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The Paleo-Orientations of Northwestern Borneo and Adjacent South China Sea Basins

Paleo-Orientasi Borneo Barat laut dan Daerah sekeliling Cekungan Laut Cina Selatan

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Abstract

Limited paleomagnetic data from West Kalimantan and southwestern Sarawak appear to indicate counter-clockwise (CCW) rotation of over 50 degrees during Cenozoic. On the other hand, similar studies from Sabah show conflicting results in terms of paleo-positions. This CCW information and other plate tectonic considerations have formed the base of Southeast Asia's plate reconstructions that have seen print in a number of updated versions. The existing publications on extensive field and exploration data, including geological stress fields from wellbore breakouts, on northwestern Borneo and basins of South China Sea have not been taken into account. The latter wealth of information already established that the region under discussion consists of a mosaic-like assemblage of diverse tectono-stratigraphic terranes, each with separate tectonic development. Stress fields changed in different ways in the different terranes indicating definitively that regional, progressive CCW rotation of Borneo is not possible.

Keywords: paleomagnetism, counter-clockwise rotation, reconstruction rotation of Borneo, South China Sea

Sari

Informasi paleomagnet terbatas dari beberapa lokasi tertentu di Kalimantan Barat dan barat daya Sarawak menunjukkan rotasi berlawanan arah jarum jam hingga 50 derajat selama zaman Kenozoikum. Sebaliknya, kajian yang sama di Sabah memperlihatkan hasil yang bertentangan. Informasi terjadinya putaran berlawanan arah jarum jam serta pertimbangan tektonik lempeng telah mendasari rentetan rekonstruksi Lempeng Asia Tenggara yang telah terlihat dalam beberapa versi pembaharuan. Usaha rekonstruksi belum memperhitungkan publikasi yang ada tentang data lapangan dan eksplorasi, termasuk nilai-nilai tegasan (stress) geologi yang diperoleh dari kajian kerusakan lubang bor di barat laut Borneo dan cekungan-cekungan di Laut Cina Selatan. Dari pengayaan informasi terakhir sudah ditetapkan bahwa wilayah yang didiskusikan terdiri atas suatu kumpulan kepingan dari beragam perkembangan mintakat tektono-stratigrafi. Perubahan keadaan tegasan lapangan dengan cara-cara yang berbeda pada mintakat yang berbeda menunjukkan bahwa keadaan demikian tidak memungkinkan secara regional dan bertahap di Pulau Borneo telah terjadi putaran berlawanan arah jarum jam.

Kata kunci: *paleomagnetisme, rotasi berlawanan arah jarum jam, rekonstruksi Borneo, Laut Cina Selatan*

Introduction

Background

Geographically, Borneo Island belongs to Sundaland, but only its pre-Tertiary crystalline basement core in West Kalimantan and southwestern Sarawak are part of the Sunda Plate proper (Figure 1). Borneo's current outline has been achieved by progressive addition of Tertiary prisms of accretion on its northwestern side. Its eastern zone has had a more complex tectonic development and was influenced by separation of Sulawesi along the

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Figure 1. Geological domains of Kalimantan, Sarawak, Sabah, and Brunei Darussalam. Structural trendlines are highlighted. B = Berau mélange; S = Semitau Inlier representing the Boyan Mélange; M = Bukit Mersing Mafics indicating a suture zone.

Makassar Strait, and activity associated with the Sulawesi and Sulu Sub-plates (Darman and Hasan Sidi, 2000). Eastern Sabah is an exotic terrane and is attached to the main island along well-developed Kinabalu Suture (Tjia, 1988). The Mangkaliat Peninsula is probably also of exotic origin which is suggested by possessing structural trends discordant to that of eastern Kalimantan.

On a SIR-A radar image, a mélange terrane in Berau area between Mangkaliat and the main island was interpreted by Sabins Jr. (1983). The mélange may be indicative of a tectonic suture. The onshore northwestern region, Sarawak, Sabah, and Brunei Darussalam, is known to consist of diverse geological terranes (Liechti *et al*., 1960; Lim 1985; Hon and Lam 1992; Sandal, 1996). For instance, southwestern Sarawak is separated by the Lupar Suture/Line from the rest of Sarawak. Bukit Mersing Line is another suture that separates Sarawak lengthwise into a northern Neogene from a southern predominantly pre-Neogene region (Figure 2). Figures 2 and 3 also show the well-established tectono-stratigraphic terranes in the petroliferous Sarawak and Sabah Basins.

