

# 'Prograding' Tectonics in Brunei: Regional Implications for Fault Sealing

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**ABSTRACT:** The Baram Delta province of Brunei (northwest Borneo) is unusual when compared with most other Tertiary deltas, as it has built up upon an active margin. Hence, the structures observed in Brunei are the result of both margin-parallel gravity-driven deltaic tectonics and approximately margin-normal transpressive tectonics associated with the active margin. Image and dipmeter logs have been examined for breakouts and drilling-induced tensile fractures (DITFs) in 46 wells throughout the basin. Breakouts and DITFs observed in 19 wells suggest that the maximum horizontal stress ( $\sigma_{Hmax}$ ) is oriented margin-normal (NW-SE) in the proximal parts of the basin and margin-parallel (NE-SW) in the distal region. The margin-normal  $\sigma_{Hmax}$  direction is perpendicular to the strike of Miocene-Pliocene normal growth faults in the delta. Hence, there has been an approximately 90° rotation of the  $\sigma_{Hmax}$  direction over time, in addition to the observed present-day spatial horizontal stress rotation across the delta. The present-day and temporal stress rotations observed from breakouts and DITFs are confirmed by observations of shale dykes, blowout-induced fractures and active growth faulting. Furthermore, the Baram Delta province also shows a very large variation in vertical stress gradient from 18.3 MPa/km at the delta front to 24.3 MPa/km in the delta hinterland, equivalent to a change in bulk density from 2.07 to 2.48 g/cm<sup>3</sup> across the delta. The present-day and temporal stress rotations and the variation in vertical stress yield a 'snapshot' of a delta that is inverting and self-cannibalising. The proximity of the active margin has resulted in uplift of the hinterland and successive inversion of normal-faults in a basin-ward direction. The region of active deltaic growth faulting is also 'prograding' as demonstrated by the margin-parallel  $\sigma_{Hmax}$  direction in the distal region of the delta. The present-day stress tensor and 'prograding' tectonic history are primary controls on fault reactivation and subsequent seal breach in the region. Hydrocarbon leakage has occurred along an inverted fault in the Miri Field and only a few small fields have been found in the distal zone of active growth faulting. However, the margin-normal  $\sigma_{Hmax}$  direction observed in the proximal part of the Baram Delta province is poorly orientated for fault reactivation and seal breach and several giant fault-bound fields are located in this region.

## 1. INTRODUCTION

The present-day state of stress is a primary control on fluid flow through faults in sedimentary basins [1, 2]. Active faults are major secondary migration pathways and fault reactivation post-charge is a key cause of seal breach and hydrocarbon column loss

[2, 3, 4]. Accurate knowledge of the present-day state of stress can be used to assess the likelihood for fault reactivation and thereby risk exploration prospects [5]. However, despite the importance of accurately determining the present-day state of stress, several aspects of the stress tensor in Tertiary deltas are often assumed. Since Dickinson's classic

paper on Gulf Coast pressure [6], it has been commonplace to adopt a value of  $2.3 \text{ g/cm}^3$  for the mean density of sedimentary rocks in Tertiary deltas, the popularity of which is partly due to the resulting overburden stress gradient being  $1.0 \text{ psi/ft}$  ( $22.6 \text{ MPa/km}$ ). Furthermore, the maximum horizontal stress ( $\sigma_{Hmax}$ ) direction in Tertiary deltas is generally assumed to be parallel to the coastal margin as a result of the convex-upwards nature of the deltaic wedge (Fig. 1) [7]. This assumption is validated by observations of borehole breakout, the formation of margin-parallel normal growth faults and structural analogue modelling [7, 8, 9]. However, the Baram Delta province is unlike classic Tertiary passive margin deltas (e.g. the Mississippi and Niger deltas) because of the proximity of the NW Borneo active margin (Fig. 2) [10]. Structures within the Baram Delta province are primarily gravity-driven and deltaic in origin, but with varying degrees of compressive or transpressive interference from the active margin [10, 11]. Therefore the Baram Delta province offers a unique opportunity to investigate the in situ stress in a Tertiary delta located on an active margin and in a region covered by an extensive petroleum industry database [10].

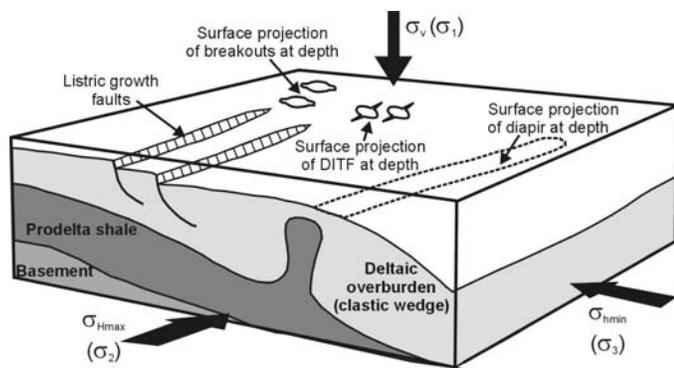


Fig. 1. Relationship between deltaic structures, borehole breakouts, DITFs and the present-day stress field in the Mississippi Delta (a typical passive margin Tertiary delta). Adapted from [1].

This paper analyses the present-day  $\sigma_{Hmax}$  orientation and vertical stress magnitude in Brunei to determine whether the present-day stresses in the Baram Delta province are controlled by 'local' deltaic stresses or far-field stresses associated with the active margin. The present-day stress orientations and vertical stress magnitudes in Brunei are then compared with previous structural styles to yield a new regional interpretation of the structural evolution of the Baram Delta province. Finally, the present-day state of stress and tectonic evolution are

used to determine the likelihood of fault reactivation and associated seal breach across the region.

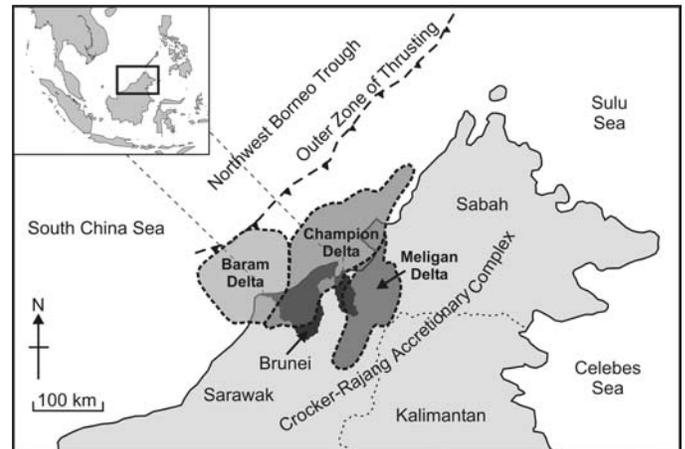


Fig. 2. Location of the three major delta systems of the Baram Delta Province, the Crocker-Rajang accretionary complex, the NW Borneo active margin (expressed at present-day by the outer zone of thrusting and the NW Borneo trough). Adapted from [10]

