Pore pressure-stress coupling in Brunei Darussalam – implications for shale injection

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ABSTRACT

Shale dykes, diapirs and mud volcanoes are common in the onshore and offshore regions of Brunei Darussalam. Outcrop examples show that shale has intruded along both faults and tensile fractures. Conventional models of overpressure-induced brittle failure assume that pore pressure and total stresses are independent of one another. However, data worldwide and from Brunei show that changes in pore pressure are coupled with changes in total minimum horizontal stress. The pore pressure/stress coupling ratio ($\Delta\sigma_h/\Delta P_p$) describes the rate of change of minimum horizontal stress magnitude with changing pore pressure. Minimum horizontal stress measurements for a major offshore field where undepleted pore pressures range from normal to highly overpressured show a pore pressure/stress coupling ratio of 0.59. As a consequence of pore pressure/stress coupling, rocks can sustain a greater increase in pore pressure prior to failure than predicted by the prevailing values of pore pressure and stress. Pore pressure/stress coupling may favour the formation of tensile fractures with increasing pore pressure rather than reactivation of pre-existing faults. This hypothesis is supported by anthropogenically-induced tensile fracturing in offshore Brunei.

Overpressured shale has migrated along both tensile and shear fractures in Brunei Darussalam (Morley et al., 1998; Morley, *this volume*). Fluids can flow along tensile fractures when open and along active shear fractures/faults (Sibson, 1996; Losh et al., 1999). Hence, the transmission of overpressured shale through fractures is controlled by the stress field, pore pressure and rock strength. In the petroleum industry, the conditions for rock failure are used to estimate the amount of pore pressure increase that would cause seal breach. It is commonly assumed that the maximum hydrocarbon column height that can be trapped is one that generates a buoyancy pressure equal to the difference between the prevailing pore pressure and minimum horizontal stress (e.g. Caillet, 1993; Gaarenstroom et al., 1993). More recently it has been recognised that seal breach may be initiated if the buoyancy of the hydrocarbon column causes tensile or shear failure (Finkbeiner et al., 2001). However, models of pore pressure related failure need to incorporate the observation that changes in pore pressure are associated with changes in the minimum horizontal stress magnitude (σ_h). Measurements of virgin pore pressures and minimum horizontal stress magnitudes (i.e. those unaffected by depletion) indicate that minimum horizontal stress increases, from shallow normally pressured sequences into deeper, overpressured sequences, over and above that due to increasing depth (Bell, 1990; Gaarenstroom et al., 1993; Yassir & Bell, 1994). The changes in minimum horizontal stress that accompany changes in pore pressure are herein termed pore pressure/stress (P_p/σ_h) coupling. The nature of the P_p/σ_h coupling relationship is a factor in determining the amount of P_p increase that can be sustained prior to failure, and the mode (shear versus tensile) of rock failure that develops with increasing overpressure. Hence, the P_p/σ_h coupling relationship controls the injection mechanism of sediment injection features such as shale dykes (Morley et al. 1998).

We use mini-fracture tests and repeat formation tests in one field in offshore eastern Brunei to determine the P_p/σ_h coupling relationship. We show that P_p/σ_h coupling allows the development of stress states in which both tensile and shear failure occurs. Both modes of failure are observed in outcrop in Brunei (Morley et al., 1998; Morley, *this volume*). However, we suggest that in the present-day stress regime it is more likely for mobile shale to be transmitted along tensile fractures than shear fractures. We describe a 1979 internal blowout of a well as an example of this failure process and subsequent injection of overpressured fluids.

REGIONAL SETTING

The onshore and offshore regions of Brunei Darussalam are composed of several Late Neogene rapidly-prograding delta systems built outwards from the Crocker-Rajang accretionary complex and deposited adjacent to the northwest Borneo active margin (Koopman & James, 1996a; Figure 1). This tectonic setting has led to fast deposition rates and exhibits complex interaction between gravity-driven deltaic and transpressional basement tectonics (Koopman & James, 1996b). Deposition rates within delta systems have reached 3000m/Ma (Koopman & James, 1996b). Rapid deposition of the fine-grained prodelta sediments has led to the development of widespread overpressures generated by disequilibrium compaction (Schreurs & Ellenor, 1996). Overpressures may also have been generated by increasing horizontal stress magnitudes with depth (De Bree et al., 1993; Yassir & Bell, 1994). Overpressured fluids have also been transmitted vertically along faults and fractures resulting in inflationary overpressures at shallow depths (Schreurs & Ellenor, 1996).

The highly overpressured prodelta shales of Brunei are the source of ancient and present-day shale diapirs, dykes and mud volcanoes (Koopman & James, 1996b). Middle Miocene-Early Pliocene shale injection features are exposed in outcrop within the Jerudong Anticline (Morley et al., 1998; Morley, *this volume*) and are observed on seismic sections within several offshore and onshore fields throughout the delta (Van Rensbergen et al., 1999). Exposed shale intrusions, (predominantly dykes) within the Jerudong Anticline exhibit shale injection along both tensile and shear fractures up to 60 cm wide (Figure 2). Morley et al. (1998) suggest that stress and pore pressure conditions during the Middle Miocene-Early Pliocene were such that mobile shale could migrate along shear fractures and also initiate tensile fractures.