Paleomagnetic studies for West Kalimantan, southwestern Sarawak, and in the Kinabalu area of Sabah (Schmidtke *et al*., 1990; Fuller *et al*., 1999)

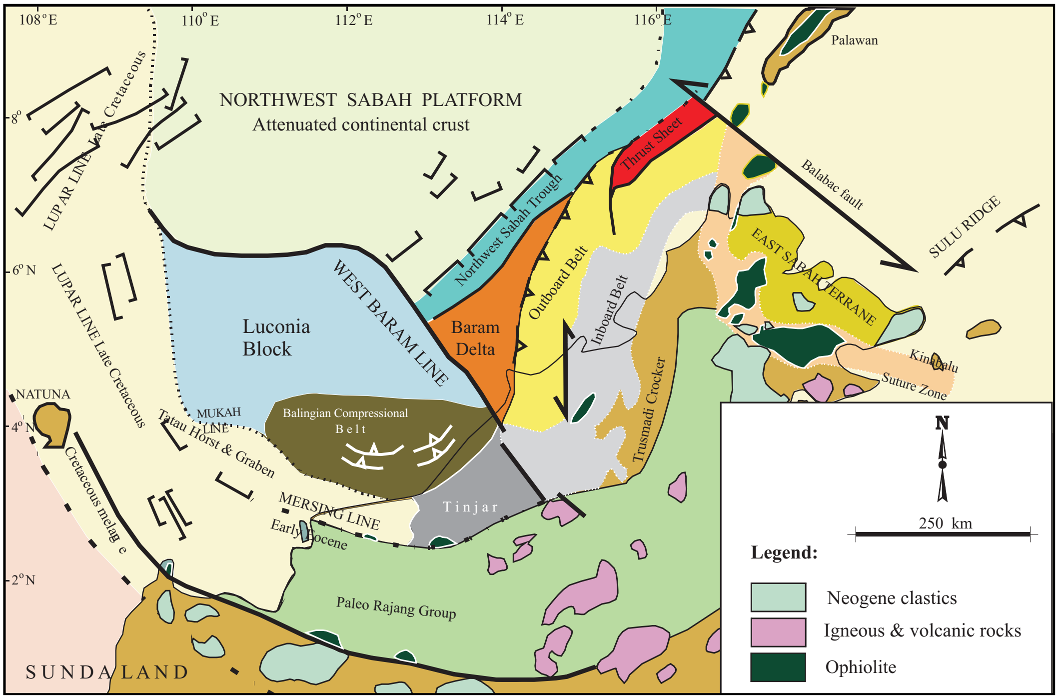

Figure 2. The amalgamated tectono-stratigraphic terranes of northwestern Borneo. The illustration uses information published in Liechti *et al*. (1960), James (1984), Tjia (1988), Sandal (1996), and Petronas (1999).

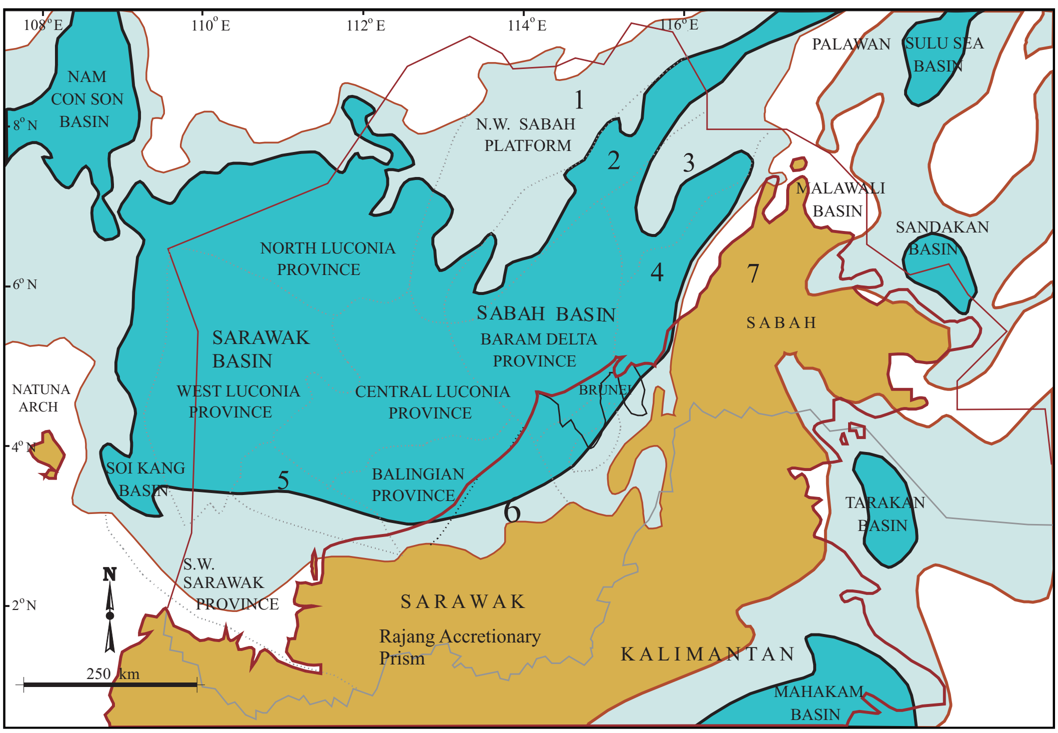

Figure 3. The hydrocarbon provinces of the Sarawak and Northwest Sabah Basins. (1) Northwest Sabah Platform, (2) Northwest Sabah Trough, (3) Outboard Belt, (4) Inboard Belt, (5) Tatau Province, (6) Tinjar Province, (7) Crocker-Trusmadi Overthrust Sheet.