## 2. GEOLOGICAL SETTING

The Late Neogene Baram Delta province is predominantly composed of three rapidly prograding delta systems: the Early Miocene Meligan Delta, the Early–Late Miocene (late orogenic) Champion Delta and the Late Miocene to present-day Baram Delta (Fig. 2) [10]. These delta systems have built outwards from the Crocker–Rajang accretionary complex and are deposited adjacent to the NW Borneo active margin (Fig. 2) [10]. Subduction and accretion along the NW Borneo active margin ceased in the Mid-Miocene following the collision of the leading edge of the South China Sea continental realm with Borneo [12, 13]. Continent-continent compressional deformation has continued in pulses into the Quaternary [13]. The proximity of the NW Borneo active margin has caused extensive uplift and inversion in the proximal and eastern parts of the basin (Fig. 3) [10]. The sub-equatorial location of the Baram Delta province resulted in the uplifted sediments being rapidly eroded, reworked and deposited further down the delta [14]. Deposition rates within the Baram Delta province have reached  $3000 \text{ m/Ma}$  [10]. Rapid deposition of the fine-grained sediments has led to the development of widespread overpressures generated by disequilibrium compaction throughout the prodelta shales [10, 15, 16]. Overpressures within the prodelta shales are

commonly of sub-lithostatic magnitude and associated with undercompaction and shale diapirism [10, 15]. Localized high-magnitude overpressures are also observed within pressure compartments in the deltaic overburden in the inner shelf [10, 16].

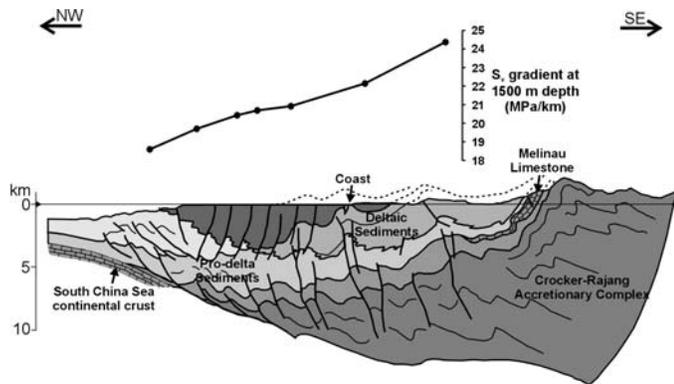


Fig.3. Schematic geological cross-section across the Baram Basin (adapted from [10]). The delta hinterland has been uplifted and eroded. Vertical stress gradients at 1500 m depth vary from 18.3 MPa/km in the distal parts of the delta to 24.3 MPa/km in the hinterland.

The active margin setting of the Baram Delta province has resulted in a complex interaction between gravity-driven ('thin-skinned') deltaic tectonics and transpressive or compressive ('thick-skinned') basement tectonics (Fig. 4) [10, 11, 13]. On a regional scale, the upper 15 km of the Baram Delta province can be divided into three layers based on their geomechanical properties [10]:

- (i) the brittle upper crust that acts as the 'structural basement' in Brunei (Cretaceous–Palaeogene rocks of the Crocker–Rajang Ranges and sediments of the Meligan–Delta system);
- (ii) the plastic overpressured deltaic substratum (prodelta shales), and;
- (iii) the relatively rigid deltaic overburden (the Champion and Baram Delta systems).

The style of deformation observed within the deltaic overburden is a function of the varying thickness and geomechanical properties of these three layers [10].

The Champion and Baram Delta systems primarily exhibit typical deltaic structures such as growth faults and rollover anticlines (Fig. 4) [10, 12, 13, 17]. However, the proximal regions of the Baram Delta province have also experienced varying degrees of basement-associated compressive and transpressive deformation, including large-scale

folding, thrust faulting, inversion of normal faults, reactive shale diapirs and extensive uplift of the hinterland (Fig. 4) [10, 13, 18].

The degree by which basement-associated compression has influenced the deltaic overburden is inversely proportional to the thickness of the overpressured prodelta shales [10, 13, 19]. Overpressured prodelta shales may act as a decoupling zone between the structural basement and deltaic overburden. However, the thickness of the prodelta substratum is non-uniform and absent in some regions [10, 13]. Regions with thick, highly overpressured prodelta shale sequences display classic deltaic deformation with little or no basement-associated interference (e.g. outer regions of the Baram Delta system) [10]. In comparison, greater amounts of compressive or transpressive deformation are observed in uplifted and eroded areas where the prodelta shales are thinner or less overpressured, such as the proximal parts of the Champion and Baram Delta systems (Fig. 4) [10].

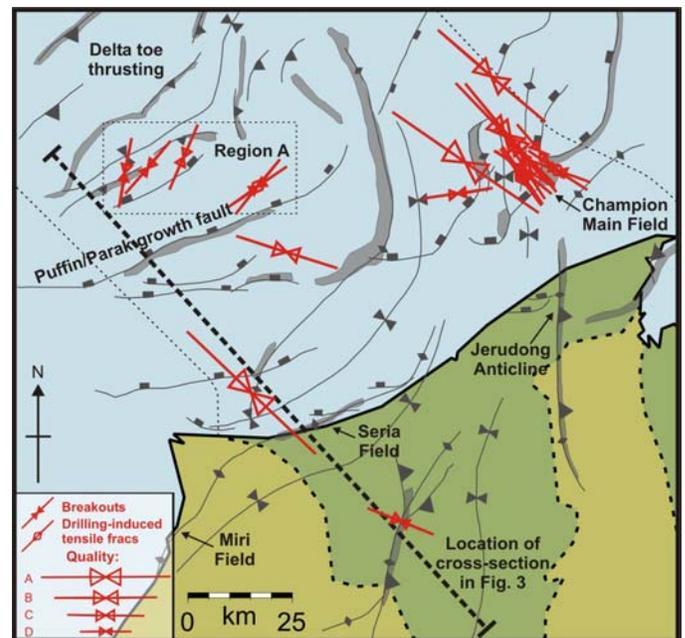


Fig. 4. Present-day maximum horizontal stress orientations and major geological structures (faults, folds, shale diapirs) in Brunei. Length of each indicator is representative of stress indicator quality. Maximum horizontal stress is oriented approximately margin-parallel in the outer shelf (Region A) and approximately margin-normal in the inner shelf.

### 3. VERTICAL STRESS MAGNITUDE

#### 3.1. Vertical Stress Magnitude Determination

The vertical or overburden stress ( $\sigma_v$ ) at a specified depth is defined as the pressure exerted by the weight of the overlying rocks and expressed as [20]:

$$\sigma_v = \int_0^z \rho(z)g dz, \quad (1)$$

where  $\rho(z)$  is the density of the overlying rock column at depth  $z$  and  $g$  is the acceleration due to gravity. The vertical stress in offshore wells is equal to the pressure exerted by the weight of the water column from the surface to the seabed plus the weight of the sediment column at a specified depth. Hence, the vertical stress at any depth is easily calculated by integrating the density log from the surface (or seabed). However, before calculating the vertical stress three issues must be addressed [21].

