Complex transtensional structures and the hydrocarbon potential of the Greater Sarawak Basin, Sarawak as defined by synthetic aperture radar

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Abstract: Synthetic Aperture Radar (SAR) is an active microwave sensor which operates both day and night and is capable of penetrating cloud cover and tropical haze. SAR has proved to be an excellent tool for mapping the critical structural elements of the Greater Sarawak Basin which strongly control the location and size of prospective hydrocarbon accumulations in East Malaysia. Interpretation of SAR data acquired for Petronas over the onshore part of the Greater Sarawak Basin combined with other geoscientific information has revealed the complex tectonostratigraphic history of the region. The high quality radar images are of primary use in exploration logistics, particularly in orienting and locating seismic acquisition programs and boreholes.

The West Sarawak Basin and the northeast part of the island of Borneo underwent complex transtensional deformation during the Tertiary related to strike-slip motion caused by the indentation of India against the Indochina-South East Asian block. These sinistral strike-slip zones are well developed as the Sabah Shear, the West Baram-Tinjar Lines and the Lupar Line-Paternoster Fault. Onshore extension of the seismically defined transverse faults in the South China Sea likely controlled the migration and accumulation of hydrocarbons in Sarawak. Thus SAR has been a critical tool in explaining existing hydrocarbon accumulations in Sarawak and delineating prospective regions.

The collision of the Australian continent with the Banda Arcs to the southeast and renewed subduction to the east and west put Borneo under compression in the Middle Miocene. Complex fold interference patterns produced by Cenozoic-aged strike-slip faults and the northward advance of the Rajang Accretionary Prism are well displayed on SAR data as are several suites of fracture lineaments corresponding to the prevailing stress regime. Lithological terrain units and structure defined in the SAR interpretation correlate well with documented field observations.

INTRODUCTION

Synthetic Aperture Radar (SAR) has been acquired by Intera for Petronas (Bird *et al.*, 1993) over the Greater Sarawak Basin as part of a larger 1991 acquisition program in Malaysia for all of Sarawak and Sabah. The purpose of the program was to provide a modern regional geological database by calibrating the SAR with pre-existing geophysical and geological data which was subsequently updated. This refined tectonostratigraphic framework has revealed the likely locations of hydrocarbon sources, migration pathways, seals and traps onshore in Central Sarawak.

The region discussed lies in Central Sarawak, Malaysia and extends from the SK-16 concession block south to the Dulit Mountain Range (Fig. 1). Access is limited and rock exposures are poor in the region which is covered by extensive tropical rainforest and/or mixed peat swamp forest. The surficial topography of this part of the Greater Sarawak Basin varies from subdued terrain underlain by recessive shales through zones of linear ridges (interbedded sandstone and shale) to rugged highlands consisting of thick resistive sandstones (Bird *et al.*, 1993).

SAR is an active microwave sensor which operates independently of day or night and is able to penetrate cloud cover and tropical haze prevalent in the jungle areas of Malaysia. The sidelooking geometry of SAR highlights bedding strike and dip and subtle but important structural highs, by generating shadows and enhancing radial and annular drainage frequently invisible on high sunangle air photographs or other remote sensing data (Fig. 2). In addition, faults and fractures often form poorly-defined linear depressions which are accentuated by shadows due to the oblique look angle of the SAR. Lithologic terrain units differentiated by radar texture have been correlated to the mapping lithologies within the recognised stratigraphic sequence.

DATA ACQUISITION/PROCESSING AND IMAGE PRODUCTION

The SAR imagery was acquired (Bird *et al.*, 1993) as east-west lines with a south look direction, over the period November 1990 to February 1991 using Intera's STAR-I SAR high resolution (6 m) system. Stereographic flight line strips and 1:100 000 scale composite mosaics (Fig. 3) were produced at Intera's Calgary production facility after the digital tapes had been processed. The overlapping flight lines were referenced to the 1:100 000 scale mosaics and stereoscopic geologic interpretation was then carried out on the images and edited for regional continuity, though no field checks were done. The geographical, geological, structure and fracture lineament maps were subsequently digitised at a 1:100 000 scale.



