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The sedimentology and tectonics of the Temburong Formation — deformation of early Cenozoic deltaic sequences in NW Borneo.

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Abstract: The sedimentology and deformation of the Temburong Formation in East Brunei are described. Original sedimentary structures are still preserved, particularly in the arenaceous sediments and paleo-environmental indicators suggest deposition mostly in a shallow water, subsaline embayment or lower alluvial floodplain environment. The style of deformation varies according to lithology and bed thickness and the rocks are metamorphosed to sericite grade. Deformation is thought to have been caused by loading rather than tectonic compression. The timing of the deformation took place probably between the Te_{1-4} and Te_5 Indonesian Letter Stages, i.e. upper Oligocene to Lower Miocene. No basal conglomerate has been found between the Temburong Formation and the overlying Setap Shale Formation and there is unlikely to be an unconformity separating the two formations although a hiatus between Te_{1-4} and Te_5 has been recognised in major platform carbonate sequences in the Melinau Limestone Formation at Melinau, Batu Gading and Keramit as well as the turbiditic limestone at Selidong.

The regional distribution of the Temburong Formation is discussed in relation to the paleogeography of NW Borneo.

PREVIOUS WORK

The Temburong area was investigated by oil company geologists who recognised sub-metamorphic features in the rocks and apart from an age determination, did little further work, concluding that the rocks were unlikely to contain hydrocarbons. Wilhelm (1926) and Morgan (1932) made traverses of the Temburong river to the top of Bukit Pagon and compiled a regional geological map dividing the area into three tectonic subdivisions comprising, from N to S, the Labu syncline, the Temburong anticline and the Ulu Temburong isoclinal area.

A later revision of the stratigraphy of Brunei using aerial photographs and data from Jordi & Wijkhuizen (1955) and Ditzel (1956) was published in Liechti, *et al.* (1960) and Wilford (1961). The Temburong area was subdivided into three Formations, the coal-bearing Belait Formation (Middle-Upper Miocene) in the north, the dominantly clayey, highly folded Setap Shale Formation occupying the middle reaches of the Temburong river and the Meligan Formation forming a synformal sequence of arenaceous sediments lying unconformably above the Setap Shale Formation and with an erosional upper boundary. Planktonic foraminifera from the Belalong confluence (Ditzel,1956) indicated a Lower Miocene age for the Setap Shale. The Meligan Formation was presumed to be Upper Miocene.

Brondijk (1962a) recognised that the Setap Shale Formation and West Crocker Formation at Pangi in the Padas Valley in SW Sabah were folded conformably and that the same fold style continued southwards into Brunei and N Sarawak affecting a large area SE of the Melinau and Batu Gading limestones to the upper Tinjar (see Brondijk, 1962a, Fig. 6). Above the Melinau Limestone and NW towards the coast, the tectonic style is different and the Setap Shale is much less deformed. Brondijk (1962a) therefore proposed a reclassification of the Setap Shale Formation and introduced the Temburong Formation for the highly folded rocks, designating a type locality in the headwaters of the Temburong river in Brunei. A clear angular unconformity at the base of the Meligan Formation was used to date the perfectly conformable folding of the West Crocker and Setap Shale Formations as Te_5 or late Te. The Temburong Formation is described also from the Padas valley (Wilson, 1964) where there is unequivocal evidence of turbidite deposition but the repetitious sequences of siltstone and shale found there are rarely seen in Brunei.

LITHOLOGY AND SEDIMENTOLOGY

The Temburong Formation consists largely of a monotonous sequence of sub-metamorphic siltstones and sandstones with an increasing proportion of sandstones east of Kuala Machang (Fig. 1). Sedimentary bedding is often poorly preserved in

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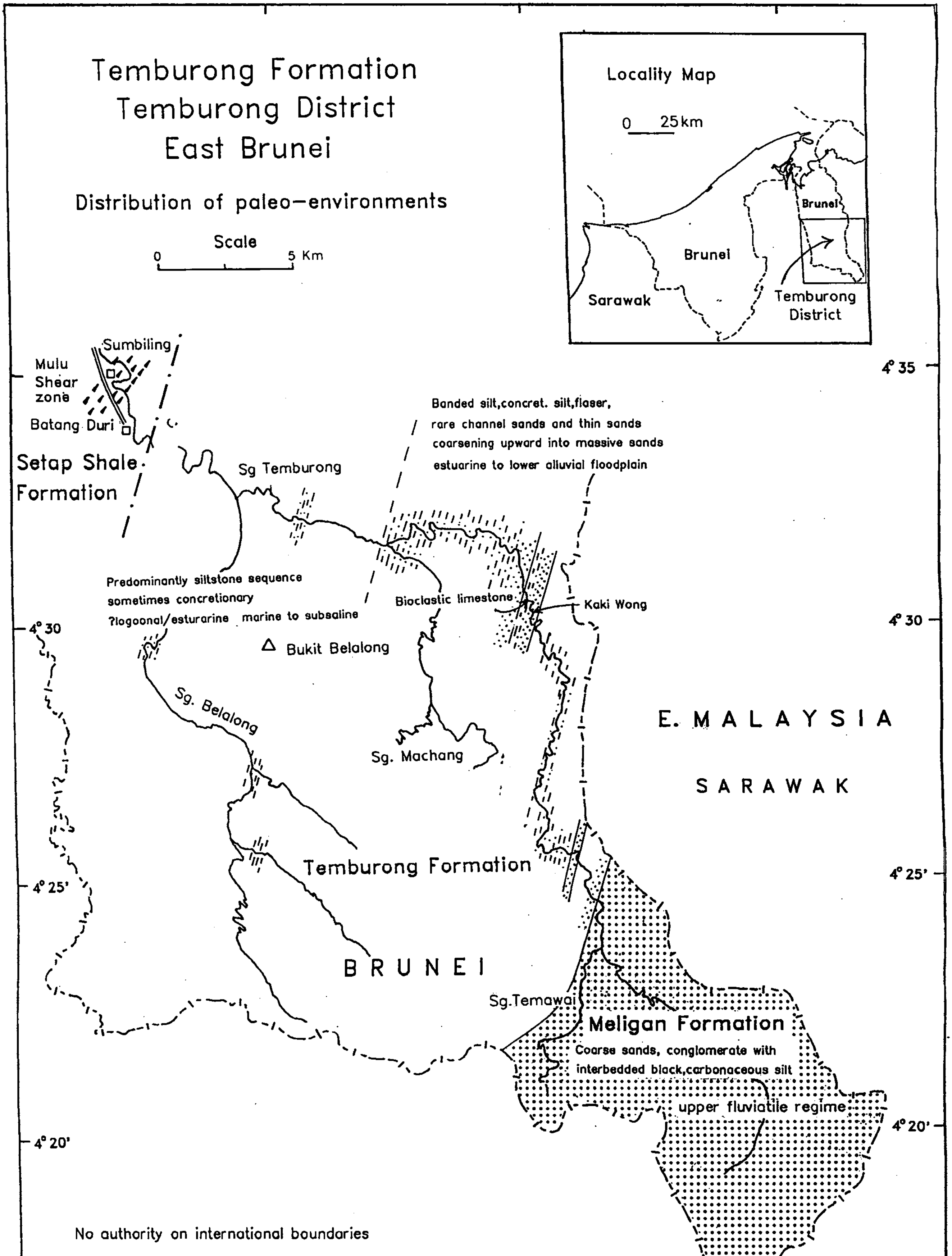

Figure 1. Distribution of paleo-environments.

the argillaceous rocks. Most shales show a cleavage which was mistaken for bedding by earlier workers and only after a careful search for slight colour or textural variations can sedimentary bedding be established in the shales.