resulted in publications that show close to almost 52° CCW rotation from the Neogene onward, but also of uncertain tectonic character, respectively. In spite of the known uncertainty, plate reconstructions for most of Southeast Asia's Cenozoic were attempted in several articles (one of a more recent version by Hall *et al*., 2009), each showing the core of Borneo and its eastern zone to have progressively rotated CCW during the past 50 Ma. The mosaic-like nature of the tectonic terranes of the northwestern Borneo region and that of the adjoining basins (which have been duly recognised in exploration ventures for hydrocarbon) as well as published well bore breakout patterns were not taken into account.

It is the purpose of this article to evaluate the CCW rotation of Borneo by putting relevant geological information in context. The study will show that no progressive CCW rotation of the northwestern Borneo region could have occurred.

Geological Domains of Borneo-Kalimantan

West Kalimantan is part of the Sunda Plate and forms the crystalline core of the island (Figure 1). The east and southeast sides consists of mainly Cenozoic fold-thrusts verging east (see compilation in Darman & Hasan Sidi, 2000). The Mangkaliat promontory structural trendlines are at a distinct angle with respect of those of East Kalimantan. A SIR-A (shuttle radar) image of the Berau area (B in Figure 1) has been interpreted as melange terrain (Sabins Jr., 1983) that would be consistent with Mangkaliat representing an exotic terrane. A larger accreted terrane is eastern Sabah whose structural orientation is distinctly normal to that of the rest of Sabah. Two other compelling lines of evidence consist of the existence of an up to 80 kilometres wide ophiolite zone, the Kinabalu Suture, and the significant presence of large quartz phenoclasts in the boulder conglomerate of the Late Miocene Tabanak Formation. The remainder of Sabah consists of island-arc material. The abundant quartz boulders point to continental plate environment for the East Sabah Terrane (Tjia, 1988).

The northwestern side of Kalimantan -the focus of this article- is composed of the geographical entities of Indonesian West Kalimantan, Malaysian Sarawak, and Sabah, as well as Negara Brunei Darussalam. Attached to the crystalline core of West Kalimantan are successively younger geological terranes called Kuching, Sibu, and Miri zones (Haile 1961; James, 1984; Liechti *et al*., 1961). These zones are composed of mainly Late Mesozoic, mainly Cretaceous-Palaeogene, and Neogene formations, respectively (Figure 1). Fold-thrusts are predominant structures in the two older zones. The accretionary terrane-character of northwestern Borneo is supported by the presence of melange/ophiolite belts: the Boyan mélange (S in the figure for "Semitau Inlier" of Pieters *et al*. (1987), located within the Kuching Zone), the Lupar Line, and the Bukit Mersing (M) Ophiolite. The bulk of original material extensively studied by the Indonesian and Malaysian geological surveys has been compiled by Tate (2001).

Geological Provinces of the Sarawak and Northwest Sabah Basins

The Cenozoic Sarawak and Northwest Sabah petroliferous basins are underlain by thinned continental crust that resulted from the South China Sea spreading. The event dated by magnetic anomalies in its oceanic crust had occurred from 32 Ma to 15.5 Ma (later Oligocene to the end of Early Miocene; Taylor & Hayes, 1983; Petronas, 1999). About four decades ago Shell Company had documented the basins to consist of several tectono-stratigraphic terranes (Figures 2 and 3). The mosaic-like geological assemblage has been modified over the years but the initial divisions have largely been utilized in exploration ventures for hydrocarbon (Petronas, 1999). The following examples indicate the diverse geological character of these so called provinces.

Luconia Block is characterised by limestone buildups, some towering to over 2 kilometres high. This province's eastern boundary, West Baram Line, is a separation from deeper-water environments of the NW Sabah Basin. One of its provinces, the Lower Tertiary Thrust Belt is recognised on seismic and may be part of the Northwest Sabah Overthrust Sheet interpreted from outcrops onshore Sabah (Tjia, 2003). The Baram Delta unit is dominantly deformed by gravity tectonics associated with growth of the current delta and its predecessors (Sandal, 1996). The structural designation for Balingian Province and for the Tatau Half-grabens are self-explanatory.

Details of the geologically segmented character of these two basins are documented by Petronas (1999).

