Geol. Soc. Malaysia, Bulletin 36, December 1994; pp. 119-126

Inversion tectonics in the Malay Basin: evidence and timing of events

H.D. TJIA

Petronas Research & Scientific Services Sdn. Bhd.
Lot 1026 PKNS Industrial Estate
54200 Hulu Kelang

Abstract: Pre-Oligocene half grabens of the Malay Basin suggest a tensional origin, while their uparched/folded Oligocene to upper Miocene sedimentary fills have been accepted to represent a later-stage compressional deformation. This structural inversion probably took place in middle to late Miocene time. The tensional regime has been attributed to "extrusion" of continental Southeast Asia (including the Malay Basin basement) as result of hard collision between the Indian subcontinental plate with the Asian Plate in the vicinity of Tibet. The regional compression of Miocene time was most probably the result of change in motion of the Pacific Plate from an earlier NNW direction to a westward direction combined with the buttressing effect of the northward progression of the Indo-Australian Plate.

New evidence of inversion tectonics in the Malay Basin comprises the following examples. (1) The planimetric shapes and patterns of fault-bounded basins along the Hinge Fault Zone on the west edge of the Malay Basin suggest them to represent pull-apart depressions formed by dextral wrenching, but the NNW-striking folds of Tertiary sediments within these depressions indicate sinistral strike-slip motion as their cause. (2) The shapes of pull-apart basins within one (Laba to Mesah) of the five major, north-trending fault zones and associated *en echelon* fracture patterns indicate sinistral wrenching, whereas drag features and approximately 30 km horizontal separation of anticlinal zones suggest dextral lateral motion. (3) The right-stepping arrays of fractures across post-Oligicene basin fill suggest sinistral wrenching on a buried NW-trending fault zone along the basin's axis. However, the east-west striking folds involving Oligocene to upper Miocene sediments display *en echelon* arrays formed by dextral transcurrent motion along the basin's axial zone.

INTRODUCTION

The Malay Basin is approximately 500 km long and 200 km wide, trending northwest and parallel to the general strike of the Malay Peninsula. In the northwest, the basin adjoins the north-striking Pattani-Kra-Western basins in the Gulf of Thailand, and to the southeast the Malay Basin is separated by Tenggol basement high from the east-west striking Penyu and the eastnortheast West Natuna Basins (Fig. 1). All these basins are underlain by continental crust that also outcrops as Mesozoic and older rocks in the Malay-Thai Peninsula, Indo China, western Borneo and island groups in the southern South China Sea and Java Sea. The geothermal gradient in the Malay Basin is moderate to high and reaches an average value of 51.8 degree Celsius per kilometre (Mohd. Firdaus Abdul Halim, 1993). More than 12 km of Oligocene and younger sediments have filled the Malay Basin to the brim, obliterating any sign of a depression. Lacustrine, coastal plain and rapid fluvial sedimentation dominated during the Oligocene. From the earliest Miocene onward, sedimentation was in extensive tidal, swamp and lower coastal plain environments. Marine conditions began to prevail in the Pliocene and continued with at least one major interruption until today. That interruption was during the last glacial, when regional sea level reached at least 100 metres below the present, the Malay Basin area was then subaerial and large river systems were carved into its surface. The Pliocene and younger sediments rest with marked unconformity upon the older beds.

The structural history of the basin has been described in many published and unpublished reports to comprise three main phases (Ng, 1987, Md. Nazri Ramli, 1988). In pre Late-Oligocene (perhaps since the mid-Eocene) the Malay Basin and most of the neighbouring basins began to develop as a result of (ex)tensional tectonics. Within the Malay Basin were also formed east-west trending half-grabens. Some authors suggest that the tensional stress regime may be related to "extrusion" of the Indo China region towards south and east along major transcurrent faults (Tapponnier *et al.*, 1982, 1986). This extrusion took place as a consequence of the Indian subcontinental plate colliding with the Eurasian Plate. The ensuing suture is now marked by the Himalayan mountain range (Fig. 2).

The stress regime during the second phase of tectonic activity was compressional and resulted in