Figure 1. SK 16 Concession Block, Study Area, Location Map.



Figure 2. Profile of airbome radar system illustrating depression angles and shadowing of topographic relief within a single flight line.

REGIONAL GEOLOGY

The Greater Sarawak Basin in the Northwest Borneo Geosyncline has developed on an extensive curved accretionary prism of a Tertiary-aged subduction complex (James, 1984; Liechti *et al.*, 1960). The South China Sea oceanic crust started to subduct to the southwest beneath the Sunda Shelf (the basement core complex of Borneo) along the northward concave arc of the Lupar Zone which stretched eastwards from western Sarawak through Indonesian Borneo (Liechti *et al.*, 1960; Doust, 1977; Williams *et al.*, 1986). The subduction resulted in major northeast-trending folds which have a regional south-east asymmetry (Hamilton, 1979; Scherer, 1980; DuBois, 1981; James, 1984; Bird *et al.*, 1993).

The regional architecture, sedimentation and post-sedimentary deformation of the South China Sea Basin is considered to have been largely controlled by northwest-trending major transcurrent sinistral strike-slip faults which formed as a consequence of extrusion tectonics related to the collision of India with Eurasia (Fig. 4; Tapponnier *et al.*, 1982).

STRATIGRAPHY

Tectonostratigraphic provinces defined in this part of the Greater Sarawak Basin are adopted from James (1984) and include the Crocker Accretionary Prism in the east, the Rajang Accretionary Prism in the southeast, the Tinjar and Balingian provinces in the center and northwest and the Baram Delta Province in the northeast (Fig. 5; James, 1984). The Tinjar Fault trend is a parallel splay of the West Baram Line which forms the eastern margin of the Tinjar Province (James, 1984).

During the Oligocene to Late Miocene, fluviodeltaic systems developed in the Tinjar Tectonostratigraphic Province and migrated from central Sarawak towards the shelf area before spreading northeastwards into Sabah (Yin, 1990). Although the tectonic effects of the Rajang Accretionary Prism extend into the Miocene in the Tinjar Province, most deposition post-dated the major phase of deformation there (Bird *et al.*, 1993). Large deltas were deposited in the Baram Delta Province from the Middle to Late Miocene (James, 1984).

Bird *et al.* (1993) have summarised the Radar Lithologic Terrain Units recognised in the Tinjar Province (Figs. 6 and 7) and how they relate to the recognised stratigraphic column.

The Upper Cretaceous to Eocene-aged Belaga and Pelagus Formations form part of the Rajang



Figure 3. Sarawak, Malaysia, 3/113/SE Digital Radar Mosaic.

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Accretionary Prism and are unconformably overlain by the Baram and Brunei Groups. The Kelalan Member of the Belaga Formation consists of dense marine lime mudstones, but elsewhere the Belaga Formation is represented by the Pelagus Member, a sequence of thick sandstones interlaminated with grey shales and thin sandstone-siltstone sequences (Liechti et al., 1960). These formations were deposited in a deep-marine fan setting basinal to the Paleo-Mekong estuary formed above a northward-migrating subduction zone (Hutchison, 1989). On the SAR images, rocks in the Rajang Accretionary Prism form a highly interbedded sequence, faulted, sheared and deformed into intrafolial, isoclinal folds, shear zones and they display well-developed conjugate fracture lineament systems.

The Older Setap (Temburong) Formation unconformably overlies the Rajang Accretionary Prism and is of Oligocene to Early Miocene in age (James, 1984). The Older Setap Formation consists of interbedded shales with some sandstone and siltstone layers (Bird *et al.*, 1993).

The Baram and Brunei Groups of Middle to Late Miocene age unconformably overlie the Temburong Formation and consist essentially of shelf, coastal to deltaic sequences. The basal Sibuti/ Tanggap marls, greenish claystones, shales and limestones were deposited in a middle to inner neritic setting (Liechti et al., 1960). The Sibuti Formation grades laterally into the Setap Formation deposited in a coastal and prodeltaic environment, which is a highly interbedded and consists of claystones and shales with a trace of siltstone and thin limestones (Liechti et al., 1960). Extensive weathering of the Setap formation has produced a dappled to mottled textural appearance on the SAR images. Distinctive weather resistant sandstone layers and lenses occur near the base of the sequence in the lower Setap Formation. The Setap Formation is often tightly folded.

