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Structural geology of Datai beds and Macincang Formation, Langkawi

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Abstract : In the Macincang terrain of northwest Langkawi are a few isolated outcrops of probably Precambrian, newly named Datai beds that consist of meta-arenite and meta-argillite intercalations. Parts of the beds are dismembered, all thoroughly fractured and strongly deformed into steeply and vertically plunging tight folds. The Datai beds are overlain by regularly bedded, moderately inclined Macincang strata. At Pasir Tengkorak the contact between the rock groups is an angular unconformity; at Teluk Anak Datai, the separation consists of a 4 m thick mylonite zone of the Datai thrust fault. Five photo-litho units and a number of major fault zones striking north and east were traced from aerial photographs and later confirmed in coastal outcrops. The Macincang beds were deformed into three major folds, the ENE-trending Buta anticline and the north-striking Datai anticline and syncline. Reliable indicators for stratigraphic facing show that in général the Macincang layers are still right-side up. This simple structural style contrasts sharply with the tight structures and overfolds that characterize the Palaeozoic beds outcropping in a narrow strip along eastern Langkawi. The situation suggests that the Macincang terrain may represent the eastern border of a micro-continent buried at the north entrance of the Strait of Malacca. Quartz clasts within quartz-mylonite zones that are parallel or subparallel to Macincang layers often exhibit results of three phases of activity; the clasts were coaxially deformed into rotated sigmoids and later warped about a different axis. Equal-area projections of structural elements also suggest that the Macincang rocks experienced three folding phases. The oldest maximum principal stress direction was NNW-SSE and developed the Buta anticline. The second phase had compression acting NE-SW and resulted in tectonic transport towards SW along the Datai thrust and along a number of other low-angle reverse faults. The youngest traceable compression direction was east-west and formed the Datai anticline and syncline. It also re-orientated earlier structures to trend in NNE-SSW direction.

Abstrak : Di beberapa tempat pada kawasan Macincang di sebelah barat laut Pulau Langkawi terdapat Lapisan Datai yang mungkin berusia Prakambria. Batuannya terdiri daripada selang lapis meta-arenit tebal dengan meta-argilit. Sebahagian lapisan terrabak, direntasi padat oleh retakan dan tercangga kuat kepada lipatan ketat yang bertunjam curam hingga menegak. Lapisan Datai ditindihi Lapisan Macincang yang berlapis teratur dan berkemiringan sederhana. Sempadan antara kedua kumpulan batuan bersifat ketakselarasan bersudut di Pasir Tengkorak, manakala di Teluk Anak Datai zon milonit sesar sungkup Datai setebal 4 m menjadi pemisah. Lima unit foto-litologi serta sejumlah sesar utama berjurus utara dan timur telah dikesan dari foto udara dan kemudian dikenalpasti pada singkapan pantai. Batuan Macincang telah dicangga kepada tiga lipatan terbuka lagi besar, iaitu antiklin Buta berjurus timur timur-laut dan antiklin serta sinklin Datai yang berjurus utara. Atas-atau-bawah stratigrafi ditunjukkan oleh sejumlah ciri yang boleh dipercayai dan mencadangkan bahawa umumnya lapisan Macincang belum terbalik. Gaya canggaan yang begitu mudah bagi kawasan Macincang sangat berlainan dibanding dengan struktur ketat yang mencirikan batuan Paleozoik pada jalur timur Kepulauan Langkawi. Keadaan demikian mencadangkan bahawa kawasan Macincang merupakan sempadan timur daripada sebuah mikro-benua Prakambria yang terpendam di kawasan utara Selat Melaka. Klasta kuarza dalam zon milonit yang selari atau hampir selari dengan perlapisan batuan Macincang sering menunjukkan kesan akibat tiga fasa kegiatan; klasta terlipat semula kepada bentuk sigmoid bergulung. Unjuran samaluas daripada unsur struktur mencadangkan pula bahawa Formasi Macincang telah mengalami tiga fasa perlipatan. Yang paling tua telah bertindak utara-laut dan menghasilkan antiklin Buta. Fasa canggaan kedua bertindak selari arah timur laut ke barat daya dan menyebabkan pengangkutan tektonik ke barat daya menerusi sesar sungkup Datai serta sejumlah sesar naik landai yang lain. Mampatan yang paling muda bertindak timur-barat dan menghasilkan lipatan Datai serta merubah kedudukan beberapa struktur lebih tua kepada jurus utara timur-laut.

INTRODUCTION

Jones (1978) published the most comprehensive geological account of the Langkawi islands. On his map the Macincang Formation is shown outcropping in the most western third of the main island of Langkawi, on Rebak Besar and Rebak Kecil islands off the southwest coast of Langkawi, and in the north central part of the main island. Stratigraphically it has been difficult to reconcile the occurrence of Macincang rocks on the Rebak islands in proximity outcropping Carboniferous Singa beds (see below; Stratigraphy) without outcrops of Ordovician-Silurian Setul limestone. Gobbett (1972) proposed to name the Rebak clastics (including those in the north part of Langgun island) as the Rebanggun beds of probable Devonian age. Teraoka *et al.* (1982) suggested a NE-striking 'Rebak fault' to resolve the stratigraphic problem posed by the sediments on Rebak. Ibrahim Abdullah (1986) interpreted an angular unconformity between two series of metaclastics on Rebak Besar as separating a lower series of Macincang rocks from an upper series of Singa rocks. I believe that the stratigraphic problem of the Rebak islands has not been satisfactorily resolved. On Rebak Besar I recorded metamorphosed layers of pebbly sandstone to siltstone that indicate local contortions suggesting soft-sediment deformation. Such slump structures in similar clastics are present in Macincang beds as well as in Singa beds. Yancey (1972) described a lower Devonian fossil collected from Rebak Besar. This occurrence led Gobbett to propose the existence of the "Rebanggun beds". The angular unconformity noted by Ibrahim Abdullah could well represent a warped bottom surface of a channel fill, a sedimentary structure that would not be inconsistent with sedimentation processes involving slumping. The rocks in the north central part of Langkawi that Jones grouped under the Macincang Formation are lithologically similar to the yellowish-reddish clastics of the Singa Formation. In this account, I will limit the discussion on the Macincang rocks to those that occur in the western third of Langkawi island.

Stratigraphy

According to Jones (1978) the stratigraphy of the Langkawi islands is as follows below. Where appropriate, newer information has also been inserted.

The *Macincang Formation* is a thick quartzitic and arkosic sequence with subordinate shale, flag [laminated siltstone], subgreywacke, grit and conglomerate of late Late Cambrian age. The deposition was in a delta. Jones noted that the quartz grains are usually angular and poorly sorted. Rare, thin bands of probably tuffaceous rock were also seen. The arenaceous layers are thick-bedded and cross-stratification suggests provenance from the northeast. The measured minimum thickness is 2010 m (6700 feet). Remains of brachiopods, trilobites and some problematics are rare and the age of the formation has been based on the faunule described by T. Kobayashi (1957, cited by Jones, 1978, p. 37) from the adjacent Tarutao island in Thai territory.

Lee (1983) made a detailed lithostratigraphic study of the Macincang and equivalent Tarutao formations. Both can be divided into a lower, middle and upper member. The lower member consists of interbedded graded siltstone-mudstone and argillaceous sandstone. Sedimentary structures are rare cross-bedding, small load structures, ripple marks, small burrows and slump features. Lee interpreted its deposition on an offshore shelf that experienced occasional storms. The middle member consists of three submembers and begins with coarse to fine grained sandstone, conglomerate, rare coarse grained felsic tuff and fine grained heavy minerals in bands; cross-bedding is common and the sediments are thought to respresent estuarine channel lag deposits. The middle submember is thin to moderately thick, wavy bedded, fine to medium grained cross-bedded sandstone with occasional pebbly, argillaceous and fine grained tuffaceous intercalations. This submember was probably deposited in the upper estuarine environment. The upper submember consists of fine to very fine grained, thick, planar bedded sandstone intercalated with very fine grained felsic tuff. Upwards this submember becomes more argillaceous. The deposition is thought to have occurred in a barrier-beach complex. The upper member is a sequence of siltstone, mudstone (some tuffaceous) and very fine grained sandstone with minor thin limestone interbeds. Trilobites and various types of shallow-marine trace fossils are present. Sedimentation took place in a lagoon protected by a barrier from an open sea.

This formation is conformably succeeded by the Setul Formation consisting of crystalline and laminated limestone with two thick bands of phyllitic-quartzitic rock. The major hue is dark gray and siliceous laminae often occur within the limestone. Rare occurrences of oolite and cross strata were seen; intraformational deformation also occurred. The less calcareous clastic bands, referred to as Lower and Upper Detrital members, consist of medium grained protoquartzite, subgreywacke, siltstone, carbonaceous shale and black siliceous rock. The Setul Formation is estimated to be approximately 1500 m (500 feet) thick, inclusive of the detrital members that are 25 m (82 feet) and 130 m (470 feet) thick. Abundant fossils (especially in the northeast indicate Ordovician to Early Devonian ages.

The Singa Formation is the next younger stratigraphic unit. It contains dark coloured siltstone and lighter coloured quartztite interbeds. The base of the formation is defined by red conglomeratic mudstone containing Late Devonian fossils (Gobbetts, 1972, Rebanggun beds). On Langgun island this mudstone unconformably overlies the Upper Detrital Member of the Setul Formation. Up to 4 m wide zones of intraformational folds and faults occur within certain parts of the formation, such as on Pulau Ular. Stauffer and Lee (1984) interpreted these contorted horizons and the presence of pebbly mudstone to siltstone as indicators of a periglacial environment. In Langkawi the formation is conformably overlain by the Cuping Formation. The entire Singa Formation may be more than 1950 m (6500 feet) thick.

The Cuping Formation is composed of thick-bedded to massive, crystalline limestone of predominantly light colour. The formation outcrops abundantly on the mainland, while in the Langkawi islands Cuping limestone occurs on Pulau Langkawi, the western shore of Pulau Dayang Bunting, and some small islands. Since the top of the formation is not known, Jones estimated the thickness in Langkawi at 750-1000 m (2500-3000 feet). Its basal beds consist of well-stratified calcareous grit, clastic limetone and chert with a rich Permian fauna. Originally, Jones included the limestone forming the Kodiang hills in north Kedah in the Cuping Formation. De Coo and Smit (1975), however, demonstrated that the Kodiang limestone is lithostratigraphically different and is of Triassic age. Conodonts from this limestone also indicates a late Permian age (Metcalfe, 1981). Current opinion holds that the Cuping limestone is Permian (see discussions cited by Jones, 1978, p. 97-106).

During the Mesozoic a granitoid body intruded the Langkawi islands and now outcrops as Gunung Raya, Bukit Sawar and a few other hills. Bignell and Snelling (1977) published dates of 217 ± 8 Ma (obtained by the K/Ar method) and 209 ± 6 Ma (Rb/Sr) of granitoid outcropping near Kuah; this late Triassic age is similar to those of most granitoid bodies occurring in the western zone of Peninsular Malaysia.

A few kilometres north of the Langkawi islands is Tarutao island where Teraoka *et al.* (1982) carried the most recent stratigraphic investigations. Teraoka *et al.* estimated that the Tarutao Formation consists of more than 3100 m thick shallow-marine arenaceous beds. They divided the formation into four members, the three lower members being conformable, while the uppermost member is in fault contact with the next lower member. Red to reddish brown hues are common in these rocks. The authors further reported that the lower two members do not contain reliable index fossils. Their third or T3 member contains late Late Cambrian faunule such as *Pagodia thaiensis, Thailandium solum,* *"Eosaukia" buravasi, Saukiella tarutaoensis and Coreanocephalus planulatum.* The uppermost of T4 member is probably still of late Cambrian age. The Thung Song Limestone Formation conformably succeeds the Tarutao Formation. The lower most of its five members contain lower Ordovician conodonts. Both formations form a large NNW-striking, asymmetrical anticline that has been sliced longitudinally by east-dipping reverse faults. The anticlinal axis runs close to the west coast; its west limb dips approximately five degrees steeper than its east limb. Close to the anticlinal axis, skirting the west coast, runs the Makham reverse fault that separates the Tarutao beds from steeply dipping to overturned Thung Song limestone. In the cross sections (Teraoka *et al.* 1982 figure 3) and on their geological map, the T1 member is shown to outcrop in the anticlinal core and to dip very steeply in contrast to the general moderate dips of the rest of the formation. Figure 1C is Teraoka *et al.* 's regional structural interpretation.

Structural Geology By Previous Authors

The majority of previous authors recognized that dynamo-metamorphic grade is somewhat higher for the rocks in the southeastern corner compared to those elsewhere in the Langkawi island group. Thermal metamorphic rocks form contact zones with the granitoid bodies.

Koopmans (1965) distinguished three generations of deformation. The lower Palaeozoic rocks in the southeast were first deformed into recumbent folds with subhorizontal axial plane cleavage. A second deformation created open folds of the cleavage and also formed crenulation cleavage in the steep fold limbs. Both deformations resulted in NNW trends. In the less metamorphosed rocks of the northern part, the first generation folds strike NNE upon which was superimposed flexural folds with NW strikes. The Carboniferous and Permian strata were only warped around the granitoid bodies. A moderately steep dipping reverse fault with west vergence on the main island and with east vergence in the central part of Dayang Bunting island was thought by Koopmans to represent a major, low-angle overthrust (the Kisap thrust) that also became warped by the granitoid emplacement (figure 1B). In places the rocks of the hanging wall are composed of Silurian strata that overrode Carbo-Permian beds. Thrusting, therefore, took place after the Permian deposition and prior to the granitoid intrusion (which has been radiometrically determined as Late Triassic). Koopmans ascribed the first two deformations to a "Langkawi folding phase" that occurred in late Silurian-Devonian time. See figure 1B.