Presented at GSM Petroleum Geology Seminar '93

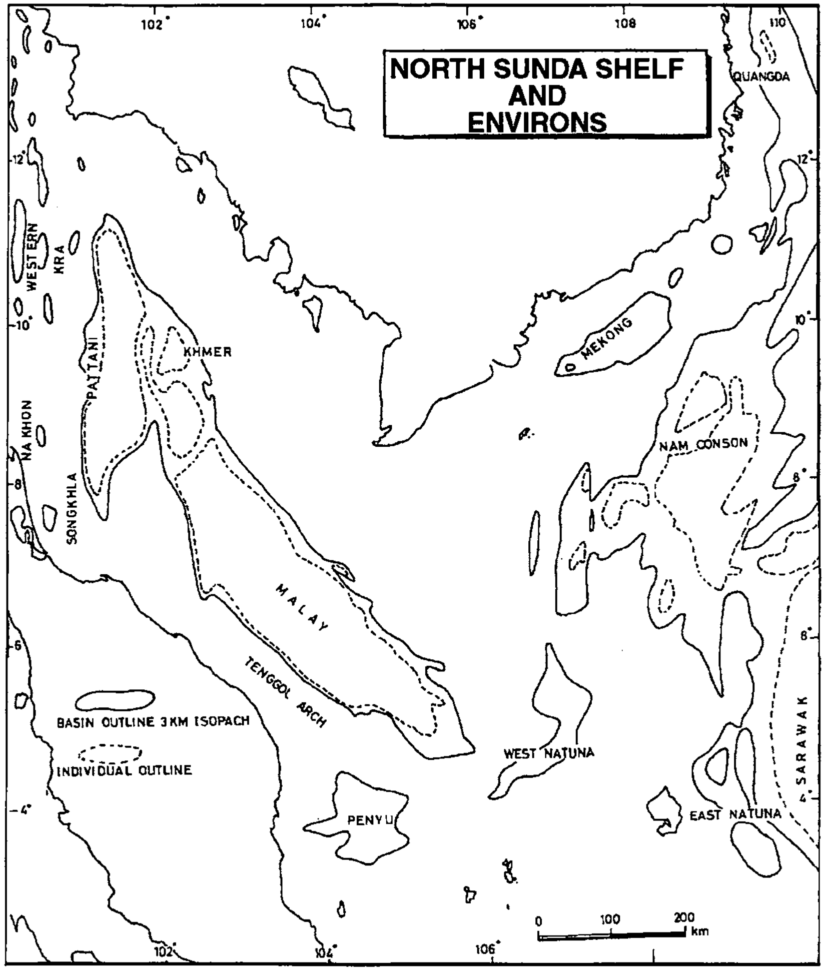

Figure 1. Tertiary basins of archipelagic Southeast Asia: Malay, Penyu, West Natuna, Pattani-Khmer, Kra-Western, Mekong, Nam Conson, Sarawak and East Natuna basins.

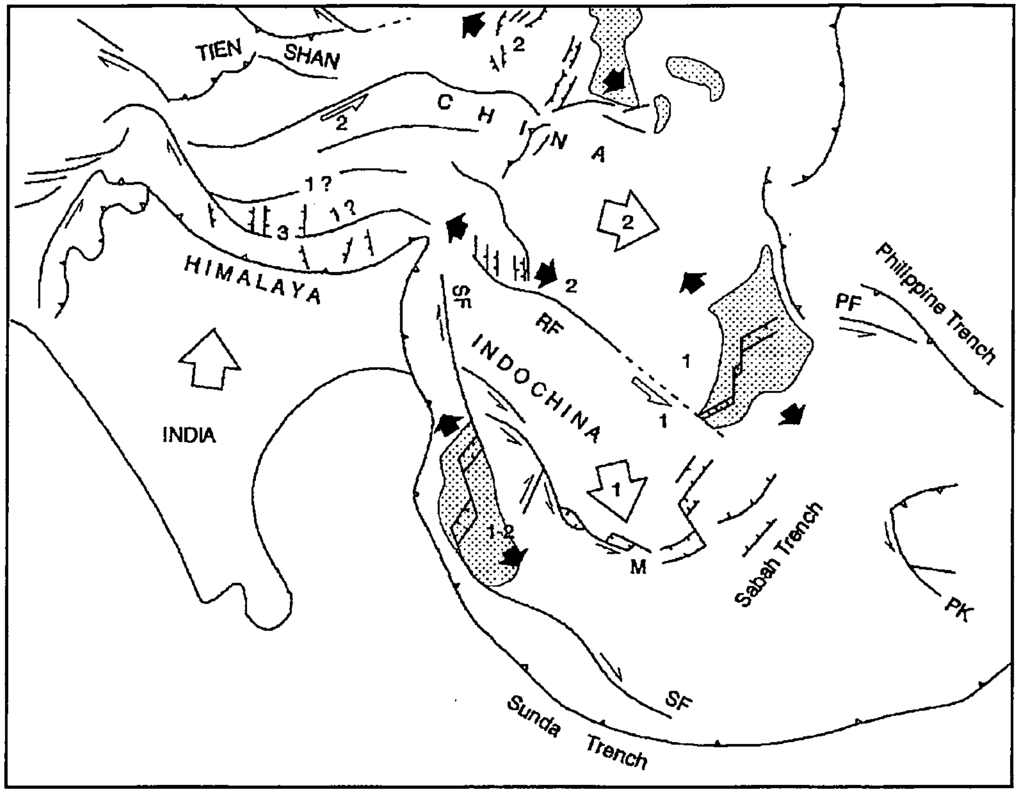

Figure 2. Extrusion tectonics in Southeast Asia resulting from collision by the Indian micro-continent. Map simplified after Tapponnier *et al.* (1982). Symbols are conventional. Extrusion phases are (1) = 50 to 20 Ma; (2) = 20 to 0 Ma; (3) most recent and future. White arrows represent major block motions with respect to Siberia; black arrows are extrusion-related extension directions. Dotted areas are extensional depressions. Faults: AF = Altyn Tagh, SF = Sagaing-Sumatra, PF = Philippine, PK = Palu.

anticlines and reverse faults; most of these structures strike east-west. The folds consist of sediments that accumulated in the half-grabens and other depressions. Regional compression may have resulted from the "extrusion" process southward being blocked by the approaching Australian Plate. In short, during this second phase of tectonism, graben fill became topographically inverted. The inversion probably occurred during the Middle to Late Miocene time.

