

# Tectonic implications of well-bore breakouts in Malaysian basins

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**Abstract:** Over a hundred well-bore breakout directions in the Malay, Sarawak, Sabah and Sandakan basins show consistent correlation with current and past tectonic stress fields. Breakout directions in the younger layers of the Malay Basin are consistent with shallow-focus earthquake stress trajectories associated with subduction of the Indian Ocean-Australian Plate west of Sumatra. In older layers, breakouts responded to north-south regional compression. In the Sarawak Basin, one set of breakout directions follows the change of tectonic grain in the Rajang Accretionary Prism. Patterns of other sets of breakout directions indicate major tectonic boundaries (West Baram Line and an unknown N-S line projecting outward from Kuala Balingian) and *en bloc* rotations of certain tectonic domains. Most of the other sets of breakout directions seem associated with the SW segment of the South China Sea spreading ridge. Breakout directional patterns in the Sabah Basin differentiate a SW and a NE domain which experienced relative clockwise rotation of 25°. The Sandakan Basin experienced compression normal to its axis and also east-west regional compression that is currently active.

## INTRODUCTION

In the late 1980s, the Exploration and Production Department of PETRONAS conducted a study entitled "Stress analysis and hydrofracturing directions in Malaysia based on borehole breakouts" with the primary objective of producing regional maps showing patterns of breakout directions, and to interpret these results in terms of structural geology and tectonics (Mohd Idrus Ismail, 1989). A secondary goal was to compile and analyze the size of breakouts and borehole stability and to interpret the associated stress magnitudes, rock strength and drilling conditions. More than a hundred wells in four Malaysian basins (Malay, Sarawak, Northwest Sabah, and also the Sandakan Basin off the north shore of the Dent Peninsula of Sabah) were studied. Among the studied wells, 81 wells show consistent regional patterns of breakout orientations.

The fundamentals of borehole breakout analysis have been explained in the report (Mohd Idrus Ismail, 1989). It suffices here to summarize the method. A borehole breakout is a phenomenon of well-bore elongation, which is generally parallel to the tension direction. Breakout directions are obtained from caliper logs which show the variations in hole shape. Symmetry of breakouts were confirmed using acoustic borehole images and downhole, wide-angle photography. Raw data were processed to eliminate non-stress related borehole elongations, such as well-deviation, drill pipe deviation, and in the case of caliper size less than

bit size. It was found that the last mentioned filtering process can be ignored, because the undersized caliper measurements do not affect the breakout readings. The results of the study show that borehole breakouts possess consistent regional orientations, and that *breakouts are perpendicular to the maximum principal stress direction*. Although there is one instance where one group of wells show remarkable vertical separation of breakout sets and excellent lateral correlation between the wells of this grouping, the breakout sets are, in general, complexly distributed within the well section. The study also found that within a single well more than one breakout orientation can occur. Systematic geographical distribution of breakout orientations became clear when several so called stress provinces were established within each basin area.

In the present report we have taken a fresh look at the breakout data in order to establish correlation with tectonic and earthquake stress fields of the region.

## MALAY BASIN

The Malay Basin is an aulacogen located in tectonically stable Sundaland, and together with the Penyu and West Natuna aulacogens are positioned on the late Cretaceous Malay Dome (Tjia, 1994). Figure 1 shows the tectonic framework of Sundaland and adjacent areas. The Malay Basin is filled with more than 12 km thick Oligocene to Recent sediments. Before early late Miocene,

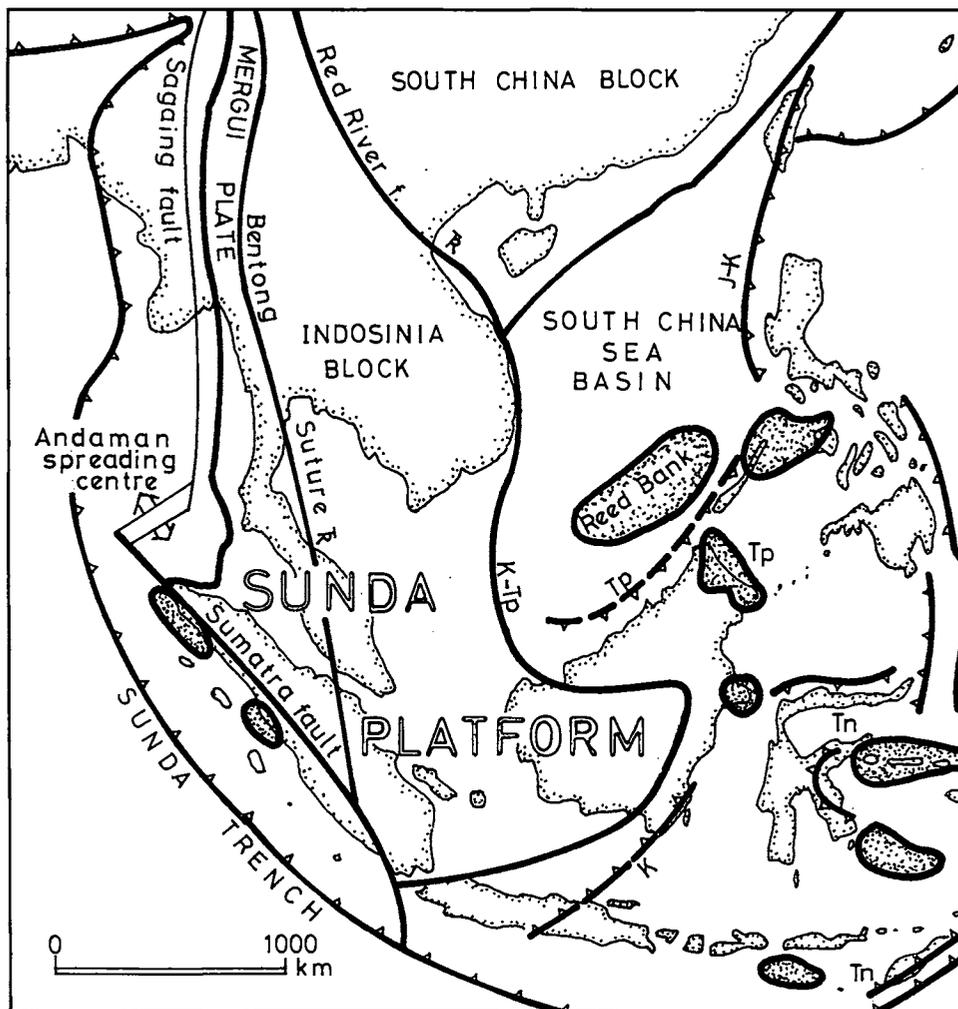
sedimentation mainly took place in continental setting, and only since then marine influence has become predominant. A NW-striking basement, left-lateral slip-fault zone along the axis of the basin has been postulated to account for the existence of east-west, pre-late Oligocene half-grabens. Towards northwest, this so called Axial Malay fault zone is believed to continue as the Three Pagodas fault in Thailand and Burma. The hot spot activity associated with the Malay Dome ceased prior to Oligocene time, allowing subsidence of the basin and accumulation of Oligocene-early Miocene terrestrial deposits. In early Middle Miocene, the regional stress field changed in such a way as to reverse lateral motion along the Axial Malay fault zone. This younger right-lateral fault slip resulted in structural inversion involving east-west anticlines in the half-graben fills, and southeast-verging thrust faults at the south end of the basin. Large, north-striking faults across the Malay Basin were probably also active during this

transpressional period and resulted in up to 45 km dextral separations of the fold patterns (Tjia, 1993). Renewed subsidence is thought to have taken place in post-Miocene time and is represented by north-south, normal crestal faults developed upon the anticlines.

