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A dextral strike-slip model for the Miri Structure

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Abstract: The Miri Structure shows complex geometry as a result of interplay between compression and tensional wrenching. Evidences for strike slip deformation are illustrated. These include the presence of:

1. *En-echelon* normal fault arrangements along a major fault with dominant normal throw (Shell Hill Fault), often accompanied by reverse fault throws and dip reversals along individual faults showing the following features:
   - Conjugate fault systems (synthetic and antithetic)
   - Small-scale faults showing negative and positive flower structures
   - Oblique and down-dip striations
   - "Ribbon effect" geometry
2. A dextral strike slip fault zone named the Canada Hill 'Thrust' Zone, characterized by:
   - Sub-horizontal striations
   - Fault zone associated with both compressional and extensional structure
   - Thrusts and extensional faults showing cross-cutting relationships in a single section
3. Presence of push-up block/ridge bounded by the Shell Hill Fault and Canada Hill Thrust zone.
4. Curved horse-tail configuration.

The main conclusions from this study are as follows:

1. The 4 sets of structural elements associated with the Miri Structure are coeval.
2. They are the result of a progressive NNE-trending dextral strike-slip deformational event.

Dextral strike-slip movement could have initiated early prior to lithification and continued after lithification.

Abstrak: Struktur Miri menunjukkan geometri yang kompleks. Geometri ini adalah disebabkan oleh perkaitan yang kompleks diantara mampatan dan tegangan dalam proses gelinciran jurus. Dalam kertas ini, bukti-bukti proses gelinciran jurus berkaitan dengan Struktur Miri ditunjukkan. Ini termasuklah kehadiran:

1. Aturan *en-echelon* sepanjang sesar major dengan alihan normal yang dominant (Sesar Bukit Shell), biasanya ditemani oleh alihan songsang dan songsangan kemiringan sepanjang sesuatu sesar, yang menunjukkan sifat-sifat berikut:
   - Sistem sesar-sesar konjugat
   - Sesar-sesar kecil yang menunjukkan struktur bunga negative dan positif
   - Kehadiran garitan-garitan serong dan dan kebawah kemiringan
   - Geometri "kesan ribbon"
2. Satu zon sesar gelinciran jurus menganan dikenali sebagai Canada Hill 'Thrust' Zone dicirikan oleh:
   - Garitan-garitan mendatar
   - Zon sesar yang dicirikan oleh struktur mampatan dan tegangan
   - Sesar-sesar songsang dan ekstensi yang menunjukkan perkauitan saling potong memotong dalam satu heratan
3. Kehadiran blok terangkat dibendung oleh Sesar Bukit Shall dan Canada Hill Thrust.
4. Konfigurasi lengkungan 'horse-tail'.

Kesimpulan utam kajian ini ialah:

1. Keempat-empat unsur struktur yang berkaitan dengan Struktur Miri terbentuk serentak.
2. Mereka terbentuk akibat canggaan progresif semasa proses gelinciran jurus menganan berorientasi UTL.

Pergerakkan gelinciran jurus menganan bermula pada peringkat awal, sebelum litifikasi dan berterusan selepas litifikasi.

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INTRODUCTION

The Miri field, the birthplace of the Malaysian oil and gas industry, underlain by a thick succession of Middle Miocene to Pliocene sand-shale sequence, hosts important hydrocarbon reservoirs and source rocks. These rocks have been extensively studied and their depositional environment is relatively well known. However considerably less is known about their deformational history.

The geology of Miri is analogous to the hydrocarbon-bearing offshore West Baram Basin. As such, an understanding of the structural history and how related structural traps are generated is of great importance in detecting possible hydrocarbon accumulations in both onshore and offshore West Baram Basin.

The geometry of the Miri Structure is relatively well established. However, neither the kinematics nor the structural history of the Miri structure have been thoroughly described. This study classifies and describes a complex fault system called the Miri Structure in the Miri area (Fig. 1a) are discussed. The complex deformation structures associated with the Miri Structure as a result of a dextral strike-slip deformation are discussed.

REGIONAL SETTING

The Miri area is part of the onshore extension of the roughly triangular shaped Baram Delta Province. Thick marine to deltaic sediments of Late Eocene to Pleistocene age were rapidly deposited in the basin. The province is characterized by the deposition of a northwestward prograding delta since the Middle Miocene (Tan *et al.*, 1999). The geological evolution, stratigraphy and trap styles are well documented by geologists from Shell and other oil companies who have worked in the area. A detailed description of the West Baram Delta Province can be found in Tan *et al.* (1999).