The latest tectonic activity consisted of regional subsidence that began in the Pliocene. Tectonic strain that accumulated in the anticlines during the second phase of tectonism was released during the third phase and resulted in north-striking normal faults perpendicular to the crests of the anticlines.

In recent years, signs of inversion tectonics for the Malay Basin and adjacent regions were noted in company reports by PETRONAS, its subsidiaries, ESSO Production Malaysia Inc. (EPMI), Khalid Ngah *et al.* (1991), and in the abstract volume on "Southeast Asia Structure, Tectonics and Magmatism" edited by Flower *et al.* (1992). The term "inversion tectonics", however, was not explicitly used in these writings. The present article discusses and analyzes new evidence for inversion tectonics in the Malay Basin. In the process, yet another phase of tectonic deformation was found to have affected the Malay Basin.

EVIDENCE FOR INVERSION

General

The half grabens such as those with east-west strikes within the Malay Basin proper and the Dungun Graben in Block PM-7 (Liew, 1993) clearly represent (ex)tensional tectonics. The bottom sediments indicate that regional (ex)tensional conditions occurred in pre Late-Oligocene time. During the ensuing sedimentation, (ex)tension continued as indicated by the occurrence of growth faults transecting Late Oligocene deposits. Subsequently, the graben-filling sediments were compressed into broad anticlines. In order to achieve this, the direction of maximum principal stress must have changed. This deformational phase was followed by a yet younger tensional condition that caused normal faulting across the anticlinal crests and general subsidence of the Malay Basin region.

New Evidence

The Western Hinge Fault Zone

The Western Hinge Fault Zone forms the western boundary of the Malay Basin. The major portion of the hinge strikes northwest but changes to a north trend from the latitude of the Bintang and Damar fields, and in the south it changes into a southerly trend beyond the nose of the Tenggol Arch. Within this Hinge Fault Zone at least nine fault-bounded depressions can be recognised, many of which are half grabens (Fig. 3). The long axes of these depressions strike NNW; in other words, at a small angle to the trend of the hinge zone. The planimetric shapes of these grabens clearly show the influence of two fault sets; one set parallel to and a second set trending oblique to the Hinge Fault Zone. These plans are consistent with that of pull-apart depressions caused by right-lateral wrenching along the trend of the Hinge Fault Zone. The anticlinal axes of sediments that include up to Group E (EPMI stratigraphic nomenclature and equivalent to upper Middle Miocene) beds strike diagonally across the depressions and in regional sense are in *en echelon* pattern. This left-stepping array of fold axes suggest transpression caused by left-lateral wrenching along the Hinge Fault Zone, or lateral fault motion opposed to the motion that developed the pull-apart basins.

Dungun Graben and Dungun Fault

The Dungun Fault (proposed name) strikes NNW and is a splay of the Hinge Fault Zone. Towards the south, the Dungun Fault is straddled by a number of half grabens and ends in the so called Dungun Graben, a depression 35 km long and less than 10 km across at its widest part. The graben boundaries consist of two fault sets, one parallel and the other at an angle to the Dungun Fault strike. Liew (1993) interpreted the Dungun Graben as a pull-apart depression formed by right-lateral wrenching in pre Late-Oligocene time, that is, similar to the pull-aparts along the Hinge Fault Zone. *En echelon* fractures across the post Oligocene graben fill (Liew, pers. com.) suggest a later left-lateral wrenching along the Dungun Fault direction. Along the Dungun Fault to the north of the Dungun Graben are three smaller fault-bounded and sediment-filled depressions (Fig. 4). The half grabens of Dungun, Dungun-A and Dungun-B are deeper towards the east, whereas Dungun-C is deeper towards west. The floor of the east half of Dungun-B is of different character than that forming the other graben bottoms. It is most likely that this different floor topography of Dungun-B and the westward deepening Dungun-C were the result of right-lateral wrenching. In other words, Dungun-C may be the displaced portion of Dungun-B. In that case, right lateral displacement of 16 km is indicated. It is not yet clear if this displacement involving Dungun-B and Dungun-C took place after or before "inversion".