### Stress Map Malay Basin (Fig. 2)

Well-bore breakouts from 27 wells at 19 localities of the Malay Basin have been analyzed (Mohd Idrus Ismail, 1989). Multiple directions of breakout are the rule. The breakout directions intersect at oblique angles, apparently with two preferential ranges: 20°–40° and 50°–60°. Tok Bidan exemplifies the less frequently occurring lower range of intersecting angles.

The direction of regional, maximum horizontal principal stress ( $P_{hmaxR}$ ) is north-south, with slight deviation of a few degrees east of north at Pilon and Ridan. The mean direction of the regional  $P_{hmaxR}$  may be represented by 05°.



**Figure 1.** Tectonic framework of Southeast Asia. Heavy lines are plate or subplate boundaries; stippled are micro-continents; Tr = Triassic, J-K = Jura-Cretaceous, K = Cretaceous, Tp = Palaeogene, Tn = Neogene. Active subduction along Sunda Trench.

The other non-regional  $P_{hmax}$  possesses two directions along  $315^{\circ}$ – $320^{\circ}$  and  $50^{\circ}$  (Fig. 2), for short indicated as PM-1 and PM-2, respectively. A north-south line that coincides with the major Dulang fault zone separates the areas of their influence, that is, PM-1 controls the area to the west of that line and also to the west of the Hinge-line of the Malay Basin (in the Malong area), while PM-2 controls the area to the east of the north-south line.

These two non-regional maximum stress directions are roughly perpendicular to each other, and could therefore be genetically related.

Figure 3 shows the spatial and directional relationships between the stresses derived from

well-bore breakouts and stresses interpreted from greater-than-magnitude-6, shallow earthquakes that occurred between 1929 and 1973 (Tjia, 1983a). The convergence direction of the Indian Ocean-Australian Plate with Southeast Asia is a few degrees east-of-north at the latitude of South Sumatra (as represented by the bold arrow in Fig. 3) and convergence gradually changes into NE-direction farther north along the Sunda Trench (Mattauer, 1973). However, the earthquake stress trajectories on the west edge of the Southeast Asian Subplate are perpendicular, and in one case parallel, to the tectonic grain of Sumatra and Java.

It was found that breakouts in the upper portion of studied wells in the Malay Basin tend to possess

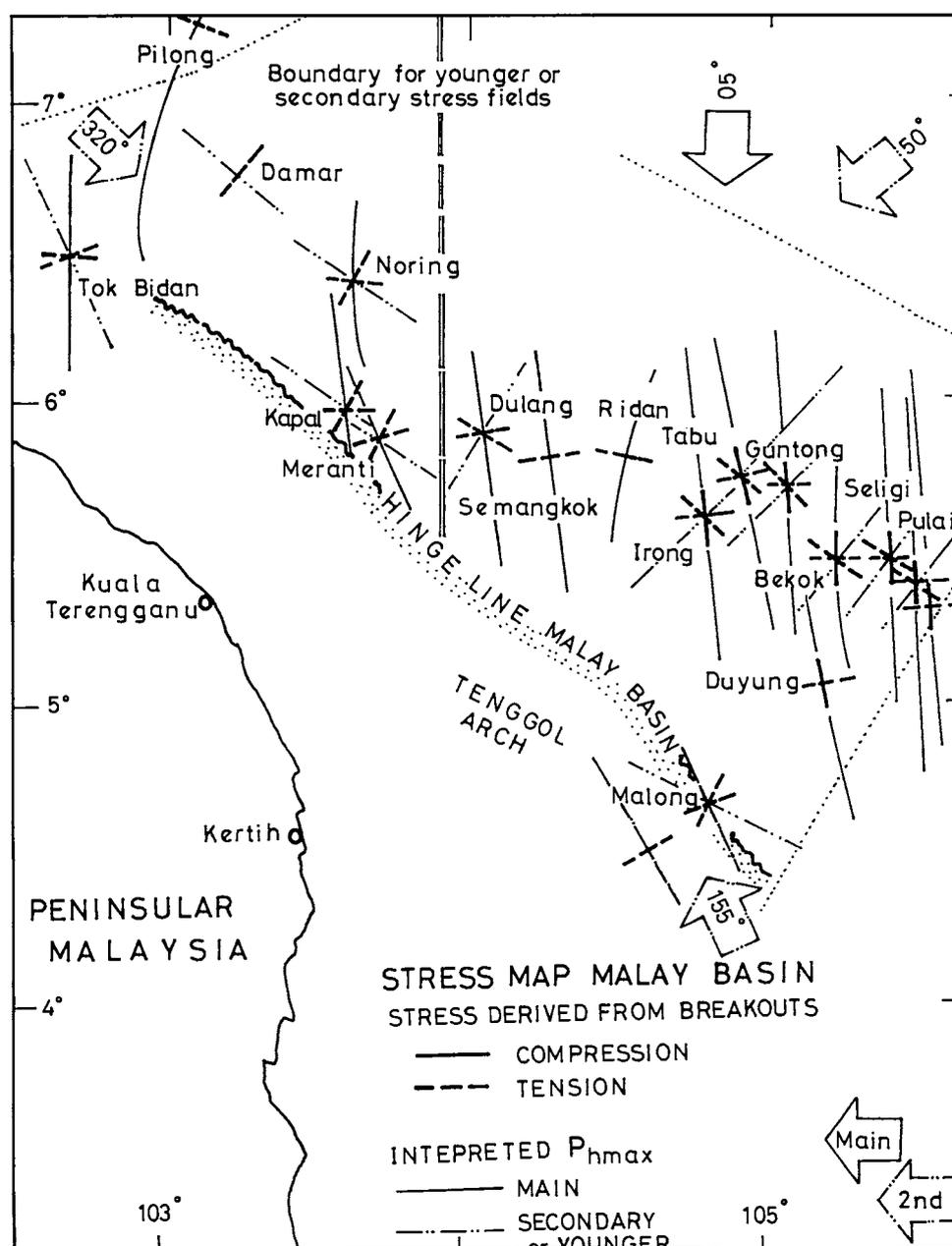
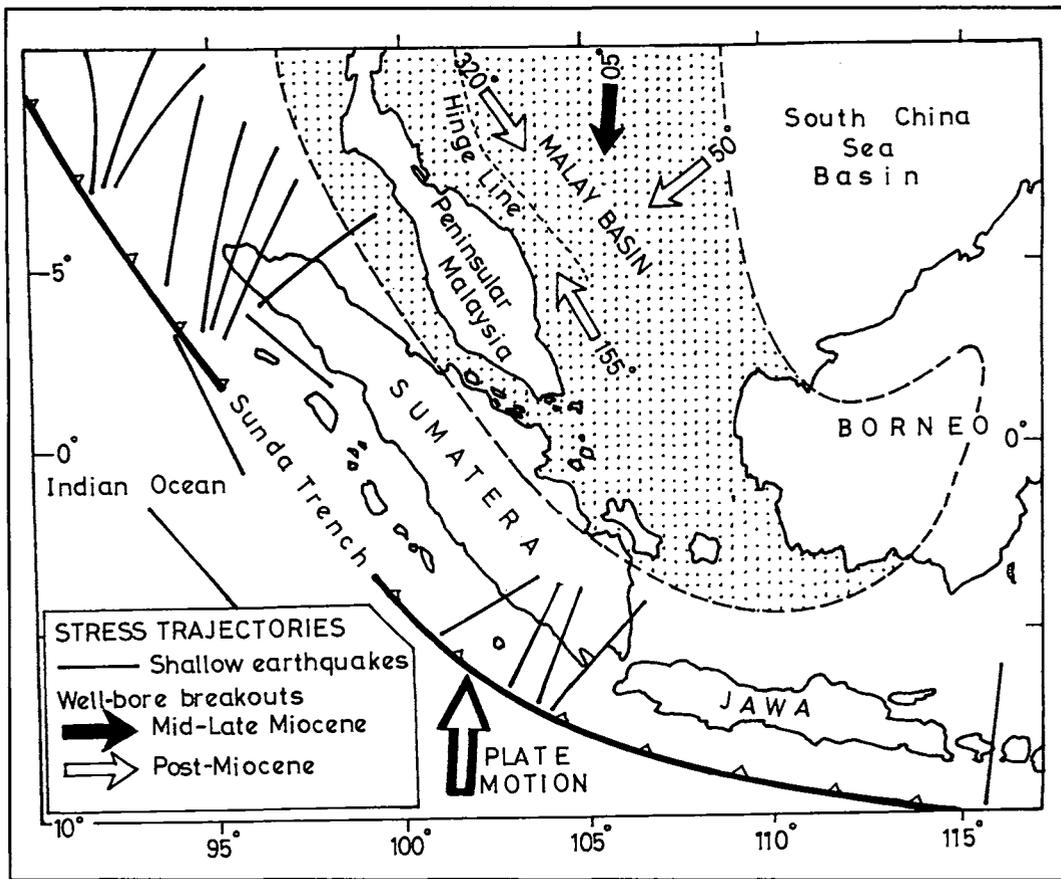
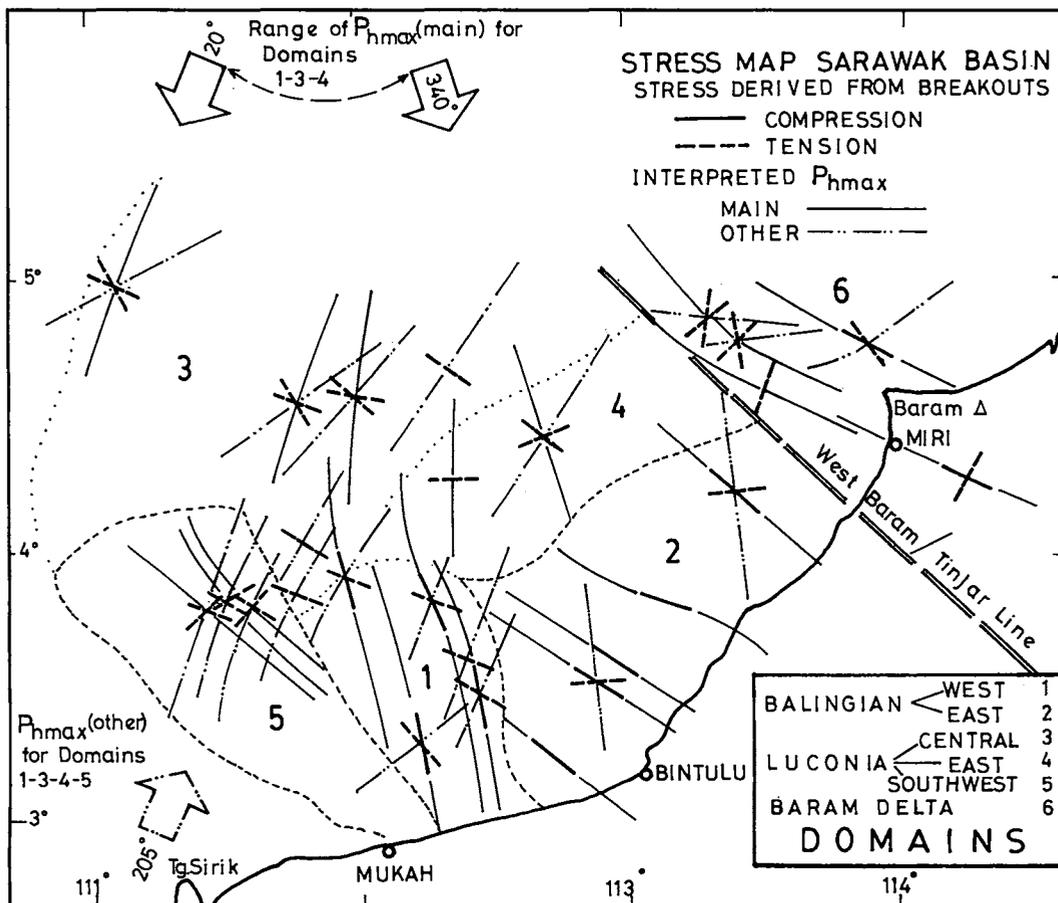