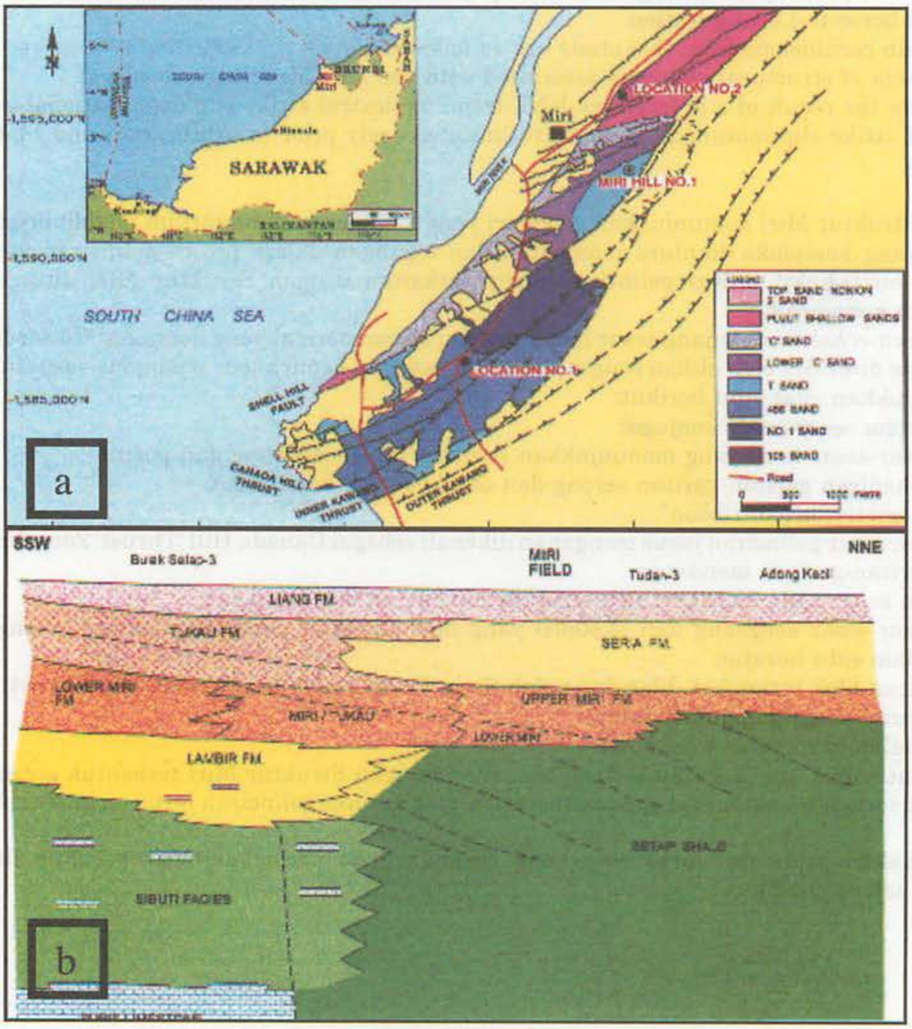

Figure 1. (a) Geological map of Miri area showing the Miri Structure and its location. (b) Generalized stratigraphy of Miri area (From Tan *et al.*, 1999).

The Baram Delta is dominated by gravity tectonics characterized by growth faults and shale diapirs that have been overprinted by basement rooted wrench related structures (James, 1984; Tan *et al.*, 1999). These resulted in a composite fault system. The counter - regional growth faults were caused by sediment loading during rapid sedimentation. A late Miocene to Pliocene regional compression has also affected the area, resulting in a series of northeast-southwest trending anticlines that intersect obliquely the earlier growth faults (Tan *et al.*, 1999). Major hydrocarbon accumulations occur at the intersection of growth faults with anticlines.

STRATIGRAPHY OF THE MIRI AREA

The onshore stratigraphy is well described by Liechti *et al.* (1960). The Neogene deltaic succession comprises the Setap Shale, Lambir, Tukau and Miri formations. Detailed description of the lithology and stratigraphy (Fig. 1b) of the Miri field can be found in Liechti *et al.* (1960), Hamid Mohamed *et al.* (1986) and Tan *et al.* (1999). The strata that crop out in the Miri Town area have been assigned to the Miri Formation (Liechti *et al.*, 1960). The sequence strata are an alternating sequence of thick arenaceous and thinner argillaceous material. Shell assigns a Middle Miocene age to the Miri Successions (Hamid Mohamed *et al.*, 1986). These sediments were uplifted from Latest Miocene time to form the Miri and Lambir Hills.

THE MIRI STRUCTURE

The general structure of the Miri Field is shown in Figure 2. Based on previous studies and present field mapping, the structural elements associated with the Miri Structure include:

a) an asymmetric slightly overturned south-easterly verging anticline
b) a set of steep north-westerly dipping faults with predominantly normal throws (Shell Hill Faults)
c) a set of conjugate predominantly normal faults arranged in an *en-echelon* manner along the Shell Hill Fault zone
d) a zone of moderate north-easterly dipping faults with predominant reversed throws but associated with similarly oriented faults with normal throws (Canada Hill Thrusts).

The Miri Structure can be generalized as an asymmetric, slightly overturned, southeast verging, northeast-trending anticline. This anticline is associated with two major northeast striking faults that are steeply dipping to the northwest. These