Kimura and Jones (1967) agreed that several periods of "tectonic stress" affected the Langkawi islands. In the lower Palaeozoic rocks two different periods of deformation resulted in NE and NW trending folds. The large thrust fault (Kisap thrust) was interpreted to have occurred as response to a younger

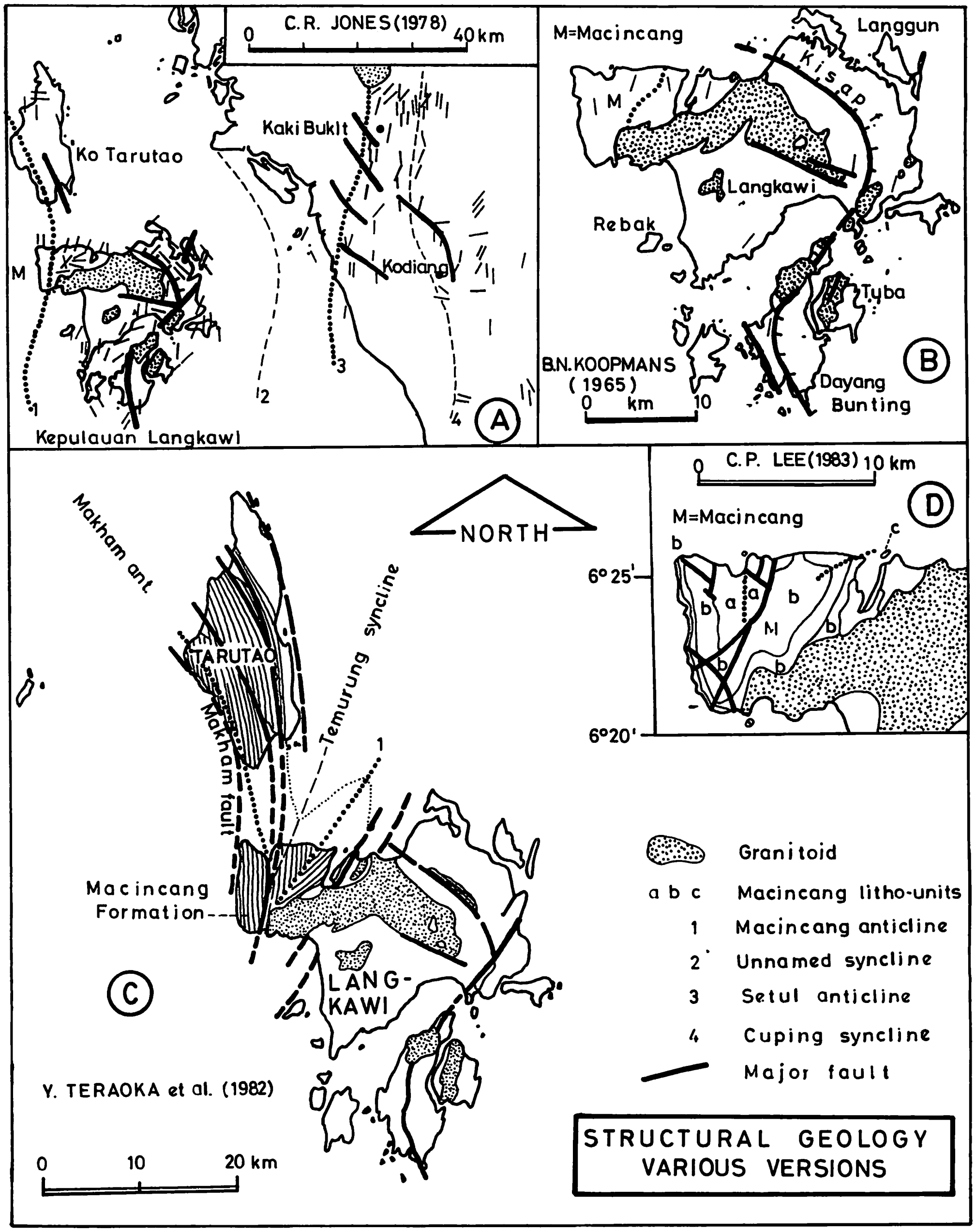


Figure 1: Structural geologic maps of the Macincang terrain and surroundings according to various authors.

deformation phase that also produced broad folds and normal faults in the lower Palaeozoic rocks of NE Langkawi and affected the upper Palaeozoic rocks elsewhere.

Diagrammatically, Jones (1978) showed regional, north-striking structures to dominate the Langkawi islands and adjacent Thai-Malay Peninsula (figure 1A). A broadly curving Macincang Anticline runs across outcrops of the Macincang and Tarutao beds. Along eastern Langkawi skirts a similarly curving zone of thrust faults. On the mainland the Setul Anticline follows outcrops of limestone and through Kaki Bukit. Jones summarized that evidence suggested two periods of deformation for the older Palaeozoic rocks and that the upper Palaeozoic beds unconformably overlie the older rocks. He believed that a mid-Devonian diastrophism was responsible for this. Further, two periods of faulting were distinguished; in the early period thrusting and counter-thrusting took place prior to granitoid emplacement; later, post-granitoid normal and reverse faulting striking NE and NW truncated and displaced the earlier formed structures.

Tan (1981) re-examined the Kisap thrust and concluded that the evidence presented by previous authors for major, low-angle thrusting cannot be accepted. His main objections are that the cited exposures display fault zones within rocks of the same formation and that the faults dip too steeply.

Teraoka *et al.* (1982) displayed their interpretation of the regional structures as shown by figure 1C. Aerial photos indicated to Lee (1983) the larger structures of the Macincang Formation as in figure 1D.

Ibrahim Abdullah (1983) suggested that the narrow strip of calcareous rock outcropping along the eastern shore of Kuala Kubang Badak belongs to the Setul Formation and does not constitute an interval in the upper part of the Macincang Formation as indicated on existing geological maps (e.g. by Jones, 1978). Ibrahim Abdullah suggested that the structure in that area is that of overturned folds with west vergence. Small to medium scale overturned folds with west vergence were indeed recorded earlier (own notebooks, March 1974 and December 1983) in Macincang beds as well as in Setul limestone that outcrop on the east shore of Kuala Kubang Badak.

STRUCTURAL GEOLOGY

Many geologists have noted the differences in structural style in the Langkawi island group. Complex structures, including small to large scale recumbent folds and thrust faults, are restricted to a strip east of the Gunung Raya batholith, eastern side of Pulau Dayang Bunting, Pulau Tuba and islets to its east. The rocks so deformed are essentially of early Palaeozoic ages. Immediately south and west of this massif, the Carboniferous Singa Formation shows only moderate deformation with open folds. Complicated structures do occur but are confined to intraformational zones, suggesting soft-sediment processes. The oldest rocks, the upper Cambrian Macincang Formation in the NW-corner of Langkawi island, are generally much less deformed than the Singa Formation. Locally, especially in the vicinity of fault zones, complex and tight structures with steeply dipping beds may occur, but in general bedding dips moderately and regional strikes are consistently northerly. This paradox in structural style interested me into beginning a close examination of the Macincang Formation. I tried to map the rivers upstream from Telaga Tujuh and the Tama Besar river and found that river outcrops are too far apart and too small for structural analysis of the Macincang beds. The coastal outcrops are much better. Aerial photographs at an approximate scale of 1 : 25,000 were studied to extrapolate inland-ward the major structures outcropping on the coast. Photo-litho boundaries could be discontinuously established by using differences in topographic relief, in vegetational tones, and actual lines on the photographs. At four localities on the coast I noticed metaclastic rocks that are closely fractured and possess different characteristics than the Macincang rocks. For these rocks I propose the informal name *Datai beds.*

Datai beds

The proposed Datai beds outcrop at Pasir Tengkorak, east shore of Teluk Anak Datai (most extensive) and near Tanjung Belua.

East shore of Teluk Anak Datai. - Generally the lower 2 to 3 metres of the rocky outcrop forming the east shore of Teluk Anak Datai consists of Datai beds. These are interbeds of meta-arenite and meta-argillite. Sometimes the coarser grained rock is disrupted and boudinaged. Irregular quartz bodies through these rocks are thoroughly fractured and appear twisted. A few of the bodies were originally veins and dykes that became deformed and dismembered by deformation(s). The meta-arenite mainly consists of medium-grained, angular to sub-rounded quartz grains. Other grains may be metaquartzite, chert, rare plagioclase and sometimes muscovite flakes or shards. The composition suggests an originally immature sandstone, very probably a graywacke. The argillaceous meta-arenite have, in addition to the grains mentioned earlier, a matrix of sericite. The meta-argillite consists of silt-size rock with compositions similar to that of the meta-arenite, well-foliated phyllite and meta-tuffite (angular quartz; rare, small muscovite, rare plagioclase in sericite groundmass) and secondary ore filling veins. The meta-argillite may also contain veinlets of dolomite/calcite and of subhedral gypsum.

The partially disrupted beds were deformed into isoclinal folds with steep to vertical axes that are also twisted. These Datai beds are separated from overlying Macincang beds (consisting of regular, medium thick arenaceous beds that dip gently to moderately) by an at least 4-metre thick metamylonite/ phyllonite. The phyllonite has isoclinal drag-folding striking NW and occurs in a zone with the general attitude of 320/20. The drag folds indicate tectonic transport towards 230° of the overlying Macincang arenite that strikes/dips 270/32. Figure 2 is a structural cross section and suggests that the fault zone represents a lag fault for which I propose the name *Datai fault* (see also detail plan of figure 3). Figure 3 clearly shows the different attitudes of the Macincang beds and the Datai beds at Teluk Anak Datai.

Figure 4 is an equal-area plot of various structural elements of the Datai and Macincang beds in this area. The following is shown by the plot. (1) A lateral compression in NNE-SSW (22-202°) direction developed the attitudes of most Macincang strata, thrusting on the Datai fault, and folds with axes normal to the compression direction. (2) Many attitudes of the Datai beds are different from those of the Macincang strata. (3) Another direction of compression in 130-310° is required to explain two reverse slips and several warp axes.

Pasir Tengkorak. - The headland east of the small sandy cove called Pasir Tengkorak shows two rock series (figure 5). The lower series consists of intensely fractured, medium to fine grained meta-arenite that were deformed into open folds. The upper series consists of well-bedded and internally laminated, fine to medium grained meta-arenite that also includes a 20 cm thick arenaceous zone composed of slump ball-and-pillow structure. The upper series is only gently warped convexly upward and overlies paraconformably and angular-unconformably the lower series (figure 5C). The upper and lower series are interpreted as Macincang and Datai beds.

The intense fracturing of the lower series consists of fracture cleavage of 10/±90 attitude. Diffraction of these fractures resulted in the rock appearing to be composed of rhombic fragments. Some of the thick beds are dismembered. Thinner (less than 10 cm thick) meta-argillite layers form interbeds. One meta-argillite interbed is greenish grey and consists of mostly angular, elongated quartz and muscovite grains and shards in a sericite groundmass. This pelite contains thin veins of fine and very fine grained quartz. The quartz is partially strained (shown by wavy extinction under cross-polarized light) and, therefore, suggests more than one injection phase. This meta-argillite was originally a felsic tuff. Another metapelite consists silt-size, angular and subrounded quartz grains, quartzite grains, rare muscovite in an argillaceous matrix. Rare and tiny ore grains are also present. Within lower series is also a quartz-mylonite zone, 8 cm thick, that parallels bedding. The asymmetrical open folds trend N to ENE. It is transected by generally upright fault zones striking 340° and 360°. Upward these up to 15 cm wide zones become closed faults upon entering the upper series and maintain this style (figure 5B). Stratification of the lower series were displaced by these fault zones, but the same faults did not offset the upper series. This situation implies that (normal ?) faulting occurred before the upper series were deposited. The thin, straight faults within the upper series were very probably transmitted effects of the fault zones in the lower series when diagenesis affected both rock sequences.

