pleistocene phases of low sea-level, of the replacement of tropical rain-forest by savanna (and even desert!) (e.g. VERSTAPPEN, 1975-a; FAIRBRIDGE, 1976; ALEKSEEV, 1977) was even more pronounced during late Miocene regression (COETZEE, 1977). 10 to 14 Ma ago in a faunal zone stretching from East Africa to India, climates that had been tropical were becoming more temperate. jungles were thinning out, and fruits normally available year round began to appear only seasonally (PILBEAM, 1972; STOLER, 1977). Some of the forest-dwelling arboreal apes began venturing into grasslands at the forest margin, developing bipedalism in their search for food. Accompanying evolution resulted in *Ramapithecus*, probably the first hominid and forebear of *Australopithecus* (and finally *Homo*), fully adapted to savanna-dwelling by the early Pliocene. A parallel change from browsing to grazing habits occurred among many mammals as an adaptation to the changing environment.

Rising late Cainozoic sea-levels with accompanying 'compartmentation of the continents' and amelioration in climate led to increasing faunal diversity and provincialism until the Middle to Late Pleistocene transition when rapid geographical shifts of shallow seas to and from continental shelves (and glacial temperature variation), resulted in drastic changes in climate and the distribution of open forest and savanna in equatorial regions. Major extinctions of savanna-adapted land mammals took place during interglacial high sea-level periods resulting from their geographical isolation and the unsuitability of increasingly homogeneous, dense rainforest habitats.

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REFERENCES

- Alekseev, M. N. 1977 Quaternary climatic variations in east Asia – Abstr. 10th Int. Assoc. Quaternary Res. (INQUA) Congr.: 8.
- Aleva, G. J. J., E. H. Bon, J. J. Nossin & W. J. Sluiter 1973 A contribution to the geology of part of the Indonesian Tin belt: the sea areas between Singkep and Bangka Islands and around the Karimata Islands – Geol. Soc. Malaysia Bull. 6: 61-86.
- Armitage, J. H. & C. Viotti 1977 Stratigraphic nomenclature – southern end Malay Basin – 6th Ann. Conv. Indonesian Petrol. Assoc. (Jakarta, May 1977).
- Ashton, P. S. 1972 The Quaternary geomorphological history of western Malesia and lowland forest phytogeography. In P. & M. Ashton (eds.): Trans. 2nd Aberdeen-Hull Symp. Malaysian Ecol. Univ. Hull Dept. Geogr. Misc. Ser. 13: 35-62.
- Bandy, O. L. 1968 Cycles in Neogene paleoceanography and eustatic changes – Palaeogeogr. Palaeoclimatol. Palaeoecol. 5: 63-75.
- Batchelor, B. C. 1976 Studies in late Cainozoic stratigraphy in parts of Sundaland as an aid to tin placer exploration in coastal and offshore areas – Ann. Discussion Meeting Geol. Soc. Malaysia (Ipo, Dec. 1976).
- (in press) Geological characteristics of coastal and offshore placers as essential guides for tin exploration in Sundaland, Southeast Asia – Geol. Soc. Malaysia Bull. 11.
- Baumann, P., H. Oesterle, Suminta & Wibisono 1973 The Cenozoic of Java and Sumatra – Proc. 1st Ann. Conv. Indonesian Petrol. Assoc.: 31-42.
- Berggren, W. A. & J. A. van Couvering 1974 The Late Neogene – Elsevier, (Amsterdam).
- Biswas, B. 1973 Quaternary changes in sea-level in the South China Sea – Geol. Soc. Malaysia Bull. 6: 229-256.
- 1976 Bathymetry of Holocene Foraminifera and Quaternary sea-level changes on the Sunda Shelf – J. Foramin. Res. 6: 107-133.
- Bon, E. H. 1977 Exploration techniques employed in the Pulau Tujuh tin discovery – Indonesian Mining Assoc. Symp. (Jakarta, June 1977).
- Bourcart, J. 1949 Géographie du fond des mers, étude du relief des océans – Payot (Paris).
- 1950 Le socle continental de Toulon à la frontière Espagnole – Centre Recherch. Études Oceanog. Conf. 3.