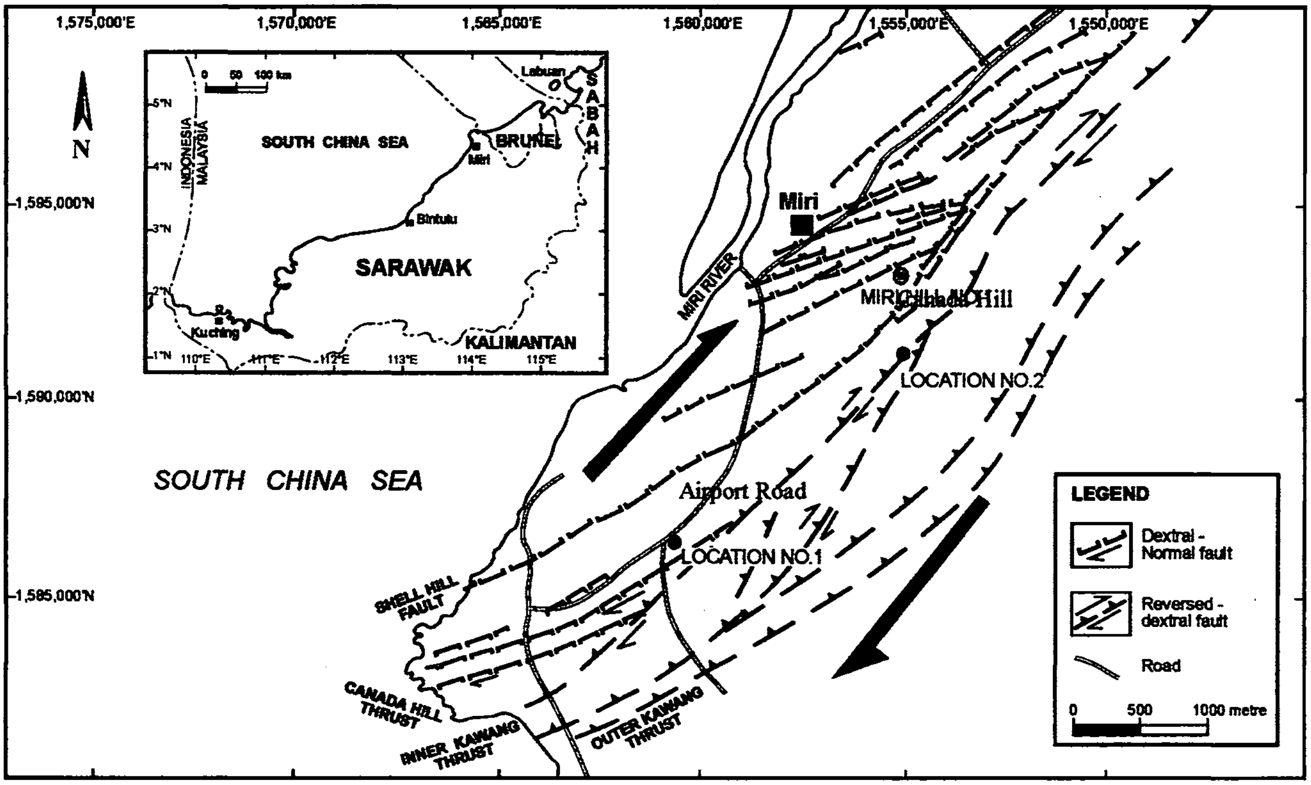

Figure 2. Structural map of Miri area (modified from Hamid Mohamed *et al.*, 1986).

are the Shell Hill Fault and the Canada Hill Thrust.

The Shell Hill Fault is a steep northeasterly dipping fault that exhibits a predominant down-to-the NE normal throw. Normal throws of some 750 m have been reported. A set of conjugate predominantly normal faults is found on the hanging-wall of the Shell Hill Fault. These minor faults are arranged in an *en-echelon* manner and are merged along the Shell Hill Fault zone. They are moderate to steeply dipping either towards the NW or SE.

The Canada Hill Thrust and the smaller Batu Kawang Thrusts bound the southeast part of the Miri Structure. These thrusts are associated with the slightly overturned sub-vertical to steeply dipping limb of the Miri Anticline.

OUTCROP DESCRIPTIONS

The Airport Road Section

The road exposure shows a strike section through a deltaic system of the Middle Miocene Miri Formation. The sandstone-shale sequence shows a repeated upward progression of subtidal-intertidal flat cycles (Abdul Hadi Abdul Rahman, 1995).

Numerous northeasterly-striking steep southeasterly and northwesterly dipping faults, with predominant normal throws, are associated with a series of gentle anticlines and synclines (Fig. 3).