Tectonic Development of Northwestern Borneo

Tectonic Stresses of the Basins

Numerous indications are known of geological stress changes, some represented in the same drill hole and other shown by successive seismic time slices of individual exploration/production blocks in the offshore basins.

In the 1980s Mohd. Idrus Ismail of Petronas, the Malaysian national oil company, studied wellbore breakouts of over a hundred wells in all Malaysian basins. At that time wellbore breakouts were determined from the oval character of drill hole cross sections as indicated by caliper logs. Eighty-one wells showed breakout directions that were considered reliable. Breakout directions are perpendicular to S_{Hmax} (horizontal maximum principal stress orientation). For the Sarawak Basin and adjacent to Baram Delta area, S_{Hmax} interpretations are in Figure 4. The breakouts were mainly from the hydrocarbon-containing stratigraphic levels, that is, latest Early Miocene to Early Pliocene. A strong correlation between consistent S_{Hmax} orientations with tectono-stratigraphic terranes are distinct. In the Luconia Province, S_{Hmax} orientations are between N35º to 55º E. In the East Balingian subprovince, S_{Hmax} are north-south. One of the unexpected findings of the study was the occurrence of different sets of S_{Hmax} in the lower, thus older, section of the well, and in the younger upper levels. For the basin this is exemplified in the Southwest Luconia Province, where the younger set of S_{Hmax} ranges between N20º E and N 30º E; in the older section, S_{Hmax} is between N 310º E and N 320º E (Figure 4). Contrary to the widely accepted opinion, we suggest

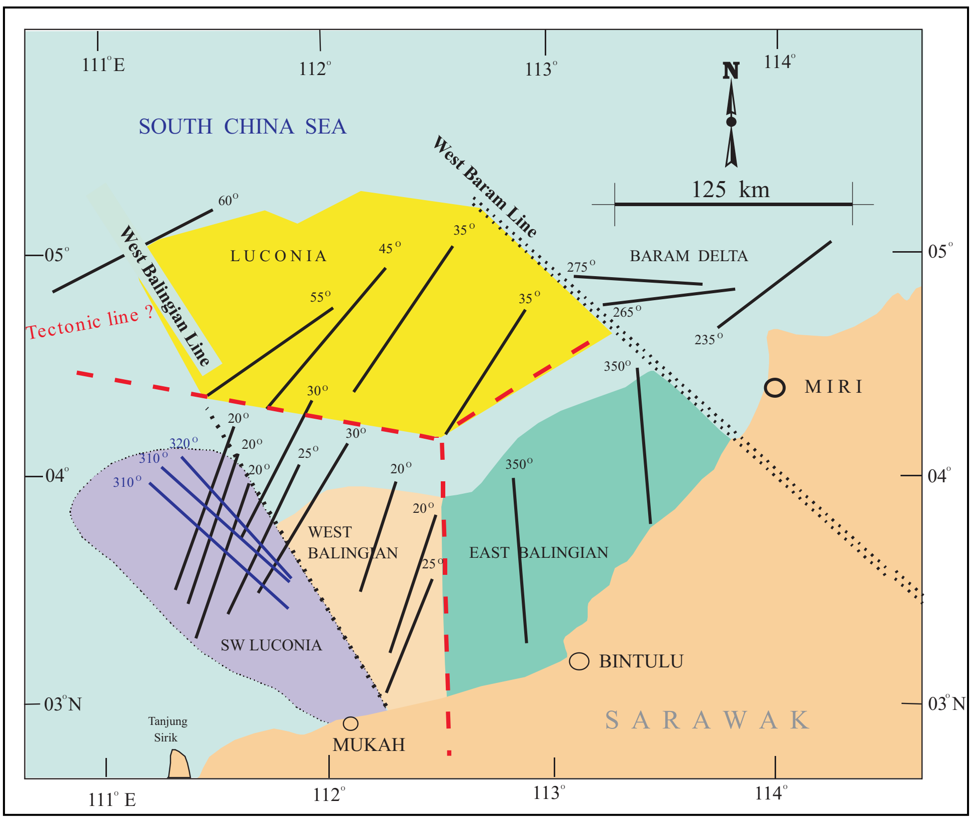

Figure 4. The Sarawak Basin stress pattern constructed from wellbore breakout study. A good correlation exist between S_{Hmax} orientation pattern and the established tectono-stratigraphic provinces. Southwest Luconia possess relics of older S_{Hmax} (blue lines) and younger (black lines) S_{Hmax} orientations occurring in the same wells. Azimuths of the younger S_{Hmax} are similar to that in the neighbouring West Balingian subprovince. Data from Tjia & Idrus Ismail (1994).

effects of older S_{Hmax} may be retained as palimpsest breakouts. Similar cases were recorded from several of the breakout sets in the other Malaysian basins (Tjia and Idrus Ismail, 1994).