- Bowler, J. M. 1976 Aridity in Australia: age, origins and expression in aeolian landforms and sediments – Earth Sci. Rev. 12: 279-310.
- Broecker, W. & J. van Donk 1970 Insolation changes, ice volumes, and the O¹⁸ record in deep-sea cores – Rev. Geophys. Space Phys. 8: 168-198.
- Brouwer, H. A. 1925 The geology of the Netherlands East Indies – Macmillan (New York).
- Burgess, P. F. 1969 Ecological factors in hill and mountain forests of the states of Malaya – Malayan Nature J. 22: 119-128.
- Chappell, J. 1974 Geology of coral terraces, Huon Peninsula, New

- Guinea: a study of Quaternary tectonic movements and sea-level changes – *Geol. Soc. Am. Bull.* 85: 553-570.
- Cline, R. M. & J. D. Hays 1976 Investigation of late Quaternary paleoceanography and paleoclimatology – *Geol. Soc. Amer. Memoir* 145.
- Coetzee, J. A. 1977 Late Cenozoic palaeoenvironments of tropical Africa – *Abstr. 10th Internat. Assoc. Quaternary Res. (INQUA) Congr.*: 88.
- Collenette, P. 1964 A short account of the geology and geological history of Mount Kinabalu – *Proc. Roy. Soc. B* 161: 56-63.
- Conolly, J. R. 1968 Submarine canyons of the continental margin, east Bass Strait (Australia) – *Marine Geol.* 6: 449-461.
- 1969 Western Tasman sea floor – *N.Z. J. Geol. Geophys.* 12: 310-343.
- Courtier, D. B. 1974 Geology and mineral resources of the neighbourhood of Kulim, Kedah – *Geol. Surv. Malaysia Map Bull.* 3.
- Curry, J. R. 1965 Late Quaternary history, continental shelves of the United States. In: H. E. Wright Jr. & D. G. Frey (eds.): *The Quaternary of the United States* – Princeton Univ. Press: 723-735.
- Curry, J. R. & D. G. Moore 1964 Pleistocene deltaic progradation of continental terrace, Costa de Nayarit, Mexico. In: T. H. van Andel & G. G. Shor (eds.): *Marine geology of the Gulf of California* – Amer. Assoc. Petrol. Geol. Memoir 3: 193-215.
- Davies, T. A., W. W. Hay, J. R. Southam & T. R. Worsley 1977 Estimates of Cenozoic oceanic sedimentation rates – *Science* 197: 53-55.
- Dickerson, R. W. 1941 Molengraaf River: a drowned Pleistocene stream and other Asian evidences bearing upon the lowering of sea level during the Ice Age – *Proc. Univ. Penns. Bicent. Conf.*: 13-20.
- Dietz, R. S. 1952 Geomorphic evolution of continental terrace (continental shelf and slope) – *Amer. Assoc. Petrol. Geol. Bull.* 36: 1802-1819.
- Dill, R. F. 1969 Submerged barrier reefs on the continental slope north of Darwin, Australia – *Geol. Soc. Amer. Abstr.* 1969 7: 264-266.
- Dillon, W. P. & R. N. Oldale 1978 Late Quaternary sea-level curve: reinterpretation based on glaciotectionic influence – *Geology* 6: 56-60.
- Dingle, R. V. 1971 Tertiary sedimentary history of the continental shelf off southern Cape Province, South Africa – *Trans. Geol. Soc. S. Afr.* 74: 173-185.
- 1973 The geology of the continental shelf between Luderitz and Cape Town – *Quart. J. Geol. Soc. London* 129: 337-363.
- Donn, W. L., W. R. Farrand & M. Ewing 1962 Pleistocene ice volumes and sea-level lowering – *J. Geol.* 70: 206-214.
- Emery, K. O., E. Uchupi, J. Sunderland H. L. Uktolseja & E. M. Young 1972 Geological structure and some water characteristics of the Java Sea and adjacent continental shelf – *CCOP Tech. Bull.* 6: 197-224.