There is little published data known to the authors concerning the present day stress field in Brunei Darusslam. Watters et al. (1999) suggest that the σ_H direction in the Seria Field is approximately NW-SE. Breckels & Van Eekelen (1982) show that $\sigma_v > \sigma_h$ in the upper sections of the delta. However, the magnitude of the maximum horizontal stress (σ_H) is difficult to determine and the full stress tensor for Brunei is poorly constrained. Tertiary deltas generally exhibit a normal fault stress regime ($\sigma_v > \sigma_H > \sigma_h$) due to the convex upward nature of the delta wedge (Yassir & Zerwer, 1997). Indeed, De Bree et al. (1993) suggest that the Brunei delta systems exhibit a normal fault stress regime ($\sigma_v > \sigma_H > \sigma_h$) in the normally-pressured upper deltaic sequences, but trends into a strike-slip regime ($\sigma_H > \sigma_v > \sigma_h$) with increasing pore pressure and depth. Herein, we have assumed that a normal/strike-slip *in situ* stress regime ($\sigma_v \approx \sigma_H > \sigma_h$) exists for all pore pressures and depths due to the difficulty in constraining σ_H.

PORE PRESSURE/STRESS COUPLING

Pore Pressure/Stress Coupling at the Sedimentary Basin-Scale

An increase in minimum horizontal stress, from shallow, normally-pressured sequences into deeper, overpressured sequences, over and above that due to increasing depth, is herein termed basin-scale P_p/σ_h coupling. Basin-scale P_p/σ_h coupling has been demonstrated in the Scotian Shelf offshore eastern Canada (Ervine & Bell, 1987), the Central North Sea (Gaarenstroom et al., 1993) and the US Gulf Coast and Brunei (Breckels & Van Eekelen, 1982). However, sedimentary basin-scale data do not provide *a priori* evidence of P_p/σ_h coupling, because contemporary (and hence, by inference, causal) changes in the pore pressure and minimum horizontal stress, with time, cannot be demonstrated. However, if it is assumed that shallow, normally-pressured sequences are representative of the overpressured sequences prior to overpressure development, then the nature of basin-scale Pp/σ_h coupling may be inferred (Engelder & Fischer, 1994; Hillis, 2001).

Determining the Pore Pressure/Stress Coupling Relationship

A number of different models have been proposed to describe the variation of stress with depth and pore pressure;

- poroelasticity (Engelder & Fischer, 1994);
- solidity (Holbrook, 1997);
- frictional limit (Zoback et al., 1995).

All models have the form:

$$\sigma_h=k(\sigma_v-P_p)+P_p,$$

and all predict Pp/σ_h coupling (Hillis, *this volume*). It is not the purpose of this paper to discuss the assumptions made in these models nor their relative merits. Herein we favour the widely used empirical approach to determine the P_p/σ_h coupling relationship (Breckels & Van Eekelen, 1982).

Basin-scale estimation of P_p/σ_h coupling requires use of data from shallow, normally pressured and deep overpressured sequences. Pore pressure and minimum horizontal stress data must thus be converted to gradients (MPa/km) to remove the normal increase in P_p and σ_h with depth and reveal the P_p/σ_h coupling relationship (Figure 3 in Hillis, 2001). However, the state of stress in the subsurface is more precisely described with respect to the vertical stress magnitude (σ_v) and not depth (Matthews & Kelly, 1967). In most sedimentary basins there is a constant relationship between σ_v (given by the weight of the overburden) and depth (z) hence depth normalising P_p/σ_h data suffices. However, in Brunei the σ_v/z relationship varies significantly across the basin, and also with depth. Hence, herein the P_p and σ_h data for the basin are normalised with respect to the vertical stress in order to reveal the P_p/σ_h coupling relationship.

Pore pressure can be accurately obtained in permeable formations from wireline tests such as the Repeat Formation Tester (RFT) or from drill stem tests, or can be approximated from mud weights (Mouchet & Mitchell, 1989). The minimum horizontal stress magnitude is most accurately estimated as the fracture closure pressure on mini-fracture tests (Enever, 1993; Engelder, 1993). Mini-fracture tests involve several repeat cycles of fracture opening and closing, and propagate the fracture beyond the disturbed stress field near the wellbore. The minimum horizontal stress can also be estimated from leak-off tests (Bell, 1996). However, leak-off tests are not as reliable as they estimate the fracture opening pressure in the disturbed stress field near the wellbore. Only fracture closure pressures from mini-fracture tests were used to determine σ_h in this study. Figure 3 shows an example of how fracture closure pressures are determined from the mini-fracture test pressure versus root time records (more details on the mini-fracture test procedure and interpretation can be found in Enever, 1993).

Pore Pressure/Stress Coupling and Sediment Injection

The injection of fluids and fluidised sediments (such as mobile shale) along faults and fractures is controlled by the stress field, pore pressure and rock strength. Tensile failure occurs when pore pressure exceeds or equals the minimum stress and tensile rock strength (eg. $P_p \geq S_3 + T$; Sibson, 1996). Suitably orientated faults slip (and may transmit fluids) when the shear stress acting on the fault exceeds or equals a function of the effective normal stress on the fault, the frictional limit to sliding and the fault cohesion ($\tau \geq S_o + \mu(\sigma_n - P_p)$; Jaeger & Cook, 1969). Basin-scale P_p/σ_h coupling has significant implications for the mode of failure that occurs with increasing overpressure, and hence, the formation of features such as the shale dykes observed in the Jerudong Anticline (Figure 2).