Results from breakout studies in the Northwest Sabah basin are shown in Figure 5. Definite breakouts are indicated by symbols of S_{Hmax} orientation, Drilling-induced fractures were classified as "other S_{Hmax} indicators". The breakout patterns suggest two domains separated by a boundary trending northwest. This boundary is an unknown geological feature. In each of the domains two maximum principal stress are indicated by breakouts and by orientations of induced-drilling fractures. The breakouts are considered representative of the current stress; the S_{Hmax} derived from drilling-related fractures are interpreted as representing older stress conditions. These two types of S_{Hmax} orientations differ in the range of 40 to 50° angle in the southern as well as in the northern domain. The positions of the older and current S_{Hmax} in each of the domains would be consistent with a CCW rotation of 30 degrees maximum. The orientation of S_{Hmax} sets between domains also differ by up to 30°. This strengthens the notion that the domains are independent geological terranes and that their palaeo-orientations are not consistent with a general CCW rotation as interpreted from palaeomagnetic data and suggested by regional plate reconstructions.

The stress history of the Northwest Sabah basin is represented by Figure 6, where Kudat Peninsula is onshore Sabah and Pulau Balambangan, an island in the area. Seismic shows structures at the top upper

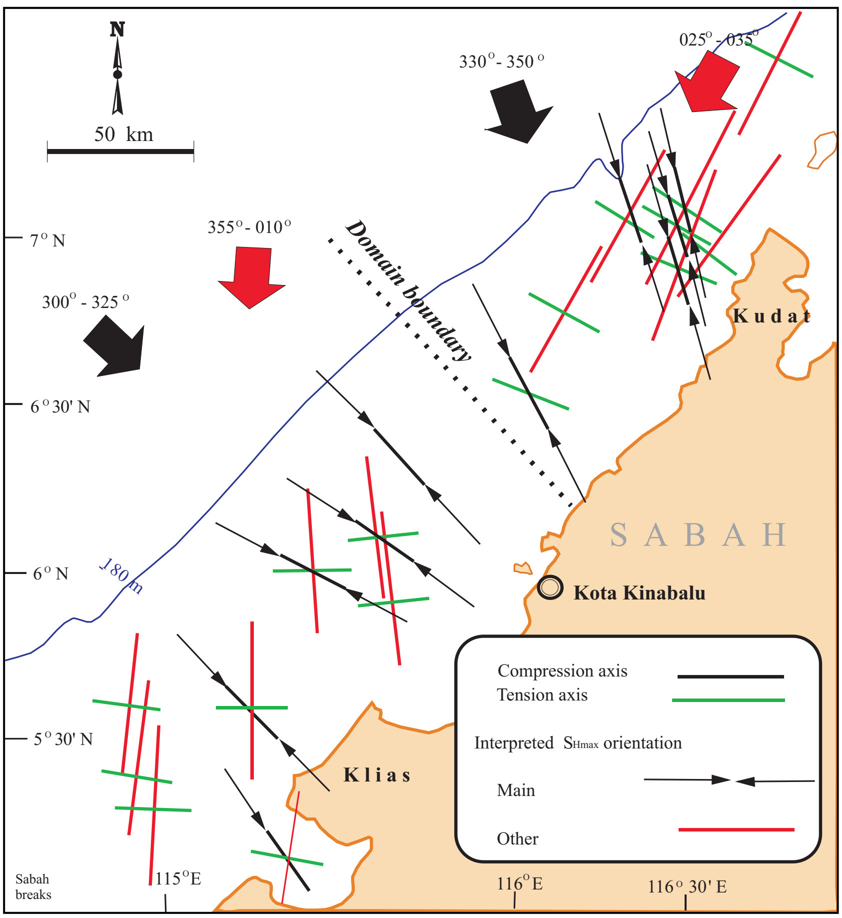

Figure 5. Compression azimuths derived from wellbore breakouts (bold black arrows) and drilling-induced fractures (bold red arrows) show patterns that characterize two different domains. In each of the domains compression azimuths obtained from the two types of information differ by a similar angle of around 50°. Combined the compression azimuth pattern between the domains diverges by around 30°. Data from Tjia & Idrus Ismail, 1994).