Figure 2. Stress map of the Malay Basin based on well-bore breakouts.



**Figure 3.** Stress trajectories of recent shallow-focus earthquakes correlated with compressive stress directions derived from well-bore breakouts in the Malay Basin.



**Figure 4.** Stress map of the Sarawak Basin based on well-bore breakouts.

NE azimuths (or  $40^\circ$  according to Mohd Idrus Ismail, 1989). In the Tabu field, NE breakouts and corresponding orthogonal set occur above 5,500 feet MRT, while East (in the original report more precisely indicated as  $80^\circ$  azimuth) breakouts and their orthogonal set are found below that depth. This implies that the system of NE-breakouts may represent the younger stress regime. In an earlier interpretation it was suggested that the system of East and North breakouts are related to the E-W fold structures and north-south anticlinal crestal faults of the Malay Basin. However, the origin of the system of NE and NW breakouts is not known (Mohd Idrus Ismail, 1989). Figure 3 suggests that the NE and NW stress system of the Malay Basin is genetically related to the current regional stress field which is represented by earthquake stress trajectories. The NE maximum horizontal stress is roughly parallel to the earthquake compressive stresses. The NW maximum horizontal stress in the NW and SW parts of the Malay Basin is roughly perpendicular to the earthquake compressive stresses and seems to represent a variation of the current stress field, that is, its maximum and minimum horizontal stresses have interchanged places. The  $05^\circ$  regional maximum horizontal stress seems to represent an older stress regime, that was also responsible for developing the east-west folds and thrust faults in the Malay Basin.

Mont and Suppe (1992) include well-bore breakouts of Sumatra in their study of possible relationship of breakout directions with secondary stress fields adjacent to large strike-slip faults. From the Central and South Sumatra basins, 27 and 25 wells were investigated. The average number of breakout intervals per well was 10 in the range of well depths between 82 and 2,128 m. The mean maximum horizontal stress directions are  $39^\circ$  and  $50^\circ$  in Central and South Sumatra, respectively. They arrive at the conclusion that the breakout orientations result from regional compression roughly parallel to the NE-SW direction of convergence of the Indian-Australian Plate with respect to Southeast Asia. In other words, the stress fields in those basins are unrelated to strike-slip motion along the 1,600 km long Sumatra Fault Zone.

## SARAWAK BASIN

The Sarawak Basin is the western part of the large Cenozoic depocentre comprising the continental shelf off the north coast of Borneo and most of onshore Sarawak. Its eastern part is the Sabah Basin, while the Baram Delta area to the east of the so called West Baram-Tinjar tectonic line marks the transition zone between these two

basins (Fig. 4). Based on structural and depositional differences, the Sarawak Basin is divided into several provinces: (i) a, since Early Miocene, relatively stable Central Luconia platform located between subsiding regions fed by major rivers, the (ii) Baram river system in the east and a palaeo-Rajang drainage system in the west. Other geological provinces are (iii) Tatau (characterized by WNW to NW striking half-grabens), (iv) West Luconia (containing the thickest sedimentary column in excess of 9 km), (v) Southwest Luconia, (vi) Balingian, (vii) Tinjar, the (viii) Rajang Accretionary Prism with strong mid-Tertiary folding (Fig. 5). The north side of the Sarawak Basin is marked by block faulting that occurred at the end of Early Miocene. Since then, the entire area has experienced tilting northward, which is also documented by Quaternary morphological features (Tjia, 1983b).