The sandstones are composed essentially of subrounded quartz grains 0.05–1 mm with silt patches. Sorting is generally good but may sometimes be difficult to estimate due to recrystallisation. Sericite, zircon, rare plagioclase, rutile and tourmaline occur as accessories. Heavy mineral separation from crushed rock has yielded zircon, tourmaline, ilmenite and garnet. Sericite is the dominant metamorphic mineral and is often aligned parallel to the cleavage. The shales are composed mostly of fine silt and some appear to be conglomeratic but individual clasts are ferruginous and not polygenetic. Comparable sediments can be found in the unmetamorphosed mudstones of Upper Miocene and Pliocene Formations exposed in W Brunei where siderite concretions occur randomly or in layers parallel to the bedding. Bed thicknesses vary from laminae in the argillaceous siltstones to decimetre and metre size in the coarser sandstones. Although the rocks are deformed, sedimentary structures and trace fossils still can be recognised mainly in the more sandy horizons and fossil burrows, ripples, cross-bedding, cross-lamination, slumping, flaser bedding and scour marks are clearly identifiable (Figs. 2, 3, 4, 5).

The sediments of the Temburong Formation can be subdivided into nine sedimentary facies described below.

Homogenous siltstone and mudstone.

Fine- to very fine-grained, dark grey or bluish-black rocks which are often featureless except for cleavage. Individual cleavage surfaces are often sericitic and in the more siliceous siltstones, the cleavage breaks conchoidally producing a scalloped or puckered fracture surface. Pyrite occurs frequently either as clusters or thin, irregular veins and quartz-filled joints and irregular quartz veins transect the rocks. The mineralogy is difficult to discern in thin section and fossils and carbonaceous matter are unrecognisable although a few agglutinating foraminifera have been abstracted. Deposition is mainly out of suspension.

Banded siltstones

Medium- to fine-grained silt, dark grey or bluish-grey without bed partings but bedding is identified by slight colour differences (Fig. 6). Banding is usually even in thickness and occasionally individual bands pinch out. Bioturbation and cross-stratification are unrecognisable in thick sequences but where siltstones are interbedded with more sandy rocks, burrowing is often prolific. Concretions derived probably from siderite occur frequently in layers parallel to the banding. Deposition is largely out of suspension.

Silty sandstones

A facies gradational with the banded siltstones and composed of coarser silt and very fine sand, lighter in colour, often banded and occasionally with sand-filled burrows at various attitudes to the bedding. Bedding more clearly defined than in the banded siltstones with parallel, planar surfaces. There are minor current-induced features on a small scale and occasional bioturbation. Deposition occurred in a low flow regime and sometimes out of suspension.

Siltstone with sandy lamination and ripples

A common rock type showing a clear distinction between sand and silt with varying proportions of sand producing differences in hardness, colour and response to cleavage (Fig. 7). Light grey to bluish grey siltstones with lighter coloured sandstones. The sand laminae range from 1–2 mm to 5 cm and where segregated into layers of one ripple thick produce "flaser" structure. Laminations may be continuous or discontinuous. Burrowing is common and discontinuities in the lamination suggest slumping. Deposition alternated between a low flow regime, sometimes with oscillatory currents, and out of suspension.

Ripple-laminated sandstone

Medium- to fine-grained sandstone, generally light grey with very thin, dark-coloured silt laminae outlining current induced layering in the form of silt "drapes" (Fig. 2). Individual bed thickness rarely exceeds 20 cm. Bioturbation is rarely visible in the sandstones but interbedded, dark coloured siltstones often contain sand-filled burrows. The top and bottom of the sandstones may be irregular, possibly due to loading into adjacent silts or small scale channelling (Fig. 3). Deposition in a moderate flow regime with tidal current influence.

Thin-bedded sandstones

Medium- to fine-grained, well-sorted grey or light brown sandstones, with clean parallel bedding planes and bed thickness ranging between 10–30 cm. Bedset sequences are often up to several tens of metres thick. Sometimes interbedded with thin, dark silts. Bioturbation rare and indistinct and internal layering usually parallel to the bounding surfaces of the bed. Deposition in a low to moderate, flow regime.

Figure 2. Bioturbated sands and silts; note silt drapes on cross bedding.

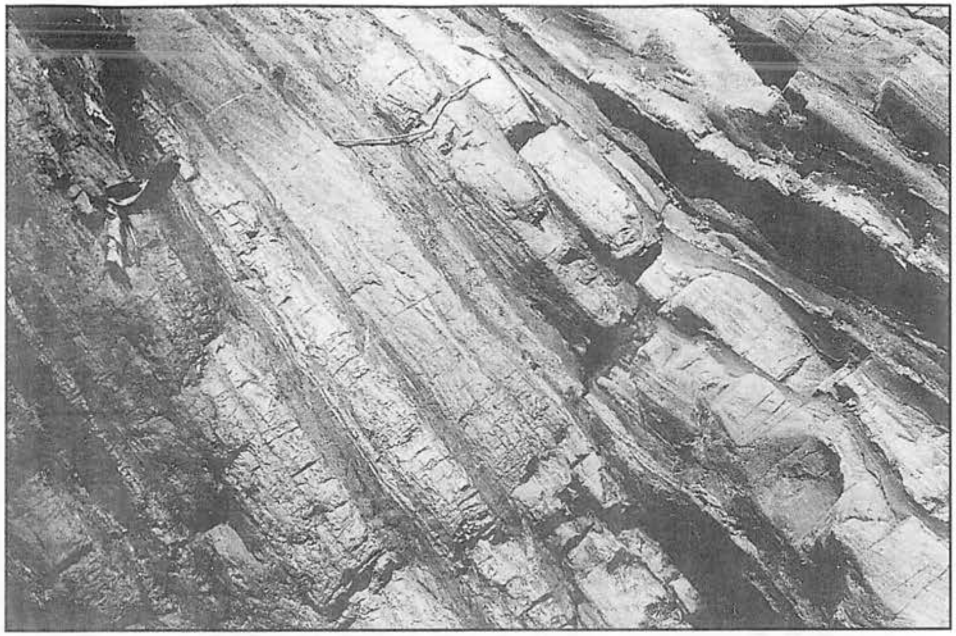

Figure 3. Cross-bedding typical of estuarine sands.

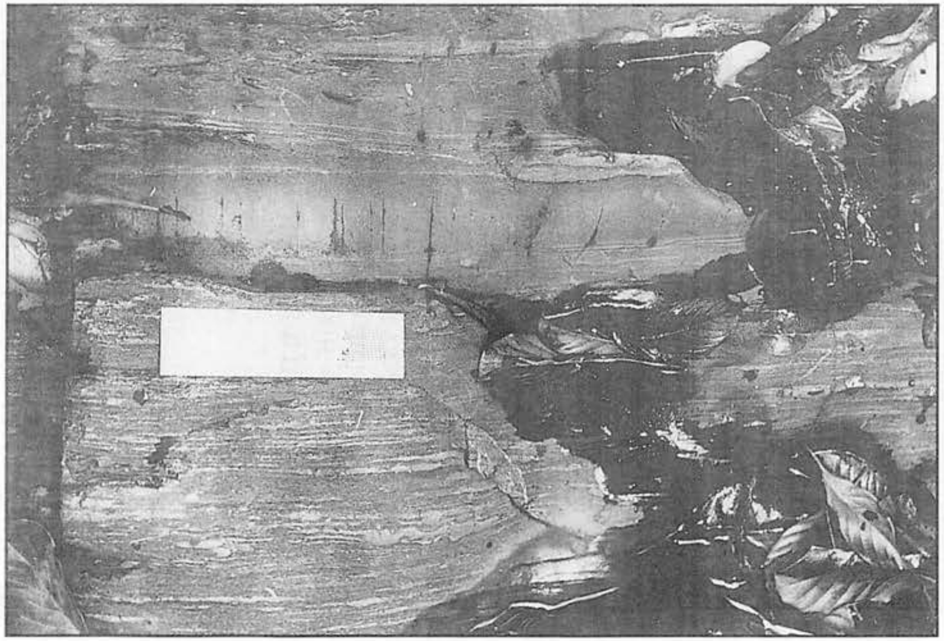

Figure 4. "Flaser" bedding comprising single ripples of sand in silt.

