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Modelling the Contemporary Stress Field and its Implications for Hydrocarbon Exploration

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ABSTRACT

The forces that act on the Earth's lithospheric plates are responsible for the stress regime within the plates at a regional scale, and thus influence issues pertinent to hydrocarbon exploration — such as the nature of fault reactivation, hydraulic seal integrity, natural and induced fracture orientation and wellbore stability. Four models of the intraplate stress field of the Australian continent have been produced by elastic finite element modelling of the forces acting on the Indo-Australian plate. All four models incorporate the push of mid-ocean ridges and of continental margins. In the four models the magnitude of the poorly constrained convergent boundary and basal drag forces are varied within reasonable limits. Despite being based on significantly different force magnitudes, regional stress orientations predicted by the three models that recognise the heterogeneity of forces acting along the convergent northeastern boundary of the Indo-Australian plate are considered reliable because they are consistent over much of the Australian continent and show broad agreement with the available in situ stress measurements.

In the absence of in situ stress measurements, for example from borehole breakouts, modelled stress orientations should be incorporated into the assessment of issues pertinent to hydrocarbon exploration that are influenced by the contemporary stress field. In the context of fault reactivation, pre-existing vertical faults striking at 30° to 45° to the maximum horizontal stress direction are the most prone to at least a component of strike-slip motion. Planes dipping in the minimum horizontal stress direction are the most suitably oriented to be reactivated in extension, and planes dipping in the maximum horizontal stress direction are the most suitably oriented to be reactivated in compression. Modelled stress orientations can also be used to predict open natural fracture orientation, with the preferred orientation being normal to the minimum horizontal stress, and to help assess the hydraulic integrity of reservoir seals, with faults and fractures normal to the minimum horizontal stress least likely to be sealing.

Keywords: Indo-Australian plate, forces, intraplate stress modelling, fault reactivation, fracture orientation, hydraulic seal integrity

INTRODUCTION

Forces driving and resisting the motion of the Earth's lithospheric plates are responsible, at a regional scale, for the contemporary stresses within the plates. Hence these forces control the stresses acting in the vicinity of hydrocarbon accumulations. The forces acting on the plates, such as the push from elevated mid-ocean ridges, can be quantified and thus the resultant intraplate stress field can be modelled (Richardson et al., 1979). This paper summarises the forces acting on the plates and models the contemporary intraplate stress field of the Indo-Australian plate (IAP), with particular reference to the Australian continent.

The nature of the contemporary stress field influences a wide range of issues related to hydrocarbon exploration and production, including the:

- nature of recent tectonism (Hillis and Williams, 1992);
- orientation of open natural fractures (Horn, 1991);
- hydraulic integrity of hydraulic reservoir seals (Caillet, 1993);
- orientation of hydraulically-induced fractures (Bell, 1990); and,
- stability of deviated and horizontal wellbores (Hillis and Williams, 1993).

Assessment of the above issues is generally undertaken with the aid of in situ stress measurements, such as borehole breakouts (Hillis and Williams, 1993) and hydraulic fracture tests (Bell, 1990). However, in the absence of boreholes in which stress indicators may be analysed, information on the stress field may be obtained from theoretical modelling of the type presented here. Modelled stress orientations are likely to play a more important role in assessing exploration-related issues than on development issues, because the latter are generally preceded by in situ stress testing. Hence this paper discusses the implications of stress modelling for the nature of recent tectonism, the hydraulic integrity of seals and the orientation of open natural fractures.

THE FORCES ACTING ON THE PLATES

The forces acting on the plates fall into three general categories: those acting within the plates (intraplate); those acting at convergent plate boundaries; and those acting at the base of the plates (Figure 1). The nature of the forces acting on the plates is summarised in this section. The following section applies a methodology for modelling the intraplate stress field of the IAP generated by these forces.

Of the three categories, intraplate forces due to lateral density variations within the lithosphere are the best constrained. Lateral density variations within the lithospheric plates (the outer 125 km or so of the crust and upper mantle) generate lateral potential energy variations, and hence horizontal forces on the plates. The detailed methodology for quantifying these forces has been described by Coblentz et al. (1994). The cooling and subsiding of plates at a spreading centre generates the so-called ridge push against old oceanic lithosphere which is about 2 to 3 x 10^{12} Nm^{-1} (ie, 2 to 3 x 10^{12} N per metre of mid-ocean ridge length). Continental margins also generate a push of around 1 to 2 x 10^{12} Nm^{-1}. The stresses arising from variations in potential energy across continental margins have generally been ignored in plate-scale stress modelling, despite the fact that they are around half the magnitude of the push from mid-ocean ridges. Continental margin push is of particular relevance to the stress field of the continental shelves where much hydrocarbon exploration is undertaken.