The conventional model for shear or tensile failure associated with pore pressure increase assumes that the total stresses are independent of pore pressure. Hence, with increasing pore pressure, the effective vertical (σ_v-P_p) and effective minimum horizontal (σ_h-P_p) stresses decrease at the same rate. This causes Mohr circles to slide, with unchanging diameters, towards the failure envelope (Figure 4a). In the conventional model, tensile failure can only occur if the differential stress (σ_1-σ_3) is low (grey circles), and consequently, the Mohr circles are small (Figure 4a). Assuming a composite Griffith-Coulomb failure envelope, differential stress must be less than four times the tensile strength for tensile failure to occur (σ_1-σ_3<4T; Sibson, 1996). However, the minimum horizontal stress is coupled with variations in pore pressure, and hence changes, whereas the total vertical stress, given by the weight of the overburden, is thought to be unaffected by P_p changes (Teufel et al., 1991; Engelder, 1993). Hence, the effective vertical stress decreases at the rate that pore pressure increases. Effective minimum horizontal stress decreases more slowly than pore pressure increases (or effective vertical stress decreases) because the total minimum horizontal stress increases with pore pressure (Figure 4b). Hence, in a sedimentary basin that has a normal fault stress regime ($\sigma_v<\sigma_H<\sigma_h$), P_p/σ_h coupling leads to a decrease in differential stress (σ_1-σ_3, here σ_v-σ_h) with increasing pore pressure, with an associated reduction in the diameter of Mohr circles, as the increasing pore pressure causes the stress state to move towards failure. P_p/σ_h coupling in overpressured sequences can cause either shear or tensile failure to occur depending on the pre-overpressured stress state, the failure envelope and the $\Delta\sigma_h/\Delta P_p$ coupling ratio.

PORE PRESSURE/STRESS COUPLING IN FIELD A

Geological Setting of Field A

Pore pressure/stress coupling has been investigated in a major field in eastern offshore Brunei herein referred to as Field A (Figure 1). The Field A structure is a large rollover anticline on the hangingwall side of a large down-to-basin growth fault (Koopman et al., 1996). A series of syn-depositional collapse grabens has developed over the crestal area of the rollover anticline. Structures in Field A have been further complicated by later transpressional deformation and uplift (Koopman et al., 1996). Faults in Field A strike between 010-040°N and dip approximately 50° to the east and west. Pore pressures in Field A are originally hydrostatic in shallow reservoirs (<1500 m depth) but can increase to pore pressure gradients of up to 22.0 MPa/km below 2900 m depth (Koopman et al., 1996).

Results

Minimum horizontal stress estimates from eight mini-fracture tests are used in this study. The mini-fracture tests were performed between depths of 1350-3250 m with pore pressure gradients between 9.8-22.0 MPa/km. Pore pressures have all been obtained from RFT measurements within at most 50 m vertically from the mini-fracture test point. All pore pressure and mini-fracture measurements have been performed in undepleted units. The plot of P_p/σ_v versus σ_h/σ_v yields a $\Delta\sigma_h/\Delta P_p$ coupling ratio of 0.59, with a coefficient of correlation of 0.95 (Figure 5). The $\Delta\sigma_h/\Delta P_p$ coupling ratio determined for Field A is similar to the 0.63 average $\Delta\sigma_h/\Delta P_p$ coupling ratio determined from 14 regions worldwide in Addis (1997). However, the $\Delta\sigma_h/\Delta P_p$ coupling ratio determined herein is somewhat higher than the 0.49 P_p/σ_h ratio determined for Brunei by Breckels & Van Eekelen (1982). Breckels & Van Eekelen (1982) investigated P_p/σ_h coupling in both depleted and overpressured sequences which may account for the different $\Delta\sigma_h/\Delta P_p$ coupling ratio. Other possible causes for the difference in $\Delta\sigma_h/\Delta P_p$ coupling ratios are that Breckels & Van Eekelen (1982) may have used data from several fields throughout the basin and data was normalised with respect to depth and not σ_v.

Pore Pressure/Stress Coupling and Rock Failure in Field A

We can use the $\Delta\sigma_h/\Delta P_p$ coupling ratio determined in this study (Figure 5) to investigate the likely mode (and orientation) of rock failure (and fluidised shale injection) with increasing pore pressure in Field A. Mohr circles from the stress estimates of the eight minifracture tests in Field A are plotted in Figure 4c. The minimum horizontal stress is determined from the mini-fracture test data and the vertical stress magnitude has been calculated by integrating density logs to determine the weight of the overburden. The vertical and minimum horizontal stresses and the pore pressures have been normalised to1500 m depth for comparison. Unfortunately there are no data known to the authors on the nature of changes in maximum horizontal stress magnitude (σ_H) with pore pressure. However, the assumption that $\sigma_H \approx \sigma_v$ reduces the problem to a two dimensional one, allowing σ_H to be ignored. Figure 4c suggests that the Mohr circles reduce in diameter with increasing pore pressure until the pore pressure, σ_h and σ_v become approximately equal.