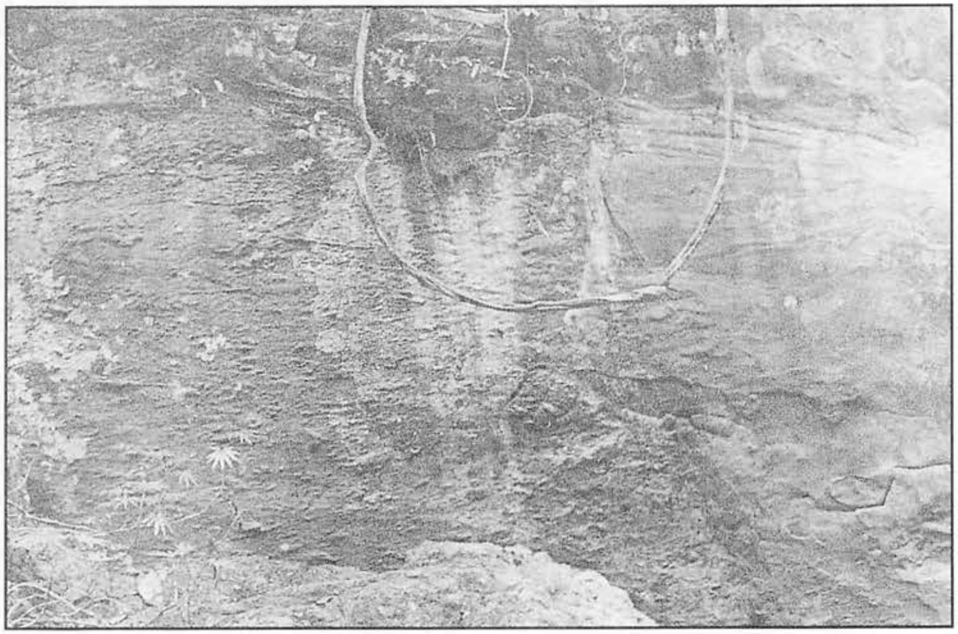

Figure 5. Scour marks on the base of sandstone bed, Kaki Wong.

Figure 6. Banded siltstones showing colour differences between adjacent layers.

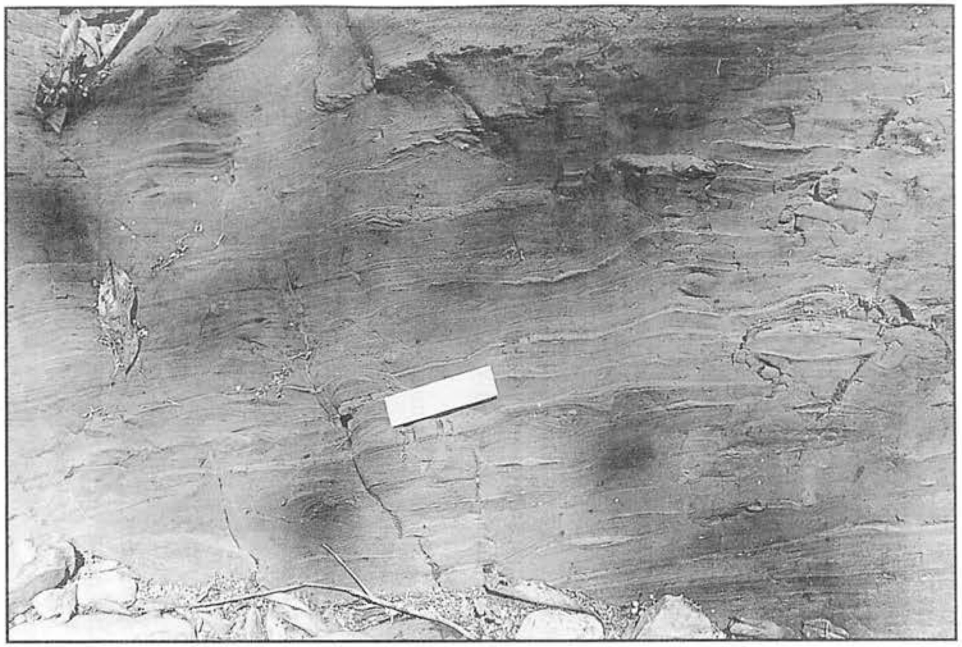

Figure 7. Sandy laminations and ripples in siltstone with soft sediment slumping.

Figure 8. Sharp-contact sandstones.

Sharp-contact sandstone

Massive in appearance and composed of medium-grained, well-sorted, hard, indurated and recrystallised sandstones with clearly defined, sharp upper and lower contact surfaces. The adjacent siltstones usually have well-defined channel sands of similar composition. Bed thickness between 20–50 cm and may occasionally be up to 1 m. Plane- or current-bedded, sometimes with flute castes or grooves on the base of beds. Graded bedding rarely observed (Fig. 8). Deposition from high flow, storm regime probably as a crevasse spay.

Medium-scale, cross-bedded sandstone

Medium-grained, light grey or brown, well-sorted, massive sandstones forming prominent geomorphology. Medium-scale cross-bedding in trough or tabular form and bed thickness between 0.5–3 m, in cosets up to 20 m (Fig. 9). Bioturbated with large burrows and occasional mud pellet bands, usually near the base of beds. Top surfaces of cosets may be curved and uneven suggesting intraformational erosion. Rippled top surfaces sometimes preserved especially where the overlying bed is silty. Deposition in a high flow regime of a major distributary channel.

Bioclastic limestone conglomerate

A hybrid rock of restricted occurrence comprising clasts of clean, foraminiferal micrite in a sandy or silty argillaceous, slightly calcareous matrix and large, elongate clasts of dark-grey micaceous, non-calcareous mudstone (Fig. 10). Occurs in channel bedform cut into and overlain by flaser-bedded non-calcareous siltstones. Deposition by mass flow as a result of a storm/landslide event in the source area.

DISTRIBUTION AND INTERPRETATION OF FACIES

Downstream and W of Kuala Machang, the rocks are predominantly very fine-grained, homogenous mudstones and siltstones, sometimes banded or concretionary with occasional thin-bedded silty sandstones. The rocks are unfossiliferous except for sparse, agglutinating foraminifera. Other fossils may have been destroyed by weathering or deformation. The silt- and mudstones are strongly cleaved. The mudstones sometimes contain concretions composed of pyrite or clay ironstone and there are occasionally quartz-filled joints, veins and tension gashes.

The general absence of current-bedding and other indications of flow and the fine-grained nature of the sediments suggests that the rocks were deposited largely out of suspension in very quiet conditions. Previously, the paleo-environment was interpreted as a pro-delta from the presence of planktonic foraminifera (Tate, 1974). However, further sampling of siltstones has yielded only dwarf agglutinating species typical of sub-saline environments. The absence of sand, predominance of silt and dwarf arenaceous microfauna suggests that the paleo-environment comprised quiet coastal embayments or lagoons with no wave action.

There is a major facies change in the vicinity of Kuala Machang, marked by the appearance of medium-grained, current-bedded sandstones 10–30 cm thick interbedded with laminated, banded silts showing bioturbation and sand flaser. Small channel sands occur at various levels throughout the silt sequence. Sorting of sediment into sand and silt and the formation of single layer, sand ripples suggests the siltstones were deposited by