The mapped faults exposed in this section are

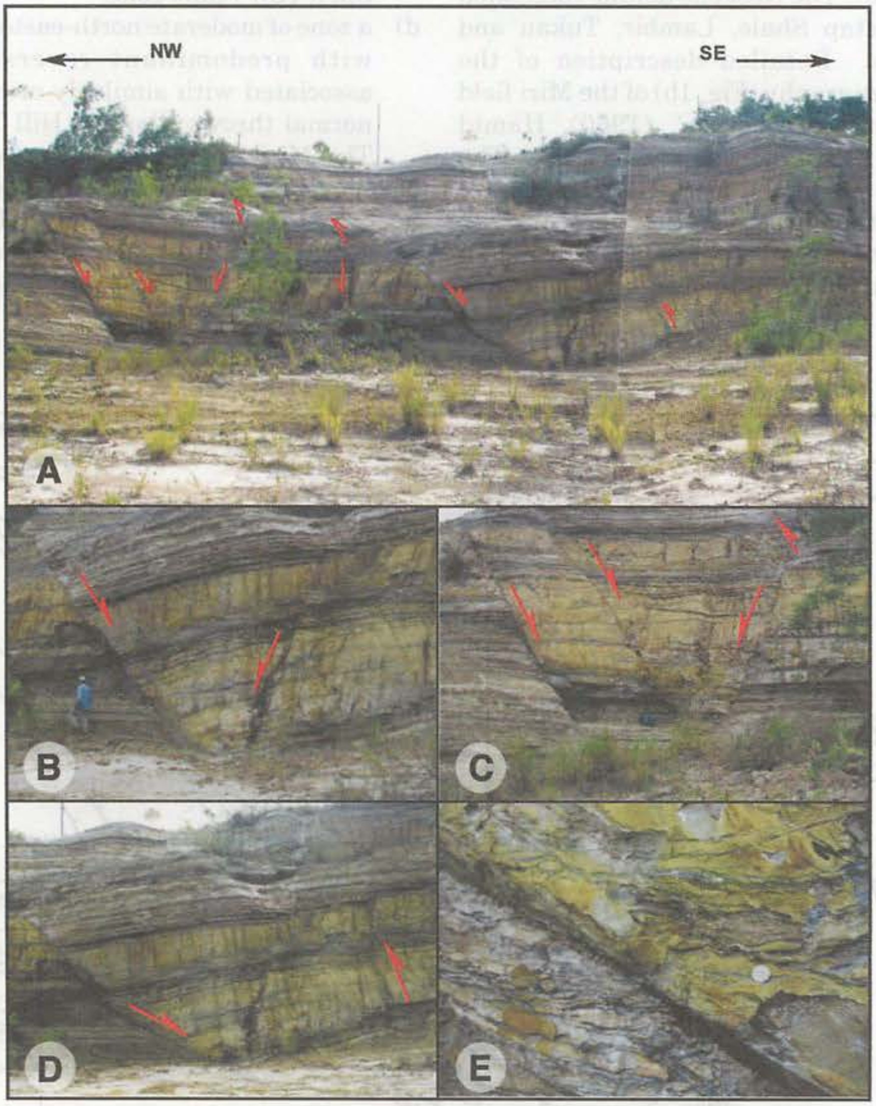

Figure 3. Photographs showing numerous northeasterly-striking, steep southeasterly and northwesterly dipping faults with predominant normal throws associated with a series of gentle anticlines and synclines exposed along the Airport Road.

shown in Figure 4. On vertical sections these faults are conjugate in nature with a predominant normal throw but occasionally accompanied by reverse fault throws and dip reversals (Fig. 3). Normal throws on the faults fall in the range of 1–5 m, their dip varies from 60° and are sub vertical dipping either northwesterly or southeasterly. On map view this forms a left stepping *en-echelon* arrangement to the Shell Hill Faults and laterally merged as splays to the Canada Hill Thrusts.

These faults display distinct slip planes defined by smooth polished slickensided surfaces or cataclastic gouge zones. On the fault surface the striations vary from down-dip to oblique to strike. The width of the fault zones is between 5 and 40 cm.

Along individual faults, although normal drags are usually seen, a reversal in sense to reversed drag is not uncommon (Fig. 3). Within the fault zones, although normal slip shear planes predominates, reverse slip shear planes are not uncommon. Individual slip-planes within the fault zones are usually accompanied by reverse fault throws and dip reversals along individual faults. These slip-planes form an interconnecting network without clear-cut crosscutting relationships. The "ribbon effect" features are typical of strike-slip faults.

Although the bigger faults show distinct slip-surfaces, the smaller slip-planes within the fault zones may show evidences of clear smear and ductile behaviour of shales and sandstones. Shear gouges are characterized by light coloured cement, and include dark micaceous streaks. The slip-planes that cut through sandstones may not be distinct, but exhibit fault-parallel laminae. These laminae are characterized by repacked sand enriched in clay and micaceous material. The features suggest that the faults initiated before the sediments were consolidated whereby the sediments were fluidized and remobilized into the developing faults. The presence of cataclastic gouge zones suggests that the faulting continued after lithification.

Small-scale conjugate normal faults, accompanied by reversed faults, occur within 2 m of the fault zones. Internal deformations within the fault blocks are characterized by small-scale normal faulting but associated with compressional structures such as small-scale thrust and thrust-related anticlines and gentle synclines. The very small-scale faults predominantly exhibit typical negative flower structure geometry and those that exhibit typical reverse fault and positive flower structure geometry are not uncommon. The associated small-scale folds are arranged in a right stepping *en-echelon* manner.

The stereographic projection of structures occurring along the sections is shown in Figure 4. The predominance of ENE-trending extensional structures suggests that the maximum compressive stress was acting along the ENE-WSW direction. It's association with compressional structures such as reversed faults and folds, is typical of strike-slip (transtensional) deformation. The oblique striations and the presence of transverse folds suggest that the structures were formed in an overall NNE-trending dextral strike-slip environment.

The geometry of these structures suggests that the strata have undergone an extensional deformation associated with a significant strike-slip component. These structures are not typical of extensional deformation but fit into the geometry of shear fractures related to dextral strike slip faulting.

The Hillside Garden Exposure (Canada Hill 'Thrusts')

The excavation works for a housing project exposes a sandstone-shale sequence exhibiting typical characteristics of the tidal, storm and wave-dominated facies of the Miri Formation (Fig. 5a).

The dominant structure is a regionally extensive SE facing highly asymmetric slightly overturned southeasterly-verging, NE-trending anticline (Fig. 5b and c). The NE limb is very gentle to sub-horizontal. The SE dipping limb is steeply dipping to sub-vertical. The anticline is very gently plunging to the SW.

This structure is associated with a 5 m wide NNE-trending fault zone (Fig. 5c), exhibiting crosscutting and anatomizing northwesterly-dipping faults showing both reversed and normal apparent displacements. The southerly bounding fault show an apparent reverse displacement but the northerly bounding faults show an apparent normal displacement that gradually changes into reverse faults up section. One of the faults shows sub-horizontal striations (Fig. 6a), and there can be no doubt about the strike-slip origin of the faults and the anticline. Within the fault zone the strata have been deformed into tight asymmetric folds cut by numerous sub-vertical shear zones exhibiting a dextral strike-slip sense of shear (Fig. 6b). These asymmetric folds may be in-line with or are transverse to the fault zones.