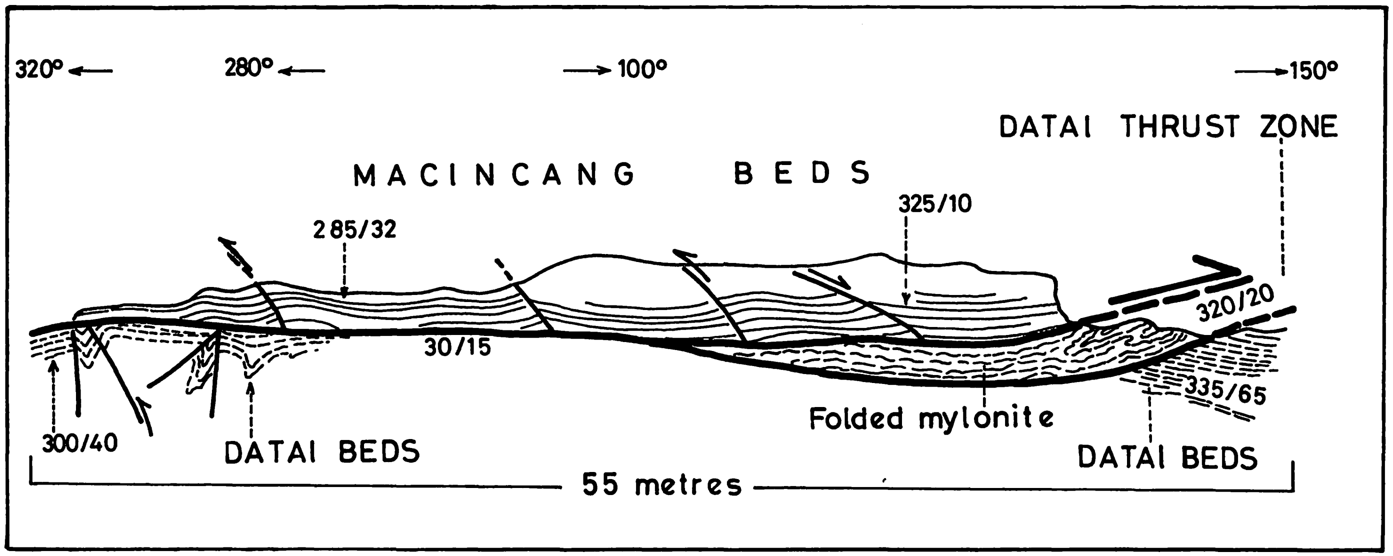


Figure 2 : Cross-section of the 4-metre thick Datai thrust zone that separates Macincang beds from underlying Datai beds. Length of the curving outcrop (note the varying compass directions) is approximately 55 metres. East shore of Teluk Anak Datai.

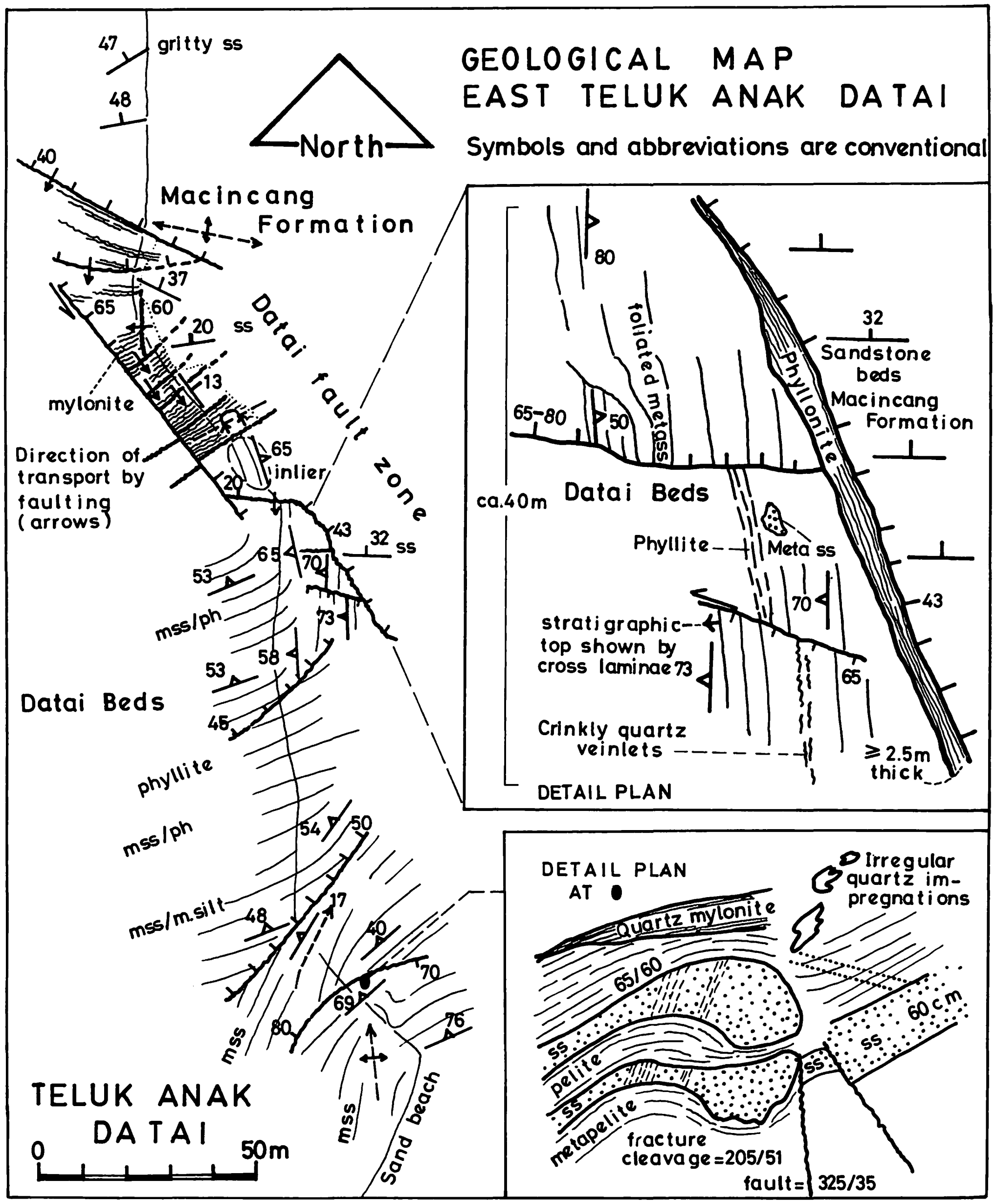


Figure 3: Geological map of the east shore of Teluk Anak Datai where Macincang beds overlie Datai beds with a fault contact. Details are shown on the two figures on the right side.

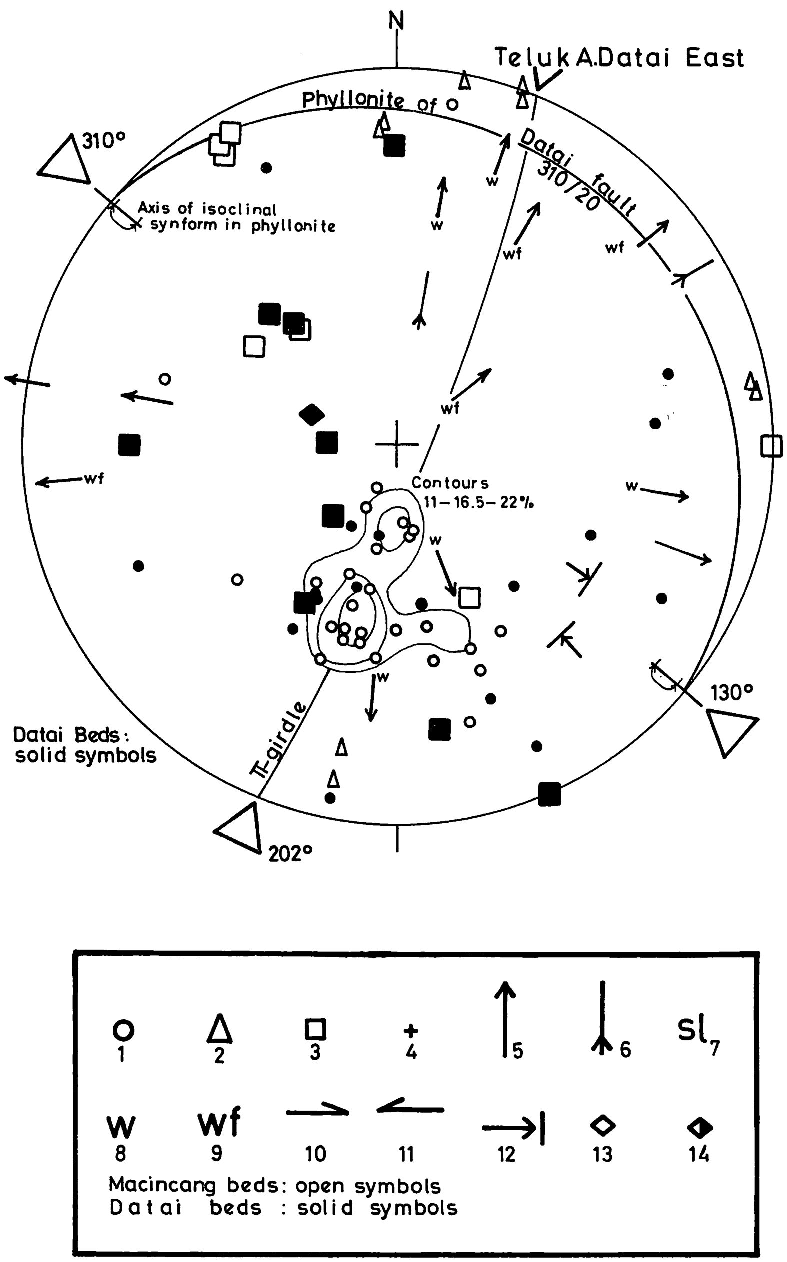


Figure 4 : Equal-area projection, lower hemisphere of structural elements in the Datai beds (solid symbols) and in Macincang beds that outcrop on the east shore of Teluk Anak Datai. Key to symbols (1) bedding; (2) parallel fractures; (3) fault, fault zone; (4) cleavege; (5) fold axis, anticline, antiform; (6) fold axis, syncline, synform; (7) axis of slump folds; (8) warp; (9) warp formed by faulting; (10) right-lateral fault slip; (11) left-lateral fault slip; (12) reverse fault slip; (13) quartz vein; (14) quartz dyke. Open symbols denote Macincang structures; solid symbols indicate Datai beds.

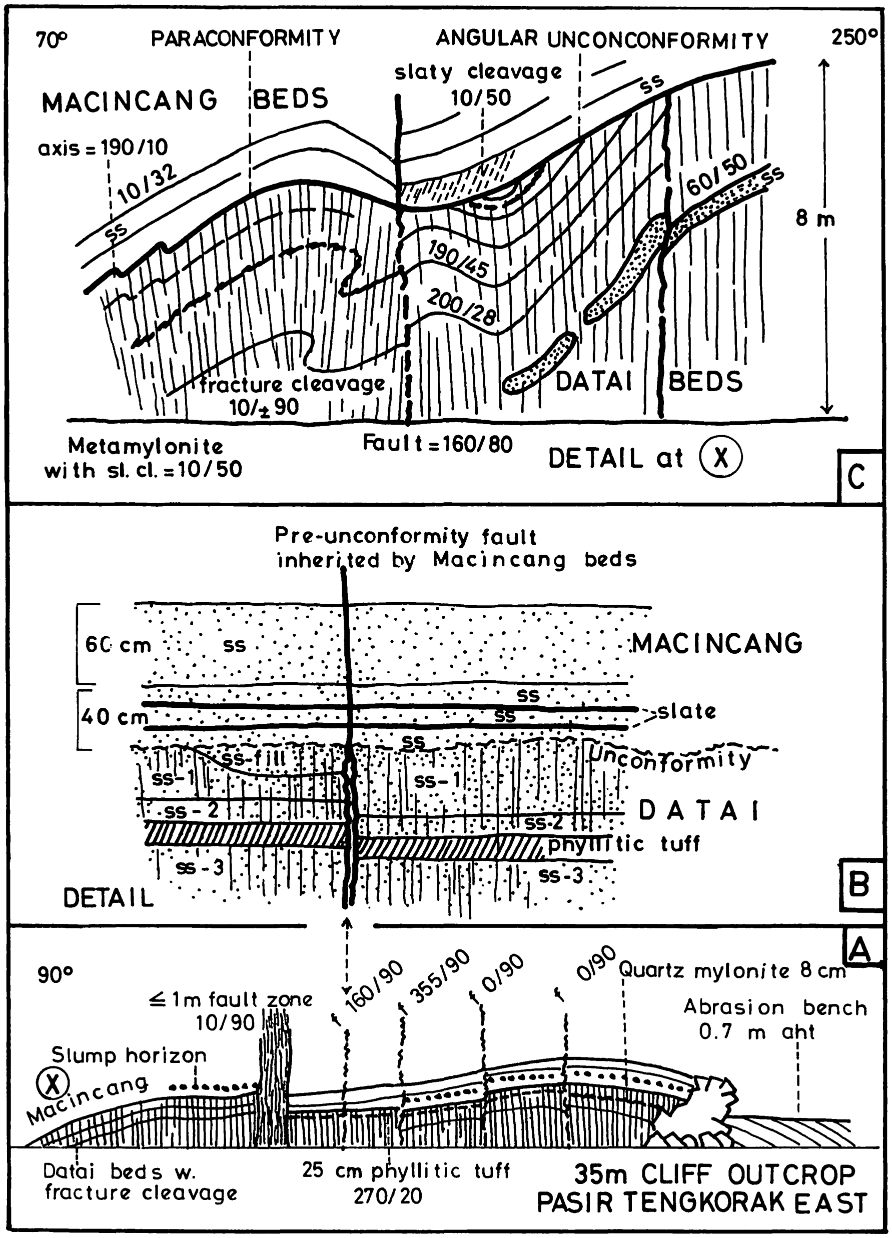


Figure 5 : (A) Cliff outcrop at Pasir Tengkorak where Macincang strata unconformably overlie very fractured Datai beds. The outcrop is a large warp.

(B) Detail of the contact between the two rock series and the change in shape of a pre-Macincang fault.

(C) The angular unconformity between the two rock series at the east end of the cliff.