- Emery, K. O. & E. F. K. Zarudski 1967 Seismic reflection profiles along the drill holes on the continental margin off Florida – *U.S. Geol. Surv. Prof. Pap.* 581A.
- Emiliani, C. 1966 Paleotemperature analysis of the Caribbean cores P6304-8 and P6304-9 and a generalised paleotemperature curve for the last 425,000 years – *J. Geol.* 74: 109-126.
- 1972 Quaternary paleotemperatures and the duration of the high-temperature intervals – *Science* 178: 398-401.
- Emiliani, C. & N. J. Shackleton 1974 The Brunhes Epoch: isotopic paleotemperatures and geochronology – *Science* 183: 511-514.
- Ewing, J., X. Le Pichon & M. Ewing 1963 Upper stratification of Hudson Apron region – *J. Geophys. Res.* 68: 6303-6316.
- Eyles, R. J. 1969 Depth of dissection of the West Malaysian landscape – *J. Trop. Geogr.* 28: 23-31.
- 1970 Physiographic implications of laterite in West Malaysia *Geol. Soc. Malaysia Bull.* 3: 1-7.
- Fairbridge, R. W. 1961 Eustatic changes in sea-level. In: L. H. Ahrens (ed.): *Physics and chemistry of the Earth*, Vol. 4 – Pergamon (New York): 99-185.
- 1966 Sunda Shelf. In: R. W. Fairbridge (ed.): *The encyclopedia of oceanography* – Reinhold (New York): 891-893.
- 1968 *The encyclopedia of geomorphology* – Reinhold (New York).
- 1971 Quaternary shoreline problems at Inqua, 1969 – *Quaternaria* 15: 1-8.
- 1976 Effects of Holocene climatic change on some tropical geomorphic processes – *Quaternary Res.*, 6: 529-556.
- Flemming, N. C. & D. G. Roberts 1973 Tectono-eustatic changes in sea-level and sea-floor spreading – *Nature* 243: p. 19-22.
- Fletcher, G. L. & R. A. Soeparjadi 1976 Indonesia's Tertiary basins – the land of plenty – *Offshore SE Asia Conf.*, (Singapore, Feb. 1976).
- Galloway, R. W. 1970 Coastal and shelf geomorphology and late Cenozoic sea levels – *J. Geol.* 78: 603-610.
- Garrison, L. E. 1970 Development of continental shelf south of New England – *Amer. Assoc. Petrol. Geol. Bull.* 54: 109-124.
- Gerard, J. & H. Oesterle 1973 Facies study of the offshore Mahakam area – *Proc. 2nd Ann. Conv. Indonesian Petrol. Assoc.*: 187-194.
- Groves, C. P. 1975 Mammalian distribution and the palaeogeography of the Sunda Shelf region in the late Quaternary – *Regional Conf. Geol. Min. Resour. SE Asia (Jakarta, August 1975)*.
- Grubb, P. L. C. 1963 Critical factors in the genesis, extent, and grade of some residual bauxite deposits – *Econ. Geol.* 58: 1267-1277.
- 1966 Distribution and genetic significance of aluminium hydrates in Southeast Johore, Malaya – *Proc. Roy. Soc. Vict.* 79: 257-265.
- Haile, N. S. 1969 Quaternary deposits and geomorphology of the Sunda Shelf off Malaysian shores – *Proc. 8th Int. Assoc. Quaternary Res. (INQUA) Congr.*: 161-164.
- 1971 Quaternary shorelines in West Malaysia and adjacent parts of the Sunda Shelf – *Quaternaria* 15: 333-343.
- 1975 Postulated late Cainozoic high sea levels – *J. Malaysian Br. Roy. Asiatic Soc.* 48: 78-88.
- Haile, N. S. & M. Ayob 1968 Note on radiometric age determination of samples of peat and wood from tin-bearing Quaternary deposits at Sungei Besi Tin Mines. Kuala Lumpur, Selangor. Malaysia – *Geol. Mag.* 105: 519-520.
- Haile, N. S. & N. D. Watkins 1972 The use of paleomagnetic reversals in Pleistocene geochronology in Southeast Asia – *Annex, Geol. Soc. Malaysia Newsletter* 34: 17-18.
