

Late Paleozoic glacial marine facies in Southeast Asia and its implications

PETER H. STAUFFER¹ AND LEE CHAI PENG²

¹Geology Dept., Palo Alto, California, USA

²Universiti Malaya, Kuala Lumpur.

Abstract: Pebbly mudstones for some years in the Paleozoic sequences of south Thailand (Phuket Group or Kaeng Formation) and the Langkawi Island of northwest Malaysia (Singa Formation) form part of a belt of such rocks extending about 2000 km from Sumatra to central Burma. The rocks form a distinct facies: typically crudely laminated, dark grey, poorly sorted mudstones with scattered megaclasts, few fossils, and much soft-sediment deformation.

Traditionally interpreted as slump deposits, these rocks are well exposed and structurally simple in the Langkawi Islands (Singa Formation), and detailed studies there justify a reinterpretation of them as glacial marine sediments. The Singa Fm. is about 1600 m thick and is Carbo-Permian in age, bracketted by fossiliferous latest Devonian and late Early Permian strata. Six lithofacies defined from measured sections include unbedded diamictite, variously bedded sand-mud combinations, and subordinate clean sandstone. Sand-size grains are mainly quartz and rock fragments.

Megaclasts (from granules to boulders) form up to 4.5% of Singa diamictites, but occur also in other facies through the formation. Size analyses (5) of diamictites yield very poorly sorted polymodal distributions with median size in the silt range. Pebbles and megaclasts are mainly blocky, subangular, often faceted and sometimes show clear dropstone characteristics. They are dominantly of sandstone, with subordinate limestone, vein quartz, granitic rock, and metamorphic rocks.

These characteristics of the Singa Formation, especially of the megaclasts, strongly indicate the sequence is glacial marine deposits with ice-rafted stones. This interpretation is supported by evidence for cold conditions, evidence against deep water, and by the presence of diamond. Implications of a glacial marine origin for the 2000-km belt of rocks include: (1) the (present) west side of the Western Southeast Asia tectonic block was marginal to (and attached to?) Gondwana in Carbo-Permian; (2) its position in Gondwana was probably somewhere between Arabia and northwest Australia; (3) warm-climate Permian floras of Southeast Asia may lie on other tectonic blocks with separate drift histories.

Questions and problems remaining or raised by this work include the long time interval and possible hidden unconformities, the origin of the deformation structures (possibly from ice push?), and the actual paleoenvironments represented by the different facies in the sequence.

INTRODUCTION

Poorly sorted clastic sedimentary rocks having scattered pebbles and other megaclasts in a finer-grained (muddy) matrix ("pebbly mudstones") have been known for some years to be present in the Paleozoic sequences of south Burma (Tenasserim), south Thailand (Phuket area), and in the Langkawi island of Malaysia (figs. 1,2). These rocks generally have a distinctive appearance in the field. They are crudely laminated to well bedded, dark grey, mainly fine-grained clastic rocks, containing megaclasts which occur singly or scattered through layers as much as a few meters thick, and locally displaying rather intense soft-sediment deformation.

Most of the earlier work on these rocks was done in the Phuket area of Thailand (Mitchell, *et al.*, 1970; Garson, *et al.*, 1975). In recent years more detailed stratigraphic and sedimen-

tological studies have been made in both the Thai (Mantajit, *et al.*, 1979; Tantiwanit, *et al.*, 1983) and Malaysian (Ahmad, 1973; Stauffer & Lee, 1984) areas of their exposure. The general stratigraphy and character of the megaclast-bearing sequence is now best known from the Langkawi Islands of Malaysia (fig. 3), where the structure is relatively simple and the contacts of the sequence (there called the Singa Formation) are exposed or narrowly bracketted, with fossiliferous strata above and below.

Previous interpretations of the pebbly mudstones have always favored an origin by slumping and mixing of coarse and fine sediments on a major submarine slope (Mitchell, *et al.*, 1971; Gobbet, 1973; Ahmad, 1973; Jones, 1981), although the possibility of ice-rafting of megaclasts has been considered (and rejected) as an alternative. This interpretation assumes some importance in paleogeographic and paleotectonic reconstructions. Mitchell, *et al.*, (1970) inferred from the relations of the pebbly mudstones at Phuket, Thailand, to contemporaneous shallow marine rocks farther east that there was a continental edge in the late Paleozoic, with the slope facing down to the west. Ridd (1980) regarded the pebbly mudstones as representing slumps into a widening submarine rift, and therefore took their time of deposition (Carbo-Permian) as dating the separation of the Malay Peninsula from a continent on its west side.

If the pebbly mudstones, however, are not slump deposits but glacial marine sediments with ice-rafted clasts, the paleogeographic implications are obviously quite different. Recent studies of these rocks, including compilation of data on their distribution in Southeast Asia (Stauffer & Mantajit, 1981) and a detailed examination of the Singa Formation in Langkawi by the present authors (Stauffer & Lee, 1984, this paper), strongly favor a glacial marine origin.

In this paper we describe the general characteristics of the pebbly mudstones and associated facies, review the evidence for a glacial marine origin, and examine briefly the implications, problems, and questions raised by this interpretation.

GEOMETRY AND GENERAL STRATIGRAPHY

The distinctive Late Paleozoic pebbly mudstones and associated clastic sedimentary rocks are known mainly from the Langkawi Island of Malaya and the Phuket area of south Thailand, only a few hundred kilometers to the north (fig. 1), but they are present much more extensively. A recent compilation (Stauffer & Mantajit, 1981) showed that they occur also not only in south Burma (Mergui Group) but also in west-central Thailand (Kaeng Krachan Formation), near the head of the Gulf of Martaban (Martaban Group), and along the west side of the Shan Plateau (Lebyin Group). Similar rocks also occur widely in northern Sumatra, where they have been named the Bohorok Formation (Cameron, *et al.*, 1980). These Carbo-Permian pebbly mudstones and associated rocks therefore occupy a belt stretching more or less continuously from Sumatra to central Burma, a distance of about 2000 km (fig. 2).

The thickness, age and vertical stratigraphy of these pebbly mudstone-bearing units are poorly documented in most of their areas of occurrence. The characteristic lack of fossils, absence of good marker beds, discontinuous exposures have made unraveling their structure and stratigraphy a difficult task. The sequence in south Thailand (Phuket Group) was long

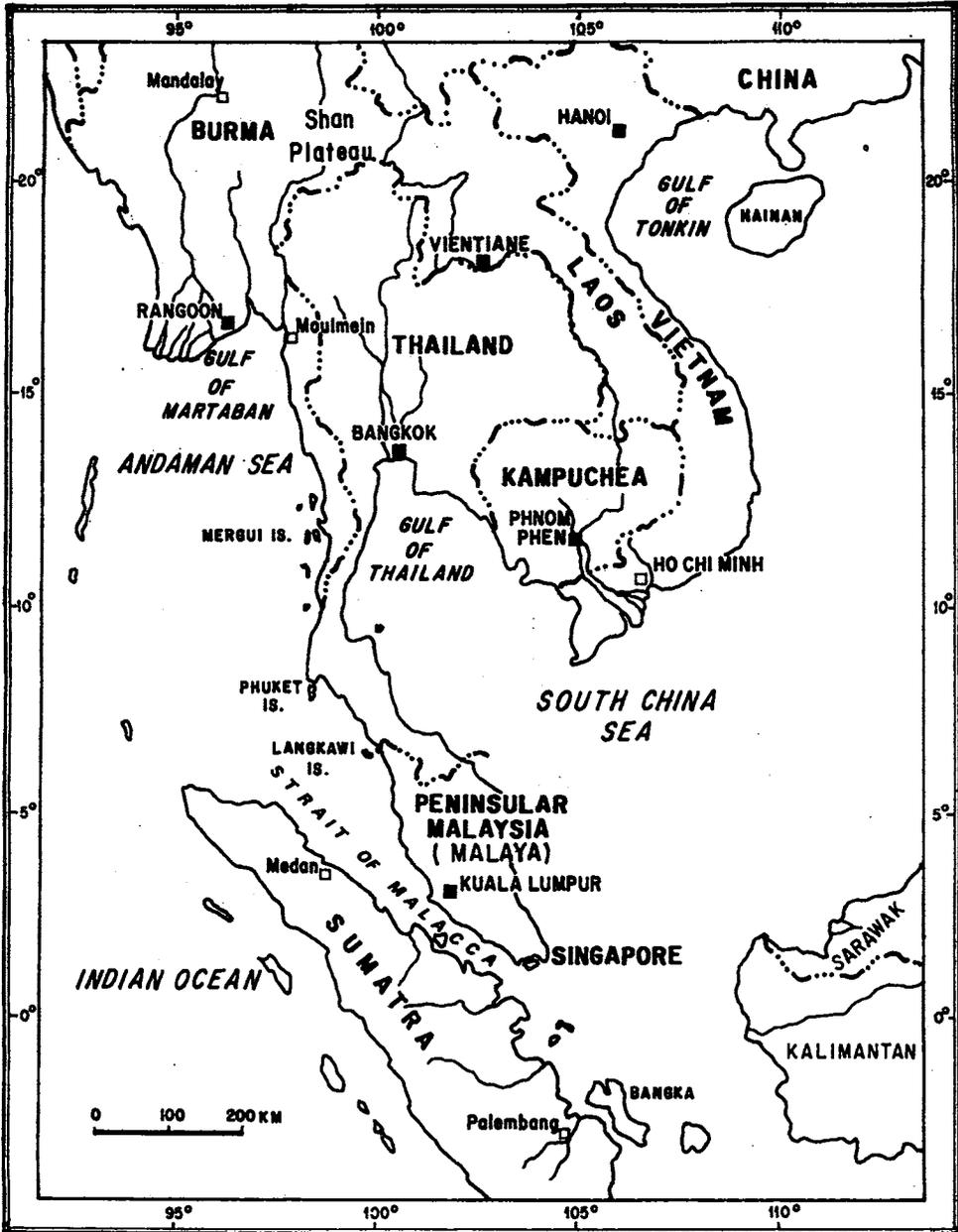


Fig. 1 Index map of Southeast Asia, showing areas and localities mentioned in the text.

thought to extend down perhaps into the Precambrian, and not many years ago was still thought to span most or all of the Paleozoic (Mitchell, *et al.* 1970).

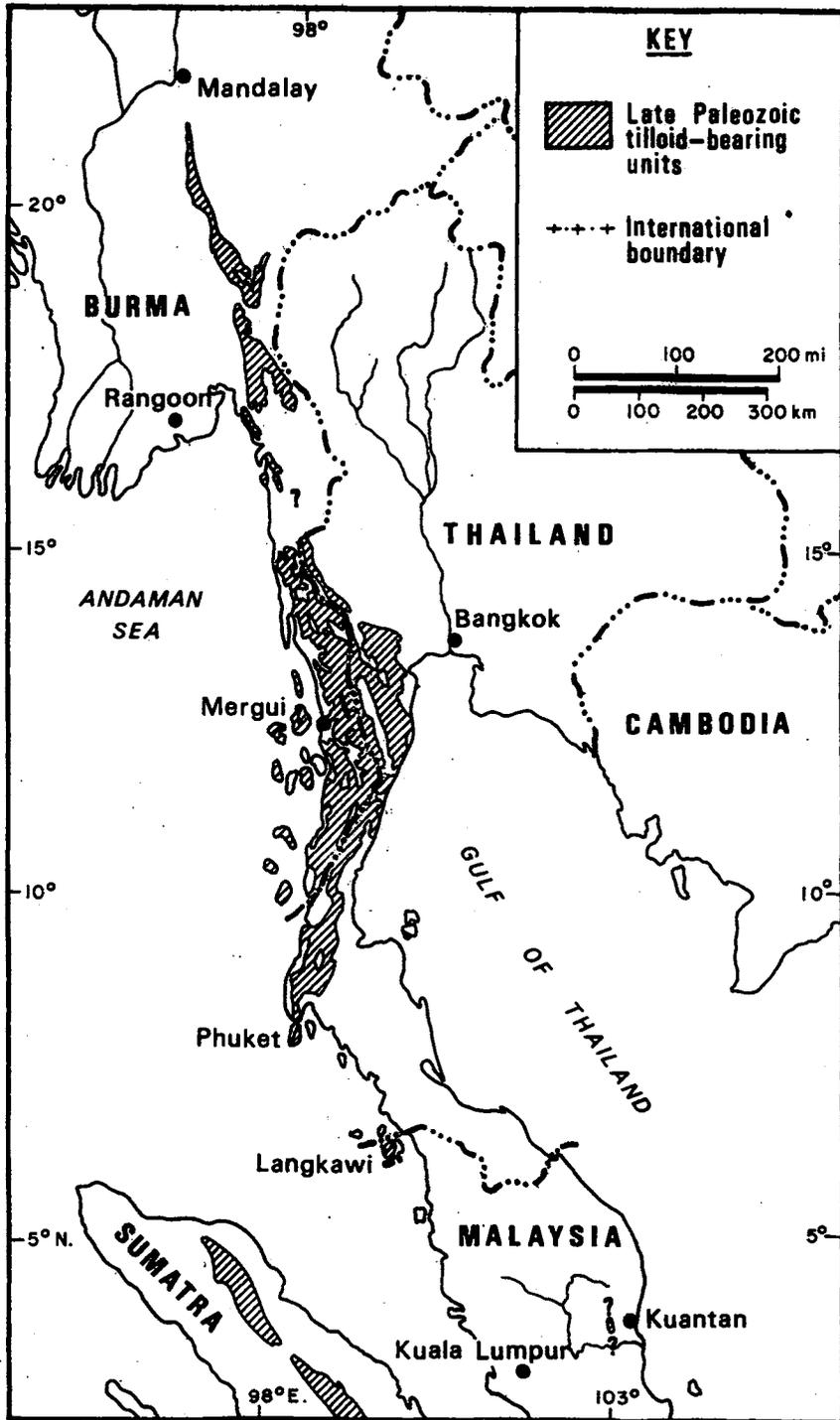


Fig. 2 Extent of Late Paleozoic sequences containing the glacial marine facies (after Stauffer & Mantajit, 1981).