The upper series of well-bedded, internally laminated meta-arenite also possesses meta-argillite interbeds and is distinctly less deformed and less fractured than the lower series (figure 5). On the east side of figure 5C the contact between the series appears conformable. Farther westward a less than 5 cm thin gap through differential erosion marks the contact, but the difference in deformatin style clearly indicates an angular unconformity. Slaty cleavage of 10/50 in the pelitic interbeds in both rock series is regarded to represent the attitude of the axial plane of the regional fold.

The geological differences between the lower and upper series at Pasir Tengkorak indicate that the older Datai beds were already tectonically deformed before the upper series consisting of Macincang beds succeeded unconformably. Renewed folding is represented by the presence of slaty cleavage, whereas the latest deformation developed the large warp exhibited by the outcrop (figure 5A).

Figure 6 is an equal-area plot of structures shown on figure 5. The constructed fold axes (by the beta-method) for Macincang and Datai beds are as shown and suggest that the generating maximum principal stresses were P_1 (older) = 156-336° and P_2 (younger) = 108-288°. The attitude of the slaty cleavage is consistent with the younger compression direction.

Northwest of Tanjung Belua. - Intensely fractured arenaceous banks with dismembered appearance form the lower 3-4 m or the cape immediately northwest of Tanjung Belua (figure 7A). The outcrop was only examined from a distance of 20 m, but the different appearance of the lower part compared to the regularly, thick-bedded upper part is distinct; each respectively representing Datai and Macincang beds. The Macincang strata seem to have been deformed into an isoclinal synform striking ESE and a metre-wide shear zone striking 45° transects the rock.

Summary of Datai beds. - Petrographically, the Datai rocks appear similar to the adjacent Macincang rocks. However, in outcrops the two rock types are quite different. Intense and close fracturing, steeply to vertically plunging folds, dismembered arenaceous beds, and fractured quartz bodies with twisted appearance characterize the Datai beds (figure 8). The nearby Macincang beds are regulary bedded, much less fractured and are generally less deformed (see figures 4, 5, 9). The unconformable contact between the two rock series at Pasir Tengkorak could have been caused by intraformational processes, but the difference in fracture density in the two lithologically similar units is more in line with fracturing having taken place in an already consolidated lower rock series before the upper series came into existence. The change from fault zones into thin straight faults characterizing the lower and upper rock series also favours a time gap between their formations.

Other outcrops of fractured meta-arenite in the Macincang terrain of Langkawi were also recorded in localities other than those discussed above.

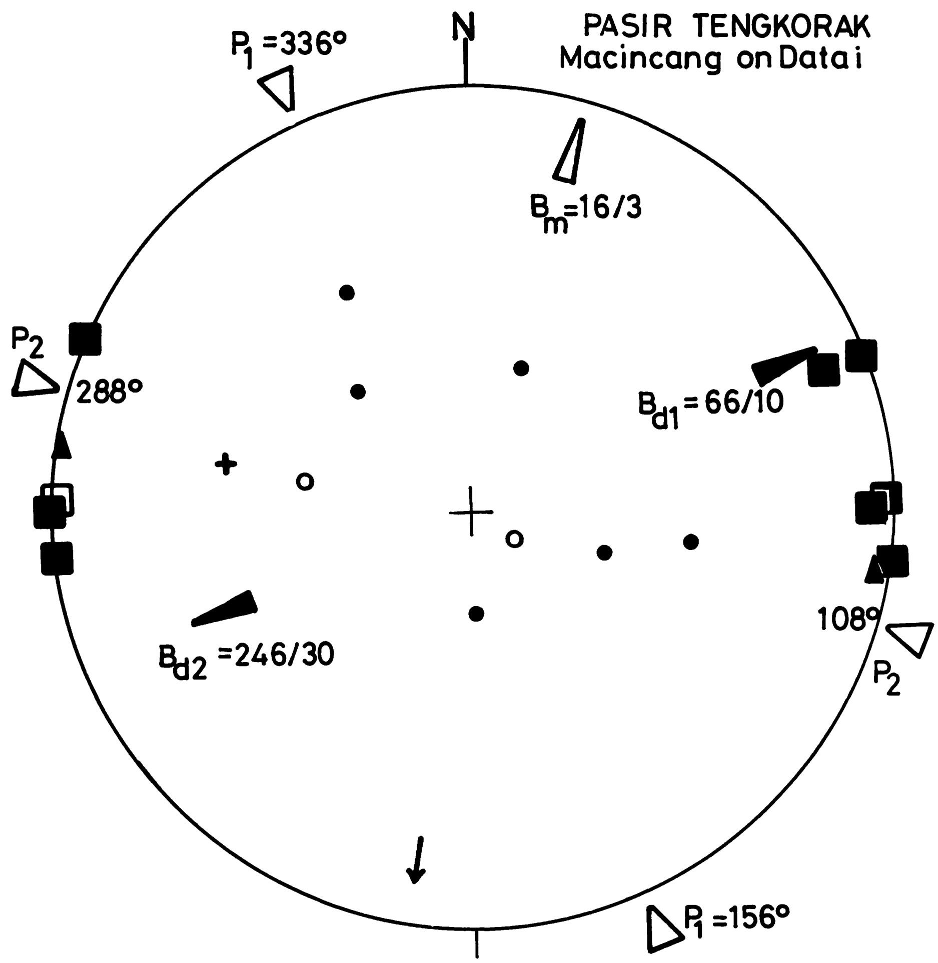


Figure 6 : Equal-area projection, lower hemisphere of structures in the cliff outcrop shown on figure 5(A), Pasir Tengkorak east. B are fold axes determined by the beta-method; B_m, B_{d1} and B_{d2} respectively are a B-axis in Macincang and two in Datai beds (opposed plunges). Other symbols are explained in figure 4.

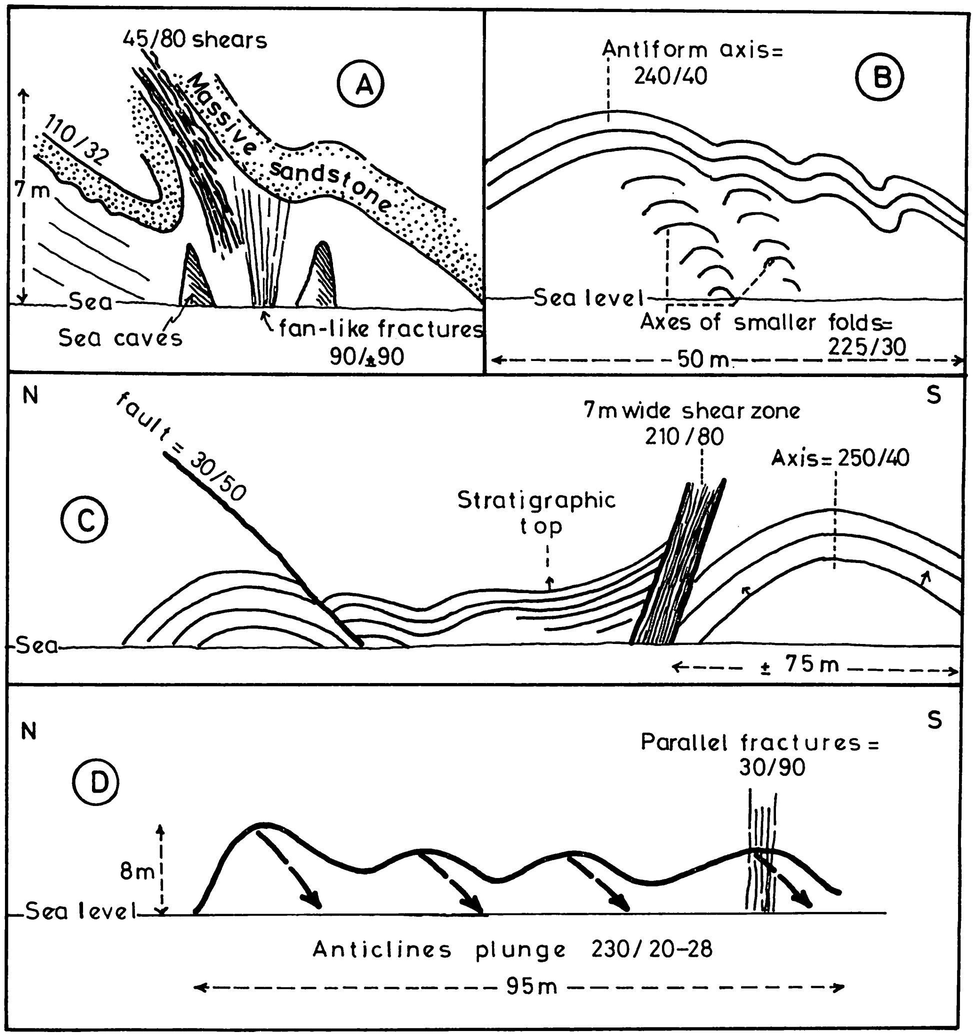


Figure 7 : (A) Fractured metasediments below the massive sandstone layer are probably Datai beds.
(B) Probable major anticlinal (antiformal) fold plunge and subsidiary folds in Macincang beds.
(C) Structural style at the SW-plunging end of the Buta anticline.
(D) Other medium scale subsidiary antiforms near the SW-plunge of the Buta anticline.

All localities are on the southwest coast near Tanjung Belua.

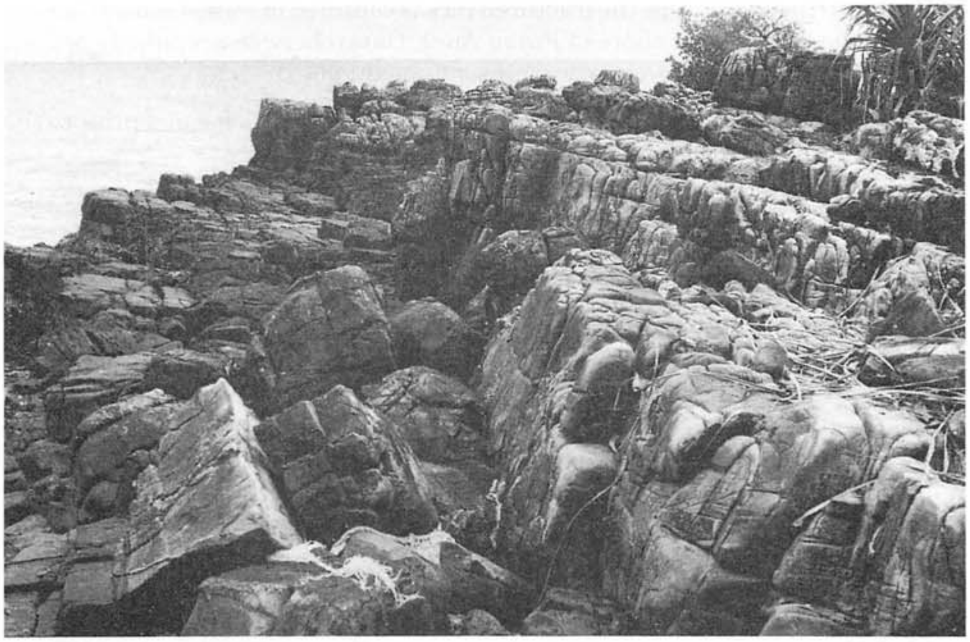


Figure 8 : Very fractured Datai beds at Pasir Tengkorak east. On figure 5A this locality is near the spot marked by an x.

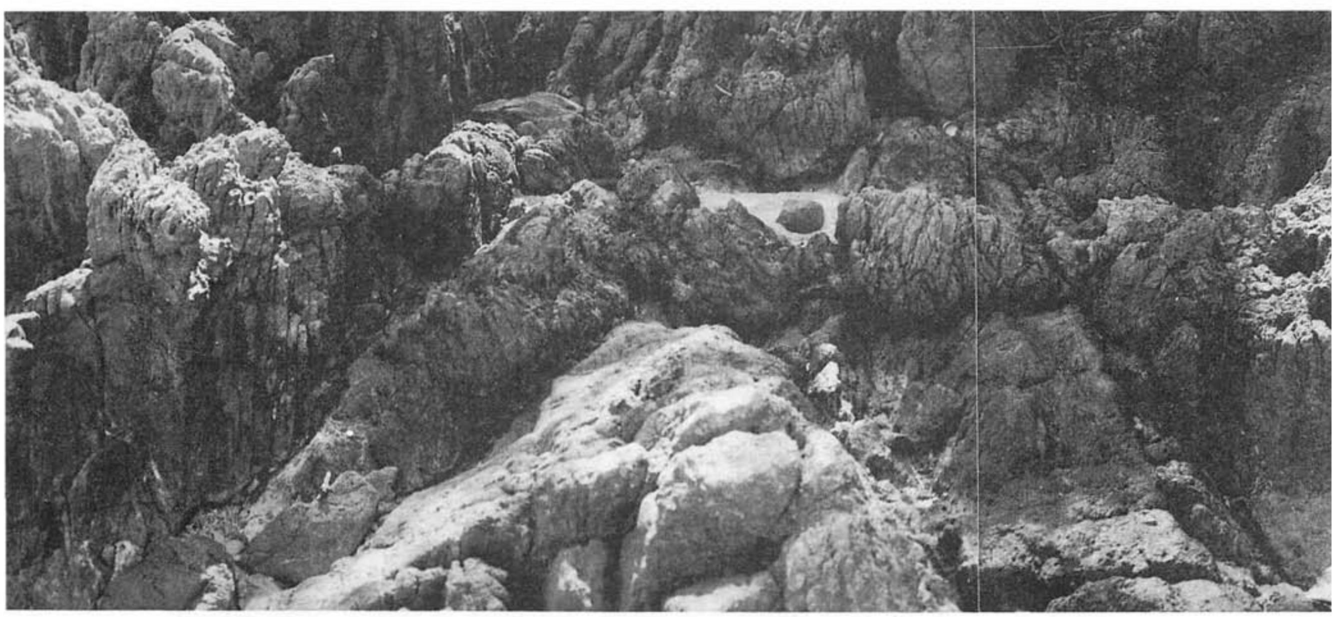


Figure 9 : Typical Macincang beds of Unit 4 near Tanjung Buta.