The gently dipping hanging-wall block exhibits small-scale conjugate normal faults (Fig. 6c and d) showing similar orientations, geometry and other characteristics to that found at the Airport Road sections.

The footwall block has been deformed into a box-like anticlinal fold (Fig. 6e) transverse to the fault zone. Immediately below the fault zone, the movement associated with the fault zone gave rise to the development of small-scale conjugate normal

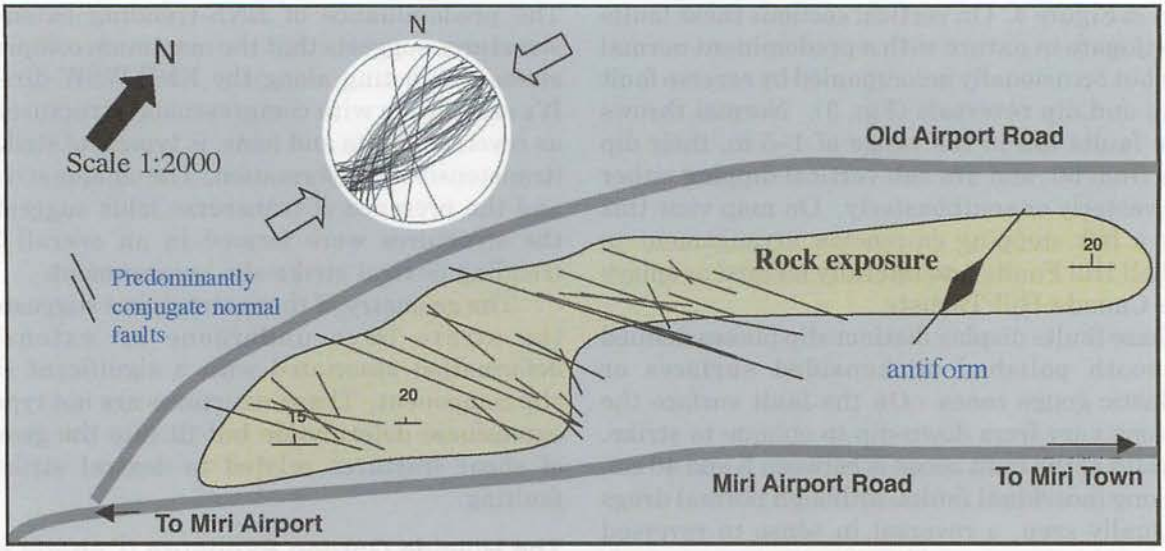

Figure 4. Structural map of the Airport Road exposure. Insert shows the stereoplot of the faults found.