In the Langkawi Islands off the northwest coast of Peninsular Malaysia, the pebbly beds and associated rocks comprise the Singa Formation (Jones, 1981). This unit forms what appears to be basically a simple homoclinal structure (fig. 3), and both underlying and overlying units are exposed and are datable by fossils. Beneath the pebbly rocks of Singa Formation are white to pale red mudstone and sandstone, which have yielded latest Devonian (or earliest Carboniferous) bivalves (Sarkar, 1972; Yancey, 1972; Gobbett, 1973). Although the contact is concealed under water, it is fairly narrowly bracketted and appears conformable. Overlying the Singa Formation conformably in continuous exposures are carbonate rocks assigned to the Chuping Formation, containing a rich late Early Permian shelly fauna (Yong & Jantaranipa, 1970; Gobbett, 1973; Jones, 1981). Rare body fossils found within the Singa and its lateral equivalents support the Carbo-Permian age implied by the bracketting units, but do little to refine it. The best fauna reported so far was found in southern Thailand and was dated as early Permian (Waterhouse, 1982). Fossils assigned to Lower Carboniferous have also been reported from the sequence in south Thailand (Gobbett, 1973), and Carboniferous fossils have recently been reported from the Lebyin Group in Burma (Myint Lwin Thein and A.H.G. Mitchell, cited in Stauffer & Mantajit, 1981).

Ahmad (1973) studied the stratigraphy of the Singa Formation in Langkawi and derived a composite thickness by measuring sections. He also divided the formation into four members, but his lowest member consists of the white to red mudstones that contain probable latest Devonian fossils, which are markedly distinct lithologically from the rest of the sequence; these are now best regarded as comprising a separate (as yet unnamed and undefined) underlying unit. Omitting this basal portion, the thickness arrived at by Ahmad for the Singa Formation was about 1600 meters, and this figure, barring undiscovered fault offsets, probably is fairly accurate.

FACIES AND LITHOLOGIC CHARACTER

Although the Singa Formation and its lateral equivalents present at first glance a monotonous appearance in the field, closer examination shows that several lithofacies types are present. In the present study we measured three detailed stratigraphic sections, in the lower, middle, and upper parts of the Singa Formation, which covered thicknesses of 128.2, 123.9, and 105.3 meters, respectively. In aggregate, therefore, these measured sections, located on Pulau Tepor, Pulau Ular, and Pulau Singa Besar (see fig. 3), account for about 22.3% of the Singa Formation thickness. Schematic plots of the three measured sections are given in figure 4. We also examined other exposures of the Singa Formation in Langkawi, particularly on P. Singa Besar, and a probable exposure of the formation on Tukun Terendak, a small islet off the Kedah coast.

Lithofacies

Lithofacies types observed in the detailed sections include the following:

- A. Laminated clean sandstone facies. Thick (0.5-2 m) beds of fine to medium-grained moderately well sorted sandstone showing regular fine lamination, low-angle (hummocky?) cross bedding, and sometimes soft-sediment deformation structures of 1 + m scale.

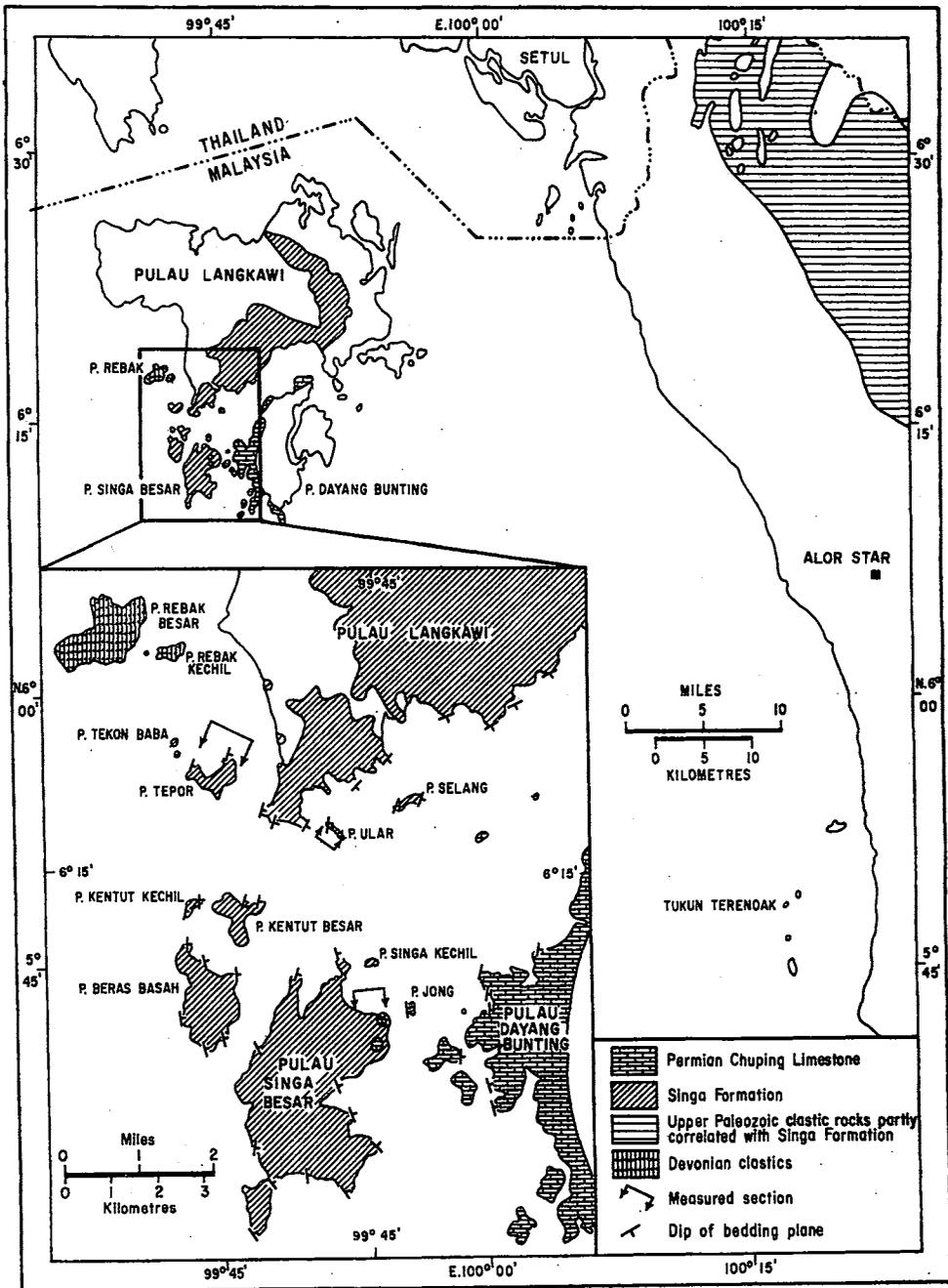


Fig. 3 Map of the Langkawi Islands showing outcrop area of the Singa Formation and location of the measured sections.

B. Rhythmically interlayered sand-mud facies. Thin ($1 \text{ cm} \pm$) beds of clean fine sand, commonly showing ripples and small-scale cross bedding, and dark sandy mud. Character of interlayering approaches flaser bedding in places. Organic burrows common, and degree of bioturbation moderate.

- C. Megaclast-bearing rhythmically interlayered sand-mud facies. Differs from facies B in the less distinct interlayering, common presence of large (meter-scale) soft-sediment structures ('slumping') and truncations suggestive of channelling, occasional occurrence of broken-up sandstone beds up to about 10 cm thick, and presence of scattered megaclasts up to boulder size.
- D. Sandy mudstone with thin graded sandstone facies. Dark poorly-sorted mudstone punctuated by thin (0.5-5 cm) graded beds of fine sandstone (probable turbidites). Rare megaclasts to cobble size.
- E. Diamictite facies. Unbedded, very poorly sorted dark clastic rock containing all sizes of clasts from clay and silt to large boulders in apparently random mixture.
- F. Laminated sandstone-siltstone facies. Differs from facies C in weathering to a light yellowish-brown color and soft, friable condition, and apparently in the greater variety of megaclasts, but shares with that facies the presence of rather large soft-sediment deformation structures and channel-like truncations of bedding.

Each of these facies will now be briefly discussed and observations relevant to the question of origin will be pointed out.

Facies A: This facies was observed in all three of the measured sections. The clean sandstones are well cemented and form resistant outcrops (fig. 5). Lamination is ubiquitous in this facies, as are rounded, concave-up bedding structures which resemble trough cross beds but commonly show overturning that suggests they are at least partly load structures. Large load structures in sandstones like these are comparable to those reported from late Tertiary nearshore sandstones in Sabah (Stauffer & Lee, 1972) and are suggestive of rapid deposition.

These laminated sands are clearly traction deposits, and the local appearance of low-angle (hummocky?) cross stratification suggests a storm-related origin above storm wave base. The inference of rapid deposition is supported by the rarity of trace fossils.

Facies B: This facies of rhythmically interlayered sand and mud was seen mainly in the section on P. Singa Besar, that is in the uppermost part of the Singa Formation, though the more widely distributed facies C is similar and possibly related.

Its outstanding characteristic is the regular alternation of thin beds or laminae of rather clean sand and dark mud (fig. 7). The thin sands commonly show ripples and small-scale cross bedding, and they are clearly transported and deposited by traction currents. The muds, on the other hand, tend to be structureless and may be suspension deposits. The regular alternation of these two bed types suggests a cyclical process such as tidal currents, and indeed the bedding pattern in this facies locally approximates the flaser bedding of tidal deposits. To suppose each pair of laminae to represent one tidal cycle, however, would imply extremely rapid deposition for this facies, and longer-period cyclical processes may be involved. The relative abundance of organic burrows and bioturbation in this facies make a slower net deposition rate more plausible.



Fig. 5 Thick sandstone beds of Facies A, in middle part of Pulau Ular section.



Fig. 6 Facies A, showing load-deformed cross beds (?), Pulau Ular.

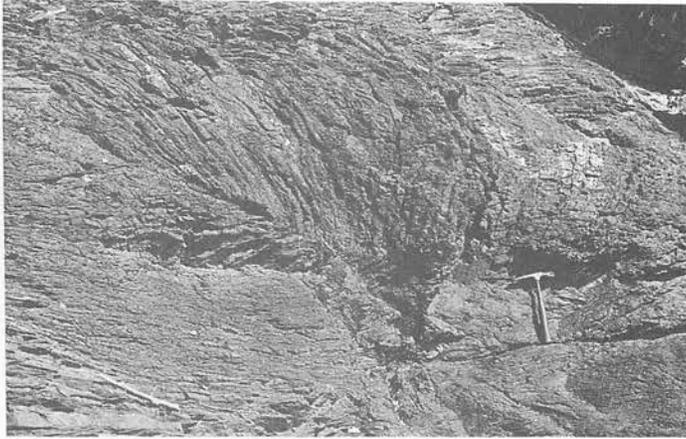


Fig. 9 Facies C, showing 'slump' structures, Pulau Tepor.