- Hammond, A. L. 1976 Paleoclimate: ice age earth was cool and dry – *Science* 191: 454.
- Hayes, D. E., L. A. Frakes, P. Barrett, D. A. Burns, C. Pei-Hsin, et al. 1973 Leg 28 deep-sea drilling in the Southern Ocean – *Geotimes* 18: 19-24.
- Hayes, J. D., H. Cook, G. Jenkins, W. Orr, R. Goll, F. Cook, D. Milow & J. Fuller 1972 Initial Rept. Deep Sea Drilling Project (Washington, D.C.) 9: 909-931.
- Hays, J. D. & N. D. Opdyke 1976 Antarctic radiolaria, magnetic reversals, and climatic change – *Science* 158: 1001-1011.
- Hays, J. D. & W. C. Pitman III 1973 Lithospheric plate motion, sea level changes and climatic and ecologic consequences – *Nature* 246: 18-23.
- Heezen, B. C., M. Tharp & M. Ewing 1959 The floors of the oceans 1. The North Atlantic – *Geol. Soc. Amer. Spec. Pap.* 65.
- Hill, R. D. 1968 The Singapore 'Deeps' – *Malayan Nature J.* 21: 142-146.
- Hocking, J. B. 1976 Gippsland Basin. In: J. G. Douglas & J. A. Ferguson (eds.): *Geology of Victoria* – *Geol. Soc. Austr. Spec.*

- Publ. 5: 248-273.
- Hooijer, D. A. 1962 Report upon a collection of Pleistocene mammals from tin-bearing deposits in a limestone cave near Ipoh, Kinta Valley, Perak – Fed. Mus. J. 7: 1-5.
- Hopkins, D. M., D. W. Scholl, W. O. Addicott, et al. 1969 Cretaceous, Tertiary, and early Pleistocene rocks from the continental margin in the Bering Sea – Geol. Soc. Amer. Bull. 80: 1471-1480.
- Hsu, K. J., W. B. F. Ryan & M. B. Cita 1973 Late Miocene dessication of the Mediterranean – Nature 242: 240-244.
- Hubert, J. F. 1977 Paleosol caliche in the New Haven Arkose, Connecticut: record of semiaridity in Late Triassic – Early Jurassic time – Geology 5: 302-304.
- Imbrie, J., J. Van Donk & N. G. Kipp 1973 Paleoclimatic investigation of a late Pleistocene Caribbean deep sea core: comparison of isotopic and faunal methods – Quaternary Res. 3: 10-38.
- Jacobsen, G. 1970 Gunong Kinabalu area, Sabah, Malaysia – Geol. Surv. Malaysia Borneo Region Rpt. 8.
- Jones, H. A., P. J. Davies & J. F. Marshall 1975 Origin of the shelf break off southeast Australia – J. Geol. Soc. Austr. 22: 71-78.
- Jongsma, D. 1970 Eustatic sea level changes in the Arafura Sea – Nature 228: 150-151.
- Jordan, G. F., R. J. Malloy & J. W. Kofoed 1964 Bathymetry and geology of Portales Terrace, Florida – Marine Geol. 1: 259-287.
- Kennett, J. P. 1977 Development of polar glaciation and late Cenozoic paleoceanography of the Antarctic region – Abstr. 10th Int. Assoc. Quaternary Res. (INQUA) Congr.: 237.
- Kennett, J. P. & R. C. Thunell 1975 Global increase in Quaternary explosive volcanism – Science 187: 497-502.
- Kennett, J. P., N. D. Watkins & P. Vella 1971 Paleomagnetic chronology of Pliocene – Early Pleistocene climates and the Plio-Pleistocene boundary in New Zealand – Science 171: 276-279.
- Knott, S. T. & H. Hoskins 1968 Evidence of Pleistocene events in the structure of the continental shelf off the north-eastern United States – Marine Geol. 6: 5-43.
- Koesoemadinata, R. P. & A. Punggono 1972 The geology of the southern Sunda Shelf with reference to the tectonic framework of Tertiary sedimentary basins of western Indonesia (abstr.) – Annex, Geol. Soc. Malaysia Newsletter 34: 36-37.