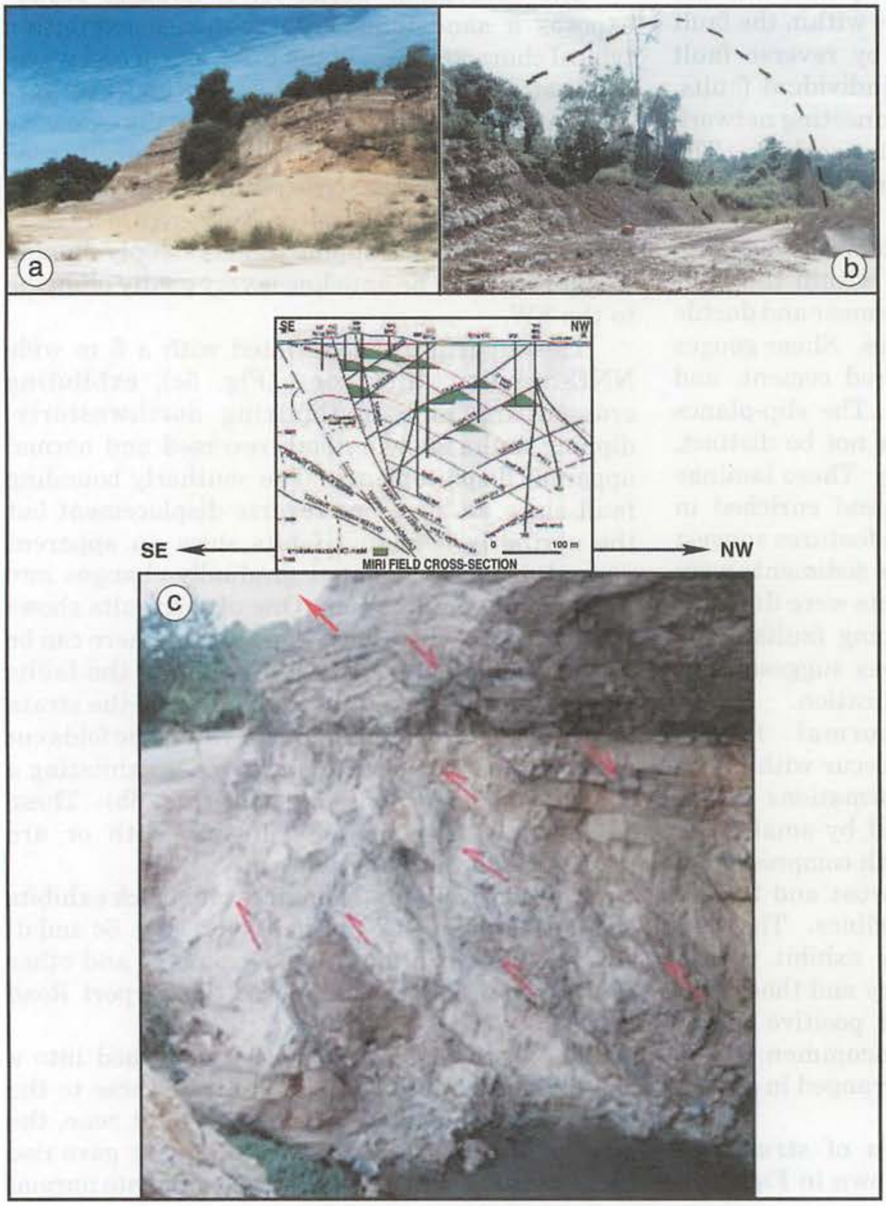

Figure 5. Photographs showing the Hillside garden exposure (a), the SE facing highly asymmetric slightly overturned southeasterly-verging, NE-trending anticline (b), and The 5m wide NNE-trending fault zone (Fig. 7c) exhibiting crosscutting and anastomizing northwesterly dipping faults showing both reversed and normal apparent displacements (c). The Hillside Garden exposure can be used as small-scale analogue of the whole Miri Structure (see insert).

faults trending NNE and E-W, associated with reversed faults and positive flower structures that merged with one another. Smaller E-W trending strike-slip fault zones are also found on the footwall block. There can be no doubt that the extensional and compressional structures found developed simultaneously.

Although the bigger faults show distinct slip-surfaces characterized by fault gouge, the smaller slip-planes within the fault zones may show evidences of clear smear and ductile behaviour of shales and sandstones (Fig. 6f) similar to the features exhibited by the faults along Airport Road. The features suggest that the faults initiated before the sediments were consolidated whereby the sediments got fluidized and remobilized into the developing faults. The presence of cataclastic gouge zones suggests that the faulting continued after lithification.

The sub-horizontal striations and the presence of transverse folds suggest that the structures were formed in an overall NNE-trending dextral strike-slip environment. The interaction between compressional and extensional structures and the associations of minor structures in the exposure suggest that the Canada Hill Thrust is a dextral transpressional fault zone.

DEFORMATION MODEL

The Tertiary tectonic activity within the West Baram Basin has been described by several workers (Ho, 1978; James, 1984; Tan and Lamy 1990; Sandal 1996; Tan *et al.*, 1999). The regional tectonic style shows the interplay between two main deformational styles. An early NE-SW to NW-SE trending syn-depositional growth faulting was superposed by Late Miocene to Pliocene NE-SW