The Nyalau Formation (Baram Group) is a thinly interbedded shallow marine sequence of fine grained argillaceous and calcareous sandstones, siltstones and shales which are not as well developed in the overlying inner-neritic to littoral Lambir Formation (Brunei Group) (Liechti *et al.*, 1960). Mudstones, marlstones, limestones, siltstones and lignite are also present in the Lambir Formation (Chung, 1982). The Nyalau Formation is considered to have been deposited contemporaneously with the Sibuti and Lambir, the upper section of the Setap Formation and the Lower Belait Formation (Waite, 1960; James, 1984). The Nyalau Formation shows "grainy to speckly" tone and a striped texture on SAR images due to interbedding.

The shallow marine Nyalau Formation is

superseded by the Early to Late Miocene-aged (Hutchison, 1989; Tate, 1976) littoral to deltaic Belait Formation that is subdivided into Lower and Upper Formations. The Lower Belait Formation is highly interbedded, fine grained sandstone and siltstone sequence probably deposited in littoralparalic conditions (Hutchison, 1989). On SAR images, the Lower Belait Formation is more recessive than the Upper Belait Formation, consists of well interbedded sandstones and siltstones, has a flatter topography and fracture lineaments are less well developed.

The Upper Belait Formation is a medium to coarse grained sandstone sequence overlying shales, siltstones and mudstones and was deposited in a nearshore to deltaic plain environment. The Upper Belait Formation forms the central sandstone dominant portion of the synclinal basins and shows shallow to horizontal bedding. Lineaments and flatirons are moderately developed in the Upper Belait Formation which is exposed as weatherresistant topographic escarpments and mesas in the Tinjar Tectonostratigraphic Province such as the Bukit Selikan Mesa in the northwest corner of Quadrant 3/114/SW.



Figure 4. Regional tectonic elements (Hamilton, 1979; and Tapponnier *et al.*, 1982).



Figure 5. Tectonostratigraphic provinces of Northern Kalimantan (James, 1984).



Figure 6. Stratigraphic column illustrating the diachronous nature of Paleogene to Neogene formations after James (1984).

During the Plio-Pleistocene, andesites erupted on the southeast margin of the Tinjar Province and formed the thick, flat Usun Apau Volcanic Plateau which unconformably conceals underlying structures and formations. These volcanics show a slightly undulating to smooth textural pattern, with few fracture lineaments and have serrate to linearscarp erosional flow-fronts.

Peat swamp forest lowlands and coastal or fluvial alluvium form the Recent sediments in the study area and are very distinctive. The Recent sediments have a low intensity speckled appearance in the low-lying and flat areas where they occur.

TECTONIC HISTORY

Folds interpreted in the Rajang Accretionary Prism on the SAR data are commonly tight, overturned and broken by thrust faults (Bird *et al.*, 1993). These folds probably developed during periods of north-northwest compression from Paleogene subduction and Australian collisional events in the southeast of Neogene-Pleistocene age (Hutchison, 1989). Subduction along the Lupar Zone Trench is considered to have been active from the Late Cretaceous to the Eocene/Oligocene (Yin, 1990) or Late Miocene (Tan, 1982). Fold patterns



Figure 7. 3/113/SE geologic map based on SAR imagery interpretation.



Figure 7. 3/113/SE geologic map based on

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within the Tinjar Tectonostratigraphic Province trend east-northeast in Central Sarawak and rotate to become oriented northeast further to the east (Figs. 3 and 7) (Bird *et al.*, 1993). The folds within the Tinjar Tectonostratigraphic Province lie parallel to the folds of the Rajang Accretionary prism and perpendicular to the regional stress field and are up to 50 km long (Bird *et al.*, 1993). These folds are more gentle in the northwest, but become more tightly folded in the southeast closer to the Rajang Accretionary Prism, and are asymmetric with southeast-dipping axial planes (Bird *et al.*, 1993).