### Stress Map Sarawak Basin (Fig. 4)

Well-bore breakouts from 31 wells at 19 localities offshore and from one locality onshore within the Sarawak Basin have been analyzed and interpreted (Mohd Idrus Ismail, 1989). The complex stress orientations show some systematic pattern when viewed separately in six stress provinces (Fig. 4). On Figure 4, **Main**  $P_{hmax}$  refers to maximum horizontal stress interpreted as compression from well-bore breakouts. **Other**  $P_{hmax}$  refers to maximum horizontal stress positioned perpendicular to breakout directions, which represents tension direction. In general, Figure 4 displays a rather systematic change in compression direction, that is from NNE in the west to North in the centre, and to WNW east of the West Baram Line. This tectonic boundary clearly separates different **Other**  $P_{hmax}$  directions in the region to its west from that to its east. The oblique angles between **Main**  $P_{hmax}$  and **Other**  $P_{hmax}$  range between  $35^\circ$  and  $60^\circ$ , but the orientation of **Other**  $P_{hmax}$  is more easterly, while in the region east of this boundary, the orientation of **Other**  $P_{hmax}$  is to the west of their respective **Main**  $P_{hmax}$  orientations. At present, we have no explanation for this phenomenon. The compressive stress pattern shown on Figure 4 is further analyzed by comparison with compressive stress directions derived from tectonic features shown in Figure 6. The range of **Main**  $P_{hmax}$  is  $020^\circ$  to  $340^\circ$  for Domains 1-3-4, the **Other**  $P_{hmax}$  is approximately  $205^\circ$  for Domains 1-3-4-5.

Figure 6 is a tectonic map of part of Borneo slightly modified from Hamilton's (1979) regional tectonic map covering the larger Indonesian region. Maximum horizontal stress directions for the coastal zone of Sarawak are marked perpendicular to structural trends. Between Tanjung (Cape) Sirik

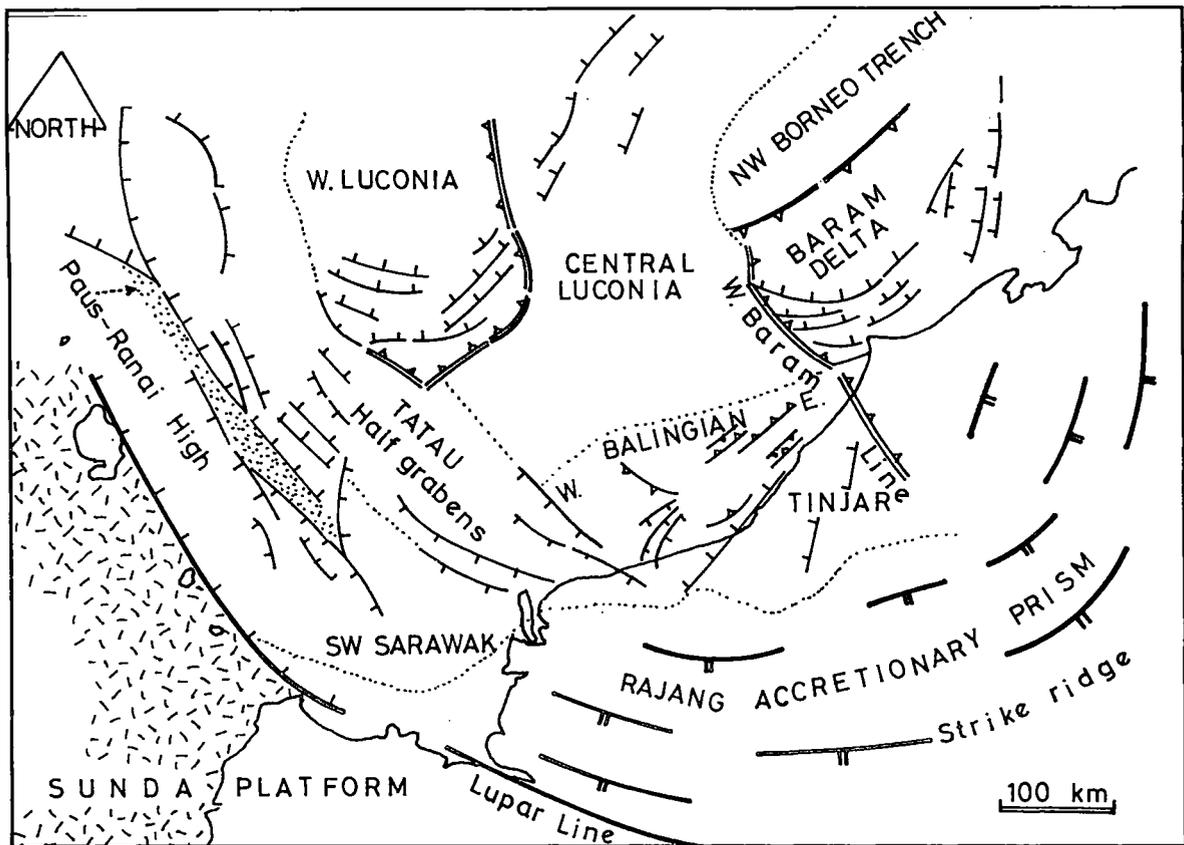


Figure 5. Tectonic domains of the Sarawak Basin. Simplified after Johnson *et al.* (1989).

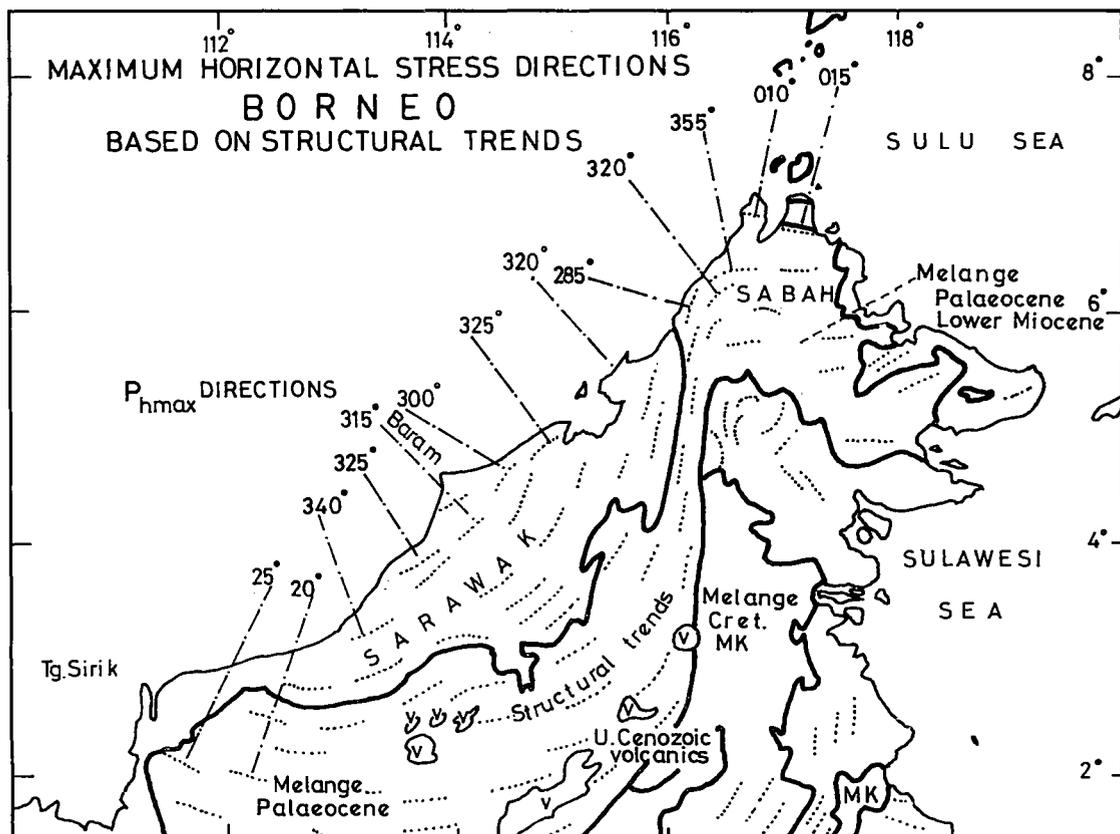


Figure 6. Maximum horizontal stress directions of part of Borneo based on a tectonic map by Hamilton (1979). Dash-dot lines indicate horizontal compression directions perpendicular to structural grain.