- Koopmans, B. N. 1964 Geomorphological and historical data of the lower course of the Perak River (Dindings) – J. Malaysian Br. Roy. Asiatic Soc. 37: 175-191.
- Koopmans, B. N. & P. H. Stauffer 1968 Glacial phenomena on Mount Kinabalu, Sabah – Geol. Surv. Malaysia Borneo Region Bull. 8: 25-35.
- Krol, G. L. 1960 Theories on the genesis of 'kaksa' – Geol. Mijnbouw 39: 437-443.
- Kuenen, Ph. H. 1950 Marine geology – Wiley (New York).
- LaBrecque, J. L., D. V. Kent & S. C. Cande 1977 Revised magnetic polarity time scale for Late Cretaceous and Cenozoic time – Geology 5: 330-335.
- Laming, D. J. C. 1973 Red bed sedimentation patterns – Geol. Soc. Thailand Newsletter 6: 103-104.
- Law, W. M. & M. L. Leamy 1966 Factors involved in the genesis of some shale-derived soils in Malaya – Proc. 2nd Malaysian Oil Conf.: 104-113.
- Lenk-Chevitch, P. 1959 Geohydrological exploration of the coastal belt of Malaya – U.N. Rept. TAO/MAL/8 (Unpubl).
- Lewis, K. B. 1974 The continental terrace – Earth Sci. Rev. 10: 37-71.
- Löffler, E. 1972 Pleistocene glaciation in Papua and New Guinea – Z. Geom. Suppl. 13: 46-72.
- McMaster, R. L. & A. Ashraf 1973 Extent and formation of deeply buried channels on the continental shelf of southern New England – J. Geol. 81: 374-379.
- McMaster, R. L. & T. P. La Chance 1968 Seismic reflectivity studies on northwestern African continental shelf: Strait of Gibraltar to Mauritania – Amer. Assoc. Petrol. Geol. Bull. 52: 2387-2395.
- McMaster, R. L., T. P. La Chance & A. Ashraf 1970 Continental shelf geomorphic features off Portuguese Guinea, Guinea, and Sierra Leone (West Africa) – Marine Geol. 9: 203-213.
- Medway, Lord 1972 The Quaternary mammals of Malesia: a review. In: P. & M. Ashton (eds.): Trans. 2nd Aberdeen-Hull Symp. Malesian Ecol. – Univ. Hull Dept. Geogr. Misc. Ser. 13: 63-98.
- Menard, H. W. 1964 Marine geology of the Pacific – McGraw-Hill (New York).
- Mercer, J. H. 1973 Cenozoic temperature trends in the southern hemisphere: Antarctica and Andean glacial evidence. In: E. M. van Z. Bakker (ed.): Palaeoecology of Africa 8: 85-114.
- Mohr, E. C. J. & F. A. van Baren 1954 Tropical soils – Interscience (New York).
- Moore, R. C. 1954 Evolution of late Paleozoic invertebrates in response to major oscillations of shallow seas – Mus. Comp. Zool. Harv. Bull. 112: 259-286.
- 1955 Expansion and contraction of shallow seas as a causal factor in evolution – Evolution (Lancaster, Pa.) 9: 482-483.
- Morley, R. J. 1977 Palynology of Tertiary and Quaternary sediments in Southeast Asia – 6th Ann. Conv. Indonesian Petrol. Assoc. (Jakarta, May 1977).
- Mörner, N. 1976 Eustasy and geoid changes – J. Geol. 84: 123-151.
- Muller, J. 1972 Palynological evidence for change in geomorphology, climate, and vegetation in the Mio-Pliocene of Malesia. In: P. & M. Ashton (eds.): Trans. 2nd Aberdeen-Hull Symp. Malesian Ecol. – Univ. Hull Dept. Geogr. Misc. Ser. 13: 6-34.
- Murphy, R. W. 1975 Tertiary basins of Southeast Asia – SEAPEX Proc. 2: 1-36.
- Murray, G. E. 1961 Geology of the Atlantic and Gulf Coast Province of North America – Harper & Row (New York).