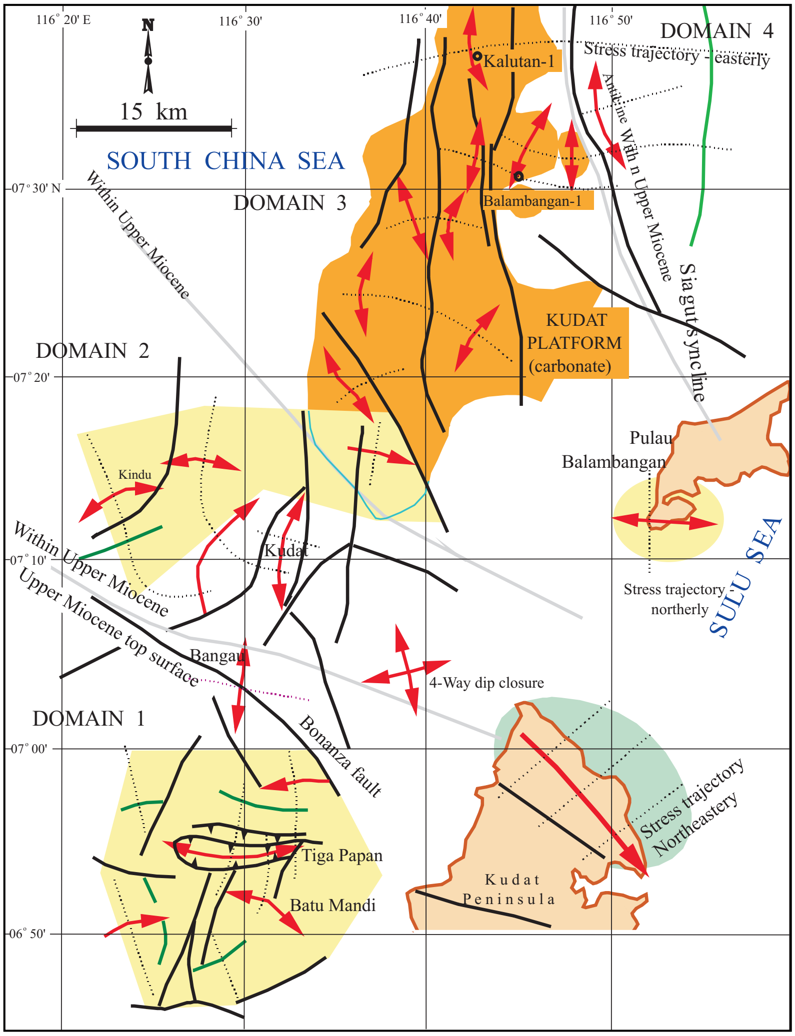

Figure 6. Stress fields of Northwest Sabah. Of the four offshore domains that shows structures at the top surface of the upper Miocene is shown in Domain 1, while the other domains display structures within the upper Miocene interval. Stress trajectories (dotted lines) are perpendicular to anticlines, most of which are doubly plunging (bold red arrows. Major faults are shown in bold black lines. This illustration is redrawn from page 516 published in the Petronas book (1999).

Miocene level (southernmost domain), while three other offshore domains show structures within the upper Miocene interval. The different structural patterns and stress fields distinctly displays five tectono-stratigraphic terranes, whose boundaries are drawn as bold grey lines in the figure. The offshore terranes actually represent time slice/intervals, where structures show maximum principal stress directions perpendicular to the fold axes. Domains 1 and 2 are associated with north-south compression; domains 3 and 4 have been subjected to east-west compression. The fifth domain is the Kudat Peninsula area that underwent northeast - southwest compression.

Two major observations are provided by the Figure: (1) This part of Sabah is a composite of different geological terranes, and (2) its diversely oriented Mid-Miocene to Upper Miocene stress fields do not support *en bloc* rotation.

Tectonic Stresses Onshore Northwestern Borneo

Kakus/Nyalau Formation

Fifty-nine structural elements of the Late Oligocene - Early Middle Miocene Kakus/Nyalau

Formation were measured in the Gabong log pond area in the Kakus River valley (coordinates: 02°43' 56" N and 113° 05' 32" E) upriver from Tatau town in north-central Sarawak. The field measurements include bedding, fold axes, strike-slip and reverse faults, and were plotted on a lower hemisphere projection (Figure 7). Two Pi-poles were determined representing general fold axes of Pi_1 = 160/22 and Pi_2 = 122/15 (Figure 8). The smaller plunge angle of the Pi_2 pole is considered representative of the younger deformation. Other deformation elements, such as reverse fault vergence and strike-slip fault sense, are consistent with the interpreted Pi-pole orientations. Sense of faulting was determined through analysis of small-scale features on fault surface (as explained in Tjia, 1967) and where available by displacement of geological boundaries shown in outcrops. The compression trend between the older and younger events differs by 47 degrees. Their respective orientations would be consistent with CCW rotation of this amount in the Kakus River area.