and the Baram delta, the maximum stress directions range between  $025^{\circ}$  and  $315^{\circ}$ . The structural trends indicate that this change is systematic. Figure 7 shows the orientations of **Main**  $P_{hmax}$  and some **Other**  $P_{hmax}$  (from Domain 5: Southwest Luconia) interpreted from well-bore breakouts in the Sarawak Basin (compare with Fig. 4). For most of the Sarawak Basin, except Domains 1 and 5, the orientation of maximum horizontal stress systematically change in accordance with the change of structural trends onshore as displayed in Figure 6. The change in orientation is from  $020^{\circ}$  in the west to  $290^{\circ}$ – $295^{\circ}$  in the east, in the Baram Delta province. The orientations of maximum horizontal stress in adjacent domains, that is Domain 1 and Domain 2 are distinctly different, and the change in orientations appears abrupt. Therefore, we interpret a provisional tectonic boundary separating these two domains. If the  $P_{hmax}$  in Domain 1 was consistent with the regional structure, it should have been orientated north-south. Its present orientation suggest  $20^{\circ}$  counter-clockwise rotation of Domain 1, which could have been produced by dextral slip along the interpreted N-S tectonic line.

Figure 8 shows the orientations of **Other**  $P_{hmax}$  of the Sarawak Basin. For domains west of the West Baram Line (except Domain 2) and west of the interpreted tectonic line between Bintulu and Mukah, the regional maximum horizontal stress (for reference's sake named PS-1) is northeast. In Domain 2 it is north-south (PS-2), and east of the West Baram Line it is between ENE and E (PS-3). In Domain 5 maximum horizontal stress of this category is orientated NW (PS-4).

Depth-slice breakout maps for the entire Sarawak Basin was prepared earlier (Mohd Idrus Ismail, 1989). The series of depth-slice breakout maps consists of 1,000 feet vertical intervals between 1,000 and 12,000 feet depth. These maps show that breakout directions seem vertically compartmentalized and it was provisionally concluded that the change in stress field propagated from deeper to shallower levels as result of subsidence at the Southwest Luconia and Baram Delta depocentres (Mohd Idrus Ismail, 1989). These depth-slice breakout maps also indicate that the NW compression direction (PS-4) in Domain 5 is contained in the older beds of Cycle I and Cycle II (Oligocene-Early Miocene). This is the only correlation suggested by the maps between geological age and stress field.

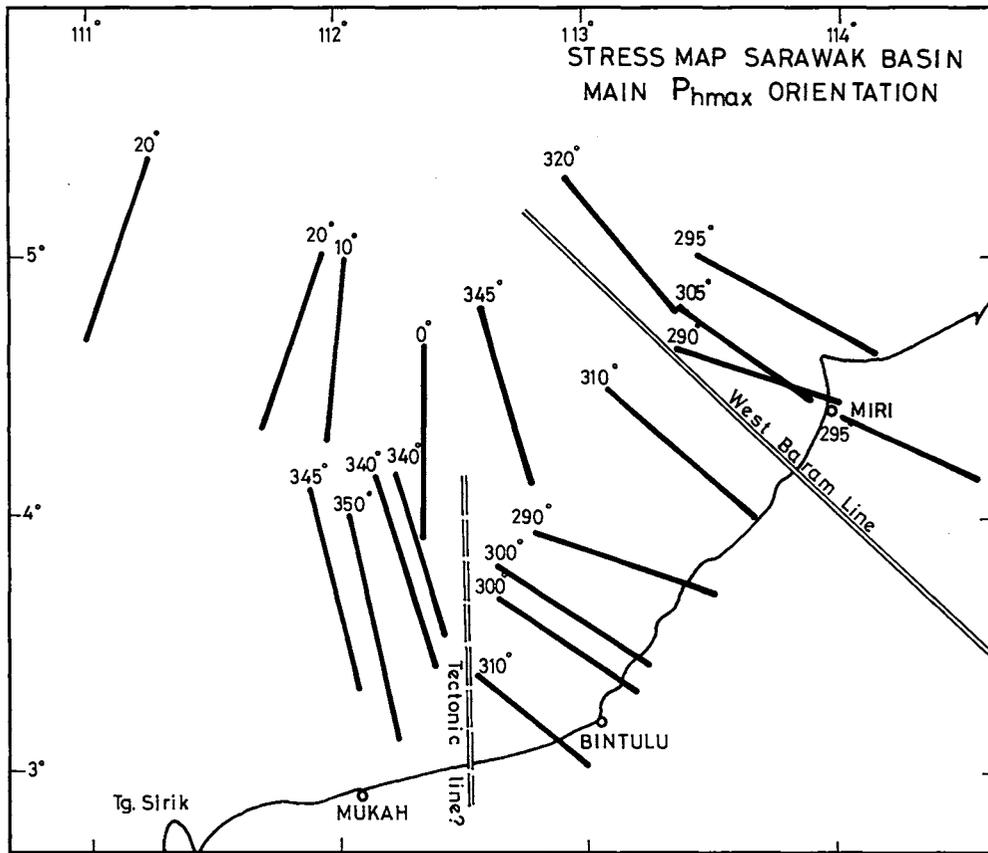
The NE-trending PS-1 and ENE to E-striking PS-3 compressions are roughly parallel to the strike of the inactive NW-Borneo subduction trench, or for that matter, parallel to the SW-segment of the currently inactive rift axis of the South China Sea Basin (Briais *et al.*, 1993). The orientation of PS-

3 probably reflects a local deviation in the regional tectonic grain. We do not know the geological cause for the PS-2 north-south orientation. The northwest PS-4 direction is roughly parallel to grabens in the Southwest Luconia Domain. If these two phenomena are genetically related, we suggest that in Domain 5, a vertical maximum principal stress orientation during graben formation subsequently interchanged position with that of the intermediate principal stress (that in the graben-formation stage was horizontal and parallel to the graben trend). It should also be noted that PS-4 is approximately perpendicular to PS-1. Therefore, PS-1 and PS-4 most probably evolved from the same tectonic cause.