- Newell, N. D. 1963 Crises in the history of life – Scientific American, Feb. 1963: 1-16.
- Oele, E., S. K. Yong, P. Supalak & A. L. Scholtens (in prep.) Two surveys for detrital cassiterite, other detrital heavy minerals and phosphates in Malaysian and Thai waters, with Dutch technical assistance.
- Paltrinieri, F., P. Saint-Marc & B. Situmorang 1976 Stratigraphic and paleogeographic evolution during Cenozoic time in western Indonesia – Offshore SE Asia Conf. (Singapore, Febr. 1976).
- Parke, M. L. Jr., K. O. Emery, R. Szymankiewicz & L. M. Reynolds 1971 Structural framework of the continental margin in the South China Sea – CCOP Tech. Bull. 4: 103-142.
- Patterson, S. H. 1967 Bauxite reserves and potential aluminium resources of the world – Geol. Surv. Amer. Bull. 1228.
- Pendleton, R. L. & S. Shanasuvana 1946 Analyses of some Siamese laterites – Soil Science: 423-440.
- Pfeiffer, D. 1975 The hydrogeologic map of the islands of Singapore 1: 100,000 (explanatory notes) – Geol. Jb. C9: 3-14.
- Pfeiffer, D. & O. Tiedemann 1975 Geologic logs of exploration boreholes drilled in 1975 in the Kota Bharu area – Geol. Surv. Malaysia Rpt. GPH2/1975 (Unpubl.).
- Pilbeam, D. 1972 The ascent of man – Macmillan (New York).
- Pimm, A. C. 1965 Seabed sediments of the South China Sea – Geol. Surv. Malaysia Borneo Region Ann. Rpt. 1964: 122-146.
- Pratt, R. N. & R. F. Dill 1974 Deep eustatic terrace levels: further speculations – Geology 2: 155-159.
- Quilty, P. G. 1977 Cenozoic sedimentation cycles in Western Australia – Geology 5: 336-340.
- Reiner, E. 1960 The glaciation of Mount Wilhelm, Australian New Guinea – Geogr. Rev. 50: 491-503.
- Richardson, J. A. 1947 An outline of the geomorphological evolution of British Malaya – Geol. Mag. 84: 129-144.
- Rona, P. A. 1970 Submarine canyon origin on upper continental slope off Cape Hatteras – J. Geol. 78: 141-152.
- 1973-a Relations between rates of sediment accumulation on

- continental shelves, sea floor spreading, and eustasy inferred from the central North Atlantic – *Geol. Soc. Amer. Bull.* 84: 2851-2872.
- 1973-b Worldwide unconformities in marine sediments related to eustatic changes of sea level – *Nature Phys. Sci.* 244: 25-26.
- Rona, P. A. & D. U. Wise 1974 Symposium: global sea level and plate tectonics through time – *Geology* 2: 133-134.
- Ryall, P. J. C., T. S. Lew, B. C. Batchelor & C. L. Samz 1977 A reconnaissance geophysical survey offshore from Kedah, west coast of Peninsular Malaysia – *CCOP Newsletter*, 4 (3&4): 69-73.
- Schellmann, W. 1977 The formation of lateritic silicate bauxites and criteria for the exploration and assessment of deposits – *Natur. Resourc. Development* 6: 119-134.
- Schlanger, S. O. 1963 Subsurface geology of Eniwetok Atoll – *U.S. Geol. Surv. Prof. Pap.* 260BB: 991-1066.
- Schwartz, C. M., G. H. Laughbaum Jr., B. A. Samsu & J. D. Armstrong 1973 Geology of the Attaka Oil Field, East Kalimantan – *Proc. 2nd Ann. Conv. Indonesian Petrol. Assoc.*: 195-216.
- Schwartz, M. L. 1972 Seamounts as sea-level indicators – *Geol. Soc. Amer. Bull.* 83: 2975-2980.
- Scrivenor, J. B. 1928 The geology of Malayan ore deposits – Macmillan (London).
- 1931 The geology of Malaya – Macmillan (London).