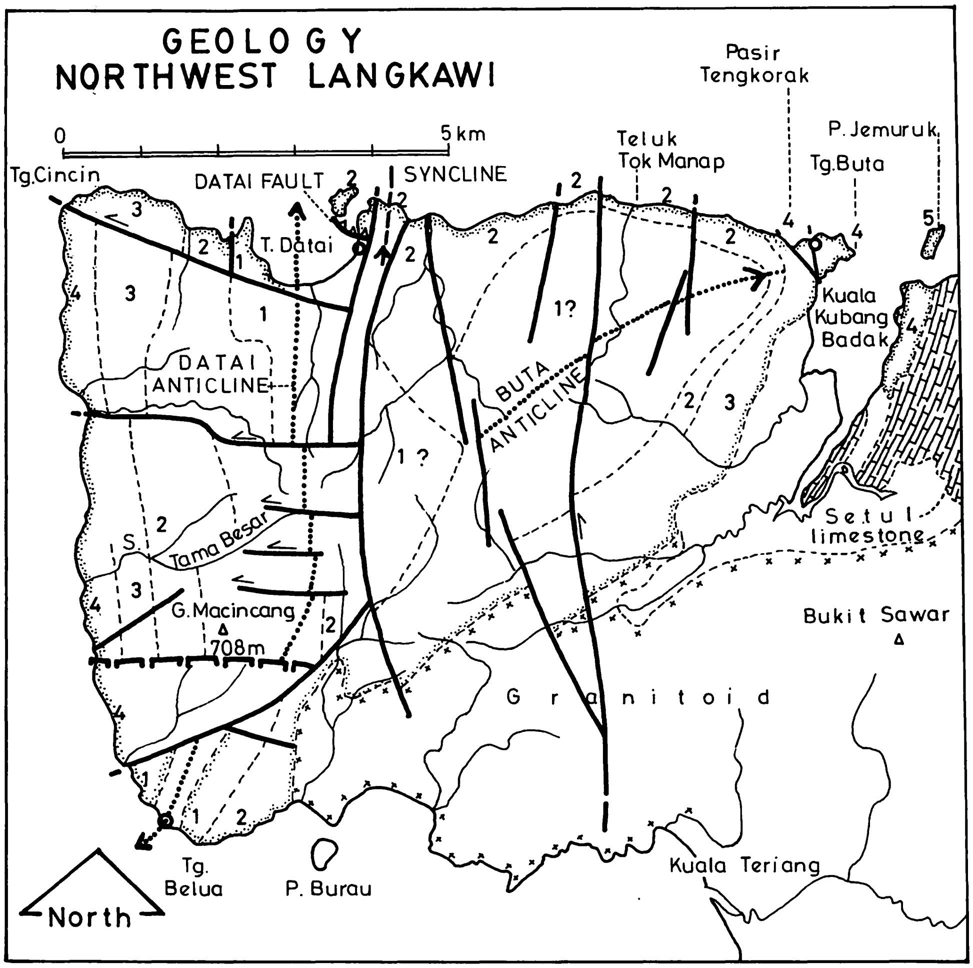
However, in these outcrops the fractured rock is confined to zones (some reaching 5 m wide as on the west shore of Pulau Anak Datai) between regularly bedded meta-arenite. Such zones clearly represent shear zones.

I interpret that the Datai beds are pre-Macincang rocks formed prior to the Late Cambrian and possibly in Precambrian time.

Macincang Formation

Figure 10 shows the structures of the Macincang rocks. Stratigraphic facing was determined through truncated cross beds, truncated slump folds, ripple marks, ball-and-pillow structures, and occasional graded beds. Two major anticlines, the Datai anticline striking north and the Buta anticline NE to ENE, and a syncline form the large folds. Medium scale asymmetrical folds with east vergence outcrop between Tanjung Cincin and Tanjung Hulur, a stretch that represents the west limb of the Datai anticline. Therefore, these asymmetrical folds appear to represent drag effects through folding of the Datai anticline. Other medium scale folds occur along the SW coast near Tanjung Belua (figure 7). These are slightly asymmetrical open folds plunging 20-40 degrees in SW-WSW direction. Wave lengths are 25 m or less. The rocks are typical, thick-bedded Macincang arenite and ripple marks indicate normal position. These folds very probably represent structures in the vicinity a large southwesterly plunging anticline that may be the continuation of the Buta anticline (figure 10). The major faults on this map have been interpreted from aerial photographs and their existence confirmed where these faults are shown to outcrop at the coast line. The fault zones dip essentially steeply to vertically, some attaining widths in excess of 7 metres (figure 7C). Some of the major faults offset photo-litho boundaries. On the map are shown five west-trending and one north-striking left-lateral fault zones. Lateral displacements are of the order of a few hundred metres. Further, topographic relief indicates an east-west fault south of the Macincang peak, downthrowing to the south. Other vertical displacements of tens of metres are also suggested by abrupt changes of the Macincang skyline (figure 11).

Figure 12 serves as an example of the complexity shown by many of the major fault zones. This is the coastal outcrop of the north-striking major fault to the west of Tanjung Hulur. The fault zone separates rocks of the Macincang Formation designated in this article (see below) as Unit 1 and Unit 2. Unit 1 consists of fine and medium grained meta-arenite intercalated with meta-argillite (slate, phyllite and yellowish meta-tuffite). Unit 2 is represented by regularly stratified, massive-bedded, brown meta-arenite intercalated with thinner meta-argillite. The 10-metre wide fault zone consists of three strips. A narrow strip in the east consists of large cataclasts of brown meta-arenite conformably enclosed by phyllonite followed by another narrow central strip of



Fugure 10 : Structural geological map of the Macincang terrain. The Macincang beds occur within the areas marked by dots at the boundary; three bold open circles indicate outcropping Datai beds; numbers 1 through 5 denote photo-litho units of the Macincang Formation; other symbols are conventional.

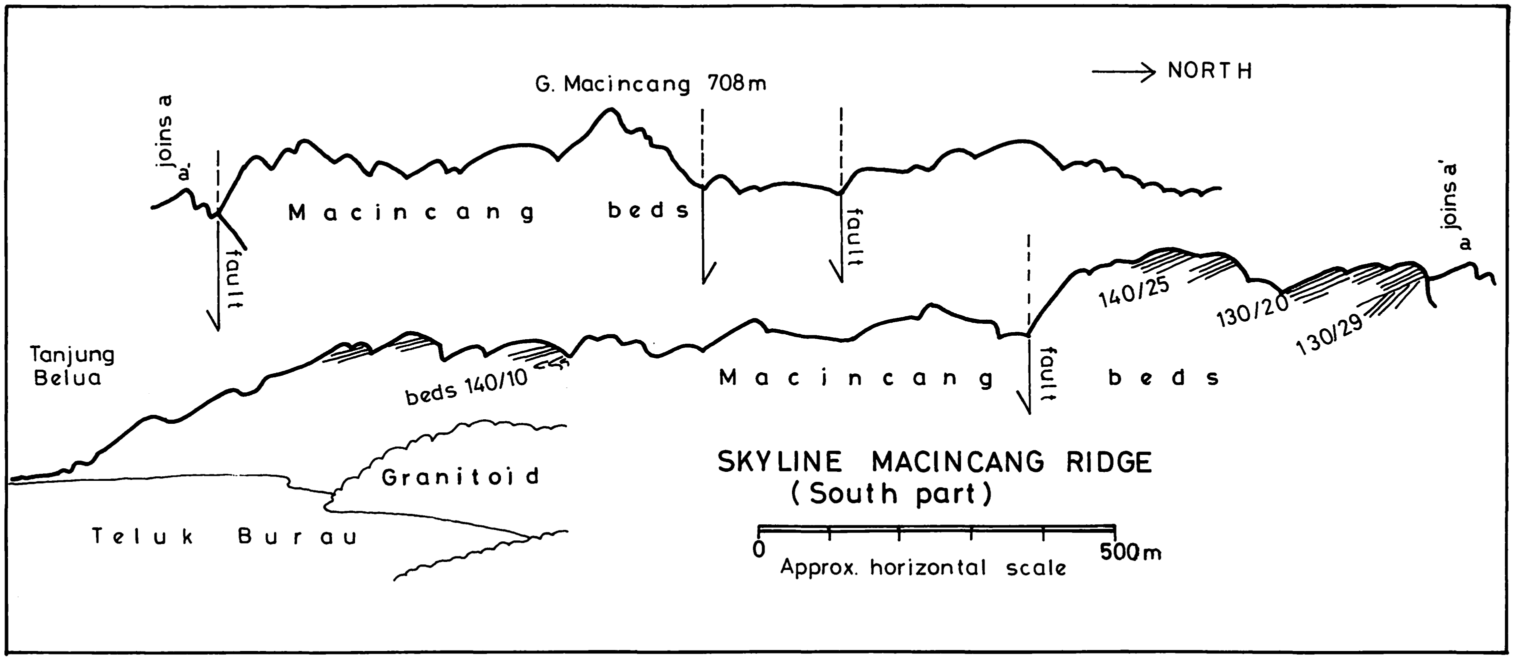


Figure 11 : The abrupt changes in the Macincang skyline probably resulted from vertical differential fault movements. This skyline consists of approximately a third of the main Macincang ridge.

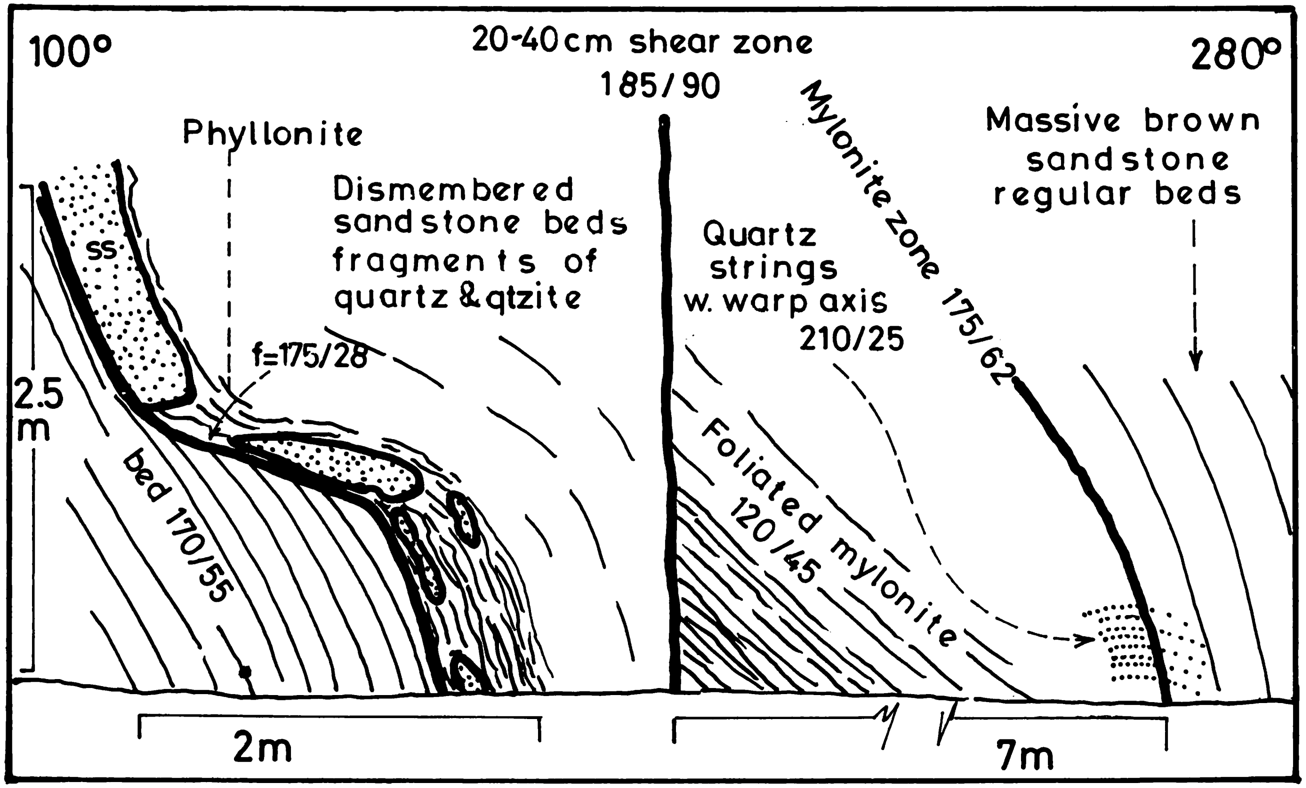


Figure 12 : Cliff outcrop of the major, north-striking fault zone west of Tanjung Hulur. The straight and vertical shear zone is a younger fault disturbing the major fault zone.

dismembered and broken meta-arenite, quartzite and quartz fragments. The central strip is separated by a 20-40 cm wide vertical shear zone (185/90) from the wide west strip of foliated mylonite. The western border is formed by a dm-thick mylonite zone that parallels bedding of rock unit 2 (175/60). Arcoss the west strip of the main fault zone run a host of parallel quartz strings that also cross the border mylonite and peter out over a distance of one metre in the adjoining brown meta-arenite. Shears of 240/70 attitude transect the major fault zone as well as the adjacent rocks of Unit 2, causing an aggregate right-lateral displacement of 2.5 m. Form this outcrop I interpret at least three episodes of faulting: (1) Development of the major fault zone; (2) succeeded by development of the vertical shear zone between the central and west strips and perhaps also of the westward dipping boundary mylonite zone; (3) finally right-lateral movement on 240/70 shears.