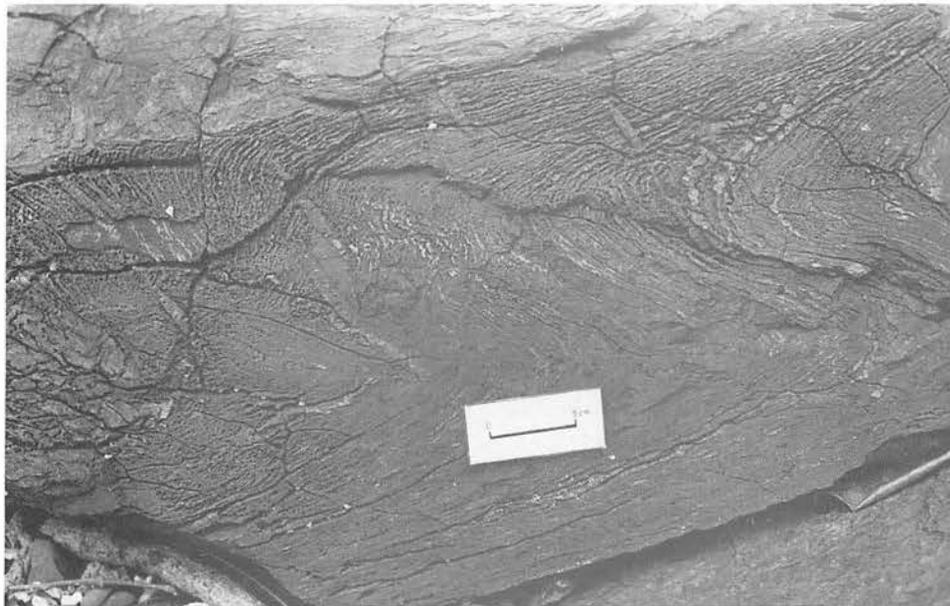


Fig. 10 Vertical organic burrows ('paired' or U-shaped type) transecting tight 'slump' folds in Facies C, Pulau Tepor.



Fig. 11 Facies D, showing thin turbidite sand beds, Pulau Ular.

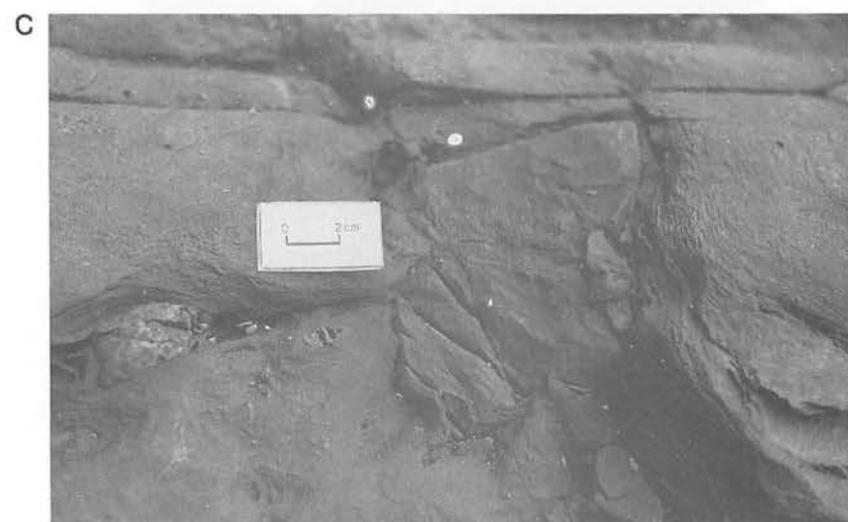
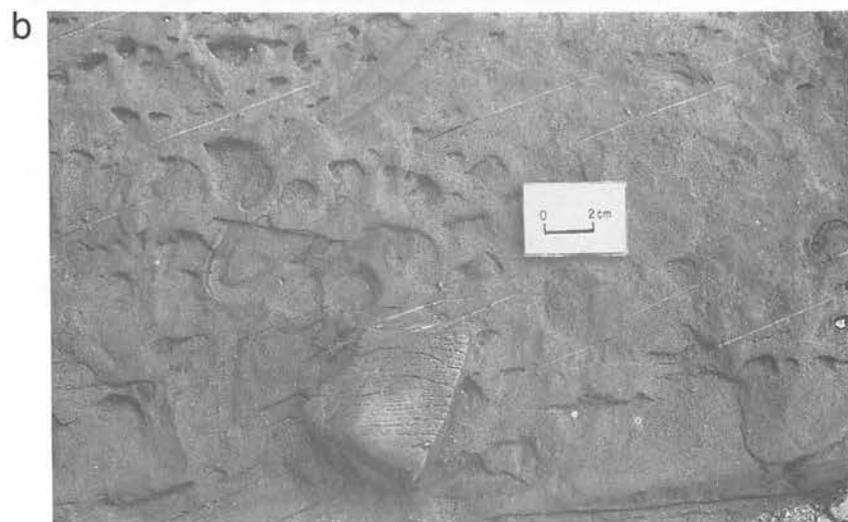
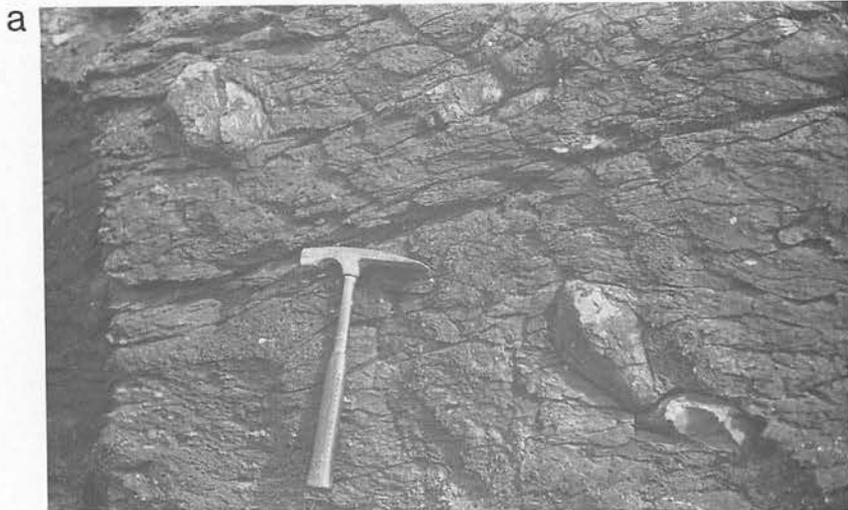


Fig. 12 Facies E, diamictites as seen in (a) Pulau Tepor, (b) Pulau Ular, and (c) Pulau Singa Besar sections.

samples representing the matrix of megaclast-bearing horizons yielded the compositions given in Table 1. The figures in the table are based on the assumption that all the fine-grained materials (sericite, iron oxides, organic (?) matter) represent original clastic constituents, variously recrystallized. It can be seen that these five samples are basically similar in composition, the major constituents always being sericitic matrix and mostly monocrySTALLINE quartz. Rock fragments represent a smaller but still significant (e.g. 15% in sample PU20) component. Sedimentary rock fragments are usually dominant, especially if one counts the chert together with other sedimentary rocks.

MEGACLASTS AND THEIR RELATION TO MATRIX

The megaclasts present in the Singa Formation received special attention during our study, both because they form a very distinctive lithologic feature of the unit and its lateral equivalents and because they provide critical evidence as to the manner of sedimentation. The larger megaclasts are so outsize relative to the grains in the matrix where they occur that it is impossible for both to have been transported and deposited together from either a traction current or a turbulent suspension (turbidity current). Virtually the only possible mechanisms for sedimentation of the megaclasts are (1) gravity mass movements and (2) some kind of rafting. We therefore consider in some detail the principal features of the megaclasts and their occurrence.

Stratigraphic distribution

Although Ahmad (1973) reported megaclasts in only a few horizons in the Singa Formation, our careful examination of the measured sections has shown that isolated or very thinly scattered megaclasts can occur at almost any level in the sequence and in almost any facies type. Nor do megaclasts only occur in poorly-bedded intervals with muddy matrix, as shown by a large (6 cm) pebble within well-bedded clean sandstones on P. Singa Besar. (fig. 14).

Size and shape

Considering (arbitrarily) all grains larger than sand size (greater than 2 mm to be 'megaclasts' in the Singa Formation, those of pebble size 4 to 64 mm diameter are most conspicuous. Cobbles and boulders are less commonly seen. The largest megaclast so far known in the Singa Formation was discovered in a megaclast-rich diamictite interval in the measured section on P. Singa Besar during the present study. It is a boulder of massive, fine-grained carbonate rock now about 65 cm in longest dimension (fig. 15). The exposed surface of the boulder is much eroded by solution, and a 'moat' around the remaining part suggests that its original size may have exceeded 80 cm. Boulders of granitic rock more than one meter in diameter have been reported from the Kaeng Krachan Formation in south Thailand (Tantiwanit, *et al.*, 1983).

Full size analyses were made of five sample sites in the Singa Formation, including four in our measured sections (two on P. Ular and one each on P. Tepor and P. Singa Besar) and one site on Tukun Terendak off the Kedah coast. These size analyses were done by two methods. An area of outcrop surface was selected in the field and outlines of all clasts larger than two millimeters (in some cases four millimeters) were traced onto a transparent plastic sheet. The outlines were later typed as to size, their areas measured, and the areal percentages

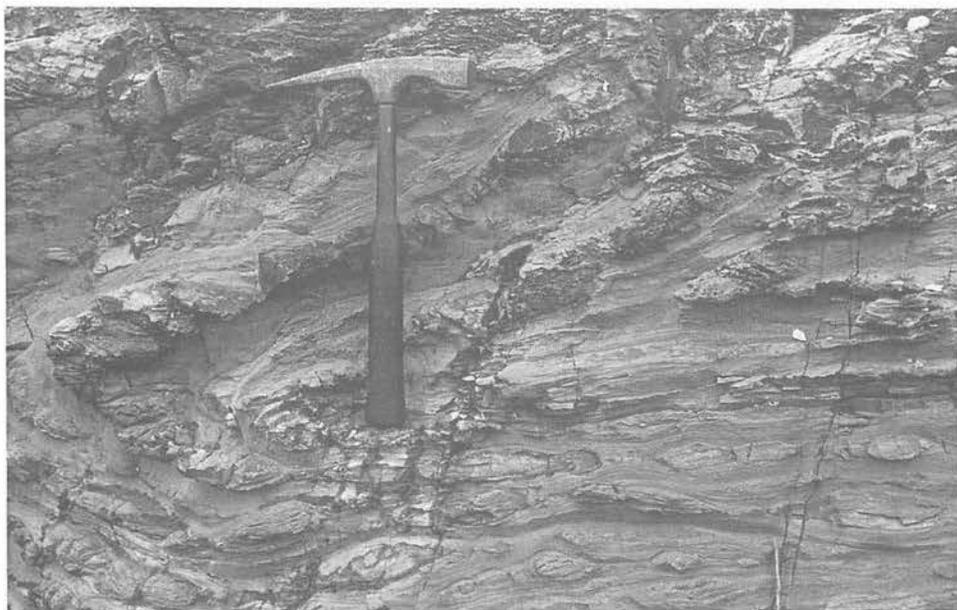
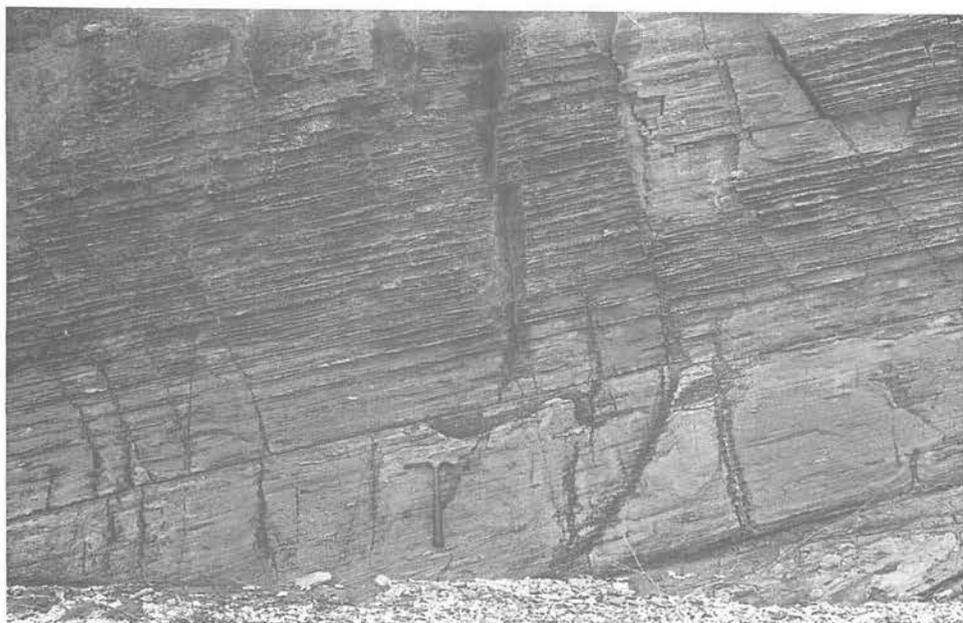


Fig. 13 Facies F, in Pulau Ular section: (a) showing flat bedding, (b) with 'slump' folds.