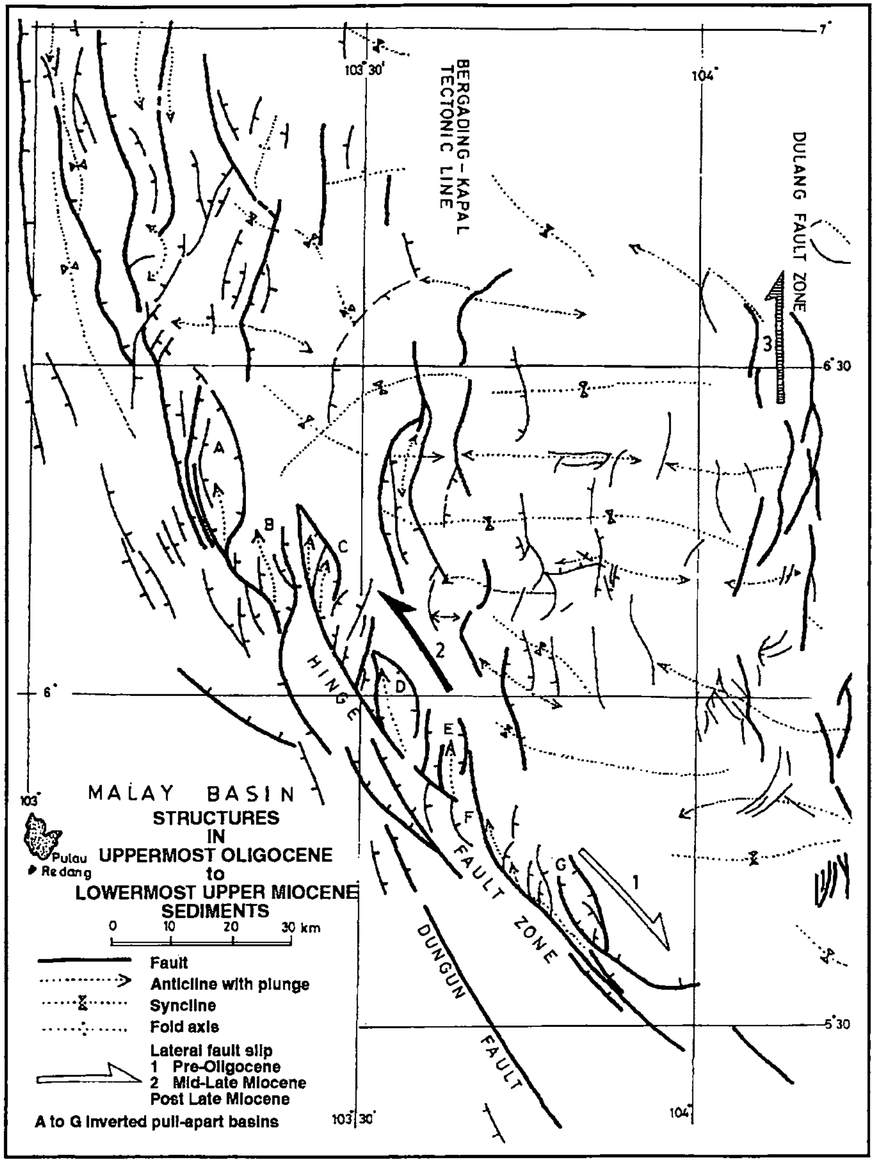

Figure 3. Structures in the northwestern part of the Malay Basin. Nature and kinematics of structures interpreted from unpublished regional maps by EPMI (1992) and WMC Petroleum (1990). Note the presence of folds within some pull-apart basins and the strongly expressed north-south fracture zones.

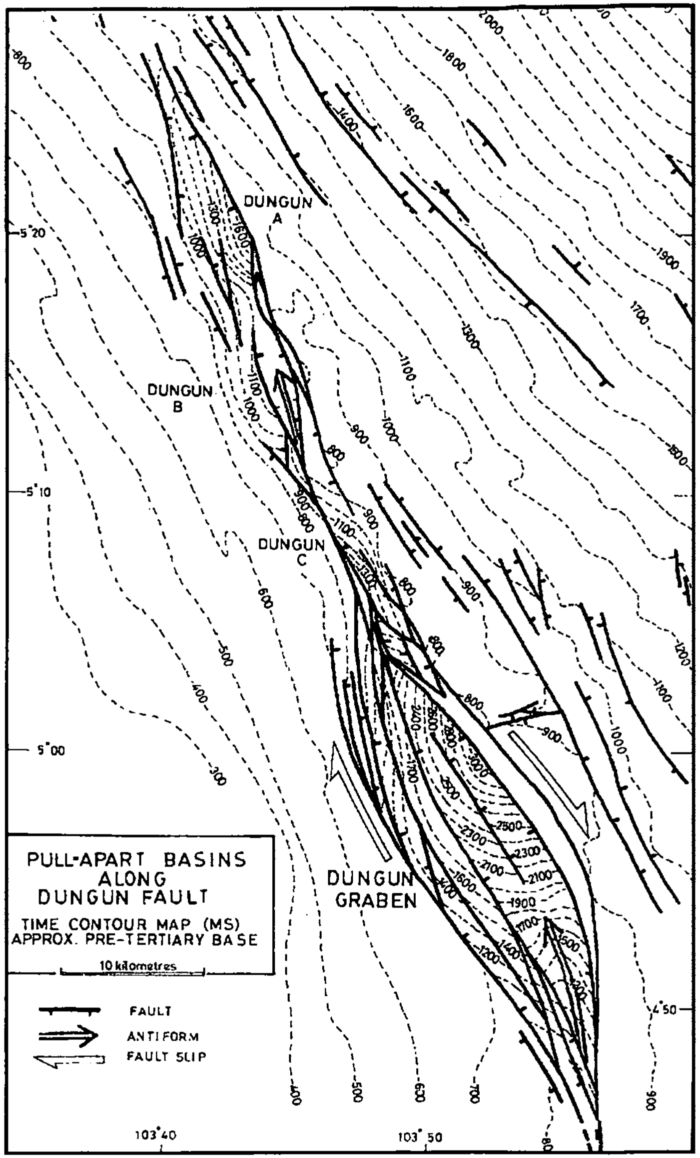

Figure 4. Dungun half-grabens as pull-apart basins along the Dungun Fault Zone. Based on WMC Petroleum (1990).