- Shackleton, N. J. & N. D. Opdyke 1973 Oxygen isotope and palaeomagnetic stratigraphy of equatorial Pacific core V28-238: oxygen isotope temperatures and ice volumes on a 10^5 year and 10^6 year scale – *Quaternary Res.* 3: 39-55.
- Shepard, F. P. 1948 Submarine geology – Harper (New York).
- 1949 Terrestrial topography of submarine canyons revealed by diving – *Geol. Soc. Amer. Bull.* 60: 1597-1616.
- 1973 Submarine geology, 3rd ed. – Harper & Row (New York).
- Shepard, F. P. & R. F. Dill 1966 Submarine canyons and other sea valleys – Rand McNally (Chicago).
- Shideler, G. L. & D. J. P. Swift 1972 Seismic reconnaissance of post-Miocene deposits, middle Atlantic continental shelf-Cape Henry, Virginia to Cape Hatteras, North Carolina – *Marine Geol.* 12: 165-185.
- Sivarajasingham, S., L. T. Alexander, J. G. Lady & M. G. Cline 1962 Laterite – *Advances in Agronomy* 14: 1-60.
- Stauffer, P. H. 1973 Cenozoic. In: D. J. Gobbett & C. S. Hutchison (eds.): *Geology of the Malay Peninsular (West Malaysia and Singapore)* – Wiley (New York): 143-176.
- Stoler, P. 1977 Puzzling out man's ascent – *Time* 110 (19): 44-51.
- Sullwold, H. H. Jr. 1961 Turbidities in oil exploration. In: J. A. Peterson & J. C. Osmond (eds.): *Geometry of sandstone bodies* – *Amer. Assoc. Petrol. Geol. (Tulsa)*: 63-81.
- Tamesis, E. V., E. V. Vanalac, C. A. Reyes & L. M. Ote 1973 Late Tertiary geologic history of the continental shelf off northwestern Palawan, Philippines – *Geol. Soc. Malaysia Bull.* 6: 165-176.
- Tanner, W. F. 1968 Multiple influences on sea-level changes in the Tertiary – *Palaeogeogr. Palaeoclimatol., Palaeoecol.* 5: 165-171.
- Thom, B. G., J. R. Hailes, A. R. H. Martin & C. V. G. Phipps 1972 Postglacial sea levels in eastern Australia – a reply – *Marine Geol.* 12: 223-242.
- Tjia, H. D. 1970-a Quaternary shore lines of the Sundaland, Southeast Asia – *Geol. Mijnbouw* 49: 135-144.
- 1970-b Rates of diastrophic movement during the Quaternary in Indonesia – *Geol. Mijnbouw* 49: 335-338.
- 1977 Inqua Quaternary Shorelines commission, Pacific and Indian Oceans Subcommission, region: Indonesia and Malaysia, status report: 1975-1976 – *Berita Direkt. Geol.* 9: 89-92.
- Tjia, H. D., S. Fujii, K. Kigoshi & A. Sugimura 1975 Additional dates on raised shorelines in Malaysia and Indonesia – *Sains Malaysiana* 4: 69-84.
- Travers, W. B. 1972 A trench off central California in Late Eocene – Early Oligocene time – *Geol. Soc. Amer. Memoir* 132: 173-182.
- Uchupi, E. & K. O. Emery 1967 Structure of continental margin off Atlantic coast of United States – *Amer. Assoc. Petrol. Geol. Bull.* 51: 223-234.
- 1968 Structure of continental margin off Gulf coast of United States – *Amer. Assoc. Petrol. Geol. Bull.* 52: 1162-1193.
- Umbgrove, J. H. F. 1949 Structural history of the East Indies – Cambridge Univ. Press.
- U.S. Department of Commerce 1970 Seismicity of Southeast Asia, 1st ed. – *Nation. Earthquake Inform. Centre.*
- Vail, P. R., R. M. Mitchum Jr. & S. Thompson III 1977 Seismic stratigraphy and global changes of sea level, Part 4: global cycles of relative changes of sea level – *Amer. Assoc. Petrol. Geol. Memoir* 26: 49-97.
- Valentine, J. W. & E. M. Moores 1970 Plate-tectonic regulation of faunal diversity and sea level: a model – *Nature* 228: 657-659.