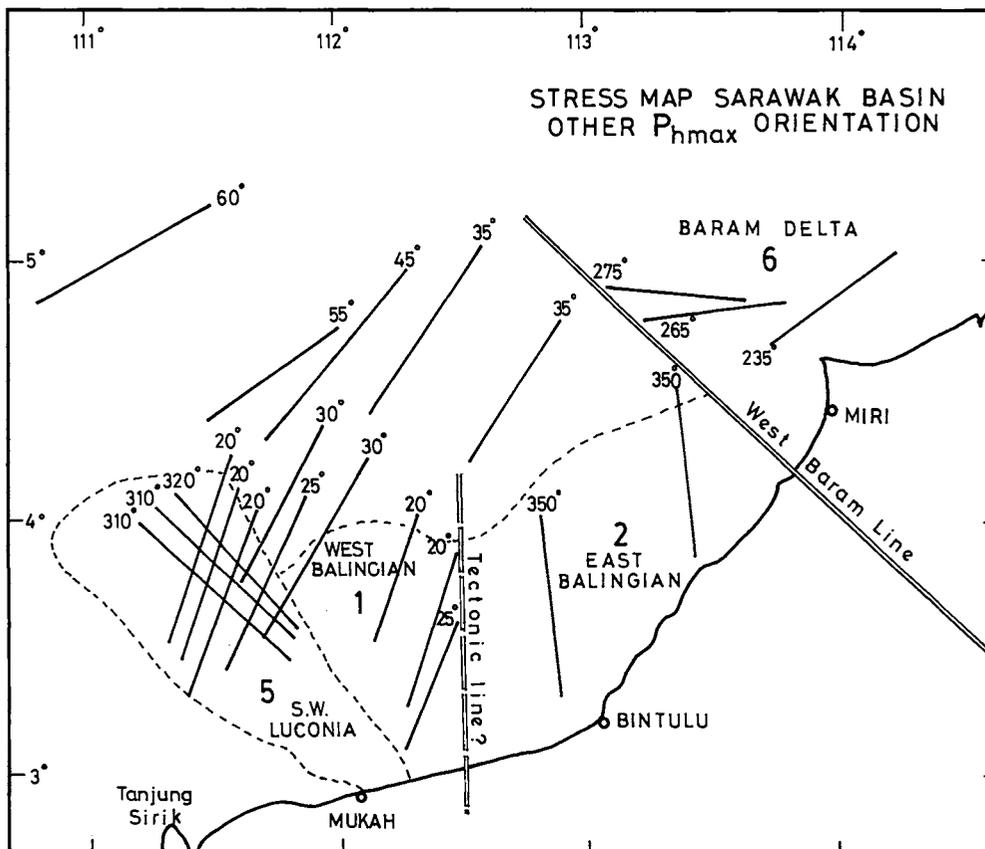
## SABAH BASIN

The divisions of Northwest Sabah on Figure 9 is simplified from Tan and Lamy (1990). The **Crocker Accretionary Prism** consists of strongly deformed, imbricated and NW-verging Lower Miocene and older rocks of deep-marine origin and zones of mélanges. Chert-spilite, mafic and ultramafic enclaves occur in a broad zone named the Kinabalu Suture (Tjia, 1988). Structural trendlines are NE and become east to the north of Kota Kinabalu. The raised part of the prism has been the provenance of Neogene clastic sediments offshore. The **Inboard Belt** is marked by strongly compressed structures. Its southern part has N-S striking anticlines with intensely faulted crests which are associated with wrench faults. In the central part, WNW interfere with N-S structural strikes forming domes. In the north are present NE and E-W structural trends. The **Outboard Belt** is marked by weaker compressional wrench-related deformation but stronger extensional features represented by major N-S, down-to-basin normal faults. This belt is essentially a late Miocene to Pliocene depocentre containing sediments that prograde NW-ward from shallow to deep marine environments. The **NW Sabah Margin** has three subunits. In the southwest this domain merges with the Baram Delta setting. Gravity sliding of large masses of the delta has masked the boundary of these two domains. Compressional features increase in intensity towards NE where imbricated sedimentary packets have been transported to the edge of the **NW Sabah Trench**. The latter is an elongated feature where Oligocene-Miocene SE-inclined carbonates are overlain by mainly clayey pelagic sediments. In the northern part of the trench, the pelagic sediments partly rest upon a lower Tertiary chaotic unit which is thrust over the carbonates.

From Oligocene to Early Miocene, its tectonic history was dominated by SW-ward subduction of



**Figure 7.** Stress map of the Sarawak Basin based on compression directions interpreted from well-bore breakouts.



**Figure 8.** Stress map of the Sarawak Basin based on well-bore breakout directions.

the South China Basin Subplate under Borneo. Resulting uplift formed the so called Deep Regional Unconformity upon which were deposited prograding sequences of middle to early Late Miocene beds over the Inboard Belt. In post-subduction time (post-5e magnetic anomaly = 17 Ma or late Early Miocene according to Briais *et al.*, 1993; Tan and Lamy, 1990 believe subduction ceased later in middle Late Miocene), the Inboard Belt experienced strong compressional deformation, that was accompanied by uplift and that formed the Shallow Regional Unconformity. A transtensional stress field resulted in two depocentres: the Outboard Belt and the East Baram delta. From the Late Miocene onward, stable conditions have persisted in the Inboard Belt. Late Pliocene deformation affected the Outboard Belt and the East Baram Delta, developing anticlinal warps transected by numerous crestal faults (Tan and Lamy, 1990).

### Stress Map Sabah Basin (Fig. 10)

Figure 10 shows  $P_{hmax}$  (maximum horizontal stress) directions interpreted through analysis of

well-bore breakout directions in 36 wells at 29 localities in the Sabah Basin, offshore to the northwest of Sabah (Mohd Idrus Ismail, 1989). The **Main**  $P_{hmax}$  and **Other**  $P_{hmax}$  were derived from compressive stress and breakout directions, respectively. The **Main** maximum horizontal stress direction ranges between  $300^{\circ}$ – $325^{\circ}$  (abbreviated as PSa-1) for the Kota Kinabalu-Klias section, and between  $330^{\circ}$ – $350^{\circ}$  (PSa-2) for the northern section. PSa-1 and PSa-2 control different areas separated by an interpreted domain boundary that strikes NW. Figure 6 indicates that the PSa-1 and PSa-2 directions closely parallel the tectonic compression directions that were derived from structural trends (Fig. 6). In other words, the well-bore breakouts associated with these stresses have a tectonic origin. A NW-trending tectonic boundary has been placed where the structural trends change from NNE to almost east-west. The orientations of these compressive stresses differ by about  $25^{\circ}$ .

The ranges of **Other**  $P_{hmax}$  directions in the Northwest Sabah Basin are  $355^{\circ}$ – $010^{\circ}$  (PSa-3) and  $025^{\circ}$ – $035^{\circ}$  (PSa-4) in the area southwest and northeast of the domain boundary, respectively (Fig.