Axial Malay Basin

No seismics has penetrated beyond the Oligocene sediments in the axial zone of the basin. Company reports by EPMI and PETRONAS Carigali mention that many of the half grabens in the Malay Basin trend east-west (Fig. 5). The east-west fractures appear as *en echelon* arrays caused by left-lateral wrenching along a wide axial zone of weakness of the basin. On the other hand, the Upper Oligocene to Upper Miocene basin sediments have been folded into east-west striking folds, some of which show right-stepping arrays. Examples are in the southeastern part of the basin. Right-lateral wrenching parallel to the basin's axis seems to have been the cause.

It should be pointed out that although the trends of the basin's axis and the Hinge Fault Zone are parallel, their contemporaneous(?) lateral motions are in opposite sense. That is, initially right lateral on the Dungun Fault but left lateral along the basin's axis; the second phase of wrenching along these two fracture zones were left lateral and right lateral, respectively.

Major North-South Fault Zones

Within the axial zone of the Malay Basin, the hydrocarbon occurrences are associated with east-west trending fields (Fig. 6). These fields appear divided by north-south fracture zones into four domains. The western-most north-south fracture zone within the basin coincides approximately with the known Kapal-Bergading tectonic zone. More to the east, a so called Dulang Fault seems to right-laterally separate the fields by some 45 km. The third north-south fracture zone stretches from Angsi to Larut and for convenience is called the Laba-Mesah fault zone which right-laterally separates the hydrocarbon fields by 30 km. Colleagues from EPMI have remarked that known north-south faults in their acreages do not indicate large-scale lateral "offsets" and suggested that the lateral separations displayed by the hydrocarbon fields were the product of earlier wrench faulting. However, the north-south faults shown in support of their argument seem to belong to the post-Miocene crestal faults across anticlines (Md. Nor Mansor and Rudolph, 1993). These fractures have short lateral extent

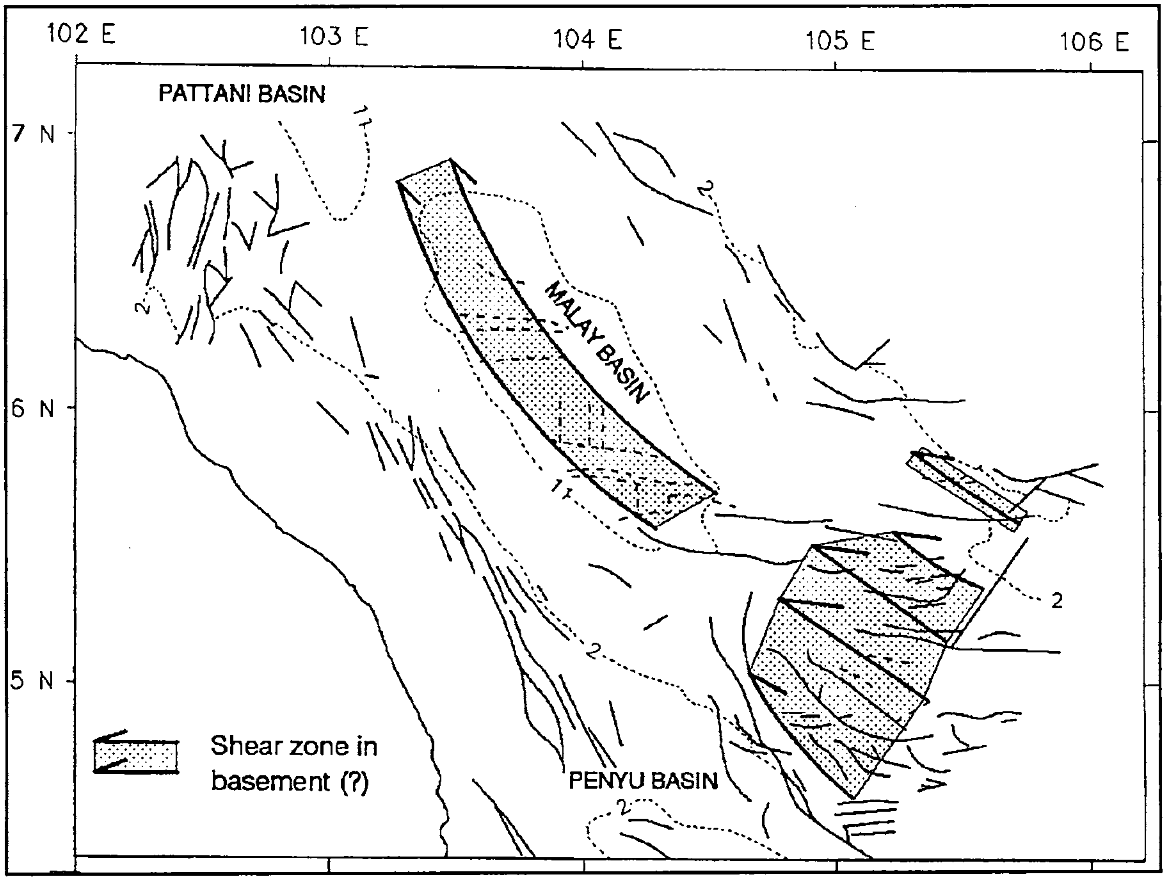

Figure 5. *En echelon* E-W fractures of the Malay Basin probably developed from left-lateral wrenching of a basement fault zone and its splays along the axis of the basin. Fractures simplified and generalised after unpublished regional maps in EPMI reports. Dots are basin outlines at 2 km and 11 km depths.