- (i) The density log must be correctly formatted.
- (ii) The density log must be filtered to remove spurious data
- (iii) The average density from the surface to the top of the density log must be estimated.

Density logs are typically measured relative to the depth along hole from the rotary table. Calculation of the vertical stress requires the density log to be transformed so that it is relative to the true vertical depth below the surface [21].

The density-logging tool needs to contact the wellbore wall firmly to yield accurate measurements [22]. If the hole is rugose and contact is poor, the density tool senses the low density fluids in the wellbore as well as the wall rock. Hence, density logs commonly show spuriously low values in sections of irregular borehole, which must be removed prior to calculating the vertical stress. The low-density spikes were removed herein by use of the density log correction curve (DRHO) and caliper log to isolate and remove spurious density measurements [21]. The filtered density logs in this study were also 'de-spiked' to remove any further anomalous measurements [21].

Density logs are generally not run all the way to the surface (or seabed in offshore wells). In order to calculate the vertical stress it is necessary to first estimate an average density from the surface to the top of the density log [21]. Herein, the average density from the surface to the top of the density log was calculated by means of checkshot velocity survey data and a re-calibrated Nafe-Drake sonic velocity-density transform [21, 23].

### 3.2. Vertical Stress Magnitude Results

The vertical stress magnitude was calculated for 24 fields throughout Brunei (Fig. 5; vertical stress

converted to gradients for clarity). Vertical stress varies both with depth and regionally across the Baram Delta province, ranging from 18 MPa/km (0.8 psi/ft) at shallow depth in the distal parts of the delta to 25 MPa/km (1.1 psi/ft) at three kilometres depth in the hinterland (Fig 5). At 1500 m depth the vertical stress ranges from 18.3 to 24.3 MPa/km (Fig. 6), which represents a variation in bulk density from 2.07-2.47 g/cm<sup>3</sup> (after effect of variable water depth is removed). Such a large regional variation in vertical stress magnitude is unique to the Baram Delta province.

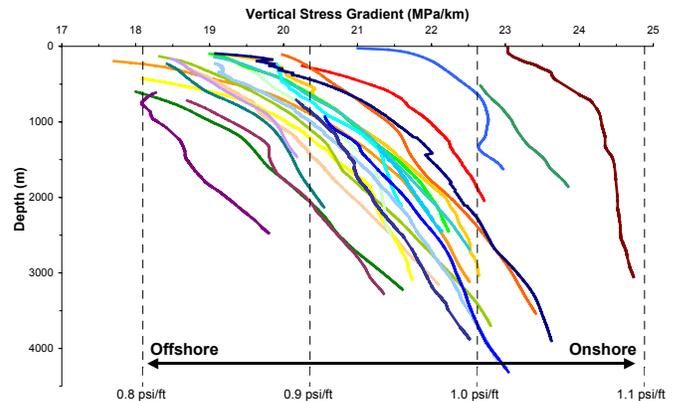


Fig 5. Calculated vertical stress gradients over the Baram Delta province. Vertical stress varies with depth and spatially between fields.

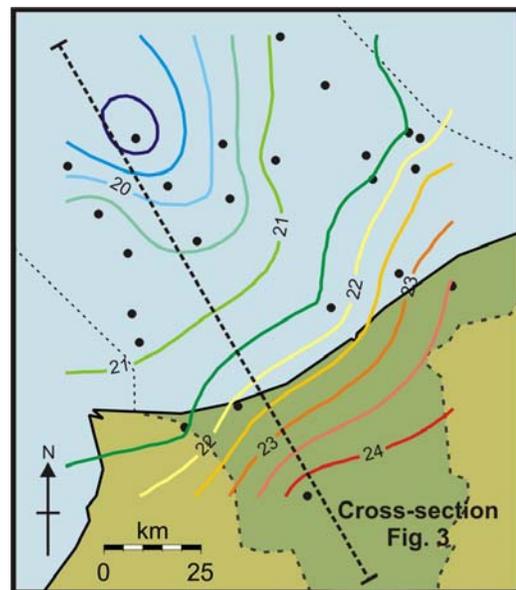


Fig 6. Contour map of vertical stress gradients (MPa/km) over the Baram Delta province at 1500 m depth below the surface.

### 3.3. Origin of the Vertical Stress Variation

The variation in average sediment density in Brunei is interpreted to be variable uplift and erosion of the delta hinterland [21]. The proximity of the northwest Borneo active margin has resulted in uplift and erosion (cannibalization) of the proximal

parts of the delta [10]. Uplift and unloading does not reverse sediment compaction. In the uplifted regions the less dense upper section has been eroded away leaving denser material nearer to the surface. Hence, sediments are more compacted (and more dense) in the uplifted, proximal regions and there is a corresponding variation in vertical stress gradient from high onshore to low offshore (Figs. 3 and 6).

#### 4. MAXIMUM HORIZONTAL STRESS ORIENTATION

##### 4.1. Horizontal Stress Orientation Determination

Present-day horizontal stress orientations in the Baram Delta province were determined from borehole breakouts and DITFs interpreted from four-arm caliper and resistivity image log data. When a borehole is drilled the material removed from the subsurface is no longer supporting the surrounding rock. As a result, a stress concentration develops in the surrounding rock (i.e. the wellbore wall) [24]. Borehole breakouts are stress-induced elongations of the wellbore and occur when the stresses concentrated at the wellbore wall (the circumferential stress) exceed that required to cause compressive failure of intact rock [25]. The elongation of the wellbore is the result of compressive shear failure on intersecting conjugate planes, which causes pieces of the borehole wall to spall off [25]. The maximum circumferential stress around a vertical borehole occurs perpendicular to the maximum horizontal stress [24]. Hence, borehole breakouts are elongated perpendicular to the  $\sigma_{Hmax}$  direction in vertical boreholes [25].

Drilling-induced tensile fractures are caused by tensile failure of the borehole wall and form when the wellbore stress concentration is less than the tensile strength of the rock [26]. The minimum circumferential stress around a vertical borehole occurs in the direction of the maximum horizontal stress [24]. Hence, DITFs are oriented in the  $\sigma_{Hmax}$  direction in vertical boreholes [27].

Breakouts are interpreted herein from Schlumberger High resolution Dipmeter Tool (HDT) logs and resistivity image logs (Formation Micro Imager: FMI; Formation Micro Scanner: FMS). The HDT is a four-arm caliper tool with two pairs of caliper arms at 90° to each other. The HDT tool tends to rotate as it is pulled up the borehole, as a result of cable torque. However, the tool stops rotating where the cross-sectional shape of the borehole is

elongated when one caliper pair becomes ‘stuck’ in the elongation direction [28]. Borehole breakouts are distinguished from other borehole elongations (e.g. washouts and key-seats) on HDT logs using the interpretation criteria presented by Plumb & Hickman [28].