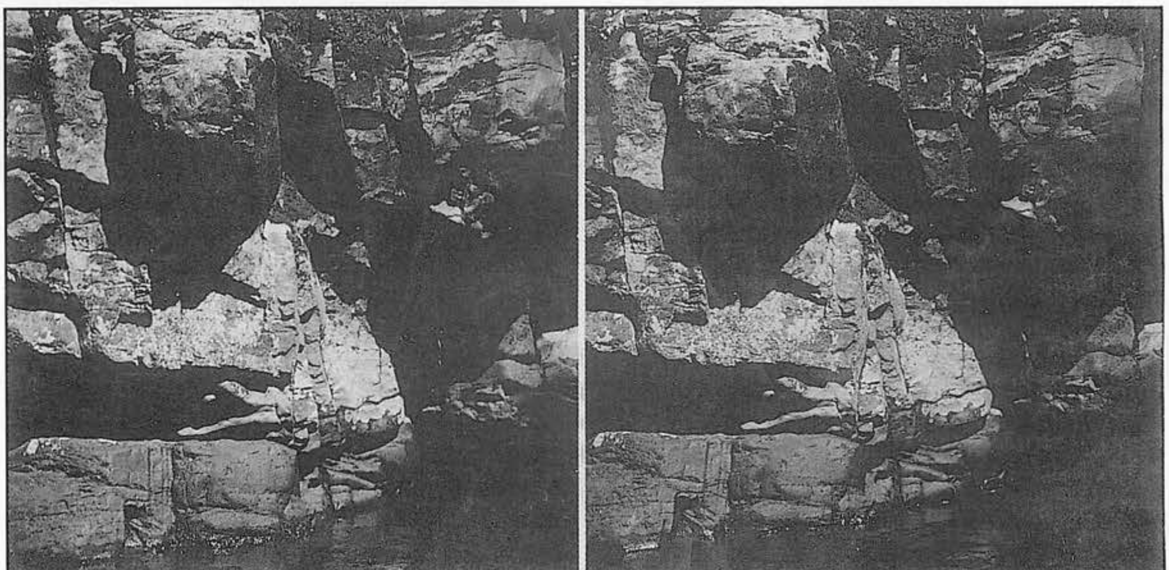

Figure 9. Medium-scale, cross-bedded sandstone (Stereo-photo).

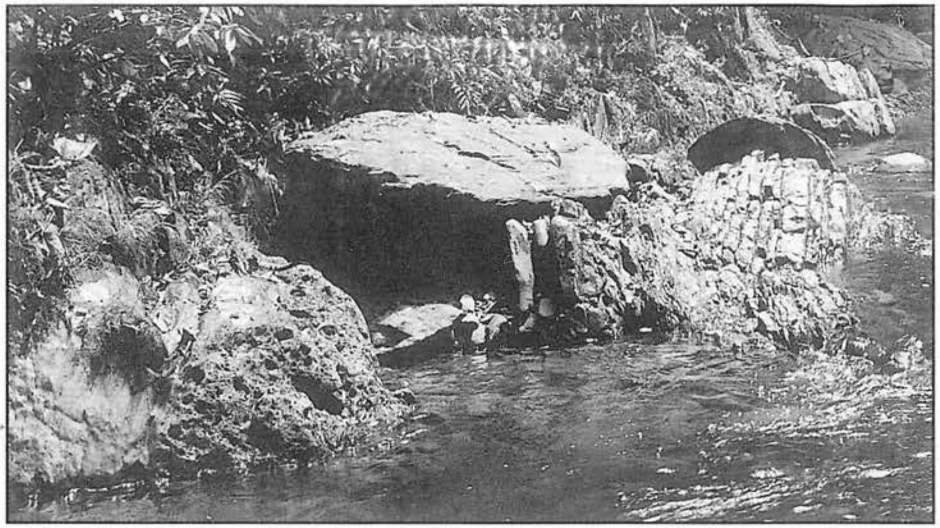

Figure 10. Bioclastic limestone conglomerate filling channel in thin bedded sand- and siltstones.

Figure 11. Massive channel sand in siltstone. Sg. Skeruop.

Figure 12. Plane-bedded sandstone underlain by channel sands, Kaki Wong.

Figure 13. Bioturbated sandy silt, upstream from Kaki Wong.

low velocity, possibly oscillatory, tidal currents. A slightly higher current velocity capable of transporting sand in suspension or with some bed load is suggested by irregular current-bedding. The burrows indicate water depth was probably shallow and there was a bottom living biota and the paleoenvironment was essentially a quiet embayment or lagoon.

Between Kuala Machang and location 4°32'N, 115°14'E where the river changes to a more southerly course, the rocks comprise homogenous siltstones and mudstones, banded siltstones, silty sandstones, siltstone with sandy laminations and ripples and subordinate sharp-contact sandstones. Occasional thick channel sands up to 2 m are found within the siltstones (Fig. 11). Relatively homogenous silty sediments, sometimes concretionary, are predominant and sands rarely exceed 50 cm bed thickness, except for the channel sands. Sharp-contact, plane-bedded sandstones occur in bedset sequences up to several tens of metres thick and represent the sudden incursion of storm-generated coarser sediment flowing into a shallow, relatively quiet environment. The apparently random sequence of sedimentary types indicates that both current strength and sediment supply fluctuated widely and deposition took place in a shallow embayment but within the influence of major rivers. The thick sand-filled channels are probably feeders to the plane-bedded sands.

Southeast of 4°32'N, 115°14'E, the sediments begin to show a more orderly pattern and comprise repeated, coarsening-upward, sequences beginning with banded siltstones succeeded by siltstones with sandy laminations and flaser ripples. Small-scale, sand-filled channels up to 30 cm across and 20 cm deep and thin sands up to 10 cm thick occur anywhere within the siltstones. At the top of each sequence, the bed thickness increases to about 3 m and the sands are well-sorted with medium-scale, cross-stratification, large burrows and rippled top surfaces representing main distributary channels of a delta. The massive sands at the top of one sequence form the waterfall at Kaki Wong (Fig. 12).

A continuously exposed succession of sharp-contact, plane bedded sandstones with a total stratigraphic sequence of 400 m occurs on a straight, SSE-trending section of the river, 5 km E of Kuala Machang. Individual bed thicknesses are up to 40 cm, and the succession is folded in a tight anticline plunging steeply SSW. Some beds contain internal slump structures but bedding surfaces are distinct and sharp, sometimes with primary current lineations on the basal surface. Load casts, scour marks, flute casts and other turbidite features are absent and graded bedding has been observed only once. The relatively coarse grainsize, sharp contact bedding surfaces, primary current directions and slumping suggest rapid deposition by strong traction currents and probably represent crevasse splays from the principal distributary of a major river.

A measured section at 4°32'N, 115°15'E is given below:

Top of section

5 m	Silt, grey, bioturbated, sand-flaser with 1 m thick channel of limestone conglomerate, bioclastic
10 m	silt, black, homogenous
————	top of minor cycle
4 m	Sandstone, fine-grained, thin-bedded (2–4 cm) dark grey
5 m	5 m silt, laminated with fine sand lenses
6 m	silt, banded, finely laminated
————	top of minor cycle
3 m	silty sand, thin, well-bedded
30 m	silt, finely banded with siliceous concretions
2 m	sand, fine-grained, thinly bedded
30 m	silt, black, structureless
6 m	silt, grey, laminated with thin sand
3 m	silt, dark grey with thin channel sands
1 m	silt, homogenous
1 m	silt, banded with thin sand
3 m	silt, homogenous
40 m	silt, banded, dark grey
————	top of major cycle
6 m	sand, well-sorted, medium-grained, cross-stratified, rippled top surface, large burrows, individual bed thickness up to 1.3 m, sinusoidal ripples, large amplitude.

Base of section

The measured section illustrates a sequence of repeated, upward-coarsening cycles associated with deposition probably in the lower part of an alluvial floodplain. The massive, cross-bedded sand at the base of the section is probably a major distributary channel. No microfossils were recovered from the silts and it is unclear whether the paleoenvironment was marine or brackish water. The author favours a brackish water environment, based on the presence of flaser bedding and the carbonaceous content indicated by the dark coloration. Each cycle is not always complete, as massive sands representing major distributaries are absent at the top of the cycle. There is, however, a general coarsening upwards from silt to fine-grained sand.

The bioclastic limestone conglomerate near the top of the section is probably the equivalent of two limestone occurrences in the Batu Apoi river, 11 km further N (Leichti, *et al.,* 1960, Wilford, 1961). The same rock type outcrops again 0.5 km upstream in the Temburong river, where two beds occur within sand-flasered silts and thin, well-bedded sands (Fig. 10). The upper bed is a deep channel with a maximum thickness of 6 m, overlain conformably by banded, non-calcareous, bioturbated silts. The lower contact is irregular and probably erosional and cuts into uniform, dark-grey, non-calcareous silt. Five metres below, another thick bioclastic conglomerate of similar composition lies conformably within non-calcareous silts and well-bedded, thin sands.