The mode of failure that occurs with increasing pore pressure is also governed by the failure envelope. We use a Griffith-Coulomb failure envelope with cohesion and coefficient of friction determined from uniaxial compressive strength testing on core from a neighbouring field (De Bree et al., 1993). Following the Griffith-Coulomb failure envelope criteria the tensile strength of the rock is equal to half of the cohesion.

Failure mode also depends on the orientation of pre-existing fractures with respect to the *in situ* stress field (Mildren et al., 2002). The present-day minimum horizontal stress in the coastal and shallow-water sections of Brunei (determined from borehole breakouts) is oriented approximately 040°N (Watters et al., 1999; Whiteley et al., 1991). The authors' own interpretation of breakouts and drilling-induced tensile fractures (from 4-arm caliper and image logs in 20 wells in Brunei) also indicate a 040°N σ_h direction in Field A (Figure 6). Faults in Field A strike between 010-040°N and dip approximately 50° to the east and west. Hence, the pre-existing faults strike sub-parallel to the present-day σ_h and are not well orientated for reactivation in a normal/strike-slip faulting stress regime (Figure 1). However, it is possible for non-optimally orientated faults to be reactivated rather than new fractures being created (Streit & Cox, 2001).

The likely mode of failure (and hence, transmission of mobile shale) that will occur with increasing pore pressure can be investigated by combining information on the existing fault plane orientations and the stress tensor (Mohr circle). Any plane can be represented on a Mohr circle in terms of the shear and normal stress that act upon it under a given stress field. Figure 4c shows that existing faults in Field A have the lowest risk of failure either in shear or in tension in the present day stress regime. The low differential stress at high pore pressures (such as Mohr circle A in Figure 4c) suggests that newly formed tensile fractures are the likely overpressure-induced failure mechanism in Field A. Hence, it appears more likely that in the present day stress field, increasing pore pressure will create tensile fractures approximately oriented in the direction of the maximum horizontal stress (130°N) rather than reactivating pre-existing faults.

The Field A 1979 Internal Blowout

The predicted propensity for tensile failure is supported by observations from the internal blowout that occurred within Field A in 1979. An internal blowout involves overpressured fluids being transmitted along the wellbore to shallower reservoir units rather than to the surface. The 1979 Field A internal blowout was associated with a seabed blowout that expelled large volumes of overpressured fluids for ten days (Koopman et al., 1996). The internal blowout has involved deep overpressured fluids and sediments being transmitted to shallow reservoirs along the uncased section of borehole (Figure 7). Pore pressures within the shallow reservoirs rapidly increased until the rock above fractured, causing the seabed blowout. High resolution seismic over the location of the surface blowout indicates that the overpressured fluids and sediments reached the surface along a vertical NW-SE striking tensile fracture, approximately perpendicular to σ_h (Whiteley et al., 1991). The creation of a new tensile fracture oriented NW-SE, in response to increasing pore pressure, rather than the reactivation of existing fractures is entirely as predicted by the above coupled P_p/σ_h model (Figure 4c).

Implications for Outcrop Observations in the Jerudong Anticline

The hydraulic fracturing and subsequent fluid expulsion during the 1979 internal blowout may be analogous to the Miocene-Pliocene shale dykes observed in the Jerudong Anticline (Morley et al., 1998; Morley, *this volume*), and the ancient and modern mud volcanoes in Brunei (Van Rensbergen et al., 1999; Koopman et al., 1996). Middle Miocene shale dykes in the Jerudong Anticline were primarily intruded into shear fractures and to a lesser extent along tensile fractures. Morley et al. (1998) documents two phases of shale intrusion:

(i) Middle Miocene intrusions prior to folding that are closely related to fault orientation.

(ii) Late Miocene-Pliocene intrusions post folding (faults rotated 60-90°) that have injected into new fractures independent of the older faults.

Middle Miocene tensile fractures in the Jerudong anticline were initiated both sub-vertically and sub-horizontally (Morley et al., 1998; Morley, *this volume*). The presence of both horizontal shale sills/laccoliths and vertical shale dykes suggests that the minimum horizontal stress was approximately equal to the vertical stress magnitude ($\sigma_h \approx \sigma_v$) and that pore pressure approached lithostatic during Miocene shale injection. Morley et al. (1998) suggest that during the Middle Miocene the minimum horizontal stress (σ_h) was oriented NW-SE (perpendicular to the present-day stress field). Hence, the existing E-W and NE-SW trending growth faults in the Jerudong Anticline were favourably orientated for reactivation, fluid flow and consequent shale dyke emplacement. In the Late Miocene-Pliocene pre-existing faults were no longer suitably oriented to be reactivated, and, analogous to the 1979 internal blowout, increasing pore pressure led to the formation of new tensile fractures into which overpressured fluids, carrying clay, were injected.