Combined with the photo-litho boundaries, the interpreted structures suggest that the older rocks outcrop in the anticlinal cores, while the younger rocks are along the synclinal axis and at the fold plunges. In this paper are distinguished five photo-litho units and designated by numbers 1 through 5 on figure 10. Their boundaries were traced discontinuously from aerial photographs, while their rock types were established from outcrops. These 5 units are not equivalent with Lee's (1983) lithostratigraphic subdivisions, although their distributions show similarities.

Unit 1 was studied along the west shore of Teluk Datai, and at Tanjung Hulur. Figure 10 suggests that the unit may also occur in the core of the Buta anticline. The unit consists of dm to several dm-thick interbeds of meta-arenite, finer grained internally laminated meta-arenite, metalutite and slate. Massively bedded arenaceous rock occur in the upper part of the unit. Often subparallel to parallel, dm to metre-wide quartz-mylonite zones follow bedding. Locally, as near Tanjung Hulur, occur laminites of dark and yellow coloured pelitic bands. The well-bedded series is vertical near the axis of the Datai anticline but becomes moderately steep towards the west (70 to 50 degrees). The strike is northerly.

The quartz bodies within the mylonite zones are of irregular to snowball shapes showing coaxially, superimposed recumbent folds plunging gently 10 to 15 degrees. A later event warped these folds around similarly SSE-striking axes or around axes of different trends. Warp axes plunge less than 10 degrees. A few outcrops show that the mylonite zones may be folded isoclinally (figure 13). Vergence towards east at this particular outcrop is consistent with its position on the west limb of the Datai anticline. In other words, the isoclinal folds may be drag phenomena. If present, younger shear zones are straight and cut across bedding.

Figure 14 shows examples of features associated with quartz-mylonite zones that strike parallel to or transect at low-oblique angle bedding in Unit 1. In figure 14A are two mylonite zones, an older parallel to bedding and a younger, a few dm-

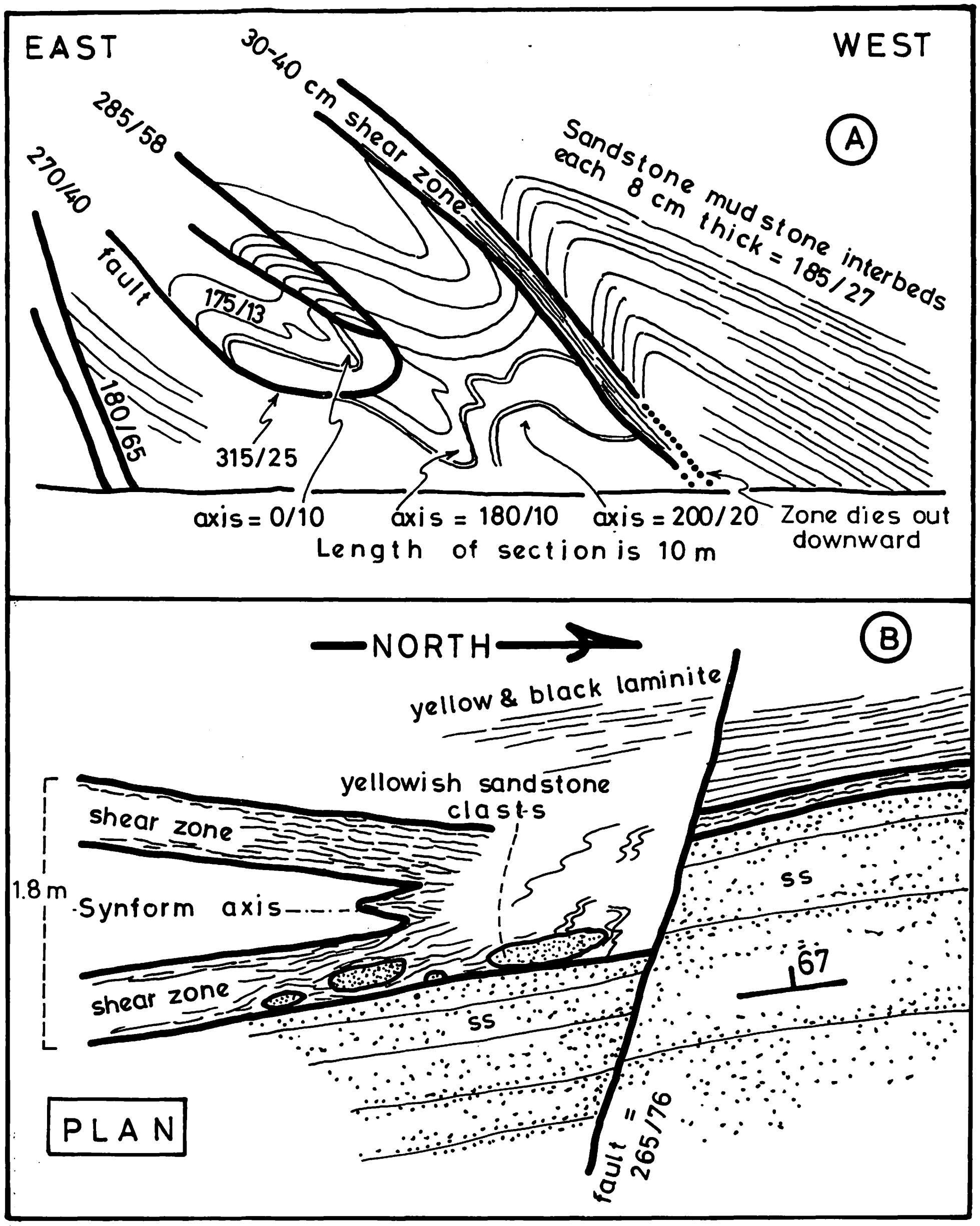


Figure 13 : (A) Cross-section and (B) plan of two outcrops showing folded mylonite zones fault in Macincang Unit 1. Both outcrops are on the west shore of Teluk Anak Datai.

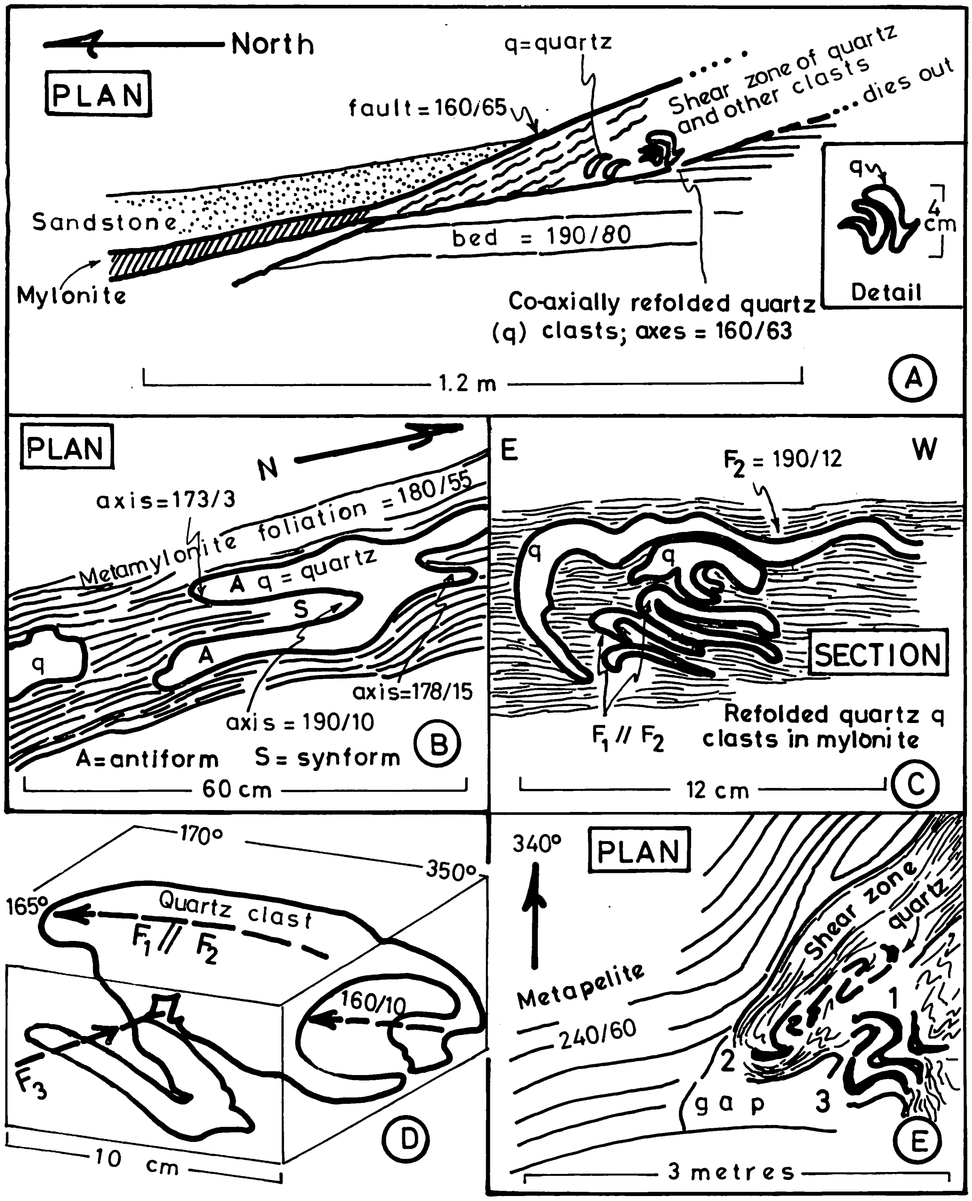


Figure 14 : Details of quartz-mylonite zones parallel or subparallel to bedding of Unit 1 strata. All localities are on the west shore of Teluk Anak Datai.

wide quartz-mylonite zone in which the quartz clasts were co-axially refolded. Their sigmoidal shapes suggest right-lateral motion along this SE-trending mylonite zone. Another bedding-plane quartz-mylonite zone is on figure 14B. The planimetric outcrop pattern of the quartz resembles that of plunging folds. The antiforms and synforms exhibited by the quartz clasts could be formed by compression normal to the fault zone. However, the convexity of mylonite foliae with respect to the quartz clast in the lower right-hand side suggests right-lateral motion along the mylonite zone. Figure 14C is a cross section of a co-axially refolded quartz clast in bedding-parallel mylonite zone. A block diagram (figure 14D) shows a quarzt clast in yet another bedding-parallel mylonite zone that was deformed by folding about three axes, two of which strike SSE and the youngest trend SE. The mylonite zone proper may also be refolded at least twice. Figure 14E is a plan view of three fold axes in a folded shear zone within Unit 1: Axis 1=30/20; 2=40/35 and 3=90/40.

Unit 2 consists of fine grained and very fine grained, quartzitic meta-arenite with internal lamination, some scour fills, tabular cross beds and occasional trough beds; thick to massively bedded and intercalated with light coloured meta-tuffite. The main colours are yellowish, brown and reddish. Also within Unit 2 are thick to massive beds of gritty meta-arenite (Pulau Anak Datai), conglomeratic argillite and conglomeratic arenite. The phenoclasts are mostly vein quartz that are typically subangular to subrounded. Along the Tama Besar river, the lower part of Unit 2 tends to be foliated.

Unit 3 consists of thick-bedded meta-arenite intercalated with dm-thick meta-lutite. Both rock types are cross-stratified. This lithology is similar to that of Unit 4, but the latter has slump horizons and a photo-boundary could be established between these units.

Unit 4 is composed of thick-bedded, medium grained and fine grained meta-arenite (some are internally laminated) with dm-thick meta-argilite intercalations. At Pasir Tengkorak were seen rare graded beds (sand to silt sizes). Conglomeratic arenite may be present as thick banks. Cross strata are tabular or concave upward. Bedding may be wavy and current marks of 30-40 cm wavelength are typical. Bedding surfaces with ripple marks are common on the seaward inclined strata along the west coast. Slump horizons, sometimes forming ball-and-pillow structures, are a few dm thick and are also typical for this unit. Further, it appears that straight quartz veins and dm-wide quartz dykes are most common in Unit 4.

Unit 5 outcrops on Pulau Jemuruk as fine grained, internally laminated, thick bedded meta-arenite. Cross lamination and graded bedding from fine grained arenite to slate are present. Grey greenish tuffite occurs as thin but extensive discs among the meta-arenite beds.

Structural features of Macincang Units. - Unit 1 is characterized by the presence of steep to vertical bedding that is paralleled or transected under low-oblique angles by quartz-mylonite zones. Where beds of Unit 1 are folded, the mylonite zones were similarly deformed (figure 13, 14E). The quartz clasts within such zones were also refolded, sometimes into snowball-like shapes.