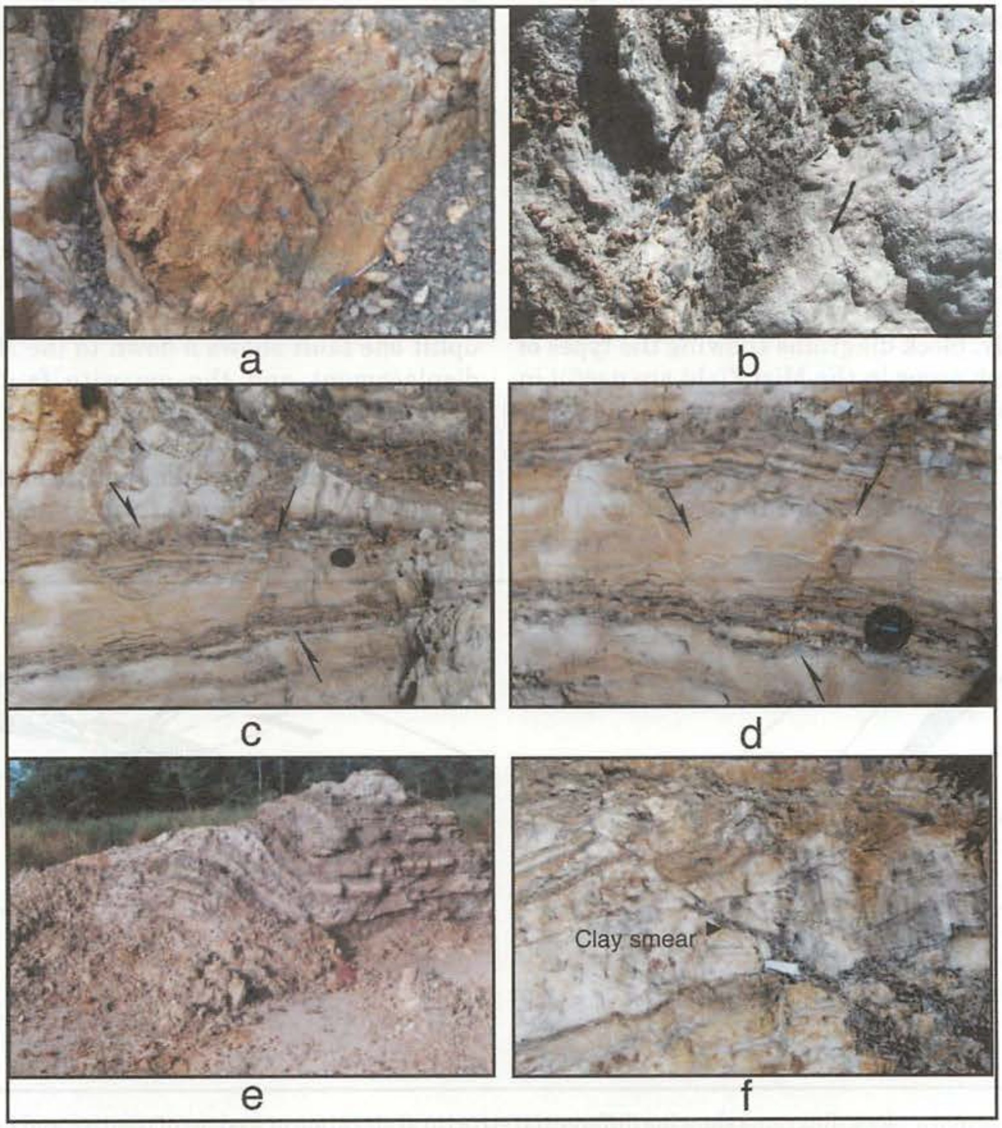

Figure 6. Minor structures found associated with the Canada Hill Thrust.

trending wrench-induced compressional folds.

Previous workers recognized that it is not easy to fit all the 4 features of the Miri Structure into a single deformation mechanism. Therefore based on regional considerations, the Miri Structure was said to be a composite fault system (Hamid Mohamed *et al.*, 1986; Tan *et al.*, 1999). The Shell Hill faults and an associated normal fault was said to be a growth fault although evidence for a systematic thickening of the hanging wall block is absent. A later compressional event deformed the structure to form the Miri Anticlne.

The outcrop data presented above, on the geometry and style of deformation associated with the Miri Structure, suggest that the traditional view that the Miri structure was the result of two separate phases of deformation needs to be modified. The deformation structures illustrate that both the extensional and compressional structures developed simultaneously and there was significant dextral strike-slip movements throughout the development of the Miri Structure.

A detailed field study incorporating the available subsurface data indicates that the degree of faulting is complex. Matching a complex fault pattern with idealized, theoretical and existing models is useful in understanding fault mechanics, and predicting fault geometry. The visual concepts displayed by fault geometry cartoons are useful in making sense of structural anomalies, which commonly occur in wrench fault systems. Consequently, block diagrams showing the types of faulting which occur in the Miri Field are useful in showing fault geometry and mechanics.

En-echelon fractures

The geological map of the Miri area (Figs. 1 and 2) shows that the faults and associated structures of the Miri Structure are disposed in a long narrow band. The predominantly NE-trending extensional faults are arranged in an left-stepping *en-echelon* manner along 2 major sub-parallel faults, one of which, the Canada Hill 'Thrust' has been confirmed as a dextral transpressional fault. This is a good criterion to show that the Miri Structure is a dextral wrench-induced structure. The outcrop observation that these *en-echelon* faults have transtensional and oblique fault geometry, support the above interpretation.

Paired uplift

The sub-parallel nature of the NNE-trending Shell Hill Fault (with large normal throws) and the Canada Hill Thrust (with a dominant reversed throw) is significant. It shows that the block in between the Shell Hill Fault and the Canada Hill Thrust is a long and narrow uplifted slab. On cross-section the uplifted slab is bounded by 2 faults with opposite separations- one with a normal throw and the other with a reverse separation. These features are indicative of wrench movements parallel to the fault planes. The dextral transpressive nature of the Canada Hill Thrust supports this interpretation.

A block diagram (Fig. 7a) illustrates this geometry as due to scissors faulting along dextral transpressional faults. A block was uplifted in between 2 dextral strike slip faults. Due to this uplift one fault shows a down to the NW apparent displacement and the opposite fault shows an apparent upthrust verging to the SE. This representation of the fault geometry is useful in explaining the sub-parallel nature of the Shell Hill fault (with large normal throws) and the Canada

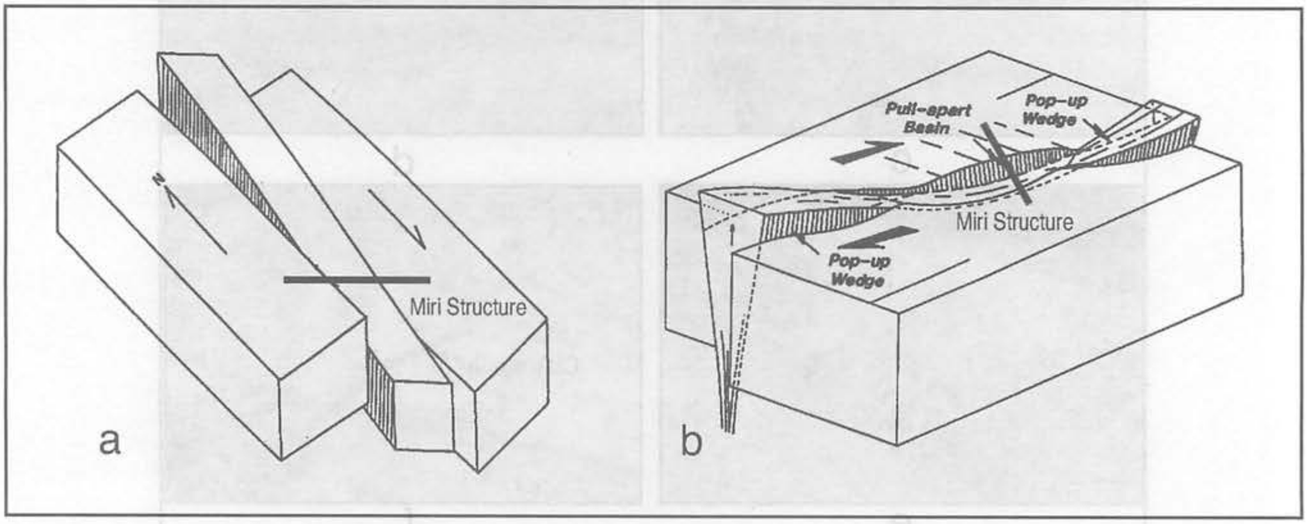

Figure 7. Schematic block diagrams showing differential structural elevation of wedges of positive and negative flower structures along dextral faults.