The complex structure of the Tinjar Province was formed by a combination of coeval folding and thrusting, and later strike-slip faulting (Bird *et al.*, 1993). At least three phases of folding have affected the region. An early Miocene phase of northwest trending folds formed during the collision of the Central Luconia Plate with the Rajang Accretionary Prism and reactivated north-northwest trending strike-slip faults in the Balingian Province (DuBois, 1981; Scherer, 1980; Doust, 1977; McManis and Tate, 1976).

In the Middle-Late Miocene, the collision of the Australian continent with the Banda Arcs put Borneo under northwest/southeast compression, generating northeast-trending folds (Bird *et al.*, 1993). Oceanic floor spreading in the South China Sea and plate subduction ceased in the Late Miocene when the Rajang Trench reached the Tatau-Bukit Mersing Line, its most northern position (Hutchison, 1989).

In the Late Miocene, west-directed stress associated with the development of the Crocker Accretionary Prism and the northward movement and counterclockwise rotation of Sabah reactivated north-trending left lateral strike-slip faults in the Balingian Province, which are sites of volcanic and thermal activity (DuBois, 1981; Scherer, 1980; Doust, 1977; McManis and Tate, 1976). The Dulit Mountain Range was likely uplifted at this time.

Left lateral strike-slip faulting was caused by regional differential plate movements associated with extrusion tectonics related to the collision of India with Eurasia (Hutchison, 1989), and this transtensional motion has controlled sedimentation patterns in the tectonostratigraphic provinces the strike-slip faults define (Tapponnier *et al.*, 1982).

The general distribution of folds, normal and strike-slip faults and thrusts can be related to periodic northwest to southeast compression (Fig. 8) or left lateral strike-slip motion along northnorthwest trending faults (Fig. 9). North-northeast trending faults show left lateral displacement, northeast trending faults right lateral displacement. East-northeast/northeast oriented faults may be thrust faults, whereas north-northwest trending faults could be normal or strike-slip faults (Fig. 10; Bird *et al.*, 1993). *En-echelon* folds up to 10 km long occur close to the Tatau-Bukit Mersing Line and were caused by transtensional movement along strike-slip faults. The Tukau Line, a major left lateral north-northeast trending strike-slip fault (James, 1984) has left laterally displaced the Tatau-Bukit Mersing Line (Bird *et al.*, 1993).

HYDROCARBON POTENTIAL

The coastal region of central Sarawak has been extensively explored because of its accessibility, the presence of oil and gas seeps, onshore discoveries and nearby offshore hydrocarbon fields (Bird *et al.*, 1993). Several dry wells were drilled along the coast of Sarawak in a belt extending from the Baram River to southwest of Bintulu (Fletcher and Soeparjadi, 1984). Some encountered tight sandstones.

This evidence was taken to imply that the onshore area was non-prospective for hydrocarbons, even though oil shows were found southwest of Bintulu and oil and gas seepages have been known onshore Sarawak, Sabah and Brunei (Bird *et al.*, 1993) since the turn of the century. Mud seepages with associated oil, gas, saltwater and salt are related to the diapiric activity in the Setap Shale Formation which lies close to the surface along faulted contacts between Tertiary and Recent sediments in west Sabah. Many Balingian Formation anticlines have diapiric shale cores (Hutchison, 1989).

RESERVOIRS

Molasse sediments in perched basins sitting on and sourced from the underthrust sediments of the Rajang Accretionary Prism were reworked during an initial Paleogene (Eocene to Early Oligocene) transgressive cycle in the Balingian and Tinjar Tectonostratigraphic Provinces (Fig. 11) (Hutchison, 1989). Sandstone development was controlled by the palaeotopography and the structure and the reservoir potential reduced by tectonically controlled metamorphic processes (Hutchison, 1989; James, 1984).

Progradational nearshore to coastal plain sandstones interbedded with coals, clays and siltstones and alluvial sandstones were deposited during the early stages of a Neogene (Late Oligocene to Early Miocene) transgressive cycle and they contain hydrocarbons (Fig. 11) (James, 1984; Fulthorpe and Schlanger, 1989).