Resistivity image logs are more advanced versions of dipmeter logs that have a number of resistivity buttons on each arm. The multiple resistivity buttons provide an image of the borehole wall based on resistivity contrasts [29]. The resistivity image of the wellbore wall allows for a more reliable interpretation of breakouts than could be made by using dipmeter data alone. Drilling-induced tensile fractures can also be recognized on image logs (DITFs cannot be interpreted on HDT logs). Breakouts appear on image logs as broad, parallel, often poorly resolved conductive zones separated by 180° and exhibiting caliper enlargement in the direction of the conductive zones (Fig. 7a). DITFs appear on image logs as narrow, well defined, conductive fractures (Fig. 7b) [1].

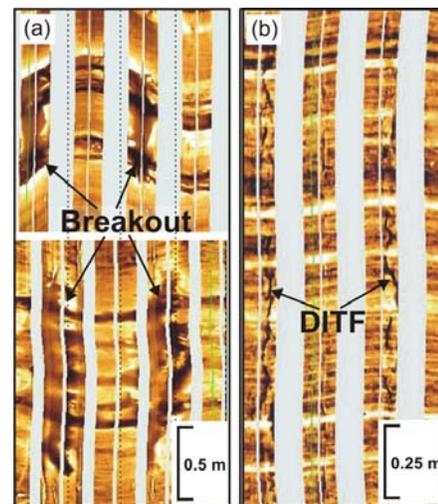


Fig 7. FMI resistivity images from offshore Brunei showing (a) borehole breakout and (b) drilling-induced tensile fractures.

Breakouts and DITFs can rotate in inclined boreholes and do not always directly yield the horizontal stress orientation [30, 31]. However, the current state of stress in the shelf region of Brunei is believed to be a normal faulting stress regime, based on minifracture test data, analysis of frictional limits to faulting, modelling of breakout and DITF formation and leak-off test variation with deviation [16, 32]. Breakouts and DITFs do not show any significant rotation in orientation and will still yield the approximate  $\sigma_{Hmax}$  orientation in boreholes with less than 20° deviation in a normal faulting stress

regime [31]. Hence, breakouts and DITFs were only used to estimate the  $\sigma_{Hmax}$  direction in wells with deviations of  $<20^\circ$ .

The mean horizontal stress orientation from each well was given a quality ranking according to the World Stress Map Project criteria, with A-quality being the highest and E-quality the lowest [33, 34].

#### 4.2. Maximum Horizontal Stress Orientation Results

Image logs or four-arm dipmeter logs were examined in 47 wells throughout the basin. Breakouts and/or DITFs were observed in 23 wells (Fig. 4). A total of 173 breakouts and eight DITFs in 19 wells were observed in intervals with wellbore deviations of  $20^\circ$  (Fig. 4). An additional 92 breakouts and one DITF were observed in wellbores with deviations exceeding  $20^\circ$  and are not used herein. The observed stress-induced features indicate that  $\sigma_{Hmax}$  is oriented approximately NW–SE (margin-normal) in the proximal parts of the delta (the inner shelf). However, in the western outer shelf region (labelled Region A in Fig. 4) breakouts and DITFs in four wells suggest an approximately NE–SW (margin-parallel)  $\sigma_{Hmax}$  direction.

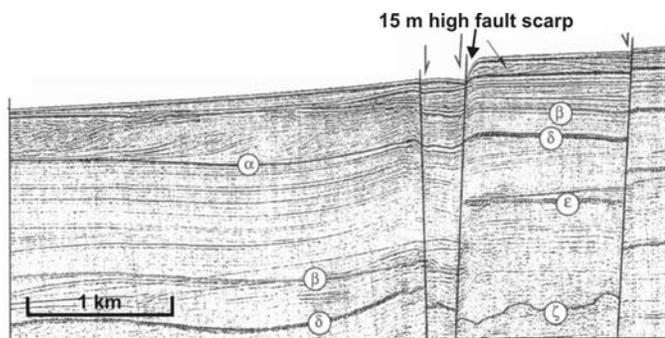


Fig. 8. Shallow seismic section across a growth fault near the Puffin/Parak Field (from [35]). Note the 15 m high fault scarp indicating the fault is active.

#### 4.3. Other Indicators of Present-Day Horizontal Stress Orientation

The  $\sigma_{Hmax}$  orientations determined herein match other significant observations in the region. Shallow seismic and bathymetric data reveal the presence of sea-bed fault scarps, indicating active NE–SW-striking growth faults in the outer shelf area (Fig. 8; in Region A) [35]. Normal growth faults typically strike in the  $\sigma_{Hmax}$  direction (Fig. 1) [7]. Hence, the presence of active NE–SW-striking growth faults in the outer shelf is consistent with the observed  $\sigma_{Hmax}$  orientation from breakouts.

The margin-normal (NW–SE)  $\sigma_{Hmax}$  observed in the inner shelf region of Brunei agrees with  $\sigma_{Hmax}$  directions determined previously from borehole breakouts in NW Borneo [36, 37]. Further supporting evidence of a NW–SE  $\sigma_{Hmax}$  direction in the inner shelf comes from blowout fractures observed after the 1974 and 1979 blowout events in the Champion Field. Both the 1974 and 1979 blowouts were primarily internal blowouts but resulted in several associated surface eruptions [38]. An internal blowout involves overpressured fluids being transmitted along the open wellbore to shallower reservoir units rather than up the well to the surface. The Champion Field internal blowouts caused pore pressures within these shallow reservoirs to increase rapidly until the cap-rock seals to the shallow reservoirs fractured, resulting in the sea-bed blowouts (Fig. 9) [38]. The 1974 internal blowout was associated with a large sea-bed blowout and crater underneath the platform, a 600 m long string of six small craters 1000 m from the platform and a second large crater 5 km SE of the platform (Fig. 9) [39]. The 1979 internal blowout was associated with two surface eruptions that expelled large volumes of overpressured fluids for 10 days (Fig. 9) [10]. Bathymetric surveys over the Champion Field show that the 1974 and 1979 blowout craters and surface eruptions occurred in approximately straight lines oriented NW–SE (Fig. 9) [39]. Nearsurface seismic amplitude time slices from high-resolution 3D seismic data in the Champion Field reveal the presence of approximately vertical NW–SE-oriented fractures underneath the crater and blowout locations (Fig. 9) [39]. A similar blowout event also occurred in the onshore Seria Field in 1953. The 1953 Seria blowout was also associated with two blowout craters aligned approximately NW–SE [39].

The blowout fractures in the Champion and Seria Fields can be considered analogous to large-scale hydraulic fractures, albeit initiated from an inflated reservoir rather than an inflated wellbore. Tensile fractures open against the least principal stress and, therefore, strike in the  $\sigma_{Hmax}$  direction in a normal or strike-slip faulting stress regime [39]. Hence, the Champion and Seria blowout fractures are consistent with the present-day NW–SE  $\sigma_{Hmax}$  direction determined by borehole breakouts and DITFs in the inner shelf region of Brunei.