Pore Pressure/Stress Coupling at the Oil Field-Scale

P_p/σ_h coupling is also observed with reservoir depletion in Field A. This is termed oil field-scale P_p/σ_h coupling (Hillis, 2001; Figure 5). At the oil field-scale, the P_p/σ_h coupling relationship is observed to occur over a time scale of years through repeated stress and pore pressure measurements during the depletion of a reservoir. The reduction in σ_h that accompanies a reduction in P_p due to reservoir depletion has been demonstrated in the Vicksburg Formation of south Texas (Salz, 1977), the C4 and C5 sands of the Lake Maracaibo region of Venezuela (Breckels & Van Eekelen, 1982), and the Danian-Maastrichtian Chalk of the Ekofisk Field, North Sea (Teufel et al., 1991). It is unclear whether P_p/σ_h coupling at geological timescales due to overpressure development and that at anthropogenic timescales of field development due to depletion of reservoir pressures are controlled by the same or different mechanisms. However, Hillis (2001) showed that $\Delta\sigma_h/\Delta P_p$ coupling ratios are similar at the field- and basin-scale in the Ekofisk Field. Two mini-fracture tests performed in depleted reservoirs in Field A show oil field-scale P_p/σ_h coupling with a $\Delta\sigma_h/\Delta P_p$ coupling ratio of 0.99 (Figure 5). The oil field-scale $\Delta\sigma_h/\Delta P_p$ coupling ratio for Field A is significantly higher than the 0.59 basin-scale $\Delta\sigma_h/\Delta P_p$ coupling ratio. However, only two minifracture tests have been performed in depleted reservoirs in Field A. Hence the estimated oil field-scale $\Delta\sigma_h/\Delta P_p$ coupling ratio of 0.99 for Field A can not be considered reliable.

CONCLUSIONS

Changes in pore pressure and minimum horizontal stress are coupled at the geological timescale at which overpressure develops in offshore Brunei Darussalam. Within Field A in the eastern offshore part of the basin, the $\Delta\sigma_h/\Delta P_p$ coupling ratio is 0.59. P_p/σ_h coupling allows much higher pore pressures to be sustained without failure than would be predicted by conventional models of rock failure. The coupled P_p/σ_h evolution associated with increasing overpressure may result in either shear or tensile failure in the basin depending on rock strength and the orientation of pre-existing fractures. Pre-existing faults within Brunei are not favourably aligned for re-activation in the present-day stress field. Hence, high pore pressures are likely to create new tensile fractures aligned approximately NW-SE, as occurred in the 1979 internal blowout. In the Jerudong Anticline during the Middle Miocene, it is suggested that faults were critically oriented with respect to the palaeostress field, resulting in shale dykes being injected primarily along shear fractures. However, during the Late Miocene-Pliocene where pre-existing faults were not favourably oriented for reactivation, shale dykes were intruded into both vertical and horizontal tensile fractures.

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Figure Captions

Figure 1. Major deltaic fault trends and localities in onshore and offshore Brunei Darussalam. The present day minimum horizontal stress is oriented sub-parallel with fault strike (adapted from Koopman & James, 1996b).

Figure 2. Shale dykes within the Jerudong Anticline within: (a) a tensile fracture, (b) a shear fracture and (c) small scale shear and tensile fractures.

Figure 3. Example of how mini-fracture tests are used to determine σ_h from the fracture closure pressure. Mini-fracture test was performed at 3250 m depth in Field A.

Figure 4. Evolution of Mohr circles with increasing pore pressure (a) conventional model where stresses are independent of pore pressure, (b) model with pore pressure/stress coupling and (c) pore pressure/stress coupling trend suggested by stress estimates in Field A normalised to 1500 m depth.

The existing faults in Field A are not well oriented for failure. Tensile failure is more likely to occur with increasing pore pressure in the present-day stress field.

Figure 5. Basin-scale pore pressure/stress (Pp/σ_h) coupling relationship for Field A in eastern offshore Brunei (Pp/σ_h ratio=0.59). Pore pressure and minimum horizontal stress have been normalised with respect to the vertical stress magnitude. The vertical stress gradient varies with depth and hence the normalised hydrostatic gradient is a range. Oil field-scale Pp/σ_h coupling is also observed in Field A from the results of two minifracture tests performed in depleted reservoirs. These two minifracs suggest an oil field-scale Pp/σ_h coupling ratio that is higher (0.99) than the basin-scale Pp/σ_h ratio. However, there is not enough data to provide a reliable estimate of the oil field-scale Pp/σ_h ratio.

Figure 6. Examples of borehole breakouts on resistivity image logs (dark patches separated by approximately 180°) in Brunei. Breakouts are oriented in the minimum horizontal stress (σ_h) direction (Plumb & Hickman, 1985). Breakouts suggest a σ_h orientation of 040°N in Field A.

Figure 7. Schematic diagram of the 1979 Field A internal blowout (adapted from Whiteley et al., 1991).