Rocks of Units 2, 3 and 4 are steeply to gently dipping, depending on their positions with respect to the large fold axes and fold plunges. Where stratigraphic facing could be established, I found that none of the beds were overturned. Unit 5 has the most gentle dips not exceeding 15 degrees. Asymmetrical folds on the west limb of the Datai anticline appear to be drag phenomena. Overturned folds on the east shore of Kuala Kubang Badak may also be drag folds as their west-vergence suggests. A few elongated with sides inclined at 15 degrees or less were mapped and may represent the youngest ductile expression of deformation. In addition to the Datai thrust fault described earlier (figure 2), only one other, at least 0.5 m wide, subhorizontal shear zone was seen on the flank of the Datai anticline in the vicinity of Tanjung Cincin. Drag of the Macincang strata on the hanging wall indicates east vergence. The major fault zones in the Macincang units 2 through 4 are usually steeply dipping to vertical.

The cross section on figure 15 shows the deformation style of the Macincang beds. The rocks were flexurally folded about large north and ENE-striking axes. Overturned beds on the east rim imply locally stronger deformation compared to elsewhere in the Macincang terrain where bedding remained right-side up throughout, except at Pulau Anak Datai where Unit 2 beds are overturned and dip 80 degrees. This and the steep beds of Unit 1 at Teluk Datai probably resulted from drag by the Datai thrust.

EQUAL-AREA PROJECTIONS

In order to sort out preferred structural orientations in the Macincang terrain, the usual structural elements were plotted on equal-area projections, lower hemisphere. In addition to determining preferred trends, it is often possible to interpret the history of deformations. The general rules that I followed are:

(a) Ductile deformation (folding) usually preceeds brittle fracturing (faulting).

(b) Steeper fold axes are older than those plunging at gentler angles; consequently the youngest fold axes are often horizontal.

(c) Warps represent the youngest ductile deformation.

(d) Folded faults (and zones) are older than straight faults (zones).

(e) Open folds may be younger than isoclinal or recumbent folds.

(f) Smaller folds (crenulation) may be younger than major folds if the two fold

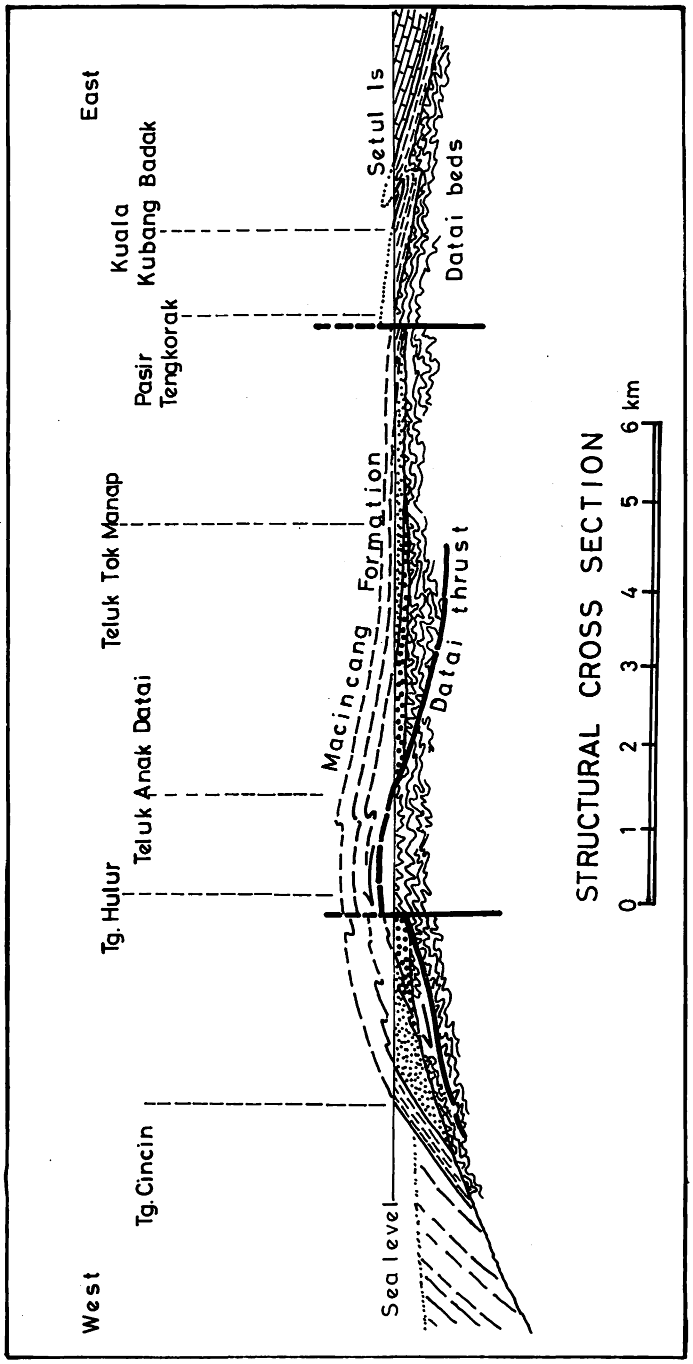


Figure 15 : Schematic structural cross section across the north shore of the Macincang terrain. The known outcrops of Datai beds are probably caused by vertical fault movement at Pasir Tengkorak and by uparching of the anticlinal core at Teluk Anak Datai. Note the fold style at the eastern boundary of the terrain.

groups have different strikes and the smaller folds occur outside plunge regions of the larger folds.

(g) Fold trends that are widely spread out, developed earlier than those of more consistent directions.

The next few equal-area plots serve as examples of the structural styles found in the Macincang terrain of northwestern Langkawi and the manner the compression directions were interpreted. Symbols are explained in figure 4.

Tanjung Sabung, *figure 16.* - This plot also incorporates structures of the Setul limestone that is exposed along the east shore of Kuala Kubang Badak. The axial plane of an overturned fold corresponds to horizontal compression in 095-275° direction. The majority of fold axes are crenulations resulting from 135-315° directed compression. If steeper fold axes denote earlier formed folds, then the oldest compression acted in 135-315° and the younger compressions were in 095-275° and 062-242° directions. No distinction of age is possible between the later two compression directions.

Pulau Jemuruk, *figure 17.* - On this equal-area projection the moderately inclined slaty cleavage suggests a horizontal compression in 045-225°. Bedding indicates response to compresion in 115-295°. If slaty cleavage represents axial plane cleavage, the associated fold structure may be at least overturned and, therefore, it developed earlier than the structure represented by the general bedding. The right-lateral fault slips are consistent with the 115-295° compression direction. The warp axis probably represents the effect of the youngest compression that acted in NNE-SSW direction.

Pasir Tengkorak east, *figure 18.* - The projection is of structures in Macincang Unit 4 that outcrops on the east side of Pasir Tengkorak. The low-angle bedding-plane faults indicate vergence towards SW and resulted from NE-SW compression. The few folds axes and bedding planes define a Pi-girdle that corresponds to E-W compression. The single elongated warp may also be formed by this compression. If folding preceeded faulting, then E-W compression preceeded NE-SW compression.

In similar fashion, the maximum principal stress directions at other localities of the Macincang terrain were analyzed. The results are listed in Table 1. The geological map on figure 10 already suggests that there are two major structural trends, that is, north and east-northeast corresponding to compression directions E-W and NNW-SSE. The table further shows that in most cases NNW-SSE compression preceed E-W compression. In addition two more groupings of compression directions are indicated, approximately NE (50-70°) and approximately ESE (150-120°).

The NE-SW compression was found in the plunge regions of the Buta anticline - in the Kuala Kubang Badak area and near Tanjung Belua - and along

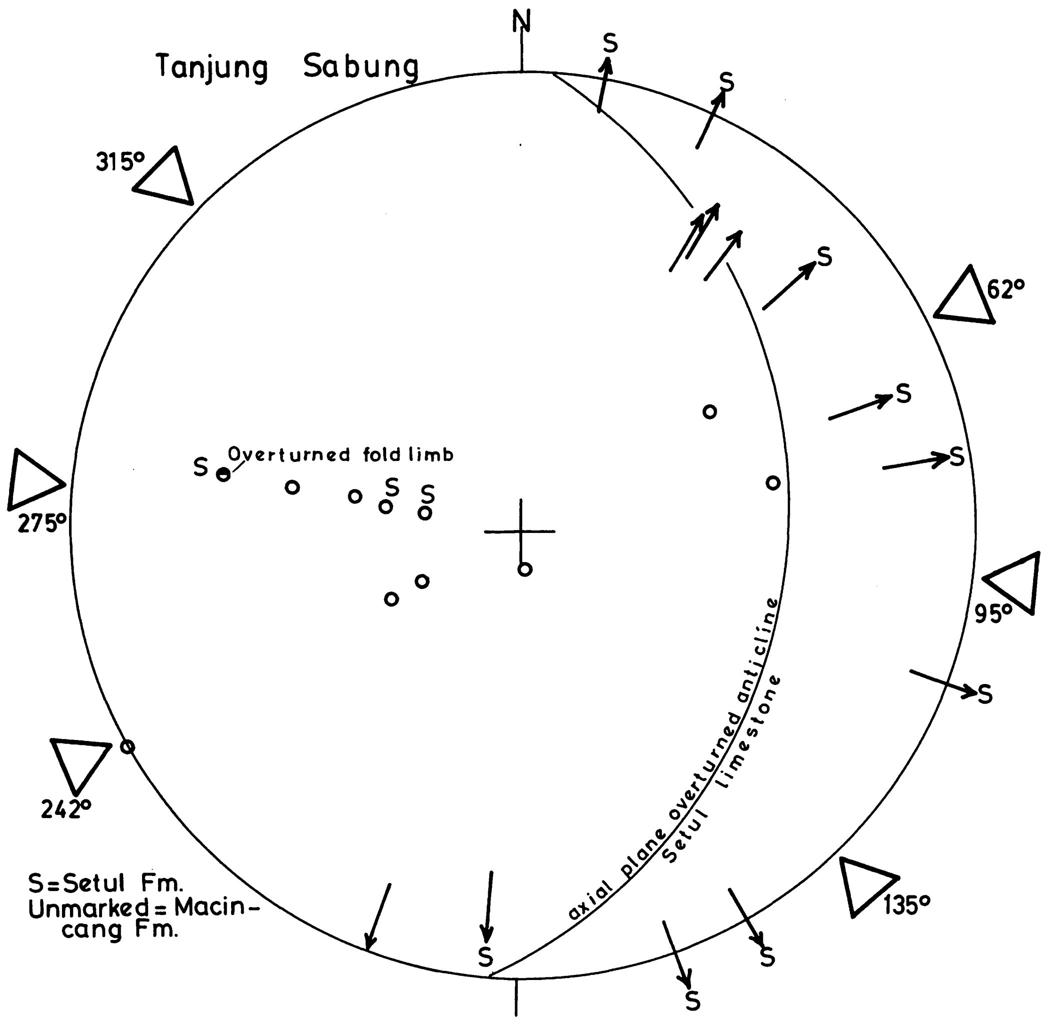


Figure 16 : Equal-area projection, lower hemisphere of structures in Setul limestone (S) and Macincang beds at Tanjung Sabung, east shore of Kuala Kubang Badak. Symbols are explained in figure 4. The major deformation style is that of overturned folds verging west. Three directions of compression (large triangles) are interpreted and discussed in the text.

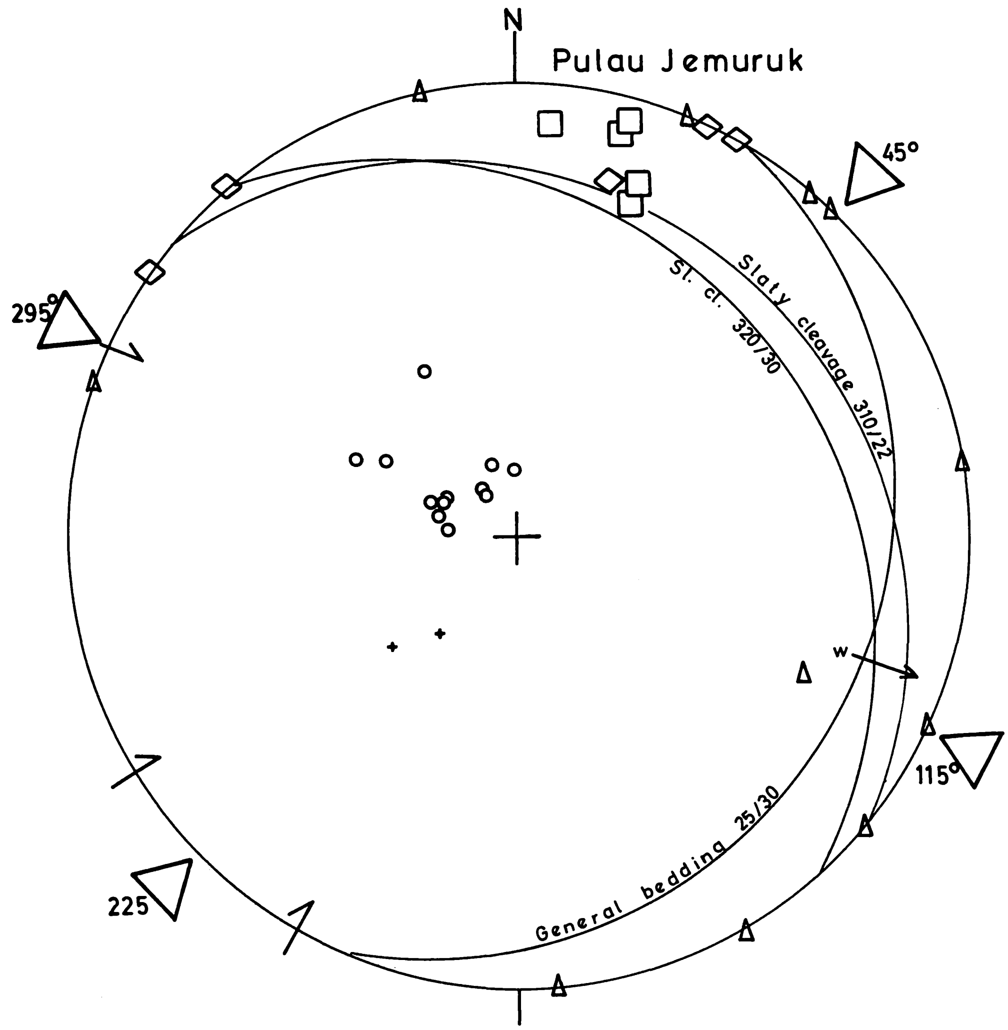


Figure 17 : Equal-area projections, lower hemisphere of structures in Macincang beds of Unit 5 outcropping on Pulau Jemuruk. Symbols are explained in figure 4. Two compression directions (large triangles) are interpreted; discussion in the text.