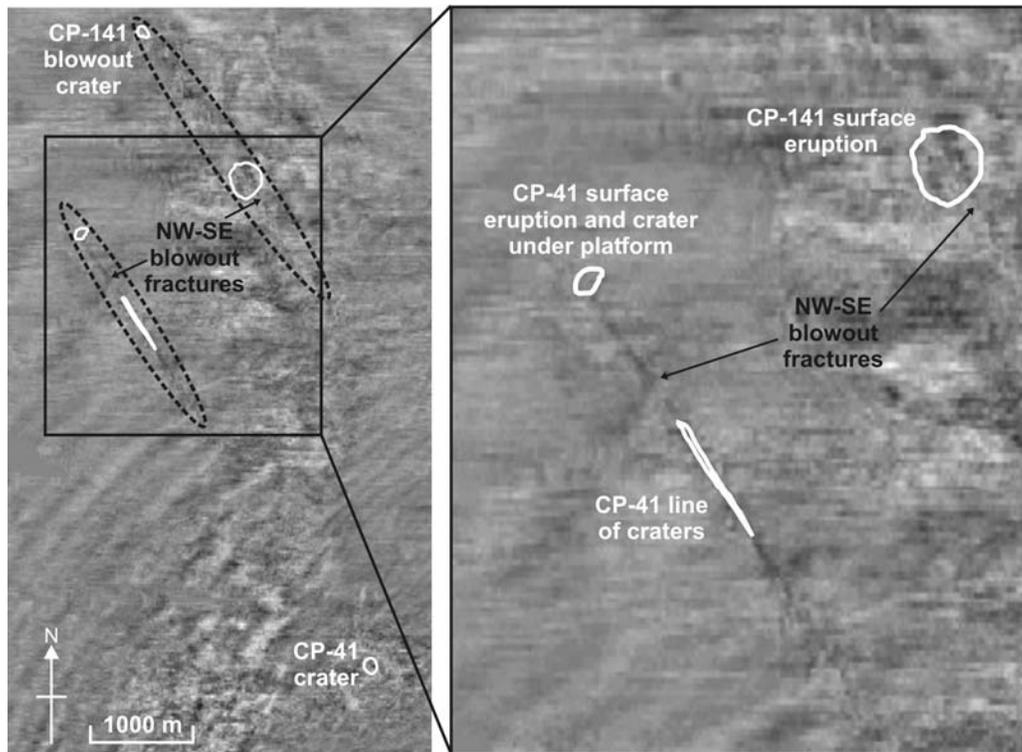


Fig. 9. Near surface seismic amplitude time-slice across the Champion Main Field. 1974 and 1979 blowout craters and surface eruption locations are outlined in white and overlie two NW-SE trending sub-vertical fractures (highlighted in black).

## 5. ORIGIN OF THE OUTER SHELF STRESS FIELD

There are a number of key points regarding the western outer shelf region (Region A) that are pertinent to understanding the margin-parallel (NE–SW)  $\sigma_{Hmax}$  orientations in the area.

- (i) Region A is in the modern Baram Delta system and is an area of present-day deposition of sediments from the Baram and Belait Rivers [10].
- (ii) Structures within the western outer shelf region are typical deltaic features such as active margin-parallel growth faults and shale diapirs (Figs. 4 and 8) [10, 35].
- (iii) Structures within Region A do not display any significant basement-associated deformation (as opposed to the inner shelf region) [10].

The stress field and associated deformation in passive margin Tertiary deltas are controlled by the geometry of the clastic wedge [7]. The shape of the clastic wedge is typically convex-upward, which promotes gravity-driven extension in the delta (Fig. 1) [8]. Hence, shelf regions of Tertiary deltas on passive margins typically display growth faults and

diapirs that strike margin-parallel (Fig. 1) [7]. Breakouts and DITFs also generally suggest a present-day margin-parallel  $\sigma_{Hmax}$  orientation in passive margin Tertiary deltas (Fig. 1) [7]. Hence, the current margin-parallel  $\sigma_{Hmax}$  direction in Region A is interpreted as a classic deltaic stress field.

## 6. ORIGIN OF THE INNER SHELF STRESS FIELD

There is an approximately 90° rotation in the present-day  $\sigma_{Hmax}$  direction between the margin-parallel deltaic stress field in the outer shelf and the margin-perpendicular (NW–SE)  $\sigma_{Hmax}$  direction observed in the inner shelf region of Brunei. Hence, an additional (non-deltaic) source of stress is influencing the stress field in the deltaic sediments of the inner shelf. There are a number of key points regarding the inner shelf region that are pertinent to understanding the NW–SE stress orientations in the area.

- (i) Inner shelf sediments are older sequences of the Baram and Champion Delta systems (predominantly of Mid-Miocene to Pliocene age).

- (ii) Structures in the inner shelf are primarily deltaic such as margin-parallel growth faults, rollover anticlines and shale diapirs [10].
- (iii) Basement-associated deformation of the deltaic structures is common in the inner shelf [10].
- (iv) The hinterland of the Baram Delta province has been variably uplifted with uplift increasing proximally (Fig. 3) [21].
- (v) There has been Late Miocene and Pliocene NW-SE oriented inversion of normal faults in most inner shelf fields [13].
- (vi) The prodelta shales are thinner and older in the inner shelf and believed to allow greater ‘attachment’ of the deltaic sequences to the structural basement [10].
- (vii) No active faulting or seismicity has been observed in the inner shelf [40].

The basement-associated deformation, uplift of the hinterland and inversion in several fields suggest that the present-day  $\sigma_{Hmax}$  direction in the inner shelf deltaic sediments may be associated with the regional or far-field stresses in the structural basement [39]. There are no data known to the authors for the in situ stress field in the structural basement underlying the Baram Delta province. However, Hutchinson suggested that the current  $\sigma_{Hmax}$  direction in the basement is likely to be NW–SE from recent structural trends observed throughout NW Borneo [41]. Furthermore, the major Pliocene inversion events affecting the inner shelf have been interpreted as ‘pulses’ of NW–SE basement-associated compression [13, 37]. Hence, the NW–SE  $\sigma_{Hmax}$  direction in the inner shelf is interpreted to be the result of far-field and/or basement stresses transmitted through the prodelta shales into the deltaic overburden.

## 7. MAXIMUM HORIZONTAL STRESS ROTATION IN BRUNEI

The rotation of the present-day  $\sigma_{Hmax}$  direction in the Baram Delta province is interpreted as the result of two competing orthogonal stress fields:

- (i) a ‘local’ margin-parallel (NE–SW) deltaic  $\sigma_{Hmax}$  orientation caused by the shape of the clastic wedge, and;
- (ii) a NW–SE (margin-normal)  $\sigma_{Hmax}$  orientation probably related to basement or first-order

stresses transmitted through the prodelta shales.

The orientation of  $\sigma_{Hmax}$  in a field or region is controlled by whichever of these two stress fields is dominant.