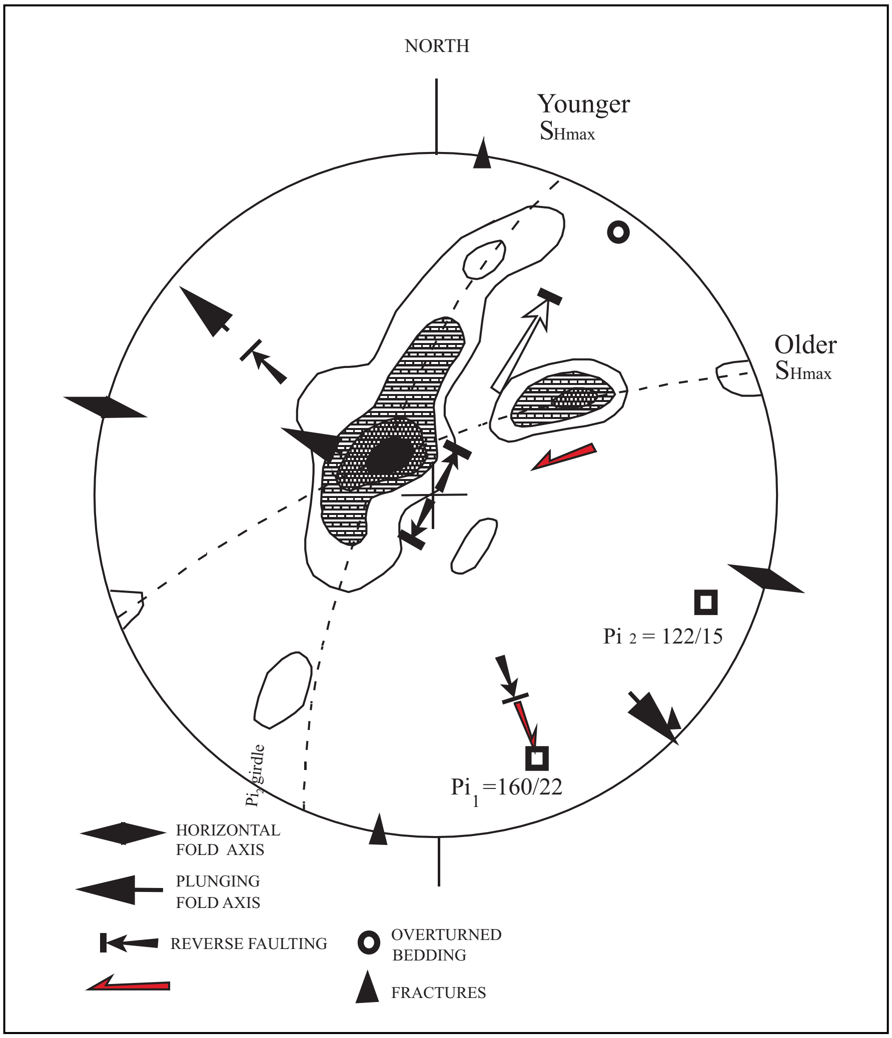

Figure 7. Equal-area, lower hemisphere projection of 59 structural elements of the Kakus Formation in the Gabong log pond area of Sungai Kakus, north central Sarawak, 2 hours upriver by boat from Tatau town. The Pi-poles constructed from bedding correspond with a younger compression azimuth of N32° - 212° East and an older (steeper plunging fold)) compression direction of N 70° - 250° East. Major reverse faulting (large blank arrow) verging northerly was produced during the younger deformation event.