Fig. 14 Isolated dropstone in sandstone bed, Pulau Singa Besar. Scale bar is 2 cm.

of megaclast size classes, at $1/2\phi$ -unit intervals, determined. A sample of matrix from the same site was collected, and a point count for grain sizes later made on a thin section of the sample. The two sets of data, which sometimes overlapped in the granule size range, were then integrated, with appropriate weighting, into a unified size distribution. Both methods used yield areal percentages which should be unbiased estimates of volume percentages in the rock.

Results of these size analyses are shown as histograms (fig. 16) and cumulative curves plotted on probability paper (fig. 17). The make-up of these samples and one diamictite from Thailand are given in terms of major size classes in Table 2. The main features of the size analyses are:

- (1) The rocks are basically fine-grained, silt and clay making up more than 50% in all samples. The rocks are properly called mudstones.
- (2) The rocks are extremely poorly sorted. Since none of the curves (fig. 17) reaches 84% (indeed, only one reaches 50%), not even the simplest of the traditional graphic measures of sorting can be applied. However, the overall slopes of the curves suggest graphic standard deviation of at least three and probably more than four ϕ -units. The range of sizes measured covers at least eleven ϕ -units, and clay and finer silt could not be determined.
- (3) The curves are distinctly polymodal (see fig. 16). The main modes may well be in the fine silt and clay ranges, which account for more than half the rock volume, but prominent modes in the defined part of the distribution are most commonly seen in coarse pebbles



Fig. 15 Large dropstone boulder of grey carbonate rock in diamictite on Pulau Singa Besar.

(ϕ -6 to 4.5), coarse sand (ϕ -1/2 to 0), and variously in the fine sand to coarse silt range (ϕ 2 to 5). There seems to be a genuine deficiency of material in intermediate sizes, around ϕ -1, and the cumulative curves (fig. 17) show major changes of slope around ϕ 1 to 2. The proportion of megaclast (larger than 2 mm) varies from about 1% to 4.5% in the Singa Formation samples (Table 2), but is reported to be as high as 9% in the Kaeng Krachan Formation diamictites of south Thailand (Tantiwanit, *et al.*, 1983). The general size distribution and poor sorting are similar in the Malaysian and Thai samples (Table 2).

Although no megaclast larger than 6 cm across was included in the counts for size analyses, non-systematic observations of the several diamictite intervals showed that cobbles of 10 to 15 cm diameter are commonly as numerous as pebbles of 2 to 6 cm size. The size distributions in the megaclasts themselves are irregular and polymodal, if the diamictites were formed by slumping and mixing of previously deposited sediments, the conglomeratic contribution to the mix must itself have been already very poorly sorted.

The shapes of the megaclasts are even more telling in regard to their origin than the size distributions. Casual observations by the authors and previous workers have noted a range of shapes from well-rounded stones to angular blocks. During the present study we traced the shapes of a number of megaclasts from the surfaces of diamictite outcrops onto clear plastic sheets. These outlines, xeroxed and reduced, are shown in fig. 18. Although the three-dimensional shapes are poorly known because most megaclasts wear down with the rock surface rather than weathering out, it is clear from Figure 18 that they are typically subangular or angular and that faceted and blocky shapes are common. Such angular and faceted shapes are most characteristic of ice-rafted clasts derived from englacial or supraglacial material

Table 1
GRAIN COMPOSITIONS OF SELECTED SAMPLES OF MEGACLAST-BEARING SINGA FORMATION, BASED ON THIN-SECTION POINT COUNTS. PERCENTAGES ARE OMITTING VOID SPACE (ALWAYS LESS THAN 1% OF ROCK).

Sample No. -----	PT 11	PU 15	PU 20	SB 12	TU 6
Location -----	P. Tepor	Pulau Ular		P. Singa Besar	Tukun Terendak
No. of pts. -----	216	201	222	227	198
Grain type	Volume Percents (tr = seen but not hit in the count)				
Quartz	25.5	32.4	33.8	25.6	33.3
Monocrystalline	24.1	30.9	32.0	24.7	29.3
Polycrystalline	1.4	1.5	1.8	0.9	3.5
Overgrowths	-	-	-	-	0.5
Chert	-	1.0	2.3	-	tr
Feldspar	-	1.0	1.4	1.3	-
Rock fragments	1.9	8.0	14.0	1.7	4.5
Sedimentary	1.4	5.0	5.0	0.4	3.0
Metamorphic	0.5	2.5	7.2	1.3	1.5
Volcanic/Plutonic	-	0.5	1.8	-	-
Sericitic matrix	58.8	54.2	36.5	41.4	52.5
Organic (?) material	6.0	1.0	6.3	18.5	-
Opagues (iron oxides?)	2.8	1.5	3.2	5.7	6.1
Muscovite (flakes)	4.2	1.0	2.3	4.0	3.5
Chlorite (flakes)	0.9	-	0.5	0.9	-
Tourmaline	tr	-	-	0.9	tr

Table 2
SIZE COMPOSITION OF DIAMICTITES IN THE SINGA FORMATION (MALAYSIA) AND KAENG KRACHAN FORMATION (THAILAND)

Unit -----	SINGA FORMATION					KAENG KRACHAN ¹
Location ---	P. Tepor	Pulau Ular		P. Singa B.	T. Terendak	FORMATION
Samples ---	PT 11/P.T.	PU 15/P.U.-1	PU 20/P.U.-2	SB 12/S.B.	TU6/T.U.	SOUTH THAILAND
Gravel (2 mm)	4.51%	2.79%	3.32%	1.05%	1.14%	9%
Sand (1/16 - 2 mm)	15.40	30.10	38.70	13.40	21.60	21
Silt & Clay (1/16 mm)	80.09	67.11	57.98	85.55	77.26	70

¹ Data from Tantiwanit, *et al.* (1983)

(Anderson, 1983). Examples of these characteristic shapes are illustrated in Figure 19 (see also fig. 12). It should be noted that the larger megaclasts tend to be more angular than smaller ones, which would not be expected if they had all been through a history of water transport and abrasion. This is true even of relatively soft carbonate clasts (fig. 18). Very similar observations on megaclast shapes have been reported for the Kaeng Krachan Formation in south Thailand (Tantiwanit, *et al.*, 1983).

Composition

No systematic count has been made by us of the lithologies represented by the megaclasts. But fairly casual examination of numerous individuals, including collection of several dozen samples, has confirmed the observations of previous workers that sedimentary rocks are dominant, accounting for most of the megaclasts. Most common are sandstones, varying from white quartzitic rock (some of which may be metamorphic quartzite) through brown feldspathic sandstone to laminated reddish rock (fig. 19C). Sandstone alone probably makes up about 50% of the megaclasts. Other sedimentary types seen include dark chert, argillite, and grey limestone, sometimes with poorly preserved shelly fossils.

Vein quartz, granitic plutonic rocks, and metamorphic rocks (mainly quartz-mica schist) each account for something on the order of 10% of the megaclasts observed. Volcanic rocks are very rare. Tantiwanit, *et al.* (1983) report very similar rough estimates for compositions of stones in the Kaeng Krachan Formation of south Thailand, but also mention rare biotite-gneiss and diorite clasts.

A granitic boulder sampled earlier from within our measured section on P. Tepor proved to be a trondhjemite and yielded a Precambrian K-Ar age (Stauffer & Snelling, 1977).

Relation to bedding structures

Although the mere presence of large stones in a finer-grained deposit does not uniquely determine a mode of origin, as there are several ways in which such stones may come to be incorporated in the sediment (see Anderson, 1983), the relation of the stones to bedding structures in the host deposit can provide critical evidence to distinguish among the possibilities.

The diamictite intervals in the Singa Formation, which generally contain the most abundant megaclasts, are by definition almost totally devoid of sedimentary layering. However, locally they contain well-developed networks of horizontal (with reference to bedding outside the interval) organic burrows (see fig. 12B). Such burrows could not survive a slump event disruptive enough to mix coarse gravel into a mud matrix, and they could not be very deep beneath the sediment surface, so that if they formed after a slump event, one would have to suppose that the diamictite intervals consist of a succession of thin sheets representing separate slumps. Actually, faint wisps of subtle sedimentary layering, reflecting slight grain-size changes, can often be seen in superficially massive diamictites.

Other facies in the Singa Formation containing megaclasts are more distinctly laminated; these include facies C, D, and F. In these one can see that the megaclasts are related to the layering in ways that argue strongly that they were deposited from directly above i.e. that they

Histograms of Singa Formation diamictite size analyses

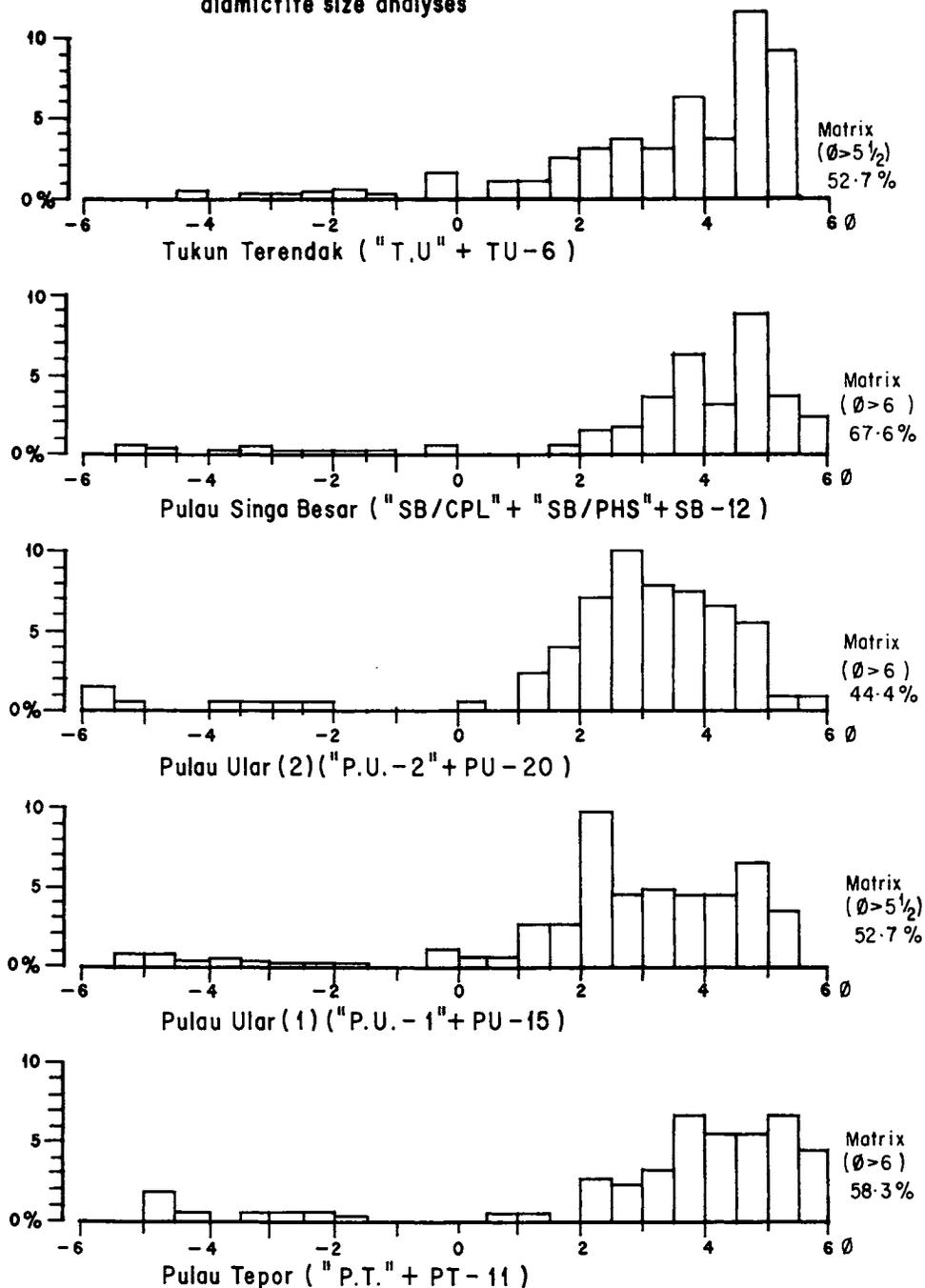


Fig. 16 Histograms of size analyses of megaclast-bearing intervals in the Singa Formation. Distribution of sizes larger than 2 mm determined from tracings made in the field; sizes smaller than 2 mm from thin section point counts (see text).