It is of particular interest that the margin-normal present-day stress orientation in the inner shelf is inconsistent with structural styles observed in seismic data and in outcrop in the area. The structures observed in the inner shelf are primarily margin-parallel deltaic features such as growth faults, rollover anticlines and shale diapirs (albeit with basement-associated interference and inversion; Fig. 4). The prevalence of deltaic structures in the inner shelf suggests that a deltaic margin-parallel  $\sigma_{Hmax}$  direction was previously dominant in the inner shelf. Hence, there has been an approximate 90° rotation in the  $\sigma_{Hmax}$  direction over time from that associated with deltaic tectonics to the present-day inner shelf stress field.

Shale dykes in the Jerudong Anticline provide further evidence of the temporal  $\sigma_{Hmax}$  rotation in the inner shelf. Some shale dykes have failed in tension and are analogous to natural hydraulic fractures (Fig. 10) [38, 39]. Other shale dykes occur in fault planes that were presumably active at the time of injection (Fig. 10) [3, 17, 18]. The Mid-Miocene shale dykes in the Jerudong Anticline predominantly strike NE–SW after rotation to their pre-folding orientation [17, 18]. Hence, the shale dykes suggest a margin-parallel  $\sigma_{Hmax}$  direction associated with a deltaic stress field during the Mid-Miocene in the Jerudong Anticline. However, shale dykes in the Jerudong Anticline that were emplaced during the Pliocene strike NW–SE [17, 18]. Thus, the Pliocene shale dykes suggest a NW–SE, margin-normal  $\sigma_{Hmax}$  direction, and this supports the rotation of  $\sigma_{Hmax}$  over time in the inner shelf [39].

The present-day stress field of the Baram Delta province is thus interpreted to reveal the following spatial and temporal rotations in  $\sigma_{Hmax}$  direction (when compared with earlier deformations):

- the rotation of present-day  $\sigma_{Hmax}$  from margin-normal in the inner shelf to margin-parallel in the outer shelf (spatial), and;
- the rotation of  $\sigma_{Hmax}$  in the inner shelf from Miocene, deltaic and margin-parallel to its present-day, basement-associated and margin-normal orientation (temporal).

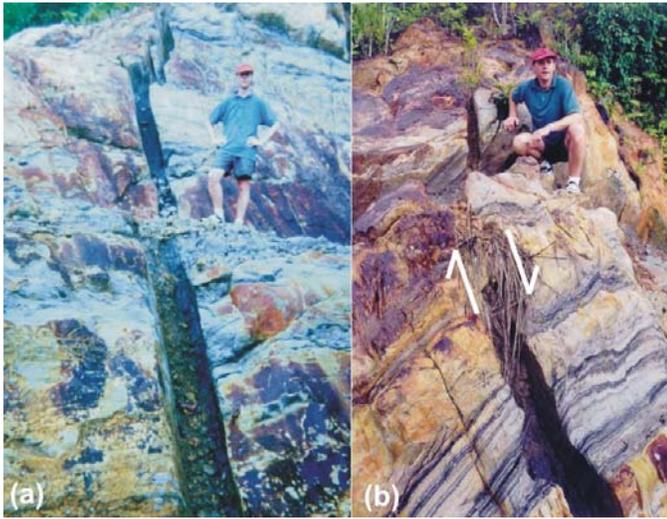


Fig. 10. Shale dykes in the Jerudong Anticline. (a) NW-SE striking Pliocene shale dyke injected along a tensile fracture. (b) Miocene shale dyke injected along a fault plane. Middle to Late Miocene shale dykes generally strike NE-SW (after rotation to their pre-folding orientation). Hence, the shale dykes suggest a 90° rotation in  $\sigma_{Hmax}$  orientation over time [18].

## 8. 'PROGRADING TECTONICS': A REGIONAL INTERPRETATION OF THE STRUCTURAL EVOLUTION OF THE BARAM DELTA PROVINCE

The temporal and spatial rotations of  $\sigma_{Hmax}$  orientation in the Baram Delta province are interpreted herein to be the result of 'prograding tectonics' in the region. The inner shelf has been subject to the following general sequence of events (Fig. 11) [13, 39].

- (i) Deposition of deltaic sediments with associated deltaic tectonics ( $\sigma_{Hmax}$  margin-parallel).
- (ii) Uplift of the hinterland causing deltaic deposition to shift distally and hence, deltaic deformation to cease (zone of deltaic deformation shifts towards outer shelf).
- (iii) Inversion of growth faults, regional uplift and erosion (i.e. basement-associated tectonics; predominantly  $\sigma_{Hmax}$  margin-normal;  $\sigma_v$  increasing towards hinterland).

Deltaic growth faulting (and the associated deltaic stress field) is syndepositional and localized in the region of deltaic deposition [42]. The uplift of the hinterland has 'forced' the rapid progradation of the Baram and Champion Delta systems [10]. Therefore, the deltaic deformation observed in the Baram Delta province has generally shifted distally over time (Fig. 11) [39]. Deltaic deformation has

moved gradually from Mid-Miocene faulting and diapirism near Jerudong, Seria and the eastern inner shelf region to the present-day growth faulting in the western outer shelf region (Fig. 11) [10, 13]. Hence, the deltaic tectonics and the associated deltaic stress field have 'prograded' basin-ward as the delta has built outwards across the shelf (Fig. 11) [13, 39].

Many fields and structures in the inner shelf have undergone uplift and inversion after the initial deltaic deposition and deformation [10]. These inversion events have occurred in progressively basin-ward regions over time (Fig. 11) [13]. Hence, the basin-ward 'prograding' gravity-driven deltaic deformation has been 'followed' by a similarly 'prograding' zone of inversion events (Fig. 11) [39].

## 9. REGIONAL IMPLICATIONS FOR FAULT REACTIVATION AND ASSOCIATED SEAL BREACH

The Baram Delta province has been an area of active petroleum exploration and production since 1899. Brunei is a major-oil producing region with 18 commercial fields (including 4 giant fields) containing over 5 billion barrels of oil and 22 trillion cubic feet of gas and is an area of current exploration focus, particularly in the outer shelf and deepwater regions [10, 43].

The sealing potential of faults is a major exploration concern in the Baram Delta province. All but one of the 36 known hydrocarbon accumulations in Brunei is laterally sealed by faults [10].

Fault seal potential is influenced by three factors:

- fault gouge (or membrane);
- juxtaposition, and;
- potential for reactivation [4].

Fault gouge relates to the permeability and thickness of the material inside the fault zone [44, 45]. Juxtaposition refers to the permeability of the rocks on either side of the fault zone [46]. Fault reactivation potential relates to the likelihood of the fault to be reactivated in the present-day stress regime and consequently be able to transmit fluids [5]. Hence, faults must either contain a sealing membrane and/or be juxtaposed against a low permeability rock, and must not be reactivated post-charge in order to act as seals [4].