The Neogene regressive cycle was marked by

the deposition of the progradational Baram and Rajang deltaic systems (James, 1984; Fulthorpe and Schlanger, 1989). The basal prodeltaic Upper Setap/Nyalau Formation is 3 km thick, is overlain by sandstones and shales of the Lambir Formation and coastal and fluvial sandstones and shales of the Miri Formation which show gradational contacts (James, 1984; Hutchison, 1989; Liechti *et al.*, 1960). These units grade laterally into the 6 km thick deltaic Belait Group, which contains alluvial clastics, point bar sandstones, coal seams and thick sandstones throughout (James, 1984; Hutchison, 1989; Liechti *et al.*, 1960).

Offshore Sarawak, the major hydrocarbon fields are located adjacent to the modern day Baram Delta Province with major sandstone reservoirs localised in the Middle to Late Miocene aged Seria, Miri and Baku Formations (Fletcher and Soeparjardi, 1984). Seven Late Miocene sandstones (Miri/Belait Formation) interbedded with shale produced hydrocarbons from the northwest flank of the Miri structure (Fig. 12) (Schaub and Jackson, 1955).

Hydrocarbon exploration activity in Sarawak, Sabah and Brunei has been summarised by Blechner, 1990; Blechner *et al.*, 1980; Courteney *et al.*, 1988; Fletcher, 1980, 1982, 1983; Fletcher and Soeparjadi, 1984; Soeparjadi *et al.*, 1985, 1986 and 1987 and others. The Miri sandstones are productive in Brunei at the Lutong West and onshore Seria Fields. Late Miocene-aged (Seria Formation equivalent) sandstones are the major producers at the onshore Baram field south of Miri. Late Miocene sandstones (Seria Formation equivalent) produced hydrocarbons from the Champion, West Ampa, Baram-Fairley, Baronia North, Baram, Tukau and Temana fields offshore Sarawak and Brunei.

Coastal, deltaic, point-bar and alluvial sandstones in the Neogene regressive cycles (Miri, Seria and Belait Formations) should therefore form effective reservoirs in the Tinjar province, particularly where buried beneath thrusts. Their reservoir quality will need to be verified (Bird *et al.*, 1993).

SOURCE ROCKS

During the initial Paleogene and Neogene transgressions, offshore carbonate banks developed in the offshore Luconia Province (Fulthorpe and Schlanger, 1989) and isolated lagoonal shelf areas where oil prone source material accumulated (Fig. 11). Hydrocarbons generated offshore could migrate southeastwards along transgressive units and unconformities and up faults into onshore traps.

Onshore the major hydrocarbon source rocks of the Neogene transgressive cycle are the coals and organic rich claystones of the Nyalau/Setap Formation (Fig. 11) (Fulthorpe and Schlanger, 1989). These source intervals may have generated hydrocarbons when they were depressed beneath the thrust front of the Rajang Accretionary Prism.

SEALS

Shales and claystones interlaminated with sandstones in the Miri, Seria and Belait Formations (Liechti *et al.*, 1960) will form effective seals where they are sufficiently thick and extensive as may overlying Plio-Pleistocene fine clastics and volcanics where they are present. Thin, regionally extensive shales of the Setap, Tubau and Nyalau Formations



Figure 8. Compressional strain ellipse.



Figure 9. Left-lateral strain ellipse (from Harding, 1974).



Figure 10. 3/113/SE structural map based on SAR imagery interpretation.

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ictural map based on SAR imagery interpretation.



Figure 11. Tertiary depositional cycles in Southeast Asia (after Fulthrope and Schlanger, 1989).

(Hutchison, 1989) may form seals for deeper traps.

TRAPS

The most common hydrocarbon traps in the Greater Sarawak Basin are northeast-southwest trending anticlines formed by northwest compression and sinistral wrenching. All of the onshore oil pools were located where these structures were defined on the surface (James, 1984; Bird et al., 1993). The Miri Field, which was originally located by testing oil seepages, is confined within an 8 km long by 4 km wide east-to-west oriented anticlinal structure that developed in a strike-slip setting (Fig. 11) (Schaub and Jackson, 1955). Closure is formed by both the antiformal structure and the faults. Box-folded elevated blocks of coastal to deltaic Belait Formation form the traps in the Belait and Jerudong fields located by surface and photogeological mapping (James, 1984).