- x Tukun Terendak ("T.U." + TU - 6)
- Pulau Ular ("P.U. - 2" + PU 20)
- △ Pulau Tepor ("P.T." + P.T. - 11)
- Pulau Singa Besar ("SB/CPL" + "SB/PHS" + SD12)
- Pulau Ular (1) ("P.U. - 1" + PU - 15)

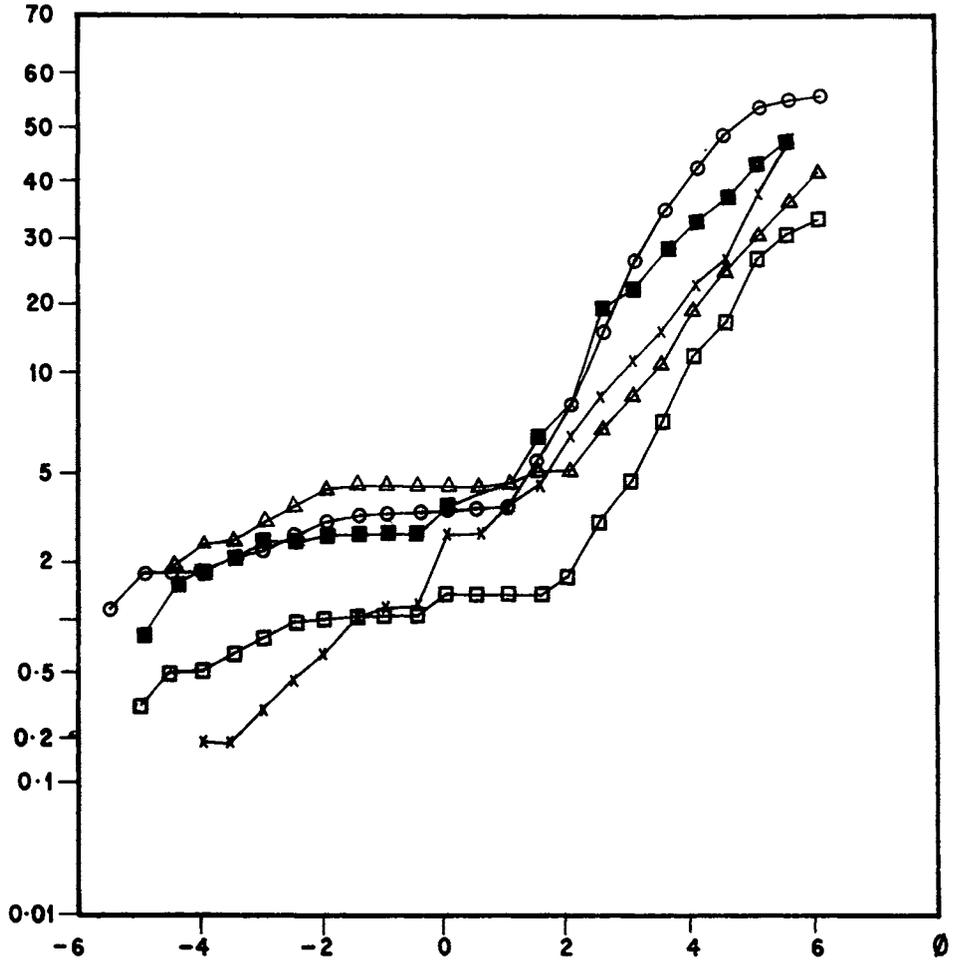


Fig. 17 Cumulative curves on probability paper from size analyses of megaclast-bearing intervals in the Singa Formation. Data derived as for Fig. 16.

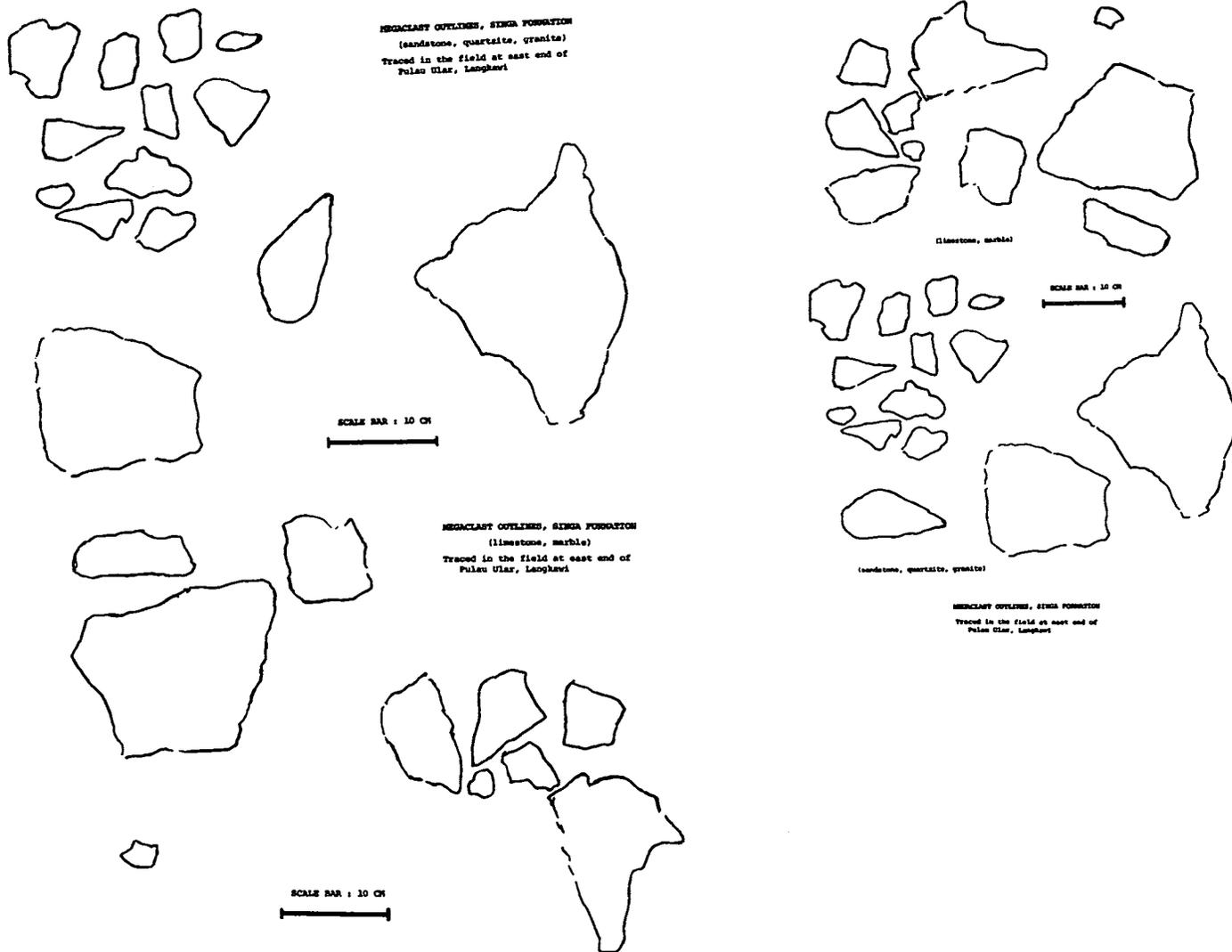


Fig. 18 Outlines of megaclasts in diamicrites in the Singa Formation. Traced on plastic in the field, reduced and copied without alteration.

a



b



c

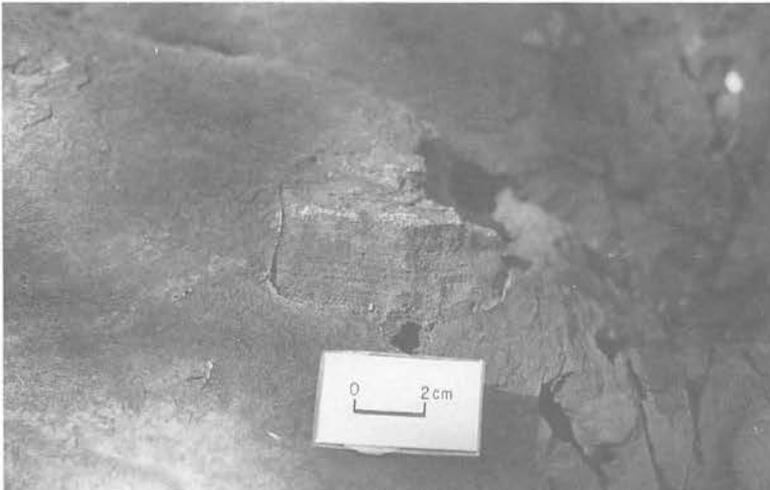


Fig. 19 Megacrasts in the Singa Formation, showing angular and blocky shapes: (a) Pulau Ular, (b) Pulau Ular, (c) Pulau Singa Besar.

are dropstones. These features include: (1) long axes of megaclasts oriented at high angles to bedding, even vertically (fig. 20A,B); (2) isolated single stones in well-laminated or bedded finer sediment (figs. 14, 20C); and (3) penetration of underlying laminae by megaclasts (fig. 20D). In addition, where outlines of megaclasts were traced from approximate bedding surfaces for purposes of size analysis, the visible long axes of the clasts could be marked and their orientation measured on the tracings. When this was done and the directions plotted, no preferred orientation was seen, except in one case where the surface used cut across bedding and a tendency of stones to lie flat on the bedding appeared. This lack of any horizontal fabric in the large clasts is again most consistent with their having been deposited individually as dropstones, since any lateral mechanism of transport, including slumps and debris flows, tends to impart a characteristic fabric to the clasts.

Discussion

From the evidence described in this paper, particularly the features of the megaclasts, we conclude that those outsize stones are ice-rafted dropstones, and that therefore the sedimentary units in which they occur, from Sumatra to central Burma as presently known, are at least partly of glacial marine origin. Several subsidiary lines of evidence support this conclusion, and most if not all relevant data appear to be at least consistent with it.

In this section we review evidence and reasoning behind our interpretation, and then examine briefly some of the implications, the remaining problems, and also consider some interesting new questions raised by the interpretation.

Origin of the pebbly mudstones

We have studied the characteristics of the Singa Formation in the Langkawi Islands in detail, and the Kaeng Krachan Formation (Phuket Group) of Thailand more cursorily, in the field, and we have some knowledge of their correlatives elsewhere (Bohorok Formation of Sumatra and Mergui, Martaban, and Lebyin Groups of Burma) from the literature, correspondence, and discussion with colleagues. We find the general features of these units to be characteristic of known glacial marine sequences (Plafker, 1981; Armentrout, 1983; Armstrong, 1983, Visser, 1983. These features include:

- (1) generally very poor sorting and low rounding of clasts;
- (2) presence of outsize stones (megaclasts) showing dropstone character;
- (3) vague but rhythmic lamination, sometimes varve-like in its regularity;
- (4) paucity of bedding structures indicating traction transport; and
- (5) rarity of fossils, though those found indicate a marine environment.

The most diagnostic characteristic of glacial marine deposits is the presence of dropstones. We have shown that megaclasts in the Singa Formation have the character of dropstones and must therefore have been deposited by rafting. Where rafted stones are common and widespread, as in these Late Paleozoic units, and especially in rocks too old for other methods of rafting to be plausible (by tree roots, birds, and such), rafting by ice is the only reasonable interpretation. The fact that the dropstones in the Singa Formation, especially the larger

ones, are angular rather than rounded implies they were dropped from glacial icebergs and were not transported by sea ice from shoreline deposits (Anderson, 1983).