Lithologically, the clasts of the bioclastic limestone show two distinct types; a clean, foraminiferal micrite, rounded to sub-rounded and a much darker, pyritic slightly argillaceous, fossiliferous micrite with shallow water Miliolids in angular fragments up to 3 cm. Additionally, large elongate pebbles of dark grey shale occur sporadically. The matrix of the conglomerate is mainly silt and sand with clay and thin sections show angular metamorphic quartz and sparse plagioclase.

Faunal identifications show that the youngest fossils occur in the micritic and pyritic argillaceous clasts and are Te_{1-4} or Te_5 (Late Oligocene–early Miocene) and the matrix contains Tc and Td foraminifers. Normally, the youngest fossils would be expected to occur in the matrix. The atypical features of the deposit raise a question of origin and indicate that the source was eroding both older Tc–Td limestone as well as syndepositional Te_{1-4} or Te_5 limestone.

The angular nature and mixed lithologies of the clasts and the channel geometry suggest rapid deposition by a strong traction current initiated perhaps by a landslide. The source area for both clasts and matrix lies S or SW of Temburong in the Melinau Limestone Formation area at either Melinau, Selidong or Keramit. At Keramit and Selidong, (Adams and Wilford, 1972) most of the limestones contain re-worked foraminifera derived from the Melinau Limestone Formation. At Selidong, there is a considerable thickness of turbiditic limestone containing planktonic foraminifera which is assumed to have been deposited in deeper water in contrast to the *in situ* shallow water, platform deposits of the Melinau Limestone Formation. The beds overlying the Selidong Limestone are dated Te_{1-4}, upper Oligocene, and are the same age as the Temburong Formation.

The rocks surrounding the bioclastic limestone occurrences are mostly non-calcareous, sand-laminated silts and thin, well-bedded fine grained sands with distinctive layering and bioturbation indicating a relatively quiet water, estuarine or inter-tidal environment. The occurrence of limestone conglomerate occupying a channel within essentially quiet water deposition suggests a single, catastrophic event.

Kaki Wong, a small waterfall on the Temburong river is formed by massive, wide channel sands, cross stratified near the top of the channels with rippled top surfaces and primary lineation and scour marks at the base (Fig. 5, 13). The channel is overlain by plane-bedded sands up to 40 cm thick and underlain by more channel sands 3 m deep and up to 10 m wide resting on a 15 m thick bed of highly contorted, slumped sand in silt.

Above the waterfall, well-bedded sands up to 1 m thick in a 20 m thick sequence are interbedded with intensely burrowed sandy silts (Fig. 13). Further upstream, the rocks are predominantly dark-coloured silts with occasional highly folded thin silty sands.

Sharp-contact sandstones representing another incursion of crevasse splay sands featuring medium-grained, plane bedded clean sands up to 30 cm thick occur 2 km SSE of Kaki Wong. There are scour marks on the base of a 1 m thick sandstone bed higher upstream but the bed is not graded.

Thin, well-stratified sands up to 30 cm thick, are exposed in sequences up to tens of metres between 1 and 4 km NNW of the Sg. Temawai confluence. The rocks between the sharp-contact sandstones and thin, well-stratified sandstones are mainly bioturbated siltstones with sandy laminations, ripples and convolute bedding. About 1.5 km downstream from Sg. Temawai, massive, cross-stratified, well-sorted, medium-grained sandstones up to 3 m thick mark an abrupt change in the sedimentary regime. The cross stratification is medium scale with dune erosion surfaces and ripples on individual beds (Fig. 9) and there are large burrows and clay pellets. Immediately above the confluence of the Temawai river, a 3 m thick bed of dark grey silty sand contains rounded, randomly orientated large blocks of finely banded sand; below the confluence, another thinner bed shows ball and pillow slump structures. The features suggest that the rapid deposition of relatively thick sand sequences was accompanied by collapse of sediments down the depositional slope.

The succession from Kaki Wong to Sg. Temawai was formed in a lower alluvial floodplain environment where deposition was largely composed of silt with occasional periods of overbank crevasse splay sands. The occasional thick, coarser sandstones represent major distributaries flowing across a relatively flat, lower alluvial floodplain. The prolific sands near Sg. Temawai were deposited in a transition zone between lower and upper fluviatile regimes.

Upstream of Sg. Temawai, thick sandstone sequences belonging to the Meligan Formation form prominent morphology and are responsible for the exceptionally rugged topography to the SE. Boulders of coarse sand and microconglomerate occur in the river alluvium at Temawai indicating the presence of much coarser sediments in the headwaters of Sg. Temburong. In the Temawai area, the Temburong and Meligan Formations appear to be concordant indicating that the Meligan and Temburong Formations in Temburong District is probably contemporaneous, the Meligan Formation being the upper fluviatile equivalent of the Temburong Formation.

Summarizing, the paleo-environment of the Temburong Formation W of Kuala Machang is interpreted as a sub-saline, quiet-water, lagoon or marine embayment with negligable siliciclastic input. Further E, deposition took place in estuarine and lower alluvial floodplain environments. Two major sequences of inter-distributary floodplain sediments are separated by a thick succession of crevasse splay sands and distributary channel deposits. Further SE, a thick succession of predominantly arenaceous rocks mapped as Meligan Formation represents upper fluviatile equivalents of the estuarine and lower alluvial floodplain deposits of the Temburong Formation. The massive sands of the Meligan Formation appear from aerial photographs to be laterally continuous for several tens of kilometres and represent probably the positions of the major fluviatile distributaries and fanglomerates aligned approximately N or NE. The source area of the sediments was located in the E or SE.