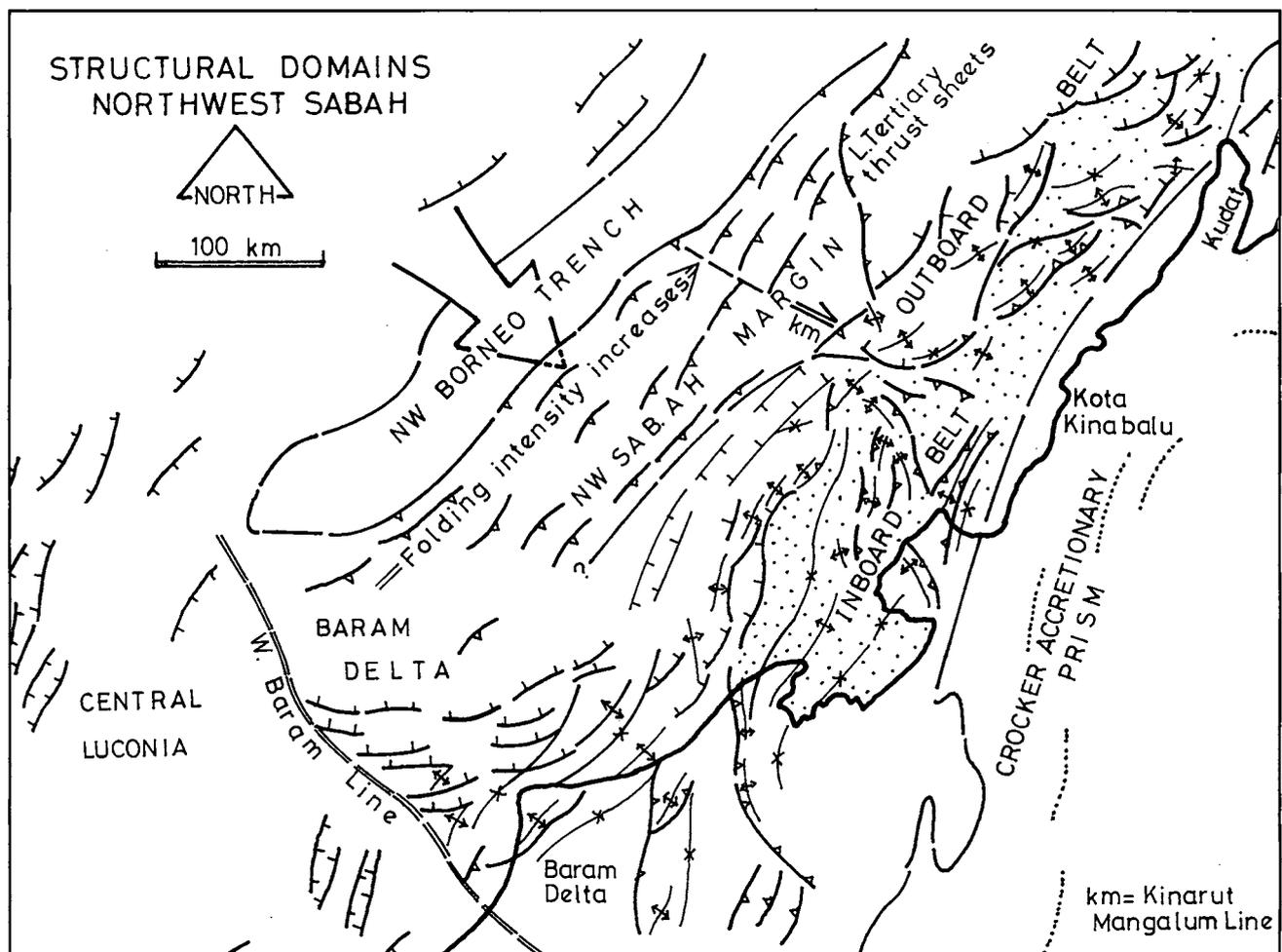


Figure 9. Structural domains of northwest Sabah adapted from Tan and Lamy (1990).

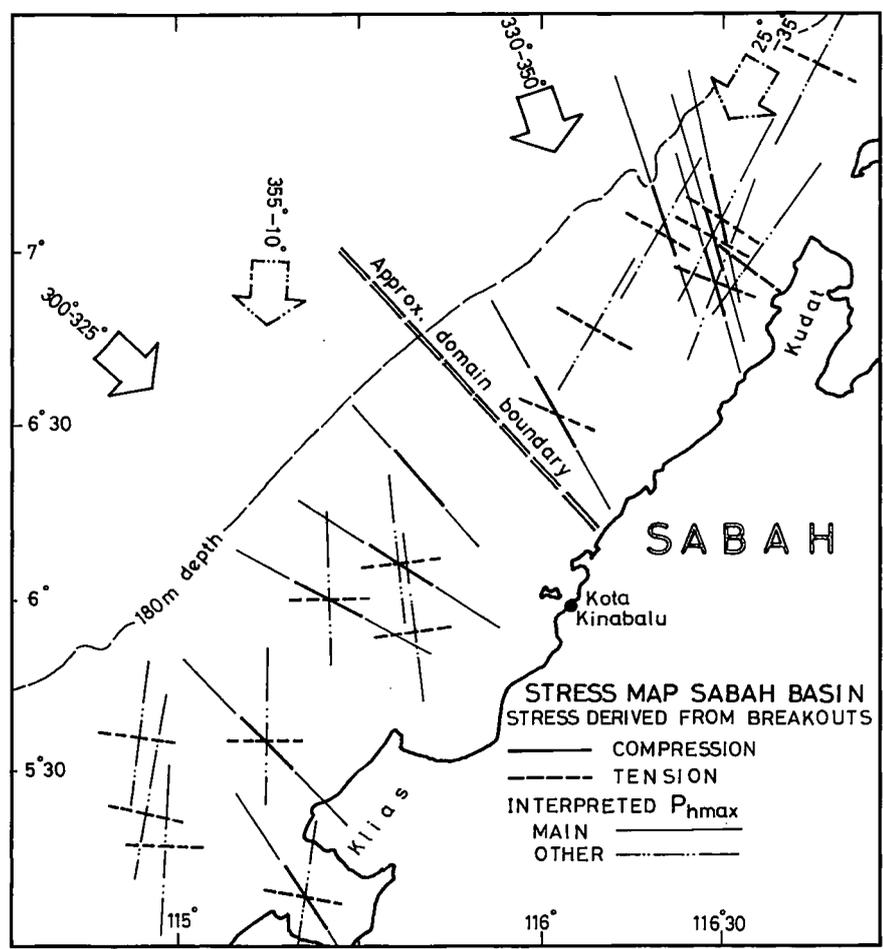


Figure 10. Stress map of the NW Sabah Basin based on well-bore breakout directions.

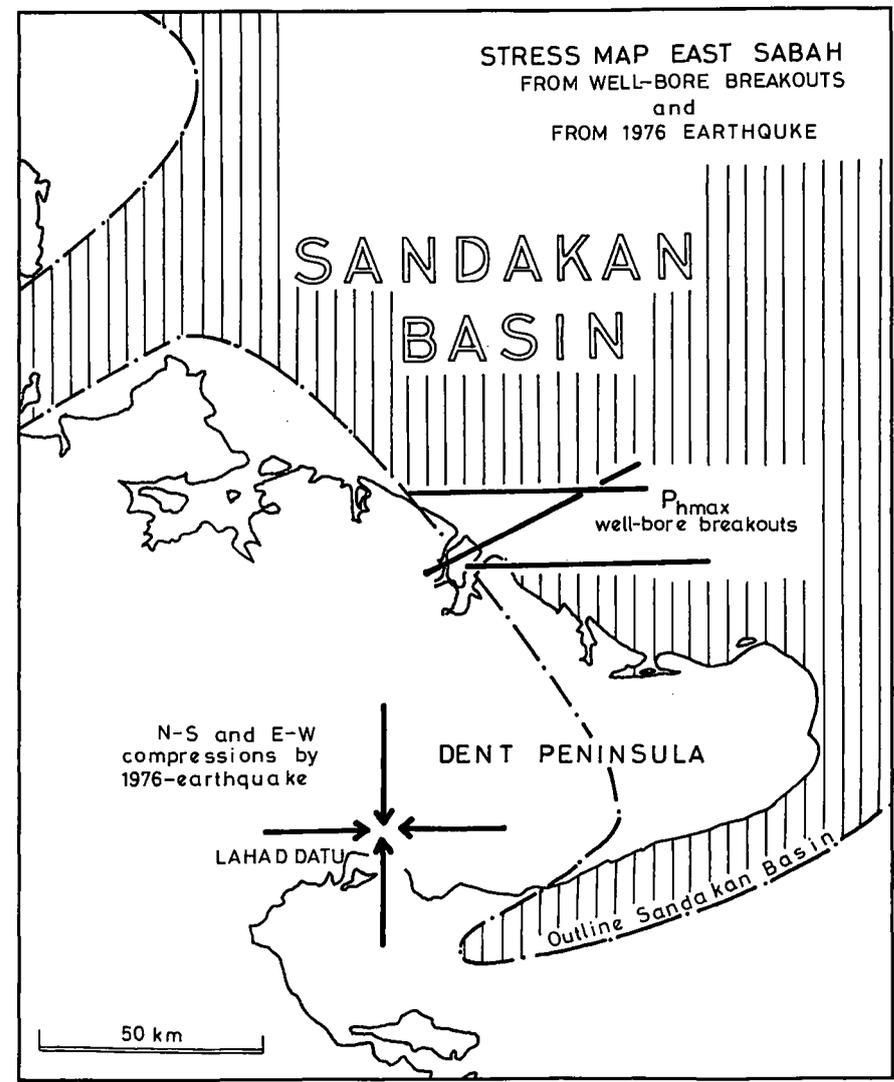


Figure 11. Stress map of the Sandakan Basin based on well-bore breakout directions and the 1976-earthquake stress field.