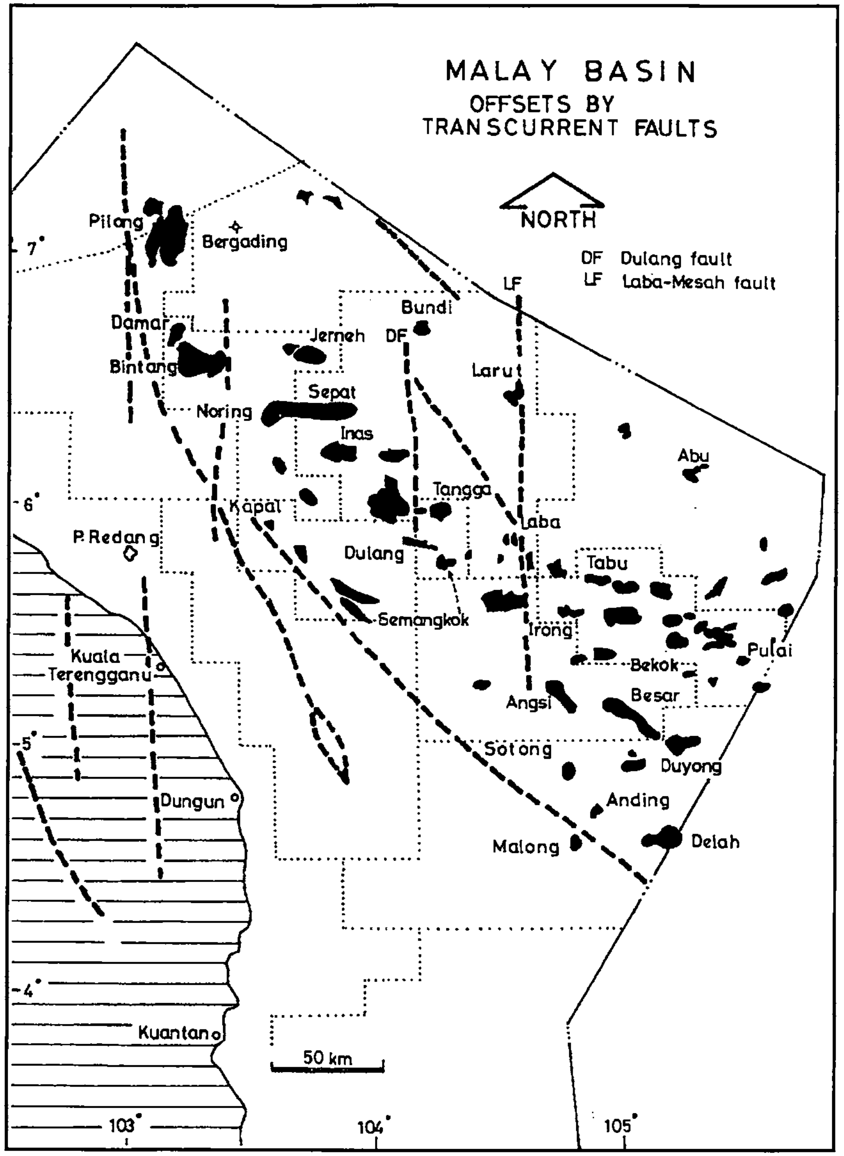

Figure 6. Major north-south transcurrent faults right-laterally separate hydrocarbon fields (black) in the Malay Basin. Lateral separations amount to 45 km on the Dulang Fault and 30 km on the Laba-Mesah fault zone. Note north-south fault zones onshore Peninsular Malaysia.