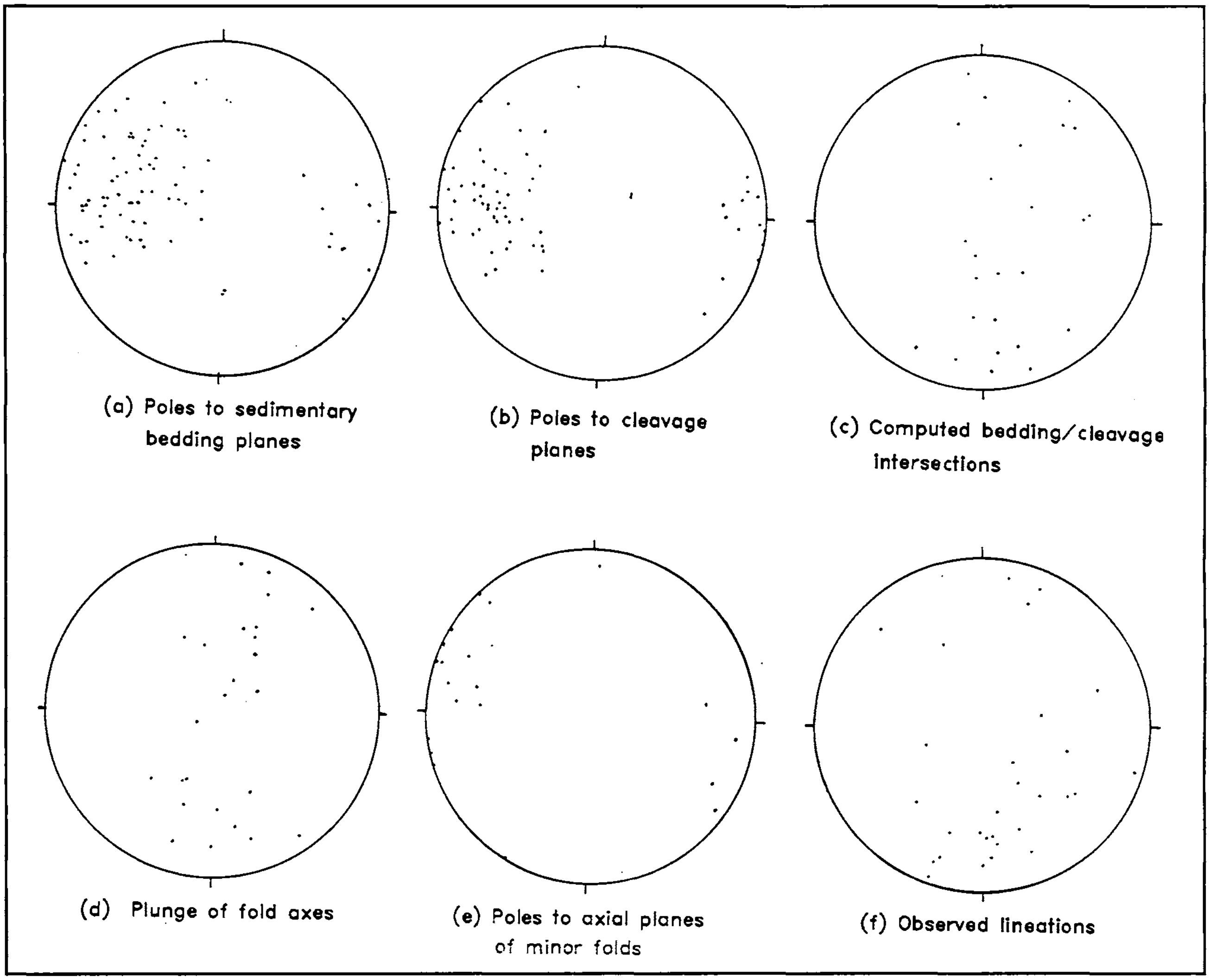

Figure 14. Plots of structural data – Schmidt net, lower hemphere.

STRUCTURE AND DEFORMATION

The widespread, monotonous lithology, absence of marker beds and general poor exposure are constraints to determining the major structure of the area. Instead, a study of minor structures is used to evaluate the major structure.

Although the rocks were recognised as highly deformed and thought to be isoclinally folded, previous geological investigations in Temburong did not distinguish between sedimentary bedding and cleavage (Morgan, 1932; Leichti *et al.*, 1960). In current mapping techniques, planar surfaces are identified as sedimentary bedding only if there is clear evidence of lithological banding or corroborative evidence marking a break in deposition between two successive beds. Cleavage is identified as a clean, fissile plane often covered with sericite and is best developed in the very fine-grained mudstones and siltstones. It is less distinct in silty sandstones which develop a conchoidal fracture. The strike of cleavage is consistently E of N and most planes dip steeply E (Fig. 14b).

Although cleavage and bedding are visible in the same outcrop the relationship between cleavage and minor folds is often difficult to determine. In a small syncline exposed in the river 4.8 km SSE of Kaki Wong, cleavage appeared to be parallel to the axial surface of the minor fold. Similar evidence occurred also 7.2 km S of Kaki Wong and it was assumed that the cleavage was axial planar and related to principal fold structures. However, subsequent analysis of the stereogram plots of bedding and cleavage indicates that bedding and cleavage are almost coincident and unrelated to the axial planes of folds.

A major fold occurs 2 km NNW of Kaki Wong where the Temburong river crosses a sequence of sharp contact sandstones which are folded into a tight anticline. Both limbs dip steeply 65° giving an inter-limb angle of 50° and the hinge of the fold plunges steeply SSW. Numerous minor folds are present between Kuala Machang and Sg. Temawai. The axial surfaces of most minor folds show some variation in strike direction although there is some bias towards a NNE symmetry (Fig. 14e). The hinge lines of minor folds show diversity in angle of plunge as well as azimuth and there is also a NNE planar symmetry.

Slumping is a common feature in the Miocene and Pliocene sediments in Brunei, for example in coastal exposures at Jerudong and in the Miri Formation at MP 19, Jalan Tutong (Tate, 1974) and some folds are the result of sedimentary slumping; soft sediment slumping is probably responsible for many of the microstructures in Figures 7 and 18. Slump folds are responsible probably for the spurious concentrations in the bedding plane plot (a) in Figure 15. If the paleoslope dipped northwards, the bedding plane poles of slump folds would dip steeply south.

The response to shearing of thin, competant sand layers within less competant silts produces a tectonic structure in which the sandstone ruptures initially into a series of rectangular blocks or "boudins" and each individual boudin is rotated so that the longest axis is parallel to the direction of maximum shear i.e. cleavage (Fig. 16, locality 6.25 km NNW of Sg. Temawai). At a locality 0.8 km N of Sg. Temawai, small multiple channel sands in silt are slightly sheared and appear at first sight to be boudins. (Fig. 17). The effects of deformation on slumped sandstones may produce complex structures (Fig. 18). The deformation of linear sedimentary features is easier to recognise. Sand-filled burrows originally perpendicular to a bedding plane and penetrating from a sand layer into silt are deformed by shear and become aligned parallel to the principal direction of shear (Fig. 19).

STRUCTURAL ANALYSIS

Plots of the poles to sedimentary bedding, cleavage and axial planes of minor folds and the pitch of lineations and plunge of minor fold axes are shown on the lower hemisphere of a Schmidt equal area net (Fig. 14). Plots were analysed statistically using a Kaarlsbeek counting net and contours drawn as percentages of the total points per 1% net area. The results are shown in Fig. 15. The data plotted on the diagrams are taken from measurements taken throughout the whole area described here and no discrimination is made between type of fold or whether a lineation is measured on a bedding plane or other surface.

The two most important plots for structural analysis are those of bedding plane and cleavage. A comparison of (a) and (b) in Figure 15 show that the maxima are almost coincident suggesting that the cleavage is not axial plane cleavage formed by shear as a result of tectonic compression but bedding plane cleavage formed by compressive strain as a result of loading. The distribution of poles to sedimentary bedding planes shows clearly a small circle centered about 285° indicating that the folds are conical rather than cylindrical which would have shown a great circle girdle. Conical folds tend to be discontinuous and die out over short distances, a fact that perhaps explains the apparent lack of continuity of folds observed in the field. The presence of only one small circle excludes the possibility of doubly plunging folds.

The structural interpretation of the coincident bedding and cleavage planes indicate one of two