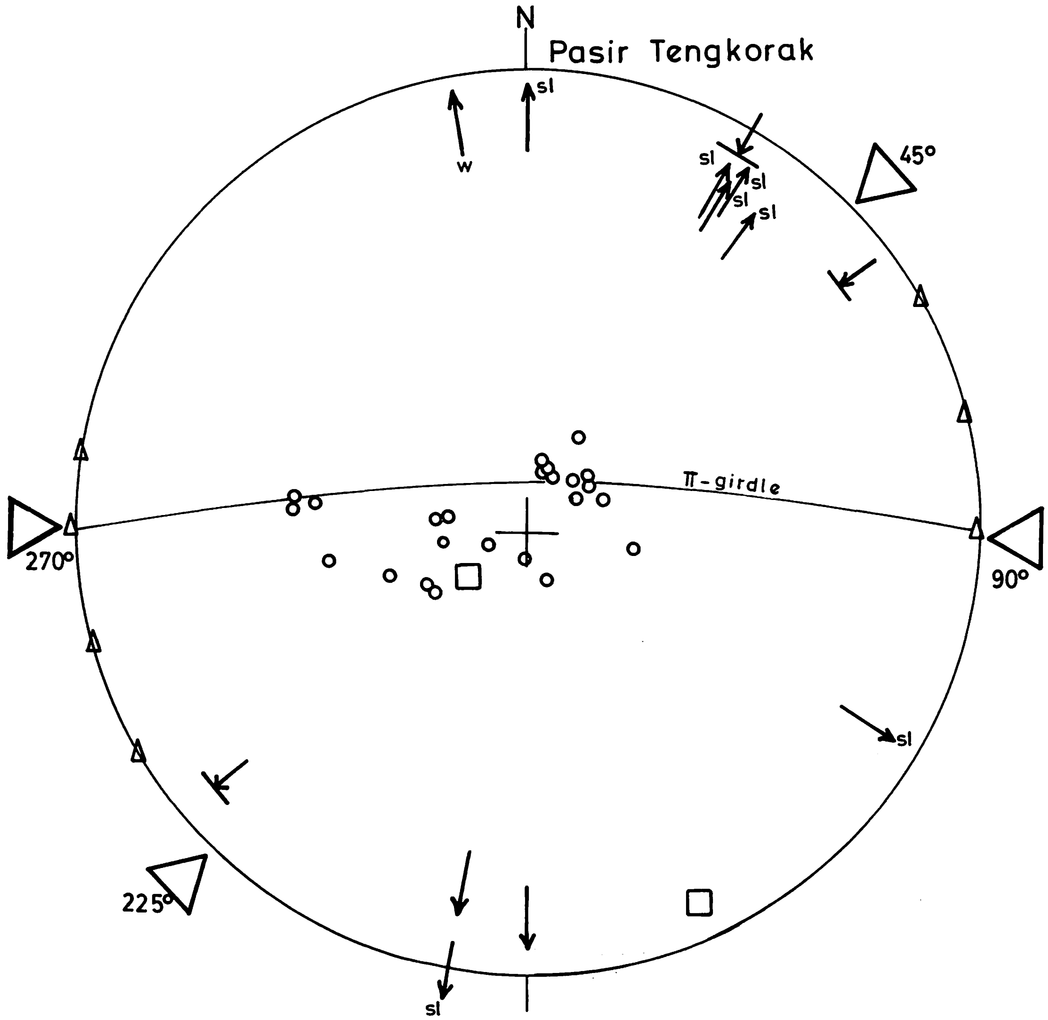


Figure 18 : Equal-area projection, lower hemisphere of structures in Macincang beds outcropping at Pasir Tengkorak. Symbols are explained in figure 4. Fold axes and the pi-girdle suggest E-W compression; striations on low-angle reverse faults indicate another compression in 045-225° direction. See text for discussion.

Table 1: Tectonic compression directions interpreted from equal-area plots

Pulau Jemuruk, Unit 5	P_1= 045-225 P_2= 115-295 P_3= NNE-SSW
Tanjung Sabung, Unit 4	P_1= 135-315 P_2= 062-242 & 095-275
Kuala Kubang Badak, West, Unit 3	P_1= 080-260 P_2= [019-030] - [199-210]
Tanjung Buta, Unit 4	P_1= 134-314 P_2= [090-115] - [270-295]
Pasir Tengkorak, East, Unit 4	P_{1+3}= 090-270 P_2= 045-225
Pasir Tengkorak, West, Unit 3	P_1= 146-326 P_2= 080-260 P_3= 106-286
Teluk Tok Manap, East, Unit 2	P_1= 110-290 P_2= 050-230
Pulau Anak Datai, Unit 2	P = 056-236
Teluk Anak Datai, NE, Unit 2 (2 localities)	P_1= 150-330 P_2= 066-246 P_3= 110-290
Teluk Anak Datai, West	
Unit 1	P = 085-265
Unit 1	P = 096-276
Unit 1	P = [050-080] - [230-260]
Tanjung Hulur, Unit 1	P_1= [100-119] - [280-299] P_2= 020-200
Tanjung Hulur, West, Unit 2	P = 092-272
Northwest cape area, Unit 3	P = east-west
Tanjung Cincin to Sungai Tama Besar, Unit 4	P_1= 082-262 P_2= 110-290
West coast, Central to SW, Units 4 and 1	P = 068-248
Southwest coast area, Unit 2	P_1= 060-240 P_2= 126-306 P_3= 085-265
Tanjung Belua, East, Unit 2	P_1= 029-209 P_2= ±090-270

the north coast between Tanjung Buta and Tanjung Hulur. This direction is absent along the north and central parts of the west coast, and between Tanjung Cincin and Tanjung Hulur. The compression is parallel to the Buta anticlinal axis. Along the north coast the compression is associated with thrust and low-angle reverse faults (the major Datai thrust included), slaty cleavage and crenulations. In the southwest, the compression direction is reflected by bedding attitudes. At localities possessing multiple compression directions, the NE-SW compression is generally older than the E-W compression and appears younger than the NW-SE compression.

The ESE-WNW compression is found in half of the localities tabled. This compression direction usually appears to be represented by the younger structures in areas where multiple compression directions could be established. I interpret the structures associated with ESE-WNW compression as reorientated features that originally trended ENE, that is, the strike of the oldest structures. Their reorientation was brought about by the NW-SE compression and/or the youngest compression in E-W direction.

CONCLUSIONS

Macincang Terrain

A major find is the establishment of pre-Macincang metasediments, the Datai beds, in northwest Langkawi. These beds outcrop along the east shore of Teluk Anak Datai as a series of strongly deformed metasediments consisting of psammitic and pelitic rock in partially dismembered strata, tightly folded and plunging steeply to vertically. Intruded quartz bodies are similarly twisted and thoroughly fractured. This rock series is separated by a 4-metre wide mylonite zone of the Datai thrust from overlying, moderately to gently dipping, regularly bedded Macincang meta-arenite. Isoclinal drag folds in the thrust zone indicate southwest vergence. Another outcrop of Datai beds is at Pasir Tengkorak where the thoroughly fractured older rock series is separated from overlying Macincang strata by an angular unconformity. A third exposure of probable Datai rocks occurs near Tanjung Belua in the southwest. Here and at Teluk Anak Datai the Datai beds occupy anticlinal cores; at Pasir Tengkorak the older rocks became exposed probably through faulting. The Datai beds are certainly pre-Late Cambrian and probably are Precambrian. This opinion is suggested by the fact that the upper portion of the 2010 m thick Macincang Formation contains late Cambrian fossils; no reliable index fossils are in the thick lower portion that may represent Middle, Lower Cambrian, or even Precambrian.

I found from aerial photographs that the Macincang Formation is composed of five photo-litho units and are cut by a number of major north and east-striking fault zones (figure 10). Several of these fault zones show left-lateral offsets of a few hundred metres. Combined with field observations, the aerial photos establish two large anticlines — a north-trending Datai anticline and the ENE as well as WSW plunging Buta anticline — and a north-striking syncline just east of Teluk Anak Datai. These major fault zones may reach widths of 7 metres; some are warped and most show evidence of multiple faulting.

Fieldwork also demonstrated that each of the photo-litho units possesses distinguishing features. Unit 1 is steeply to vertically inclined and contains many dm-wide quartz-mylonite zones parallel or subparallel to bedding. Their quartz clasts often exhibit co-axial refolding upon which may have been superimposed a third deformation consisting of warps elongated parallel or oblique to the older fold axes. Unit 2 includes a series of thick to massive-bedded conglomeratic sandstone and gritty sandstone. Unit 3 resembles rocks of Unit 4, but decimetre to metre-wide slump horizons are typical for Unit 4. Units 2 through 4 dip moderately to steep. Unit 5 consists of thick arenaceous beds that are internally laminated and cross-laminated. Beds of this unit incline at gentle angles of less than 15 degrees.

Stratigraphic facing is indicated by truncated cross beds and slump structures, by scour fills, ripple marks, graded beds and slaty cleavage. These structures indicate that the Macincang beds are usually right-side up. Only (1) in the core of the Datai anticline beds are vertical or steeply overturned (80 degrees), and (2) at Tanjung Sabung Macincang strata together with conformably overlying Setul limestone form overturned folds. The axial planes of these folds dip 30-35 degrees eastward, implying vergence westward. Asymmetric, medium scale folds on the west limb of the Datai anticline are drag folds resulting from the development of the regional fold.

Equal-area projections of various structural elements of the Macincang Formation indicate that the strata may have been subjected to three different stress systems. Following certain criteria, I found that the earliest maximum principal stress acted in NNW-SSE direction. The Buta anticline strikes normal to this direction and was probably the result of that compression. A second phase of tectonic deformation is indicated by low-angle reverse faults and the Datai thrust that caused tectonic transport towards southwest. The responsible maximum principal stress acted in NE-SW direction. The youngest deformation phase was the result of East-West compression which formed the short north-striking Datai anticline, the adjacent syncline, and several asymmetrical drag folds between Tanjung Hulur and Tanjung Cincin. This stress system also folded the Datai thrust and caused re-orientation to some of the older structures. Many of the older structures tend to be re-orientated into NNE-SSW trends.

Langkawi and Tarutao Islands

Of the three compression directions interpreted from the Macincang terrain (NNW-SEE, NE-SW and E-W) the younger two are reflected by major structural trends of the Langkawi island group (figures 1A and 1C). The Kisap thrust in NE

Langkawi island parallels the Datai thrust. I believe that Jones (1978) has been correct in considering this particular segment of the Kisap thrust as a fault zone separate from the fault thrust trending more northerly through SE Langkawi island and through Dayang Bunting island. The general strike of the later mentioned thrust zone appears consistent with the younger east-west compression.

The structural cross section (figure 15) suggests that generally the Macincang Formation has only been moderately deformed into large open folds. Locally stronger deformations can be attributed to activity on nearby fault zones. The geological map by Jones (1978) and descriptions by Koopmans (1965) indicate that deformation intensity is moderate for the central part of the Langkawi islands and only becomes high to the east of the thrust zones (Kisap thrust). In the narrow eastern strip of the islands, I noted medium to large scale recumbent folds in the Setul limestone. West vergence could be established at Tanjung Cawat and on Pulau Tuba. From this it appears that since the Cambrian, or even since the Precambrian, during the Palaeozoic and early Mesozoic the Macincang terrain has been a transitional region between a tectonically active area in the east and a stable platform to the west.

Peninsular Malaysia

The lower Palaeozoic rocks of Selangor, Negeri Sembilan and Melaka show evidence for tectonic transport towards the W-SW and S-SE sectors (Tjia, 1986). The transport towards S-SE could have been developed in the stress field that formed the Buta anticline and asscociated structures. The other transport in southwesterly direction could have developed in the same stress field that caused the Datai thrust and other low-angle reverse faults verging SW in northwestern Langkawi.

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