One very characteristic feature of the Singa and Kaeng Krachan Formations is their dark grey weathering color, forming an especially sharp contrast to the light reddish to white colors of the underlying Devonian mudstones. Interestingly, such a grey color is also characteristic of the Cenozoic glacial marine Yakataga Formation of Alaska, where the upward change from reddish brown to grey is taken as a marker of the onset of glacial conditions (Plafker & Addicott, 1976). Reasons for this distinctive grey color are not known, but may be related to the fact that the fine fraction in glacial deposits is typically rock flour, much poorer in clay minerals than terrigenous mud.

We have sometimes been asked why, if the megaclasts in the Singa Formation are glacial debris, no one has yet found one showing glacial striations. It would indeed be gratifying to find this most diagnostic feature of glacial and transport among the megaclasts. However, it is unlikely that this will happen, for the following good reasons:

- (1) Even in undoubted Quaternary glacial tills, the proportion of stones showing striations is small, only a few percent for most rock types;
- (2) striations are even less common on glacial marine dropstones, many of which were transported on or within a glacier (rather than beneath it) and hence are not so likely to have been scraped against other stones;
- (3) the Singa Formation has been thoroughly consolidated and hardened by burial and incipient metamorphism, so that delicate surface features of clasts may have been lost; and
- (4) the stones in general do not weather out such that one sees their original exterior surface—rather, the matrix of the Singa Formation is so hard that the stones normally wear down with it and one sees really a section through a stone's interior. Nonetheless, one day we may be pleasantly surprised by finding (or hearing of someone finding) a nicely striated megaclast weathered out of the Singa Formation or its correlatives.

Evidence of cold climate: If the pebbly units are primarily glacial marine in origin (or even if only occasional icebergs traversed the area), one would expect that their site of deposition must have been in a region of cold climate. In fact, several lines of evidence suggest exactly that.

Feldspar grains seen in the matrix of the Singa Formation tend to be quite fresh and do not show much chemical weathering. Similarly, megaclasts of granitic rocks are relatively unweathered. Equally suggestive of a cold climate source area are the angular large clasts of limestone. Such clasts tend to form only in very cold climates (from glacial erosion and frost-cracking) and in dry desert climates, where they would normally remain as residual deposits or in local terrestrial fanglomerates. In addition, any such clasts, no matter how formed, would round quickly if transported by water.

Fossils in the pebbly mudstone units, though rare, are also consistent with an inference of cold climate. Waterhouse (1982) has interpreted a sparse marine fauna from pebbly beds

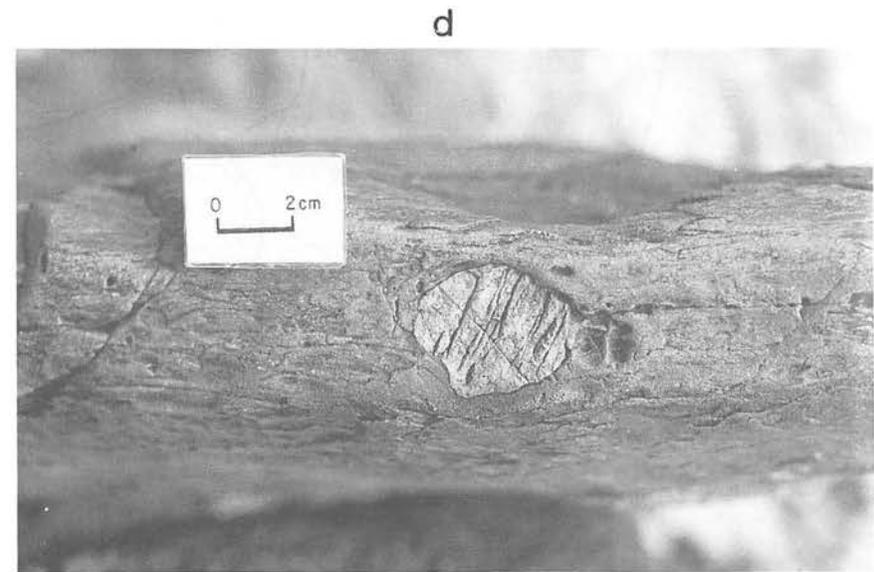
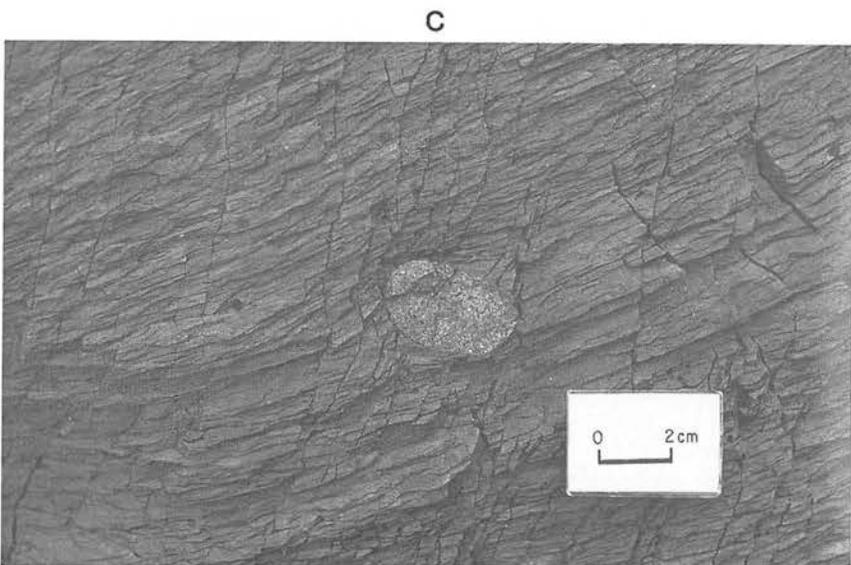
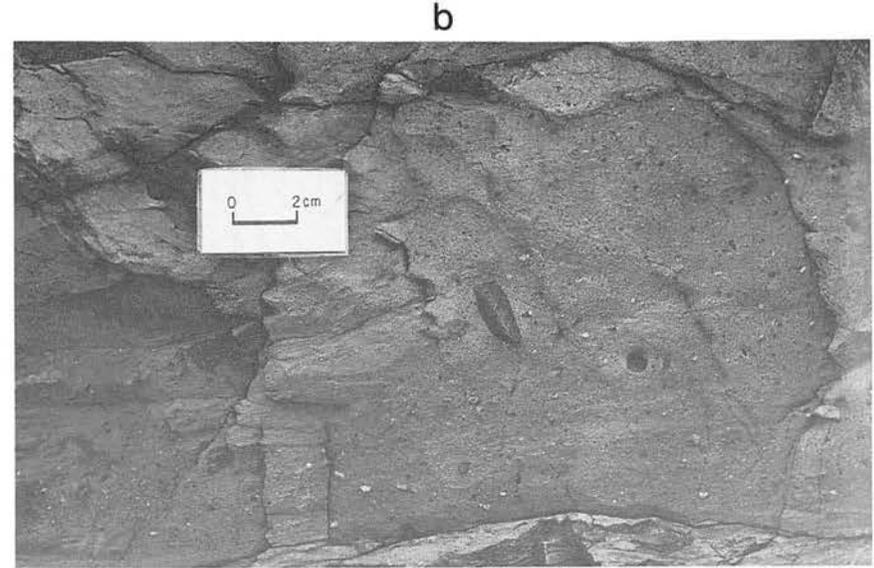
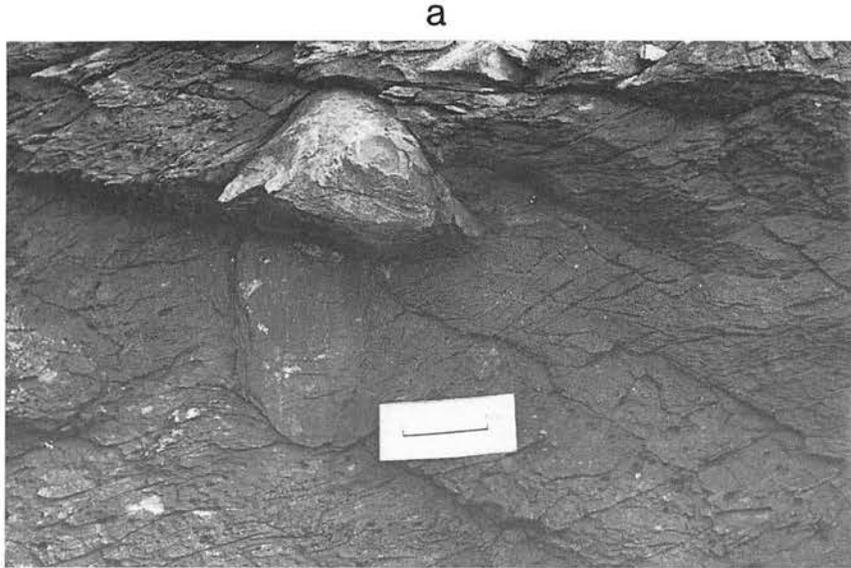


Fig. 20 Megaclasts in the Singa Formation, showing relationship to bedding: (a) with long axis vertical to bedding; (b) with long axis at steep angle to bedding, Pulau Ular; (c) isolated in flat-laminated sequence, southwest coast of Pulau Singa Besar, lamination, only faintly visible, is parallel to scale bar; (d) showing clear dropstone character, penetrating laminae, in float block on Pulau Ular.

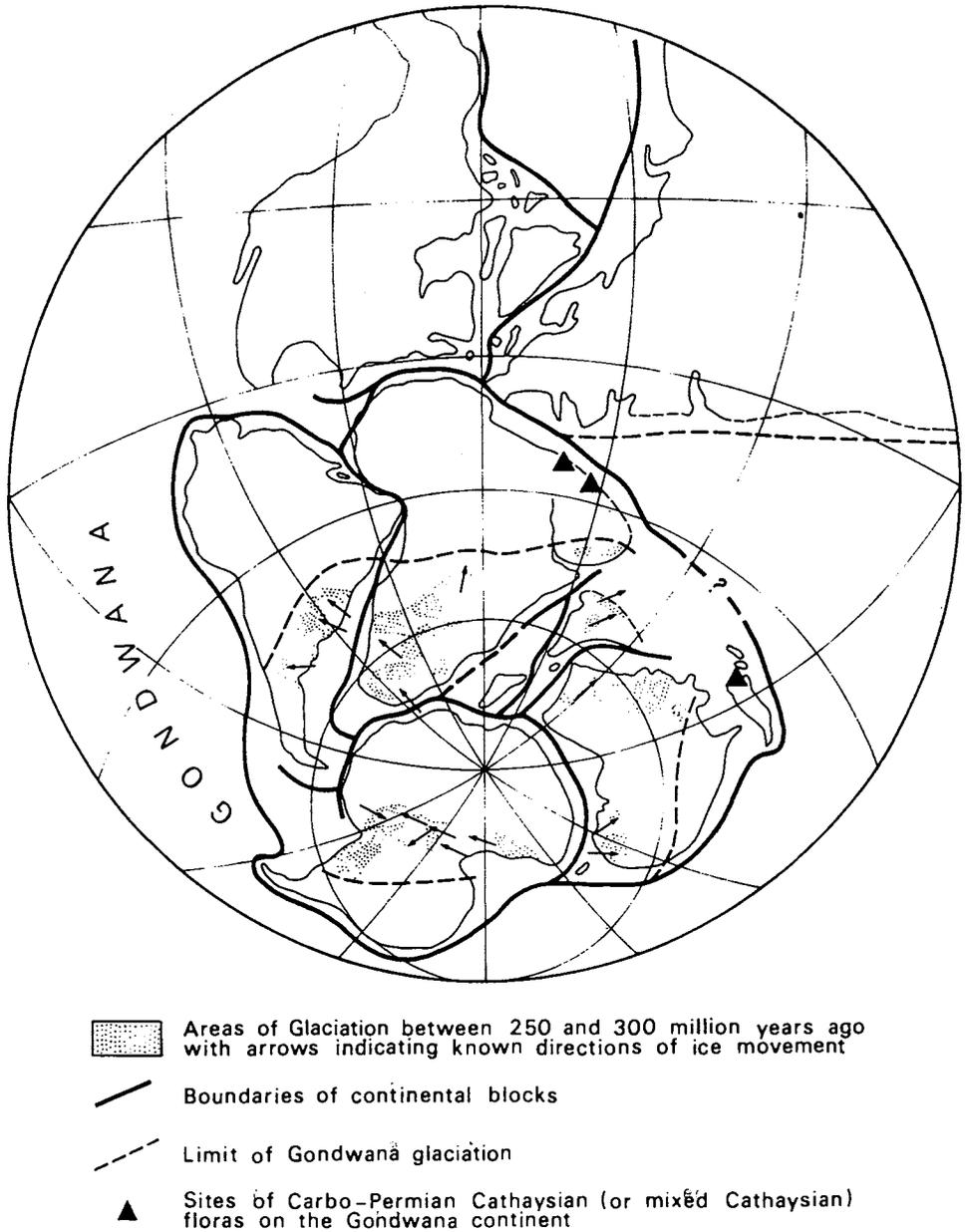


Fig. 21 Map of the Gondwana continent Late Paleozoic, showing known extent of glaciation. After Tarling & Tarling (1971, fig. 18), with the sites of Cathaysian or partly Cathaysian Carbo-Permian floras autochthonous to Gondwana added.

of the Phuket Group (Kaeng Krachan Formation) in south Thailand as indicating cool water. Rao (1984), using both faunal characteristics and the mineralogy of primary cements, finds that the Permian carbonate unit immediately overlying the Singa Formation in Malaysia (the Chuping Formation) was deposited in cool temperate to possibly subpolar conditions.