Hill Thrust (with a dominant reversed throw). A Pop-up geometry along a right lateral fault as shown in Figure 7b could equally well explain the paired uplift.

Horsetail splays

Both the Canada Hill Thrust and the Shell Hill Fault show imbricate arrays of WNW-trending sub-parallel curved predominantly normal throw faults with a significant strike-slip component, as shown by the Airport Road sections. On map view, each of the oblique-slip faults is linked to the main faults at one end but loses displacements to a fault tip at the other end. These features shows trailing extensional imbricate fan geometry typically found at the end or terminations of NNE-trending dextral strike-slip faults.

The Hillside Garden exposure can be used as a small-scale analog of the whole of Miri Structure as shown in Figure 5c. Based on detailed field study and observations, incorporating the available published sub-surface and map data, it has been shown that the structural elements associated with the Miri Structure are all coeval. These structures can develop by NNE-trending dextral strike-slip movements. Therefore it is proposed here that the Miri structure developed by a single phase of progressive NNE-trending dextral strike-slip movement.

These strike-slip movements were initiated very early, prior to the lithification of the sediments and continued after lithification until the sediments were uplifted by Latest Miocene to Pliocene time.

CONCLUSION

The Miri Structure shows a complex structural geometry. This complex geometry is the result of a complex interplay between compression and tensional wrenching. Classifying the geometry of the structures, especially the style of faulting and its timing, is important in reconstructing the history and trapping of hydrocarbons. Simply mapping of the faults is not enough — a better understanding of how the complicated structures formed is needed to predict where the potential traps were located.

Evidences for strike slip deformation associated with the Miri Structure include the presence of:

1. *En-echelon* normal fault arrangements along a major fault with dominant normal throw (Shell Hill Fault), often accompanied by reverse fault throws and dip reversals along individual faults, exhibit the following characteristics:
   - Conjugate fault systems (synthetic and antithetic)
   - Small-scale faults showing negative and positive flower structures
   - Oblique and down-dip striations
   - "Ribbon effect" geometry
2. Canada Hill Thrust Zone exhibits the following characteristics:
   - Dextral strike slip fault zone
   - Sub-horizontal striations
   - Fault zone associated with both compressional and extensional structure
   - Thrusts and extensional faults showing cross-cutting relationships in a single section
3. Present of push-up block/ridge bounded by the Shell Hill Fault and Canada Hill Thrust zone
4. Curved horse-tail configuration

The main conclusions from this investigation are as follows:

- The 4 sets of structural elements associated with the Miri Structure are coeval.
- They are the result of a progressive NNE-trending dextral strike-slip deformational event.

Dextral strike-slip movement could have initiated early prior to lithification and continued after lithification.

The geology of Miri is analogous to the hydrocarbon-bearing offshore West Baram Basin. This detailed description of the Miri Structure may act as a model for other local prospects in both onshore and offshore West Baram Basin.

REFERENCES

ABDUL HADI ABDUL RAHMAN, 1995. *Reservoir characterization of the Upper Cycle V (Late Miocene) of Baram Field, Baram Delta, offshore Sarawak, East Malaysia.* Unpubl. PhD thesis, University of Reading, England, 333p.

HAMID MOHAMAD, A., BUDDING, M.C. AND JOHSON, H.D., 1986. *Miri Hill field trip.* Reservoir Geology/Sedimentology team, Sarawak Shell Berhad. 18p.

HO, K.F., 1978. Stratigraphic framework for Oil Exploration in Sarawak. *Bull. Geol. Soc. Malaysia, 10*, 1–13.

JAMES, D.M.D. (Ed.), 1984. The geology and hydrocarbon resources of Negara Brunei Darussalam. *Muzium Brunei Special Publication*, 169p.

LIECHTI, P., ROE, F.N., HAILE, N.S. AND KIRK, H.J.C., 1960. The geology of Sarawak, Brunei and the western part of North Borneo. *British Borneo Geological Survey, Bull. 3*, 360p.

SANDAL, S.T. (ED.), 1996. *The Geology and Hydrocarbon Resources of Negara Brunei Darussalam*, 2nd Edition 1996. Brunei Shell Petroleum & Brunei Museum Publication, 243p.

TAN, D.N.K. AND LAMY, J.M., 1990. Tectonic evolution of NW Sabah continental Margin since the Late Eocene. *Bull. Geol. Soc. Malaysia, 27*, 241–260.

TAN, D.N.K., ABDUL HADI ABDUL RAHMAN, AZLINA ANUAR, BAIT, B. AND CHOW, K.T., 1999. West Baram Delta. *In: The Petroleum Geology and Resources of Malaysia.* PETRONAS Publication, 665p.

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