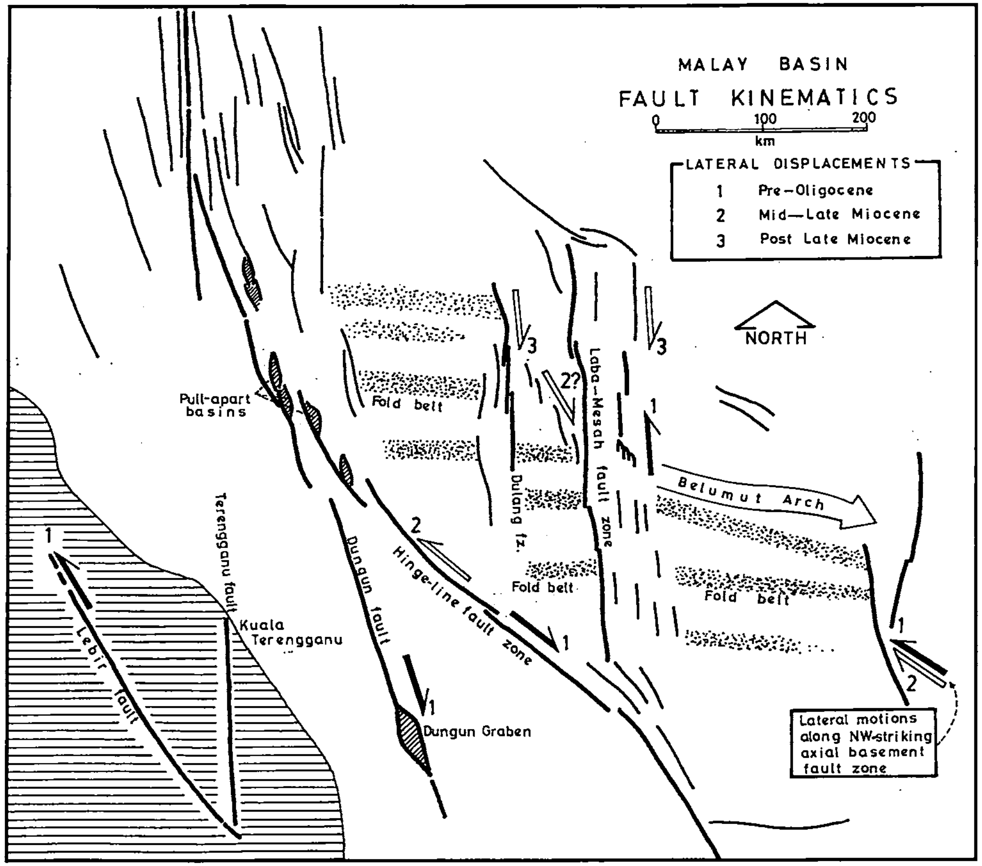

Figure 7. Fault kinematics of the Malay Basin. Note the lateral offsets of fold belts. Numbers 1 (oldest), 2 and 3 (youngest) indicate relative ages of fault motion along a particular fault zone. Provisionally, the ages are equated as follows: (1) = pre-Oligocene; (2) = Middle to late Miocene; (3) = (?)Post Late-Miocene.

and have been accepted to represent gravity faults that developed in the post-deformational tensional stress field.

In the vicinity of the main Laris Field, segments of the Laba-Mesah fault zone are curving and form at least three small pull-apart depressions that suggest left-lateral wrenching as their original cause. In other words, the Laba-Mesah fault zone, and by virtue of its parallel strike most probably also the Dulang fault zone, initially moved in sinistral sense. The later transcurrent motion was right lateral and displaced the hydrocarbon fields.

TIMING OF STRUCTURAL EVENTS

Along the Hinge Fault Zone and its splay, the Dungun Fault, graben formation represented by pull-apart depressions began in pre Late-Oligocene time before the bottom sediments were laid down. The pull-aparts were results of transtension developed by right-lateral motion along the Hinge Fault Zone (Fig. 7). Tensional conditions persisted during part of the basin filling as indicated by growth faults across the Upper Oligocene to Lower Miocene sediments. During the middle to late Miocene, the Hinge Fault Zone experienced transpression that folded the basin fill and caused left-lateral strike-slip motion.

A buried major, basement fracture zone along the axis of the Malay Basin most probably exists (Fig. 5). I propose to name the faults belonging to this fracture zone as ***Axial Malay Faults***. Left-lateral shearing on this northwest-striking fracture zone should account for the formation of east-west striking half grabens within the basin. This transtensional stress regime affecting the basin existed prior and during the deposition of the Oligocene beds. During the deposition of middle to upper Miocene beds, the stress conditions changed into a transpressional regime. Graben fills were compressed into regional east-west folds. In other words, tectonic inversion took place. The overall *en echelon* fold pattern suggests right-lateral transcurrent movement along the basin's axis during the middle to late Miocene (Fig. 7). In post-Miocene time, the basin area experienced tension. Extensional fractures striking north-south developed across the crests of anticlines

The east-west regional folds and associated hydrocarbon fields are transected and apparently displaced right-laterally. Dextral slip on the Dulang Fault approaches 45 km; on the Laba-Mesah Fault the dextral separation is 30 km (Figs. 6 and 7). These fault motions should have taken place during the late stages of Miocene sedimentation, or more likely, contemporaneous with the development of the angular unconformity separating "Pliocene" and younger beds from the deformed "Upper Miocene" and older sediments. On Figure 7, this dextral fault motion is indicated by half-tipped arrows and the number 3. Within the wide Laba-Mesah fracture zone are *en echelon* fractures and small pull-apart grabens that indicate left-lateral motion (half-tipped arrow and the number 1 on Fig. 7). These structures resulting from brittle deformation are depocentres and are therefore interpreted to have developed prior to the late Oligocene sedimentation.

FAULT KINEMATICS

Figure 7 shows the major structural elements of the Malay Basin and two onshore fault zones in the pre-Tertiary basement rocks of Peninsular Malaysia. Left-lateral slip on the onshore Lebir Fault has been interpreted earlier (Tjia, 1972). Based on the geological history of the Peninsula it is widely accepted that tectonic deformation involving regional stress fields other than gravity ended at the beginning of the Cenozoic, at the latest. The Terengganu Fault was interpreted by Tjia (1989) on a SAR image taken by a NASA space shuttle in 1981. This fault and other north-trending onshore faults are probably part of the ubiquitous regional fault set in the Gulf of Thailand and farther north in Thailand. The latest detectable motion on these faults has been of normal sense. However, their great lengths and linear plans suggest a transcurrent nature. Both dextral and sinistral slips may have occurred on these faults during various deformational periods in pre-Tertiary time, and for those faults in the Gulf also in the Cenozoic.