Evidence of shallow water depth: One reason we have been skeptical of the 'slump' interpretation of the pebbly mudstones is that the deposits contain indications that they were deposited in shallow and possibly in part very shallow water. If units as thick and extensive as these represent resedimentation on a slope, one is forced to think in terms of a very major slope — most likely a continental margin transitional to deep ocean — and the depositional (deeper) part of such a slope would be in water depths of probably one to several kilometers.

That we are not dealing with such depths of water in the Singa Formation is indicated, first of all, by the absence of typical slope and deep-water deposits. There are no turbidites (other than the rare and very thin ones described above), no mass-flow sandstones, no deep-sea fan facies, no pelagic marine sediments. The sporadic presence in the sequence of thin to thick beds of clean sandstone showing ripples, small- and medium-scale cross beds, and possible hummocky cross beds indicate at least occasional activity of significant traction currents (and probably wave action) such as are very rare in the modern oceans at depths greater than 100-200 m.

Another indication of shallow-water deposition is the abundance and types of trace fossils in the Singa Formation. Horizontal, vertical and spreiten-type burrows occur, including *Rhizocorallium*, *Thalassinoides*, and others that appear to belong to the shallow-water *Cruziana* ichnofacies. Traces are locally abundant (despite the rarity of body fossils) and are often of large size. Burrows are sometimes quite abundant in thick diamictite horizons (fig. 12B), where they must post-date any possible slump movement of the sediment. Interesting for the present discussion are the long (up to one meter or more) vertical 'paired' (presumably U-shaped) burrows that are very common in the lower part of the Singa Formation, as represented by the measured section on Pulau Teopor. Such long vertical burrows reflect a need to escape some threatening condition at the sediment surface (strong storm waves, erosion, exposure at low tide, or such) and are considered most typical of very shallow-water environments. These burrows are sometimes seen to cut straight through 'slump' folds in the Singa Formation (fig. 10). Such a relationship means not only that the burrows post-date the 'slumping', but also that the deformation was in a thin, near-surface layer on the order of one to a few meters thick. In the absence of evidence for any major slope, such thin-skin deformation is intriguing. The possibility should be considered that the 'slump' deformation in the Singa Formation is partly or entirely the result of the impingement on the sea bottom of grounded icebergs or an intermittently grounded ice shelf. The other open possibility is that the deformation structures seen in the Singa Formation represent genuine slumps of rapidly deposited and water-rich glacial marine sediments on very gentle and (or) local slopes under or near an ice shelf. Too little is known of conditions in adjacent marine environments during continental glaciations to evaluate these possibilities. Detailed mapping of the structures might shed some light.

Diamonds: An indirect bit of evidence in favor of a glaciation-related origin for these Late Paleozoic pebbly sequences is the apparent occurrence in them of diamonds. Rounded to

subrounded diamonds up to several millimeters across occasionally turn up in alluvial tin mines in the Phuket area of Thailand (Garson, *et al.*, 1975) and also in east-central Sumatra (K.F.G. Hosking, personal communication). Since the local bedrock in the areas of these mines comprises, apart from granitic intrusives, only Late Paleozoic pebbly sequences (Phuket Group and Bohorok Formation), it has been inferred that the diamonds weathered out of the pebbly mudstones (Garson, *et al.*, 1975). Erosion and transport of diamonds from their presumed original source rocks to the edge of a continent, where they could become incorporated in slump deposits on a submarine slope, would be difficult to accomplish by non-glacial processes, as diamond is a heavy mineral. Entrainment and distant transport would, however, be easy and expected if a continental ice sheet were eroding the craton surface, and diamonds are known from some Pleistocene glacial deposits in North America.

Implications for paleogeography and paleotectonics

The interpretation of the megaclast-bearing sequences in the Upper Paleozoic of Southeast Asia as glacial marine deposits has obvious and far-reaching implications. The great lateral extent of this facies (more than 2000 kilometers as known) implies that these sediments are related to the activity of a large continental ice sheet, not local mountain glaciers. The only large continent known to have been glaciated in the Late Paleozoic was Gondwana. Hence the first important conclusion arising from our interpretation is that the belt of pebbly rocks formed originally in a marine setting marginal to the Gondwana continent.

This conclusion, in turn, sheds some light on paleotectonic history. All of the known areas of the pebbly facies in Southeast Asia lie within one tectonic block, variously referred to as the '*West Malaya Block*' by Stauffer (1974), the '*Thai-Malay Peninsula Block*' by Ridd (1980), and the '*Western Southeast Asia Block*' by Mitchell (1981). That this block represents a fragment of old continental crust rifted off a major continent has been accepted by many workers, but there has been disagreement over which continent the fragment was derived from, when the separation occurred, and even over which of the present edges of the block represents the rifted margin. Mitchell, *et al.* (1970), Garson, *et al.* (1975), Ridd (1980), and Helmcke (1982) all inferred a continental slope down to the west on the basis of a slump-deposit interpretation of the pebbly mudstones, and therefore concluded that deep ocean lay to the west of this tectonic block by Late Paleozoic. Most of these authors considered that any previously-attached continent had to have been on the block's (present) east side, and that there never had been a continent attached on the west side. Ridd (1980), however, saw the pebbly mudstones as early post-rift sediments shed into the widening gulf, and therefore inferred that the rifting off of a continent on the west side of the block occurred probably during the Carboniferous.

A glacial interpretation of the pebbly mudstones removes the evidence for deep water and a continental slope in the area of their deposition. Instead, the evidence for shallow or very shallow water, combined with the occurrence of contemporaneous rocks of more normal (non-glacial) facies farther east in Malaya and south Thailand, supports the inference (Jones, 1968; Stauffer, 1974) that the attached continent was on the (present) west side and deep ocean to the (present) east. Rifting off from Gondwana would have to post-date the glacial marine facies (which extends up into early Permian), and has been suggested on geologic grounds to have occurred as late as Jurassic (Stauffer, 1974, 1983).

If this fragment of Southeast Asia rifted off the margin of Gondwana, an obvious question is from which part? A map of the Gondwana glaciation (fig. 21) is suggestive in this regard. In only three regions did major glaciers apparently reach the (known) edge of the Gondwana continent and this offer the potential for developing large-scale glacial marine facies: (1) between southwestern South America and West Antarctica, (2) between West Antarctica and southeastern Australia, and (3) between northwestern Australia and the Arabian Peninsula. The first two can be virtually ruled out as possible sites for the former position of western Southeast Asia, because each would require a highly improbable, long, and complicated drift path since separation. Clearly the only likely region where western Southeast Asia could have been attached to Gondwana and receive the extensive glacial marine deposits inferred here is the interval from Arabia across the poorly known northern edge of 'greater India' to northwestern Australia. That portions of India and northwest Australia were glaciated in Late Paleozoic has been known for a long time. Recent evidence strongly indicates that such glaciation also affected at least the southeastern portion of the Arabian Peninsula (Roland, 1978; McClure & Young, 1981). Hence there is nothing in the glacial evidence that points preferentially to any one part of this stretch of Gondwana margin.

The glacial interpretation of the Late Paleozoic pebbly mudstone belt, with its implications of moderate to high paleolatitudes and cool or cold climate, suggests a re-examination is needed of earlier ideas on paleoclimatic conditions in Southeast Asia in those times. These earlier interpretations of the Late Paleozoic lithofacies and biota (e.g. Stauffer & Gobbett, 1972; Stauffer, 1974) generally indicated tropical or subtropical conditions in the Permian. These earlier ideas are, however, indeed in need of revision. They were partly based on the abundance of Late Paleozoic limestones and on the apparently tropical character of the known Permian floras in the region.

The idea that extensive development of thick carbonate sediments implies warm water has been shown to be false (Rao, 1981) and examination of the Permian carbonates of western Malaya indicates deposition mainly in cool to cold water (Rao, 1984).

The Permian floras are an interesting study. All those known in Southeast Asia are dominantly of the large-leaved Cathaysian type, interpreted as indicating warm humid climate and characteristic of the Cathaysian Permian and late Carboniferous floral province, including China, Korea, Japan, Southeast Asia, and parts of central Asia (Chaloner & Lacey, 1973). Though it was formerly thought that these floras, and the apparent absence of the *Glossopteris*-bearing Gondwana flora indicated lack of land connections with Gondwana, in recent years it has become clear that Cathaysian floras (or mixed, partly Cathaysian floras) were in fact established on some areas of crust that form parts of Gondwana: in Anatolia (Wagner, 1959; Archangelsky & Wagner, 1983), in Iraq (Ctyrok'y, 1973), and (in the late Carboniferous) New Guinea (Jongmans, 1940). These floras are indicated on Figure 21. Both the Anatolian and New Guinea floras show the definite presence of elements of the *Glossopteris* flora, confirming that they are autochthonous to the Gondwana landmass.

The Permian floras of the Malay Peninsula and Sumatra, which are distinctly Cathaysian in character (see review in Stauffer, 1974) pose a problem because of the proximity of these warm-climate assemblages to the cold-climate glacial marine facies. The floras in the southern Malay Peninsula (Kon'no & Asama, 1970; Kon'no, *et al.*, 1971) are Late Permian,

significantly younger than the glacial marine rocks, which are no younger than Early Permian, but the Djambi flora of Sumatra (Posthumus, 1927; Jongmans & Gothan, 1935) is Early Permian. The Malayan Permian floras all occur to the east of the Bentong-Raub Line, the eastern boundary of the Western Southeast Asia tectonic block, and they lie in terrane(s) whose position in the Permian relative to that block is not well known but possibly distant (Stauffer, 1983). The tectonic basement structure of Sumatra is also insufficiently known at present, but it seems to consist of a number of fault-bounded blocks, whose relative movements are unknown (Cameron, *et al.*, 1980). A combination of age differences and relative displacements probably explains the present juxtaposition of these separate indications of cold and warm climate in the Permian of Southeast Asia.

Other occurrences of climatic indicators may help to resolve the pattern of tectonic blocks and their relative movements. We may mention here, for example, the occurrences of diamictite-like beds in late Paleozoic sequences in Malaya near Raub (Ong, 1974) and at Genting Sempah, just outside the west end of the highway tunnel (both of these are probably autochthonous to the Western Southeast Asia block) and the report of a leaf tentatively identified as *Gangamopteris*, an element of the *Glossopteris* flora, in Carbo-Permian 'slumped' pebbly mudstones in eastern Malaya (Azhar, 1977). This occurrence of 'tilloid' (shown on fig. 2) lies to the east of the Permian warm-climate floras and on yet another separate tectonic block.

PROBLEMS AND QUESTIONS FOR FURTHER RESEARCH

The recognition of a widespread Late Paleozoic glacial marine facies in Southeast Asia sheds light on a number of aspects of the regional geologic history, as discussed above, it also, however, raises some intriguing questions and problems for further investigation. We wish to briefly mention some of these here, in the hope that it may encourage work and thought toward their solution.

1. *Time* : The time interval bracketted by the faunas underlying and overlying the Singa Formation in Langkawi (from latest Devonian to late Early Permian) is about 90 million years. It seems highly improbable that all of this time is represented in the glacial marine sediments, both because continuance of glacial conditions in one region for so long is unlikely and because the total thickness of the deposits (less than 2000 meters) could give an unrealistically low sedimentation rate (about 2 centimeters per 1000 years) for this mode of deposition. Are there diastems or unconformities in the section that have not been recognized, either in the deformation structures or elsewhere? Is there perhaps an unconformity at the base of the sequence, representing a large fraction of the total time? The basal contact is, as far as we know, nowhere well exposed, and a time gap could be concealed there.