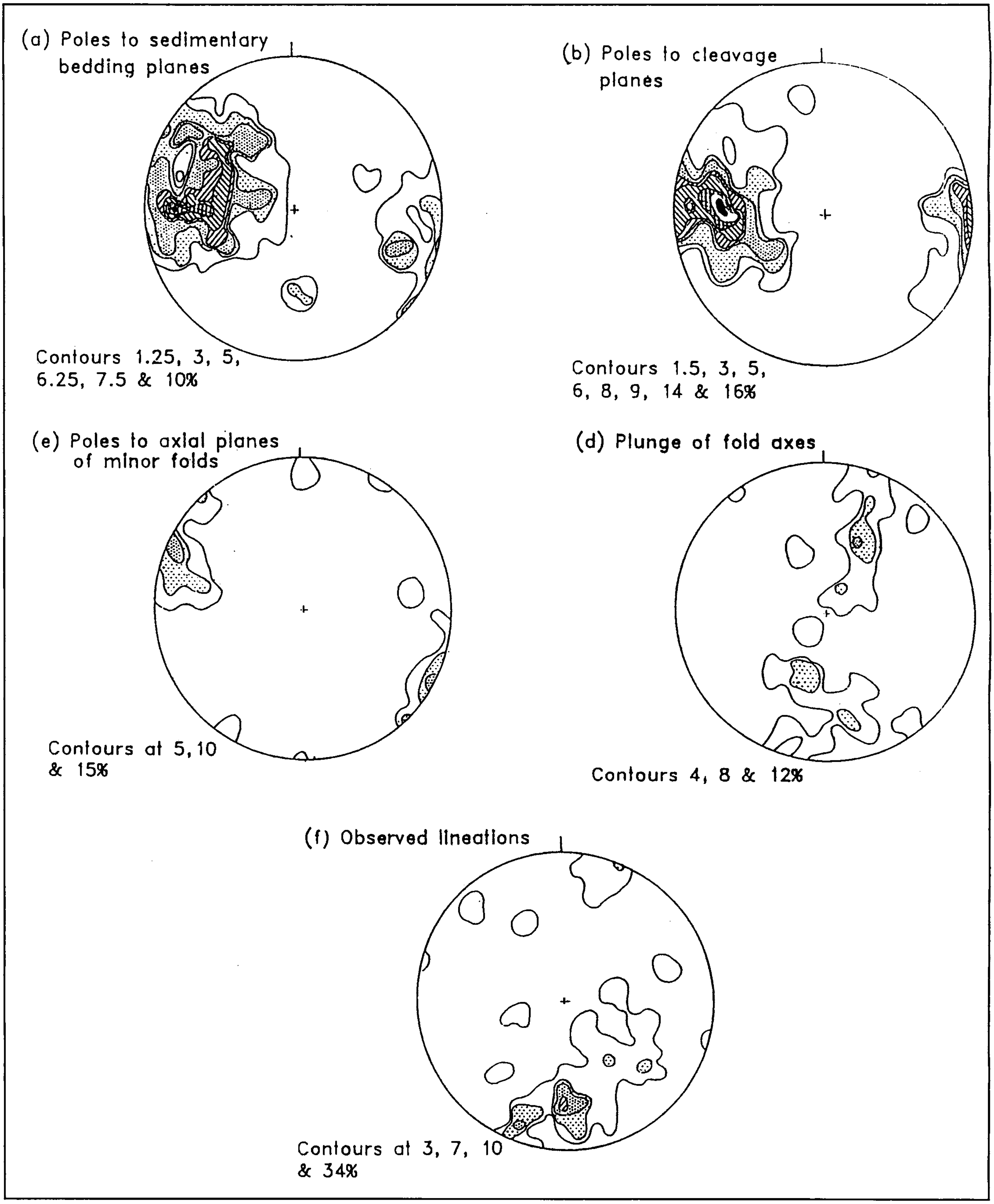

Figure 15. Contoured plots of structural data shown in Figure 14.

Figure 16. Disrupted sandstone bed; sandstone "boudins" rotated parallel to the direction of maximum shear (cleavage).

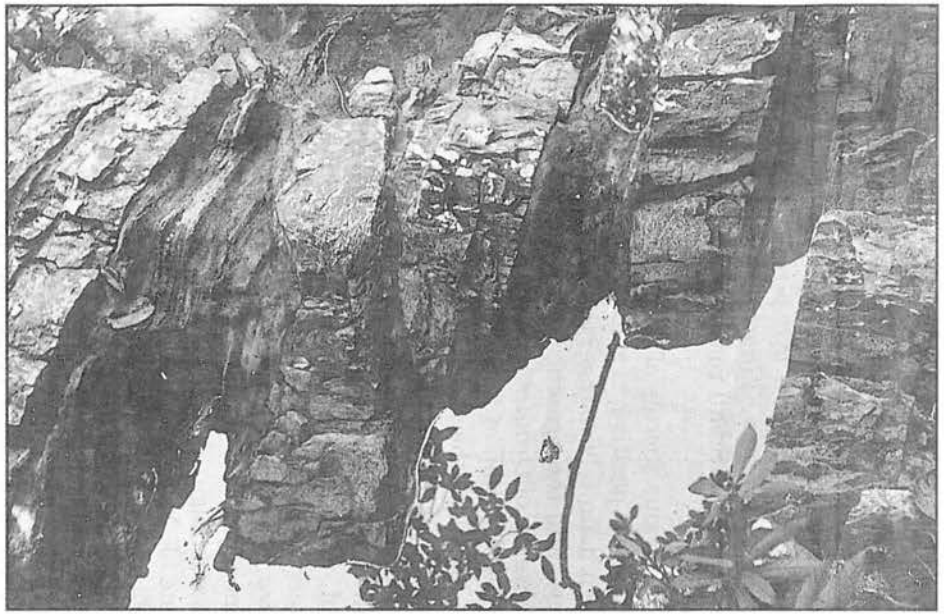

Figure 17. Deformation of small channel sands to resemble boudins. Dip vertical.

Figure 18. Slumped sandstones folded into recumbent folds.

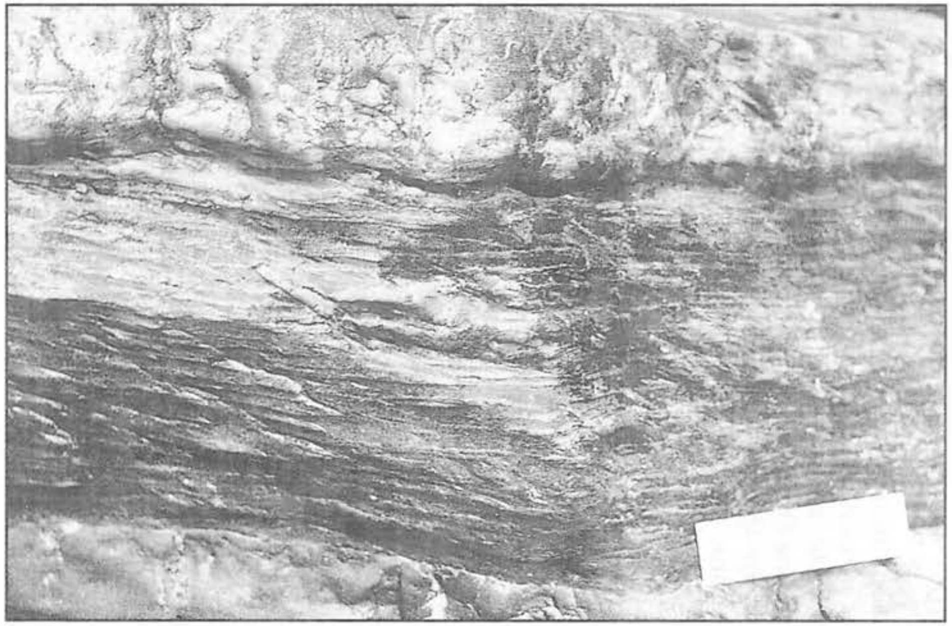

Figure 19. Sand-filled burrows in siltstone rotated parallel to the direction of maximum shear.

possibilities; that the rocks are isoclinally folded (as a result of intense tectonic compression); or, that the cleavage has developed parallel to the bedding during high loading pressures. The author favours the latter interpretation for the following reasons:

a. excess loading can cause bedding plane cleavage, and also low-grade metamorphism
b. on regional evidence, the deformation appears to be restricted to Temburong District; to the SW, the rocks in the Limbang valley are unaffected and to the NE, there seems to be a gradation into a transition zone with the West Crocker turbidites with the effects of bedding plane cleavage dying out. If the rocks were isoclinally folded, intense deformation across a much greater area would be expected.
c. rocks belonging to the Belait Formation nearer the coast in Temburong District show recrystallization and are much more lithified than their counterparts in West Brunei and this is thought to be the result of being subjected to a greater burial history (James, 1984).

METAMORPHISM

Sericite on cleavage planes and the recrystallisation of quartz in the arenaceous rocks indicate a low metamorphic grade. Pyrite in clusters and spots is found mainly in the siltstones and is derived either from jarosite, a hydrated ferric sulphate or from siderite both of which characterise mangrove-dominated, brackish water deposits. Redistribution of pyrite and quartz into areas of low pressure, usually tension gashes, joints and veins is more common in the more competant, arenaceous sequences which deform by fracturing.

Summarizing the tectonic history of the Temburong Formation, an analysis of stereo plots suggests that the deformation is caused by loading as a result of substantial thicknesses of overlying sediments. Deformation was accompanied by quartz recrystallisation, low-grade sericite metamorphism and the formation of pyrite and marcasite from iron-rich layers.

STRATIGRAPHY

Dating the Setap Shale and Temburong Formations is constrained by lack of diagnostic faunas as well as destruction of fossils by weathering and deformation.

A sample of Setap Shale Formation from near the mosque at Kg. Salangan, 18 km N of Kp. Batang Duri, was examined by S. Buchan and S.F. Schuyleman (personal communication) who reported a very sparse fauna of planktonic and small benthonic foraminifera comprising:

Globigerinoides quagrilobatus quadrilobatus, Globigerinoides quadrilobatus immaturus, Globoquadrina altispira altispira, Globoquadrina altispira globulosa, Hastigerina sp. (rare), *Lenticulina* sp., Small rotalids and agglutinating foraminifera.