During each deformational period, the transcurrent motions on the Hinge Fault Zone and Dungun Fault on the one hand and lateral slips on the basin axial zone on the other, are in opposed sense. In other words, the elongated crustal slab bounded by these fault zones moved laterally as a unit. In pre-Oligocene time the slab moved towards southeast (arrow 1). During the mid-late Miocene the slab slid northwestward (arrow 2). This differentially sliding fault-slab model is mechanically consistent with the extrusion model proposed by Tapponnier *et al.* (1982, 1986). However, the timing of deformations is different and will be presented in the near future after a tectonic analysis of the entire Southeast Asian region is completed.

The large dextral displacement on the Dulang and Laba-Mesah faults requires a maximum horizontal stress direction that acted within the north to east quadrant. The cause of that compression could be the westward convergence of the Pacific Plate with the Eurasian Plate in the South China Sea region.

CONCLUSIONS

Inversion tectonics in the Malay Basin comprises transtension followed by transpression that manifestates in successive lateral motions of opposed sense on large fault zones, and in folding of sedimentary fill of pull-apart basins. As a consequence, the elongated crustal slab bounded by the Hinge Fault Zone and an interpreted axial fracture zone of the Malay Basin, slid as one unit southeast in pre-Oligocene time and slid towards northwest during mid-late Miocene. A third deformational period, probably during the late Miocene to early Pliocene consisted of dextral slip along north-striking faults crossing the basin. These transcurrent movements caused displacements of 30 km and 45 km of the hydrocarbon fields. The horizontal compression responsible for the youngest strike-slip movements was probably generated by the westward moving Pacific Plate relative to the Eurasian Plate.

Harding (1990) wrote that "reliable identification" of wrench faults need to consider alternative structural styles as profile geometries may superficially resemble those of wrench faults. From the present findings it appears that the to-and-fro motions on strike slip faults, such as those of the Malay Basin, may be a most significant cause for confusion in interpreting flower structures from seismic profiles. Such motions are very probably not unique and could be expected to occur along many strike-slip faults elsewhere.

ACKNOWLEDGEMENT

I am grateful to Mr. Effendy Cheng Abdullah, Senior Manager, Exploration Department of PETRONAS, and the Management of PRSS for granting permission to publish this article.

REFERENCES

FLOWER, M., MCCABE, R. AND HILDE, T. (Eds.), 1992. *Southeast Asia Structure, Tectonics and Magmatism.* 1992 Geodynamics Research Institute Symposium, Texas A&M University.

HARDING, T.P., 1990. Identification of wrench faults using subsurface structural data: Criteria and pitfalls. *American Association of Petroleum Geologists Bull.*, 74(10), 1590–1609.

KHALID NGAH, TJIA, H.D. AND MAZLAN MADON, 1991. Pre-Tertiary structural patterns: Implications for formation of the Malay and Penyu basins. *Warta Geologi*, 17(6), 273 (abstract).

LIEW, K.K., 1993. Structural development of the west-central margin of the Malay Basin (basement of Blocks PM 2 and PM 7). *Geological Society of Malaysia, Annual Geological Conference 1993, Programme and Abstracts of Papers*: 37 (abstract).

MD. NAZRI RAMLI, 1988. Stratigraphy and palaeofacies development of Carigali's operating areas in the Malay Basin, South China Sea. *Geological Society of Malaysia Bull.*, 22, 153–187.

MD. NOR MANSOR AND RUDOLPH, K.W., 1993. Seismic recognition of incised valleys in the Malay Basin. *Geological Society of Malaysia, Petroleum Geology Seminar 1993, Programme and Abstracts of Papers*: 29 (abstract); also in: *Warta Geologi*, 19(6), 278–279.

MOHD. FIRDAUS ABDUL HALIM, 1993. Geothermics of the Malaysian sedimentary basins. *Geological Society of Malaysia, Annual Geological Conference 1993, Programme and Abstracts of Papers*: 17 (abstract).

NG, T.S., 1987. Trap styles of the Tenggol Arch and the southern part of the Malay Basin. *Geological Society of Malaysia Bull.*, 21, 177–193.

TAPPONNIER, P., PELTZER, G., LE DAIN, A.Y., ARMIJO, R. AND COBBOLD, P., 1982. Propagating extrusion tectonics in Asia: New insights from simple experiments with plasticine. *Geology*, 10, 611–616.

TAPPONNIER, P., PELTZER, G. AND ARMIJO, R., 1986. On the mechanics of collision between India and Asia. *In:* M.P. Coward and A.C. Ries (Eds.), *Collision Tectonics*. Geological Society Spec. Publ. 19, 115–157.

TJIA, H.D., 1972. Strike-slip faults in West Malaysia. *24th International Geological Congress, Montreal, Canada, Section 3 Tectonics*, 255–262.

TJIA, H.D., 1989. Major faults of Peninsular Malaysia on remotely-sensed images. *Sains Malaysiana*, 18(1), 101–114.

Manuscript received 10 May 1994