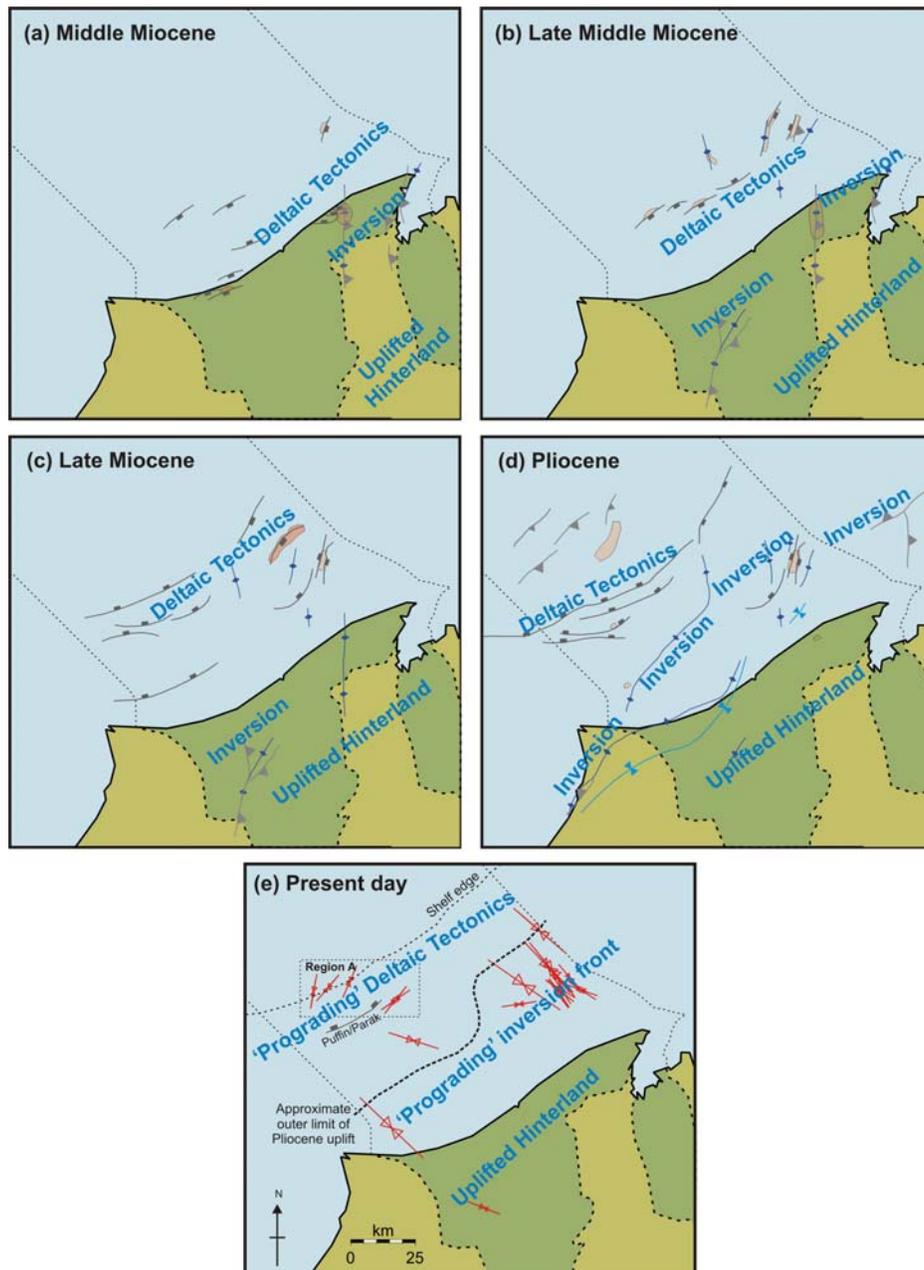


Fig. 11. Evolution of structures in the Baram Delta province from Middle Miocene to present (structural history adapted from [10] and [13]). Zones of hinterland uplift, deltaic tectonics and inversion have ‘prograded’ over time. Red shaded regions are areas of major shale diapirism.

The Baram Delta province is a mud-rich system and studies of regional seal potential, conducted internally by Brunei Shell Petroleum, indicate that faults in Brunei generally have high quality membrane seals, with average shale gouge ratios approximately in excess of those observed in the Mississippi and Niger Deltas [10]. The capacity for faults in Brunei to act as good quality seals is demonstrated by the highly overpressured compartments observed in some fields [10, 16]. For example, a pore pressure difference of over 20 MPa (at 2000 m depth) is supported by a single minor fault in the Iron Duke Field [10, 16]. However, despite the high quality seals that exist in Brunei,

there is a significant and proven risk of seal breach due to fault reactivation.

Fault reactivation is known to have caused seal breach and hydrocarbon column loss in the Miri Field in neighboring Sarawak, Malaysia. The Miri Field is a slightly overturned anticlinal structure separated into several elongate segments by normal growth faults [15]. Extensive production of the Miri Field revealed that all major normal faults in the Miri Field trapped live hydrocarbon columns, with the exception of the Canada Hills fault [13]. Outcrop and seismic analysis of the Miri Field reveals that the Canada Hills fault was also the only

major normal fault in the Miri Field to be reactivated during the most recent (Pliocene) inversion event. Furthermore, oil staining in the fault zone reveals that the Canada Hills fault was a conduit for hydrocarbons, suggesting that oil columns were trapped by this fault, but were lost when the fault was inverted (Fig. 12).



Fig. 12. Hydrocarbon staining in fractures within the Canada Hills fault, Miri Field, Sarawak. The Canada Hills fault is the only major inverted fault and the only fault that does not trap any hydrocarbons in the Miri Field [13]. Seal breach was most likely associated with the Pliocene inversion of this fault.

The present-day stress field of the Baram Delta province has major implications for post-charge fault reactivation and subsequent seal breach in Brunei. The present-day stress tensor can be used to calculate the relative likelihood of faults to be

reactivated in the present-day [4, 5]. The shear and normal stress acting on any given fault plane can be calculated for the known stress tensor (Fig. 13). The risk of reactivation on a given fault plane can then be estimated in terms of the pore pressure increase required to cause failure (Fig. 13) [5]. Therefore, the relative risk of reactivation of all possible fault planes in the in situ stress tensor can be determined and plotted on a stereonet (Fig. 14) [5].

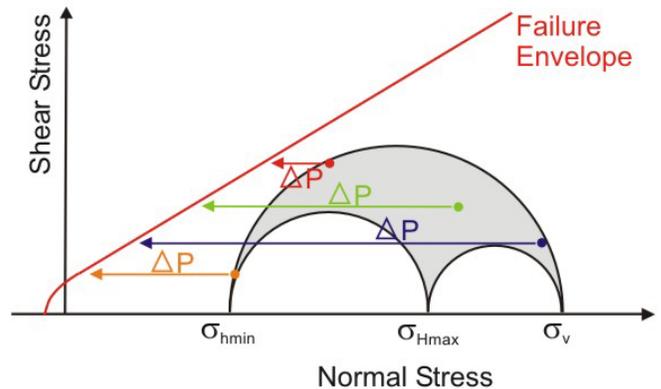


Fig. 13. Example of determining relative reactivation risk of all possible fault orientations, from the inner shelf. All possible planes will plot as a point in the grey region of the Mohr circle. The relative risk is determined as the pore pressure increase ( $\Delta P$ ) required to cause failure on each fault plane [5].