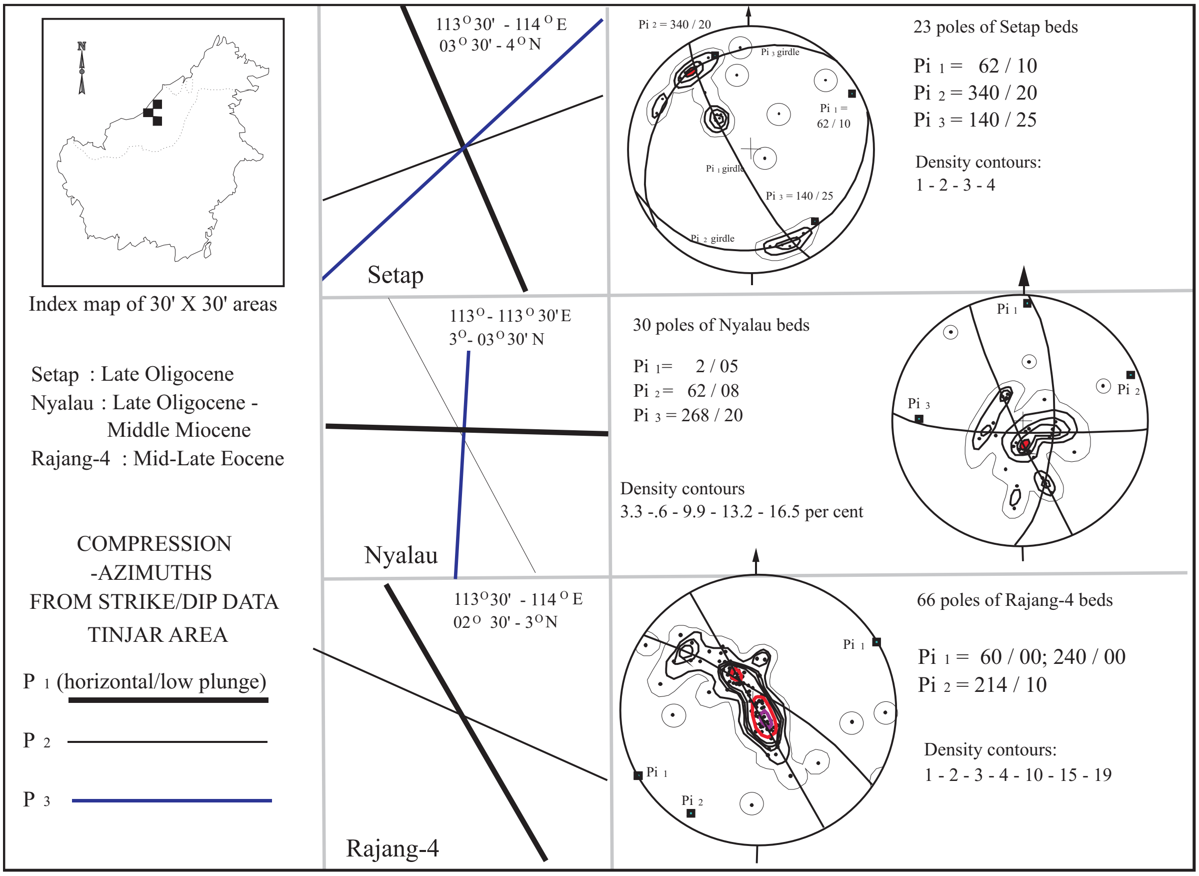

Figure 8. Strike and dip data from Geological Survey maps (Kirk 1957 and Liechti *et al*., 1961) were obtained and plotted on lower hemisphere equal-area projections. The structural data from 30º by 30º areas, each representing Rajang-4, Setap and Nyalau formations occurring in the three different areas of north-central Sarawak (index map) show two Pi-poles for the Rajang-4, and three Pi-poles each for the Setap and the Nyalau. For each formation the smaller plunge angle of Pi-poles is considered to represent the younger deformation event. For all three formations, the corresponding compression azimuths are similar and trend NNW - SSE. The older compression azimuths in the Setap and the Nyalau with respect to their younger representative azimuths diverge by 50 to 60º and could support CCW rotation having taken place in the period between the two events. Other explanations are equally possible and are discussed in the text.

Compression Azimuths in Tinjar Province

The Tinjar Province is the onshore exploration area in north-central Sarawak (Figure 8). Numerous strike-dip information has been published on the regional maps of Sarawak. The illustration shows structural information plotted on lower hemisphere equal-area projections of bedding attitudes of three different formations occurring in three 30 minutes by 30 minutes areas of the Tinjar Province (Index map of Figure 8). The formations are Rajang-4 (Mid-Late Eocene), Setap (Late Oligocene), and Nyalau (Late Oligocene to Middle Miocene). The Rajang-4 rocks are separated by angular unconformities from the other two formations. The latter two formations are capped by the regional unconformity of the Middle Miocene. Pi-poles were constructed on the equal-area projections. The smallest plunge on each plot is considered to respectively represent the latest deformation event. The Rajang-4 beds have two Pi-poles, each associated with compression azimuths of north-northwest and with an older west-northwest. The Setap and Nyalau formations each hosts three compression azimuths. Pi-pole 2 of the Nyalau plunges a low 8 degrees and may have been produced by the same deformation event that was responsible for Pi-pole 1. Pi-pole 3 of the

Nyalau differs in orientation by 52° from that of the Setap.

The derived compression azimuths for all three formations suggest the youngest deformation event trended north-northwest. The older compression azimuths in the Nyalau and in the Setap could be consistent of CCW rotation before the younger deformation event occurred. A second explanation for the orientation pattern of older and younger compression azimuths in the Setap and the Nyalau plots could also have been produced by change of the stress field without block rotation.

Conclusions

The mosaic-like assemblage of tectono-stratigraphic terranes of the northwestern Borneo region precludes providing information on systematic and progressive rotation. On the other hand, the terranes have become part of Borneo island by the Neogene. Individually, their stress history have been different and as such plate reconstructions of Southeast Asia as exemplified by a steadily CCW-rotating Borneo is an improbable hypothesis. The dynamics of the spreading of the South China Sea basin, the strong west-verging Pacific Plate, the northward progression of the Indian Ocean-Australian Plate, and possibly extrusion of continental Southeast Asia appear to have impacted the region differently at different times of the Cenozoic. In turn, the regional stresses could cause stress re-orientation within the terranes. In certain areas onshore of Sarawak changes of compression azimuths would be consistent with CCW rotation, but the changes in the stress fields could be attributed to other causes as well.

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