10). The difference in orientation between PSa-3 and PSa-4 is also 25° to 30° or similar to the orientation difference between PSa-1 with PSa-2. This consistent deviation in the orientations of **Main**  $P_{hmax}$  and **Other**  $P_{hmax}$  suggests that the region northeast of the domain boundary rotated clockwise some 25° relative to the southern region (Fig. 6). In other words, the original position of PSa-3 and PSa-4 may have been north-south similar to PS-2 in the East Balingian Domain of the Sarawak Basin. We do not know the geological cause of this north-south compressive stress in this part of Borneo.

## SANDAKAN BASIN

The Sandakan Basin strikes 330° off Eastern Sabah and contains more than 7 km Cenozoic sediments (Fig. 11). Breakouts studied in three wells show one  $P_{hmax}$  direction approximately perpendicular to the basin orientation, while the other two are orientated east-west (Mohd Idrus Ismail, 1989). Ground-surface deformation by the 1976 earthquake in the Dent Peninsula shows evidence of N-S alternating with E-W compressions (Tjia, 1983a). In other words, the three breakout directions in the Sandakan Basin appear associated with tectonic processes, that is, regional compression perpendicular to the basin's elongation (one case) and horizontal east-west compression that also manifestates in a recent earthquake.

## SUMMARY AND CONCLUSIONS

1. In the Malay Basin, well-bore breakout directions in the younger layers (above 5,500 feet MRT) are consistent with the stress field determined from shallow-focus earthquakes with epicentres to the west of Sumatra. This set of breakouts is orientated NE and its orthogonal representative is SE. In older layers (below 5,500 feet MRT) breakouts had occurred in response to approximately N-S maximum horizontal stress direction. That same stress field was probably also responsible for the formation of east-west folds and east-west thrust faults in the basin.
2. In the Sarawak Basin, the range of one regional set of well-bore breakout directions is consistent with the "swing" in tectonic trends onshore as exhibited by Cenozoic sediments in the Rajang Accretionary Prism. However, an abrupt change in breakout directions in the West Balingian Domain compared to those in the East Balingian Domain suggests the existence of a tectonic line (provisionally drawn north-south) midway between Bintulu and Mukah. Other sets of breakout directions are restricted to certain domains. Breakouts resulting from NE-maximum horizontal stress (PS-1) occur in domains 1-3-4-5. In Domain 6, the Baram Delta, the originally NE orientated maximum horizontal stress (PS-3) probably rotated to ENE or E-W. Sinistral slip along the West Baram Line may have caused the clockwise rotation of Domain 6. The trends of PS-1 and PS-3 are parallel to the SW segment of the currently inactive South China Sea spreading ridge. Therefore, a genetic relationship is implied. In Domain 2, maximum horizontal stress (MHS) direction is N-S. This orientation could have been achieved through 30° counterclockwise rotation of originally NE directed MHS in Domain 2. Domain 5 also contains northwest MHS in Oligocene-Early Miocene Cycle I and Cycle II sediments.
3. Well-bore breakouts in the Sabah Basin possess consistent orientations within each of the two domains separated by a tectonic line that approximately coincides with the so called Kinarut-Mangalum Line (Tan and Lamy, 1990). In each domain, the angular relationship between multiple breakout directions remains constant in the range of 25° to 30°. The difference in breakout orientations to southwest and to northeast of the interpreted domain boundary (Fig. 10) suggests a relative clockwise rotation of 25° between the two domains. In the southwest domain, one breakout orientation is related to the NE tectonic grain of western Sabah. The other breakout direction resulted from north-south maximum horizontal stress, for which no geological explanation is known yet.
4. In the Sandakan Basin, one well-bore breakout direction is parallel to the basin's axis and implies compression of its sedimentary fill; two other breakouts represent east-west compression related to earthquake stress.
5. This paper demonstrates that the majority of well-bore breakout orientations is related to current and past tectonic stress fields. Certain tectonic domains appear to have rotated independently from neighbouring domains. This evidence explains why conflicting results may be obtained through palaeomagnetic studies which apply locally restricted findings to include larger regions composed of multiple tectonic domains.

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## REFERENCES

- BRAIS, A., PATRIAT, PH. AND TAPPONNIER, P., 1993. Updated interpretation of magnetic anomalies and seafloor spreading stages in the South China Sea: Implications for the Tertiary tectonics of Southeast Asia. *Journal Geophysical Research* 98(B4), 6299–6328.
- HAMILTON, W., 1979. *Tectonics of the Indonesian Region*. U.S. Geological Survey Prof. Paper 1078, 345p.
- JOHNSON, H.D., KUUD, T. AND DUNDANG, A., 1989. Sedimentology and reservoir geology of the Betty Field, Baram Delta Province, offshore Sarawak, NW Borneo. *Geological Society of Malaysia Bulletin* 25, 119–161.
- LIECHTI, P., ROE, F.W. AND HAILE, N.S., 1960. The geology of Sarawak, Brunei, and the western part of North Borneo. *British Territories in Borneo, Geological Survey Department, Bulletin* 3, 360p.
- MATTAUER, M., 1973. *Les Deformations des Matériaux de l'Ecorce Terrestre*. Hermann, Paris, 493p.
- MOHD IDRUS ISMAIL, 1989. Interim report on the final phase of stress analysis and hydrofracturing directions in Malaysia based on borehole breakout studies. *Committee for Coordination of Joint Prospecting for Mineral Resources in Asian Offshore Areas (CCOP)*, Proceeding of 24th Session, 227–252.
- MONT, V.S. AND SUPPE, J., 1992. Present-day stress orientations adjacent to active strike-slip faults: California and Sumatra. *Journal Geophysical Research* 97(B8), 11, 995–12,013.
- TAN, D.N.K. AND LAMY, J.M., 1990. Tectonic evolution of the NW Sabah continental margin since the Late Eocene. *Geological Society of Malaysia Bulletin* 27, 241–260.
- TJIA, H.D., 1983a. Earthquake stress directions in the Indonesian Archipelago. In: T.W.C. Hilde and S. Uyeda (Eds.), *Geodynamics of the Western Pacific — Indonesian Region*. American Geophysical Union, Geodynamics Series 11, 413–422.
- TJIA, H.D., 1983b. Quaternary tectonics of Sabah and Sarawak, East Malaysia. *Sains Malaysiana* 12(2), 191–215.
- TJIA, H.D., 1988. Accretion tectonics in Sabah: Kinabalu Suture Zone and East Sabah accreted terrane. *Geological Society of Malaysia Bulletin* 22, 237–251.
- TJIA, H.D., 1993. Inversion tectonics in the Malay Basin: Evidence and timing of events. *PETRONAS Research and Scientific Services*, Report No. RP5-93-04, July 1993.
- TJIA, H.D., 1994. Origin and tectonic development of Malay-Penyu-West Natuna basins. *PETRONAS Research and Scientific Services* (Technology Week, 20–21 June 1994).

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