In the Balingian Province offshore central Sarawak, Middle to Late Miocene deltaic and shallow marine sandstones form productive hydrocarbon traps in northeast-to-southwest trending anticlinal structures (Fletcher, 1982). Early to Middle Miocene reef and shelf limestones on the Luconia Platform produce gas from their upper parts (Hutchison, 1989).

Major anticlinal structures, normal and strikeslip faults recognised offshore on regional seismic lines can be traced on SAR from coastal Sarawak near Miri southeast into central Sarawak, where they are considered to have hydrocarbon potential (Bird *et al.*, 1993). The most likely traps in the



Figure 12. Structural cross-section through the Miri Field (Schaub and Jackson, 1955).

Tinjar Province are northeast-to-southwest trending compressional anticlines, *en-echelon* anticlines, tilted blocks, overthrust structures and closures formed at the margins of pull-apart basins developed at bends in the strike-slip systems (Fig. 13; James, 1984; Harding, 1974, 1990). Numerous stratigraphic traps likely to occur in fluvial, deltaic and coastal environments, but require additional geologic data for specific identification.

MATURATION

The Baram Delta Province is an area of major oil and gas production offshore of North Sarawak, Southwest Sabah and onshore and offshore Brunei (James, 1984; Chung, 1982), Geothermal gradients



Figure 13. Strike-slip complex (modified after Harding, 1974).

in the Baram Delta Province average 28° /km (Hutchison, 1989). The Baram Delta Province geothermal zone extends from west of Labuan Island south-southwestwards towards the Belait syncline in Brunei (SEAPEX and IPA, 1977). Similar deltaic conditions prevailed further southwest in the Tinjar Tectonostratigraphic Province during the deposition of the Miri, Seria and Belait Formations. The geothermal gradients in the Tinjar Province are therefore expected to be comparable to that of the Baram Delta Province. The conditions appear favourable for the generation and preservation of oil in the Tinjar Province as evidenced by gas seeps and shows (Bird *et al.*, 1993).

Temperature gradients are higher in the Balingian Province offshore (average 41°C/km) where thick marine shales occur on the continental shelf (Hutchison, 1989; SEAPEX and IPA, 1977). Even higher gradients (43°C/km) (Hutchison, 1989) are found in the offshore gas field region on the Luconia Platform and can exceed 50°C/km (SEAPEX and IPA, 1977).

CONCLUSIONS

The most prospective reservoirs in the Tinjar Tectonostratigraphic province are likely to be the Middle to Late Miocene-aged Miri, Seria and Belait Formations. The most likely source intervals are coals and organic rich shales of the Nyalau and Setap Formations and Neogene transgressive sapropelic lagoonal shales. Geothermal data implies that much of the source and reservoir formations in the Tinjar Province are in the main stage of oil generation and preservation.

Hydrocarbons may have migrated updip and inland from lagoonal, prodeltaic and deltaic source intervals along sandstone conduits, unconformities and faults to large antiformal and sub-thrust closures developed within the Tinjar Tectonostratigraphic Province. Other traps may have been filled by the northwest migration of hydrocarbons generated in the Nyalau and Setap shales depressed beneath the thrust front.

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SAR has proved to be an effective tool in deciphering the tectonic history and complex structure of the Greater Sarawak Basin, which can be further evaluated by analysing in detail the complex interference fold patterns present on the SAR images and by three-dimensional basin analysis.

A preliminary assessment of Exploration Concession Blocks can be achieved by the integration of SAR with other geological and geophysical information and by modelling the sedimentary basin on regional structure maps. Probable migration directions and related structural and stratigraphic hydrocarbon traps can be further refined and isolated.

An additional advantage of SAR is very critical to an exploration program. Because SAR reveals the structure so clearly, it can be used in selecting and delineating seismic acquisition programs and in locating the most prospective drilling locations.

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