Figures

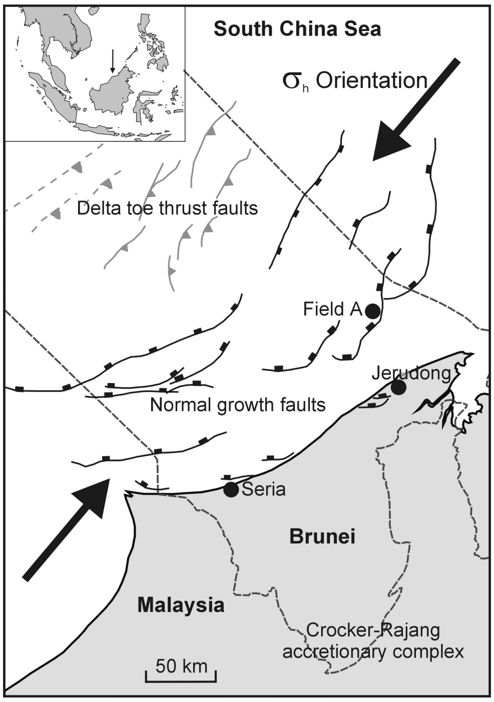
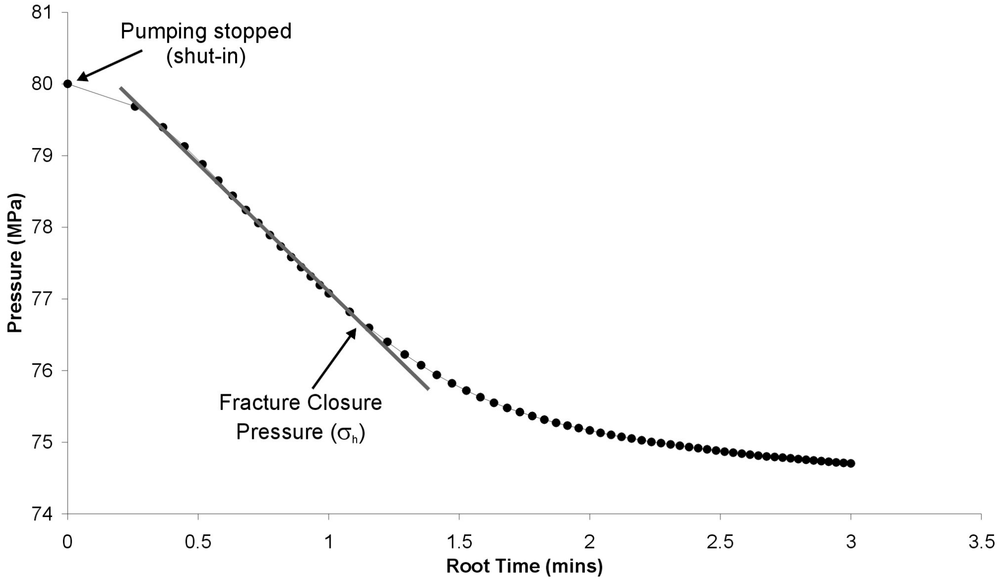


Fig 1

Fig 2



Pumping stopped
(shut-in)
Fracture Closure
Pressure (σh)
Pressure (MPa)
Root Time (mins)
81
80
79
78
77
76
75
74
0
0.5
1
1.5
2
2.5
3
3.5