- Van Andel, T. H. & S. E. Calvert 1971 Evolution of sediment wedge, Walvis Shelf, Southwest Africa – *J. Geol.* 79: 585-602.
- Van Andel, T. H., G. R. Heath & T. C. Moore 1975 Cenozoic history and paleoceanography of the central equatorial Pacific Ocean – *Geol. Soc. Amer. Memoir* 143.
- Van Andel, T. H. & J. J. Veevers 1965 Submarine morphology of the Sahul Shelf, northwestern Australia – *Geol. Soc. Amer. Bull.* 76: 659-700.
- Van Bemmelen, R. W. 1949 The geology of Indonesia, Vol. 1A – Govt. Printing Office (The Hague)
- Van Donk, J. 1976 O^{18} record of the Atlantic Ocean for the entire Pleistocene epoch – *Geol. Soc. Amer. Memoir* 145: 147-163.
- Van Eysinga, F. W. B. 1975 Geological time table, 3rd ed. – Elsevier (Amsterdam).
- Van Overeem, A. J. A. 1960 The geology of the cassiterite placers of Billiton, Indonesia – *Geol. Mijnbouw* 39: 444-457.
- Van der Voort, M. 1950 The lateritic soils of Indonesia – *Trans. 4th Int. Congr. Soil Sci.* 1: 277-281.
- Verger, F. 1970 Les rivages quaternaires de la plateforme continentale de l'ouest de la France – *Quaternaria* 12: 197-206.
- Verstappen, H. Th. 1964 Geomorphology of the Star Mountains, Nova Guinea – *Geology* 5: 101-158.
- 1975-a On palaeoclimates and landform development in Malaysia. In: G. Bartstra & W. A. Casparie (eds.): *Modern Quaternary research in Southeast Asia* – Balkema (Rotterdam): 3-35.
- 1975-b The effect of Quaternary tectonics and climates on erosion and sedimentation in Sumatra – *Proc. 4th Ann. Conv. Indonesian Petrol. Assoc.*: 49-53.
- Walker, D. 1956 Studies on the Quaternary of the Malay Peninsula I. Alluvial deposits of Perak and the relative levels of land and sea – *Fed. Mus. J.* 1 & 2: 19-34.
- Warburg, O. 1897 Zwei neue fossile Phanerogamen Gattungen von der Insel Bangka – *Jb. Mijnb. N.O.I.* 26: 229-234.
- West, R. G. 1968 Pleistocene geology and biology – Longmans (London).
- Westerveld, J. 1937 The tin ores of Banca, Billiton and Singkep. Malay archipelago – a discussion – *Econ. Geol.* 32: 1019-1041.
- Whittle, A. P. & G. A. Short 1977 The petroleum geology of the Tembungo field, East Malaysia – *ASCOPE Conf. (Jakarta. Oct. 1977)*.
- Wilford, G. E. 1969 Sundaland bauxites and sea levels – *Geol. Soc. Malaysia Newsletter* 19: 5.
- Wing-Easton, N. 1937 The tin ores of Banca, Billiton and Singkep, Malay Archipelago – *Econ. Geol.* 32: 1-30 & 154-182.
- Wise, D. U. 1972 Freeboard of continents through time – *Geol. Soc. Amer. Memoir* 132: 87-100.
- Wolfe, J. A. & D. M. Hopkins 1967 Climatic changes recorded by Tertiary land floras in northwestern North America. In: K. Hatai (ed.): *Tertiary correlations and climatic changes in the Pacific, Symp. (Sasaki, Sendai, Japan)* 25: 67-76.

Wolfenden, E. B. 1965 Geochemical behaviour of trace elements during bauxite formation in Sarawak, Malaysia – *Geochim. Cosmochim. acta* 29: 1051-1062.

Woollands, M. A. & D. Haw 1976 Tertiary stratigraphy and sedi-

mentation in the Gulf of Thailand – Offshore SE Asia Conf. (Singapore, Febr. 1976).

Zeuner, F. E. 1959 *The Pleistocene period*, 2nd ed. – Hutchison (London).