2. *Relation to sea level*: One would expect the glacio-eustatic sea level changes during a major glaciation to produce an alternation between marine and non-marine conditions in near-shore environments and between shallow and deeper water farther offshore. No evidence of actual subaerial exposure has yet been recognized in the Singa Formation (unless the yellowish color of part of the Pulau Ular section represents deep subaerial weathering), but depth alternations may be recorded in the repeating facies we have described. If the diamictites represent glacial break-up at the beginnings of interglacials, they should be preceded by relatively shallower-water deposits and succeeded by relatively deeper-water

deposits. If they represent grounded or subaerial ice sheets, however, they should be bracketted by deeper-water sediments (where abundant trace fossils are present in diamictites this possibility can be ruled out).

3. *Origin of deformation structures*: Detailed mapping, where that is possible, of the soft-sediment deformation structures in the Singa Formation and its equivalents might answer the question of whether those are caused by gravitational slumping, ice-push, or some other process. Unraveling the origin of these structures could in turn shed considerable light on the environment of deposition. Ice-produced deformation of marine sediments is as yet very poorly documented.

4. *Proportion of glacial marine material*: The presence of glacial dropstones establishes a glacial marine contribution to a sedimentary sequence, but it does not prove that all the sediment in the sequence is glacial marine or even of glacial origin. Evidence has been given above that much of the matrix in the Singa Formation is also glacial marine, but some beds are clearly at least reworked by other processes, and a contribution of material from other, non-glacial sources cannot be ruled out. Only detailed petrographic and chemical studies can resolve these questions, and their resolution should assist paleogeographic reconstructions.

5. *Paleoenvironments*: Although we have established, we believe, that the Singa Formation was deposited in a marine environment of relatively shallow water marginal to a glaciated portion of Gondwana, the details of this environment are still obscure. In particular, the paleoenvironmental significance of the facies types found in the sequence should prove a fruitful line of further work.

Continued research on these problems seems to us well justified and promising of significant results. Glacial marine deposits remain one of the poorer-documented sedimentary facies, despite their volumetric significance and their clear paleogeographic and paleoclimatologic importance. The Southeast Asian Late Paleozoic belt of glacial marine sediments described and discussed in this paper is extensive and locally well exposed. When studied in greater detail it may provide a useful model which, together with Quaternary analogs, will give us an understanding of sedimentation marginal to glaciated continents.

ACKNOWLEDGEMENTS

Field work in the Langkawi Islands, in November 1982, and subsequent laboratory work were supported by a Universiti Malaya Research Grant (F-Vote) to the authors. We are happy to acknowledge the unfailing assistance in the field of our boatman and friend, Enche Mirin bin Abdul Latif of Kampung Pasir Hitam. Dr. C. P. Rao of the University of Tasmania accompanied in the field for four days, and his observations and comments on the Singa Formation exposures helped to clarify our ideas and understanding of those rocks. Discussions with colleagues, both supportive and skeptical, have provided an intangible but significant stimulus to our work; we should like to mention particularly Dr. Ian Metcalfe and Dr. Khoo Teng Tiong. Finally, the line drawings were produced by the drafting section, University Malaya Geology Department, and they and the photographs, all taken by the authors, were reproduced and printed by Jaafar bin Hj. Abdullah.

REFERENCES

- AHMAD BIN JANTAN, 1973. Stratigraphy of the Singa Formation (Upper Paleozoic) in the southwestern part of the Langkawi Island Group, West Malaysia. Unpubl. M.Sc. thesis, University of Malaya, 250 p.
- ANDERSON, J.B., 1983. Ancient glacial-marine deposits: their spatial and temporal distribution. In Molnia, B.F. (ed.), *Glacial-marine sedimentation*. New York: Plenum Press, 3-92.
- ARCHANQELSKY, S., and WAGNER, R.H., 1983. *Glossopteris anatolica* sp. nov. from uppermost Permian strata in south-east Turkey. *Bull. Br. Mus. nat. Hist. (Geol.)* 37 (3), 81-91.
- ARMENTROUT, J.M., 1983. Glacial lithofacies of the Neogene Yakataga Formation, Robinson Mountains, southern Alaska Coast Range, Alaska. In Molnia, B.F. (ed.), *Glacial-marine sedimentation*. New York: Plenum Press, 629-665.
- AZHAR BIN HAJI HUSSIN, 1977. Geology of the Bukit Jaya area, Pahang. Unpubl. B.Sc. (Hons.) thesis, Department of Geology, University of Malaya, 63 p.
- CAMERON, N.R., CLARKE, M.C.G., ALDISS, D.T., and ASPDEN, J.A., 1980. The geological evolution of northern Sumatra. *Ninth Indonesian Petroleum Association Convention, Jakarta, May 1980*, 53 p.
- CHALONER, W.G., and LACEY, W.S., 1973. The distribution of Late Palaeozoic floras. *Palaeont. Assoc. Spec. Pap. in Palaeont.* 12, 271-289
- CTYROK'Y, P., 1973. Permian flora from the Ga'ara region (Western Iraq). *Neues Jahrbuch Geol. Paläont. Mh.*, 383-388.
- GARSON, M.S., YOUNG, B., MITCHELL, A.H.G., and TAIT, B.A.R., 1975. The geology of the tin belt in Peninsular Thailand around Phuket, Phangnga and Takua Pa. *Inst. of Geol. Sciences (London) Overseas Memoir* 1, 112 p.
- GOBBETT, D.J., 1973. Upper Paleozoic. Chap. 4 in Gobbett, D.J., and Hutchison, C.S. (eds.), *Geology of the Malay Peninsula (West Malaysia and Singapore)*. New York: Wiley-Interscience, 61-95
- HELMCKE, D., 1982. On the Variscan evolution of central mainland Southeast Asia. *Earth Evolution Sciences* 2, 309-319
- JONES, C.R., 1968. Lower Paleozoic rocks of Malay Peninsula. *Am. Assoc. Pet. Geol. Bull.* 52, 1259-1278
- JONES, C.R., 1981. The geology and mineral resources of Perlis, North Kedah and the Langkawi Islands. *Geol. Survey Malaysia District Memoir* 17, 257 p.
- JONGMANS, W.J., 1940. Beiträge zur Kenntnis der Karbonflora von Niederländisch Neu-Guinea. *Geol. Stichting Netherland Medd. Jaarverslag. 1938-39*, 263-274
- JONGMANS, W.J., and GOTHAN, W., 1935. Die paläobotanischen Ergebnisse der Djambi-Expedition 1925. *Jaarb. Mijnwezen in Nedr. Indie 1930, Verhandl.*, 71-201
- KON'NO, E., and ASAMA, K., 1970. Some Permian plants from the Jengka Pass, Pahang, West Malaysia. *Geol. and Paleont. S.E. Asia* 8, 97-132
- KON'NO, E., ASAMA, K. and RAJAH S.S. 1971. The Late Permian Linggiu flora from the Gunung Blumut area, Johore. Malaysia. *Geol. and Paleont. S.E. Asia* 9, 1-85
- MANTAJIT, N., TANTIWANIT, W., and RAKSASAKULWONG, L., 1979. Stratigraphy of Phuket - Phang Nga area (Permo-Carboniferous). *J. geol. Soc. Thailand*
- McCLURE, H. and YOUNG, G.M., 1981. Late Paleozoic glaciation in the Arabian Peninsula. In Hambrey, M.J., and Harland, W.B. (eds.), *Earth's pre-Pleistocene glacial record*. Cambridge: Cambridge Univ. Press, 275-277
- MITCHELL, A.H.G., 1981. Phanerozoic plate boundaries in mainland SE Asia, the Himalayas and Tibet. *Jour. geol. Soc. London* 138, 109-122
- MITCHELL, A.H.G., YOUNG, B., and JANTARANIPA, W., 1970. The Phuket Group, Peninsular Thailand: a Palaeozoic ?geosynclinal deposit. *Geol. Mag.* 107, 411-428
- ONG, G.B., 1974. Geology of an area southwest of Raub, Pahang. Unpubl. B.Sc. (Hons.) thesis, Department of Geology, University of Malaya, 94 p.
- PLAFKER, GEORGE, 1981. Late Cenozoic glaciomarine deposits of the Yakataga Formation, Alaska. In Hambrey, M.J., and Harland, W.B. (eds.), *Earth's pre-Pleistocene glacial record*. Cambridge: Cambridge Univ. Press, 694-699
- POSTHUMUS, O., 1927. Some remarks concerning the Palaeozoic flora of Djambi. *Kon. Akad. Wetenschappen, Amsterdam, Proc.* 30, 628-634
- RAO, C.P., 1981. Criteria for recognition of cold-water carbonate sedimentation: Berriedale Limestone (Lower Permian), Tasmania. Australia. *Jour. sed. Petrology* 51, 491-506
- RAO, C.P., 1984. Sedimentology of some Permo-Triassic carbonates of Malaysia. *Fifth regional Congress on Geology, Mineral and Energy Resources of Southeast Asia (GEOSEA V). Abstracts of Papers.* 28 only
- RIDD, M.F., 1980. Possible Palaeozoic drift of SE Asia and Triassic collision with China. *Jour. Geol. Soc. London* 137, 635-640

- ROLAND, N.W., 1978. Jungpaläozoische Glazialspuren auf dem Arabischen Schild. *Eiszeitalter u. Gegenwart* 28, 133-138
- SARKAR, S.S., 1972. On the *Posidonia* from Rebak Islands, Langkawi, West Malaysia. *Geol. Soc. Malaysia Newsletter* 37, 5-9
- STAUFFER, P.H., 1974. Malaya and Southeast Asia in the pattern of continental drift. *Geol. Soc. Malaysia Bulletin* 7, 89-138
- STAUFFER, P.H., 1983. Unraveling the mosaic of Paleozoic crustal blocks in Southeast Asia. *Geol. Rundschau* 72, 1061-1080
- STAUFFER, P.H., and GOBBETT, D.J., 1972. Southeast Asia a part of Gondwanaland? *Nature phys. Sci.* 240, 139-140
- STAUFFER, P.H., and LEE, C.P., 1984. Late Paleozoic glacial marine facies in Southeast Asia and its implications. *Fifth regional Congress on Geology, Mineral and Energy Resources of Southeast Asia. Kuala Lumpur, April 1984, Abstracts of Papers*, 31-32
- STAUFFER, P.H., and LEE, D.T.C., 1972. Sedimentology of the Sandakan Formation, East Sabah. *Geol. Survey Malaysia Geological Papers, 1*, 10-17
- STAUFFER, P.H., and MANTAJIT, NOPADOM, 1981. Late palaeozoic tillioids of Malaya, Thailand and Burma. In Hambrey, M.J., and Harland, W.B. (eds.), *Earth's pre-Pleistocene glacial record*. Cambridge: Cambridge Univ. Press, 331-337
- STAUFFER, P.H., and SNELLING, N.J., 1977. A Precambrian trondhjemite boulder in Palaeozoic mudstones of NW Malaya. *Geol. Mag.* 114, 479-482
- TANTIWANIT, W., RAKSASKULWONG, L., and MANTAJIT, N., 1983. The Upper Palaeozoic pebbly rocks in southern Thailand. *Workshop on stratigraphic correlation of Thailand and Malaysia, Haad Yai, Thailand, Sept. 8-10. 1983, Papers*, 96-104
- TARLING, D.H., and TARLING, M.P., 1971. *Continental drift*. London: G. Bell & Sons. 112 p.
- VISSER, J.N.J., 1983. The problems of recognizing ancient subaqueous debris flow deposits in glacial sequences. *Trans. geol. Soc. S. Afr.* 86, 127-135
- WAGNER, R.H., 1959. On a mixed Cathaysian and Gondwana flora from SE Anatolia (Turkey). *Congres Strat. Geol. Carbonifere. 4me. Heerlen 1958, Compte Rendu.* 3, 745-752
- WATERHOUSE, J.B., 1982. An early Permian cool-water fauna from pebbly mudstones in south Thailand. *Geol. Mag.* 119, 337-354
- YANCEY, T.E., 1972. Devonian fossils from Pulau Rebak Besar, Langkawi Islands, West Malaysia. *Geol. Soc. Malaysia Newsletter* 37, 10-12
- YOUNG, B., and JANTARANIPA, W., 1970. The discovery of Upper Palaeozoic fossils in the 'Phuket Series' of Peninsular Thailand. *Proc. geol. Soc. London* 1662. 5-7

Manuscript received 17th January 1985