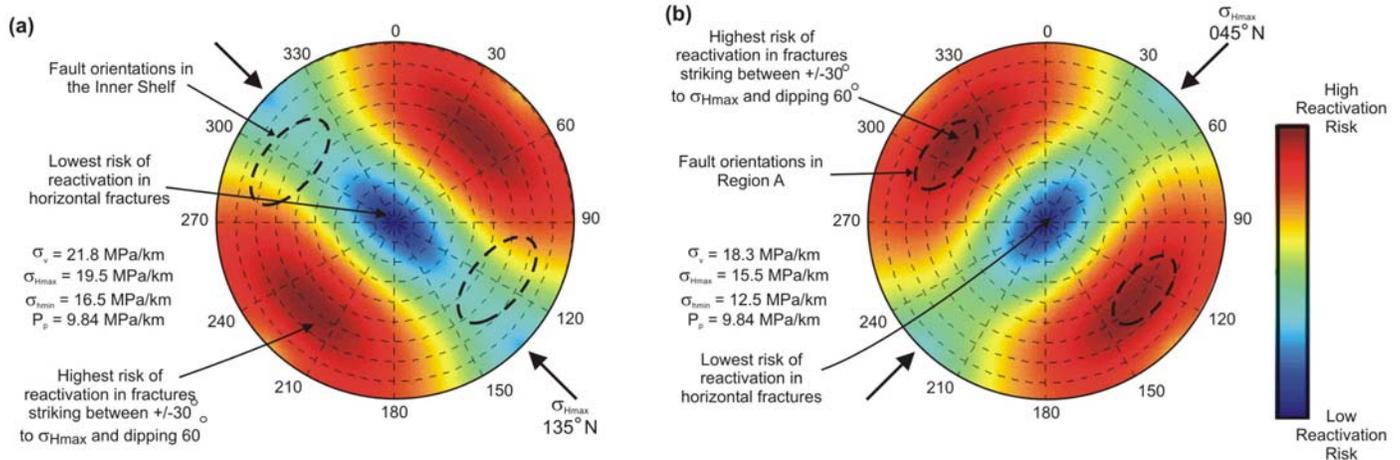


Fig. 14. Reactivation risk plots for (a) the Champion Main Field (inner shelf) and (b) the outer shelf region (stress magnitudes from [16]). Plots are stereographic projections of normals to all possible fault planes. Faults are poorly oriented for reactivation in the inner shelf. However, faults are optimally oriented for reactivation in the outer shelf region and active faults are present.

Faults typically strike NE-SW and dip 50-70° in the inner shelf [10]. Hence, faults in the inner shelf are at a low risk of reactivation in the present-day stress tensor (Fig. 14a). This is confirmed by the absence of seismicity in the inner shelf region and the initiation of new tensile fractures during the CP-41 and CP-141 blowouts, rather than reactivation of

pre-existing faults [38, 40]. However, the active growth faults in the outer shelf region strike northeast-southwest and have the highest risk of reactivation in the present-day stress field (Fig. 14b) [35]. Hence, fault reactivation and subsequent seal breach is a serious exploration concern in the outer shelf region. This is further illustrated by the

distribution of hydrocarbon accumulations discovered to date in Brunei. All major fields (including the 4 giant fields) are located in the inner shelf region of Brunei where faults are not optimally aligned for present-day reactivation and seal breach (Fig. 15). In comparison, only small accumulations have been discovered in the outer shelf region where faults are favourably oriented for reactivation and active growth faulting is present (Fig. 15).

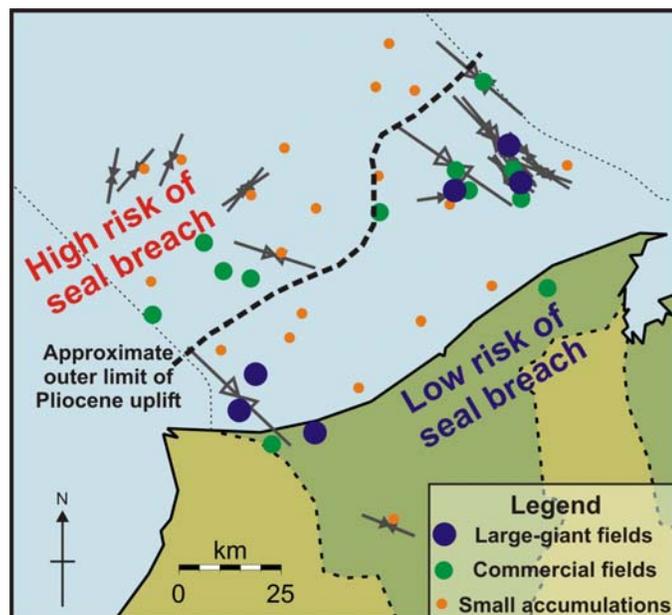


Fig. 15. Location and relative size of hydrocarbon accumulations in Brunei (from [10]). All major hydrocarbon accumulations discovered to date are in the inner shelf where present-day fault reactivation risk is low. Only minor accumulations have been found in the outer shelf.

## 10. CONCLUSIONS AND DISCUSSION

This paper is the first detailed study known to the authors of present-day stresses in a Tertiary delta on an active margin and thus provides a unique insight into the tectonic development of rapidly prograding delta systems. The Baram Delta province exhibits varying vertical stress magnitudes and maximum horizontal stress orientations. Vertical stress gradients vary from 24.3 MPa/km (1.1 psi/ft) to 18.3 MPa/km (0.8psi/ft), in stark contrast to the commonly used value of 22.63 MPa/km (1.0 psi/ft). The Baram Delta province exhibits a margin-normal basement-associated stress field in addition to a margin-parallel deltaic stress field. Hence, the stress field in the Baram Delta province is inconsistent with the purely margin-parallel deltaic stress fields observed in Tertiary deltas on passive margins. Furthermore, comparison of structural styles with the present-day stress field reveals that both the

margin-parallel deltaic and margin-normal basement-associated stress fields have ‘prograded’ basin-wards over time as the delta has built outwards. The variation in vertical stress magnitudes and the in rotation of the present-day  $\sigma_{Hmax}$  orientation from the inner to the outer shelf yields a ‘snapshot’ of ‘prograding tectonics’ in the Baram Delta province: the dynamic evolution of a rapidly prograding and self-cannibalising Tertiary delta system captured in a single geological ‘instant’. Furthermore, The ‘prograding’ deltaic and basement-associated stress provinces revealed herein has played a key role in the regional distribution of hydrocarbon accumulations. The outer shelf contains active, leaking faults and is a zone of poor exploration success. However, the highly prospective inner shelf has experienced a stress rotation over time, a consequence of which is that faults in this region are poorly oriented for reactivation and seal breach in the present-day stress tensor.

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