Fig 3

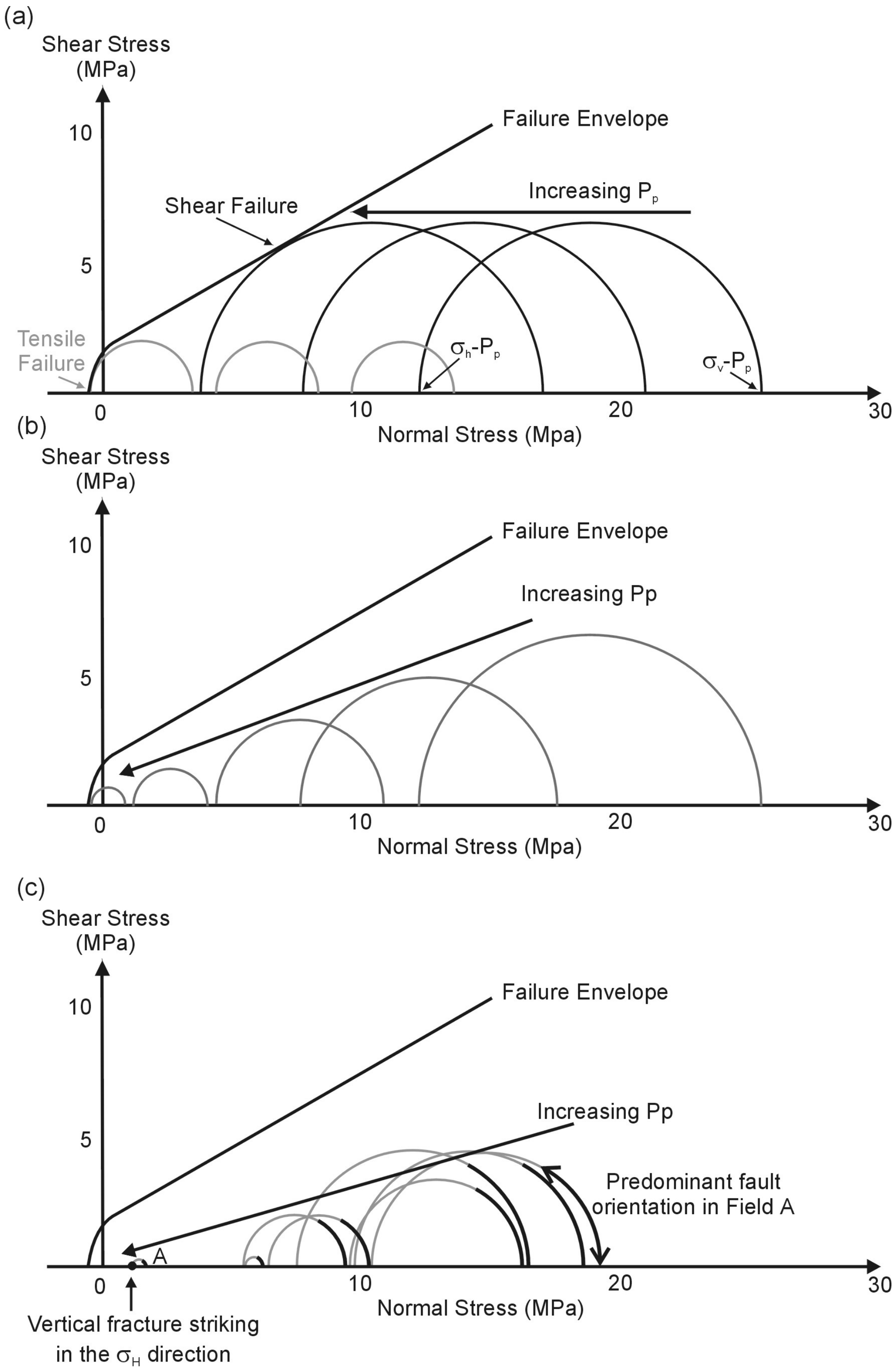
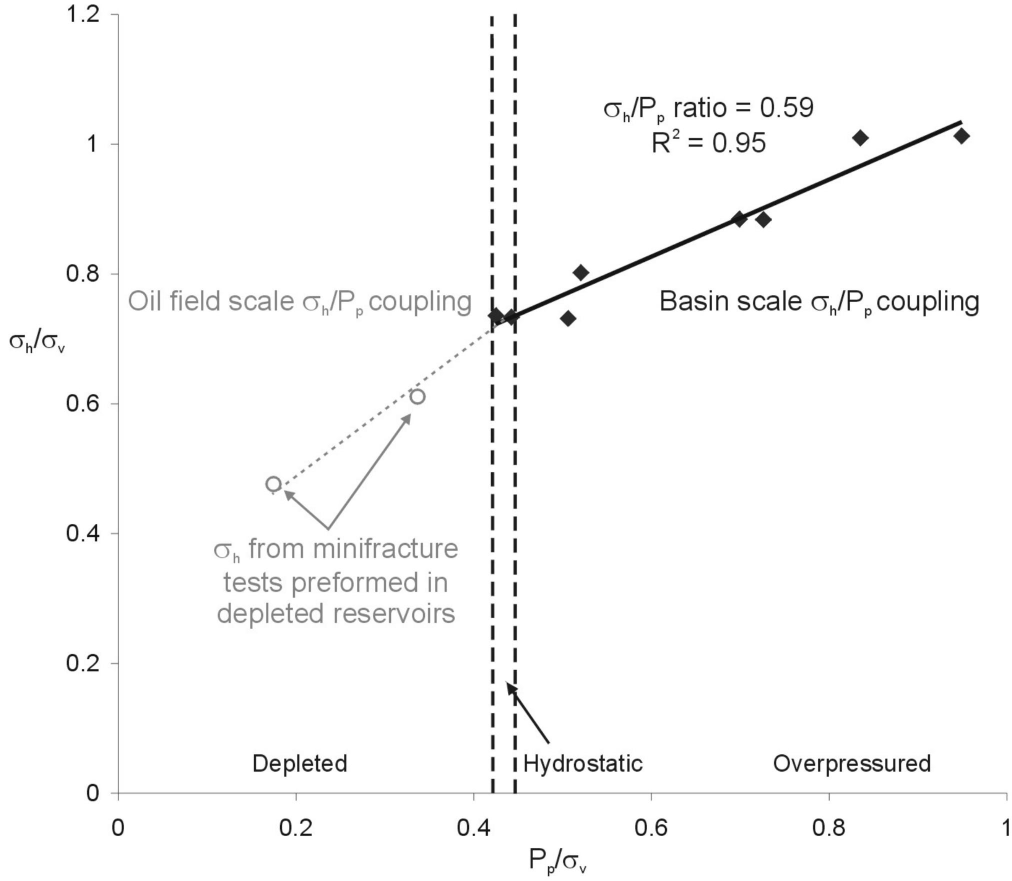

(a)
Shear Stress (MPa)
10
5
Failure Envelope
Increasing P_p
Shear Failure
Tensile Failure
σh-Pp
σv-Pp
0
10
20
30
Normal Stress (Mpa)
(b)
Shear Stress (MPa)
10
5
Failure Envelope
Increasing Pp
0
10
20
30
Normal Stress (Mpa)
(c)
Shear Stress (MPa)
10
5
Failure Envelope
Increasing Pp
Predominant fault orientation in Field A
A
0
10
20
30
Normal Stress (MPa)
Vertical fracture striking in the σH direction