The various species of planktonic foraminifera do not allow positive age determination but the sample is definitely younger than N.4 (lowest Lower Miocene) and the presence of *Hastigerina* sp. and total absence of *Orbulina* would indicate an age of young as N.7, (top of Lower Miocene).

At MP10 on the road between Kg. Sumbiling Lama and Kg. Batang Duri, the splintery rocks in Setap Shale Formation have yielded a microfauna identified by J. Murray (formerly University of Bristol, U.K.) as *Globigerinoides immaturus, Globigerinoides trilobus*, and *Globoquadrine altispira*. The oldest possible age is topmost Lower Miocene (Zone N.8 of the Blow zonation, 1970) but the assemblage also ranges to youngest Lower Pliocene (J. Murray, personal communication).

A feature common to all microfaunas abstracted from the Setap Shale Formation in Temburong District is that they are dwarf forms indicating a brackish water, sub-saline estuarine environment. Some have test walls cemented by silica which could be an original depositional characteristic or the calcareous material may have been leached or replaced as a result of shearing or excessive loading.

The faunal content of the bioclastic limestone near Kaki Wong was examined by S. Buchan and S.F. Schuyleman (B.P. Ltd., Singapore) who reported as follows:

> The clean foraminiferal micrite contains well preserved *Spiroclypeus* and *Lepidocyclina (Nephrolepedina)* indicating a Te age. The pyritic darker argillaceous micrite contains abundant *Neoalveolina pygmaea* and broken forams including *Nummulites fichteli* (common), *Lepidocyclina (Eulepidnia)* (common), *Lepidocyclina* spp., *Discocyclina* spp. (rare), *Heterostigina* and ?*Cycloclypeus*. The *Discocyclina* are reworked Eocene. The *Nummulites* could be Tc or Td and the *Eulepidina* Td or Te. *Neoalveolina pygmaea* is more common in the upper Oligocene or the lowest part of the Lower Miocene (Te_5) and this young age is confirmed by the *Spiroclypeus*.

The paleontological evidence from the bioclastic limestone conglomerate in the Sg. Temburong is not entirely satisfactory as most of the fossils are re-worked. The youngest fossils are Te_{1-4} or lowest part of Te_5 and the age agrees with paleontological evidence from the 30 m thick Melikut limestone in the Temburong Formation in SW Sabah (Wilson,1964). The Melikut limestone was described by C.G. Adams of the British Museum (in: Wilson, 1964) as "bioclastic" but Wilson states that it contains no re-worked fossils. The Pulun limestone forms a minor reefoid mass in the Meligan Formation in the same region and is dated also Te_{1-4} to Te_5 (Wilson, 1964). However, in a footnote (Wilson, 1964, p. 67), the lower part of the Meligan is Te_{1-4} to lowest Te_5; the upper part of the Meligan is late Te_5 or younger and there would therefore appear to be Meligan lithofacies sediments both above and below the mid-Te_{1-4} unconformity. In the Gunong Lamaku area, the most northerly outcrop, the Meligan Formation overlies unconformably both West Crocker and "Setap Shale" (i.e. Temburong Formation) (Leichti, 1960, p. 298). The age of the Temburong Formation is probably Te_{1-4} to lower Te_5 (top Oligocene to lowest Lower Miocene) and somewhat older than the overlying uppermost Lower Miocene Setap Shale. The Meligan Formation in Brunei is probably a paleo-environmental facies equivalent of the Temburong Formation and is probably the same age.

The stratigraphic position of the Temburong Formation in the type locality is complicated by the existence of a shear zone, probably related to the Mulu Shear Zone (Tate, in press) which occurs in the Setap Shale Formation in the vicinity of Kg. Sumbiling where there is intense shearing, disruption and ptygmatic quartz veining. The Temburong Formation is assumed to be overlain by Setap Shale Formation but field relationships are unclear and no contact or basal conglomerate has been found. The cleavage which typifies the Temburong Formation is absent in the adjacent Setap Shale Formation near Batang Duri (Fig. 1). Exposures in the Setap Shale Formation along the road linking Bangar with Batang Duri show evidence of over-consolidation with fracturing and spalling into rock splinters but it is not clear whether this kind of deformation is due to the effects of the Mulu Shear or due to loading.

The existence of a gap in the geological record of NW Borneo was referred to (Wilford, 1961) and dated approximately as Oligocene. The gap in the record was recognised paleontologically in the Melinau, Selidong and Keramit limestones by Adams (1965) who noted a pronounced break visible in the field between Tc and Td zones in the early Oligocene and he suspected another break between Te_{1-4} and Te_5, the Oligocene/Miocene boundary because of abrupt faunal changes.

The presence of any Oligocene/Miocene gap in Temburong District is largely circumstantial and no clear evidence has been found there. If the determination on the bioclastic limestone is accepted, the Temburong Formation is clearly older than the Setap Shale Formation further N. The absence of a basal conglomerate suggests that there was no tectonic activity at the Oligocene/Miocene boundary but perhaps there was a break in deposition. Moreover, the paleo-environment of the Temburong and Setap Shale Formations is essentially similar — i.e. shallow water. Brondijk (1962a, b) described the sedimentology of the rocks in the Padas gorge and assumed that the rocks in Temburong were similar, concluding that the Temburong Formation formed in a deepwater, marine environment based on the presence of planktonic foraminifera and occurrence of turbiditic sands. The conclusion is questionable; although Ditzel (1956) identified planktonic species from Kuala Belalong, no planktonics have been recovered by the author; instead, only sparse, agglutinating species of indeterminate age are present. The sandstones are not turbiditic and many contain shallow water features including cross bedding and abundant bioturbation. The silts are generally dark coloured and originally contained abundant, carbonaceous material. Dwarf agglutinating foraminifera also occur in the Setap Shale Formation indicating a similar environment.

REGIONAL DISTRIBUTION OF THE TEMBURONG FORMATION

It is reasonable to assume that the Temburong Formation extends NE from Brunei to the Padas river in SW Sabah where it interfingers with the Crocker Formation. The more distinctive turbiditic affinities in the Padas area signify a change from a lower alluvial floodplain to a deeper water, marine environment. There is also some justification for returning to earlier subdivision of the Crocker Formation into "West" and "East" Crocker, as outlined on the second edition of the Geological Map of Sabah (Wilford, 1967), the West Crocker being Oligocene-Lower Miocene in age. However, the well-developed cleavage seen in the Temburong Formation in Temburong is generally absent in the transition zone exposed in the Padas gorge although there is local fissility in tight folds (Sivalingan, 1984). The deformation in Temburong therefore would appear to be restricted to a relatively small area.

The SW and SE continuation of the Temburong Formation from Brunei is less certain. A recent traverse by the author across Ulu Baram from the lower Tinjar to beyond Long San show that the sediments belong to the Setap Shale Formation *sensu stricto*, as mapped originally and shown in the Leichti *et al.* (1960) interpretation. They show no evidence of cleavage or metamorphism but there are several zones of NE-trending shearing. Samples collected on the traverse are barren of nannofossils (H. Soediono, pers. comm.) but it is not known whether this is a depositional feature or post-depositional weathering or leaching.

To return to Brondijk's original proposals for the Temburong Formation, the geographical extent of the Formation is much less than he surmised. In Temburong, the Formation is restricted to an area NE of the "Jerudong line" which is known to be a major tectonic boundary offshore and the cause of complex faulting in the Bandar Seri Begawan and lower Limbang valley (James, 1984). A SW extension of the Formation into Ulu Baram is unlikely. Until re-mapping of the areas between Temburong and Panggi as well as E of the Mulu massive is undertaken, the extent of the deformational effects of the loading seen in Temburong can be only conjecture. In conclusion, excessive sedimentary loading can create circumstances under which in one area, sedimentary rocks are deformed, metamorphosed and develop a cleavage while in an adjacent area, sediments remain unaffected even though they are the same age and lithology.

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