Fig 4



1.2
1
0.8
0.6
0.4
0.2
0
σ_h/σ_v
σ_h/P_p ratio = 0.59
R^2 = 0.95
Oil field scale σ_h/P_p coupling
Basin scale σ_h/P_p coupling
σ_h from minifracture tests preformed in depleted reservoirs
Depleted
Hydrostatic
Overpressured
0
0.2
0.4
0.6
0.8
1
P_p/σ_v

Fig 5

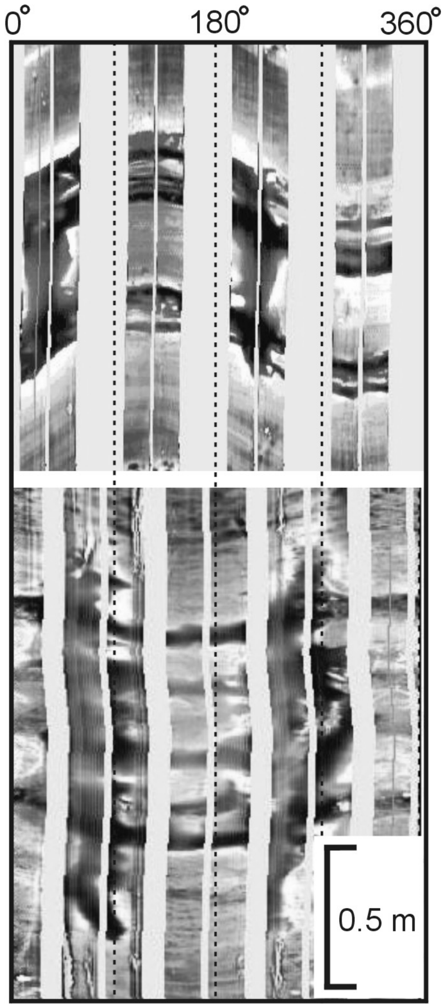


Fig 6

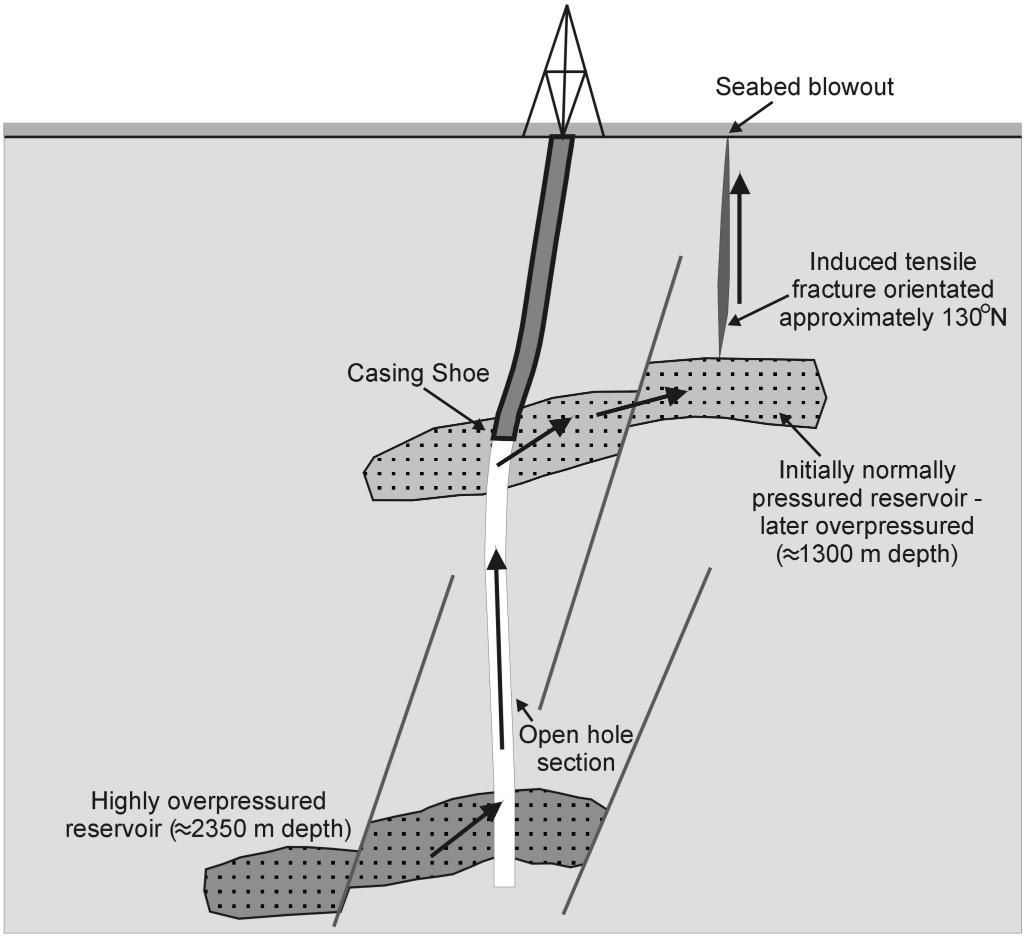

Seabed blowout
Induced tensile fracture orientated approximately 130°N
Casing Shoe
Initially normally pressured reservoir - later overpressured (≈1300 m depth)
Open hole section
Highly overpressured reservoir (≈2350 m depth)

Fig 7