In comparison with intraplate stress sources, the magnitudes of stresses imposed at convergent margins, and the drag at the base of the plate, are poorly understood, and estimates vary by orders of magnitude (cf. Cloetingh and Wortel, 1986; Richardson, 1992). A large negative buoyancy force, known as slab pull, acts on the tongue of old, cold sinking lithosphere at a subduction zone (Figure 1). However, seismicity associated with subduction zones indicates that a large amount of this energy is dissipated by resistance to subduction, and thus the surface plates may not experience a large slab pull force (Richardson, 1992).

Where plate convergence is accommodated by subduction, a tensional slab pull force may be imposed on the subducting plate. Where convergence leads to continent–continent or continent–island arc collision, a

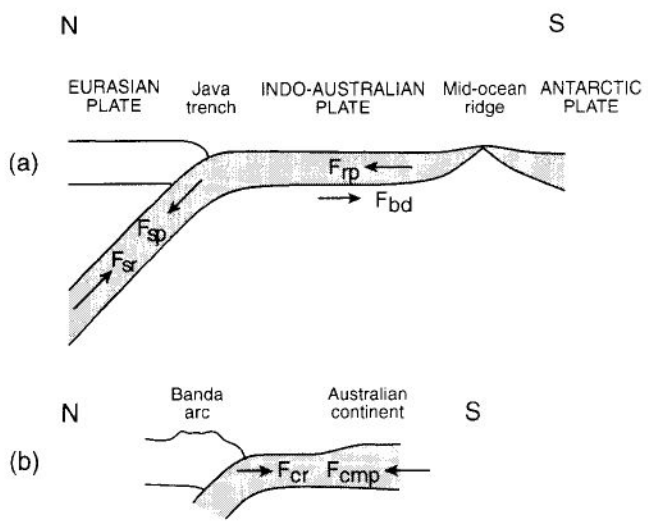

Figure 1. Schematic illustration of the forces modelled to act on the Indo-Australian plate. (a) Frp: ridge push; Fsp: slab pull; Fsr: subduction resistance; Fbd: basal drag (b) Fcmp: continental margin push; Fcr: collisional resistance.

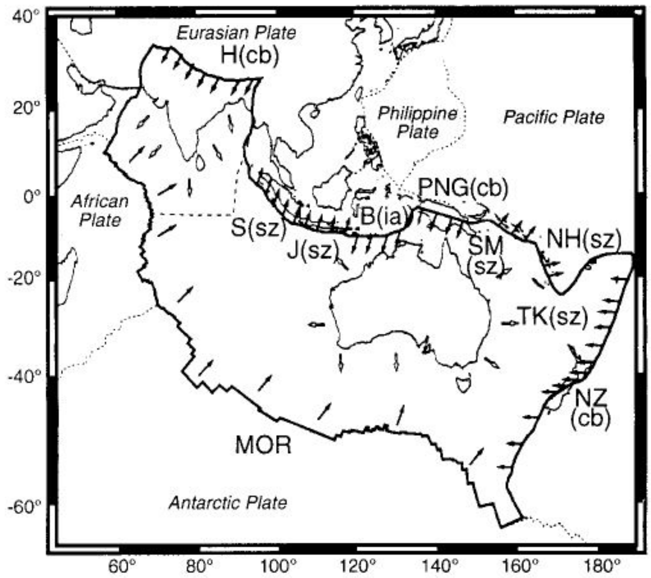

Figure 2. The Indo-Australian plate and its boundaries. Solid arrows represent the boundary forces acting on the plate. Open arrows represent continental margin push. Force arrows are not drawn to scale. The plate boundaries are characterised as cb: collisional boundary; sz: subduction zone (ie, convergent but not collisional); and ia: island arc. H: Himalayas; S: Sumatra trench; J: Java trench; B: Banda arc; PNG: Papua New Guinea; SM: Solomon trench; NH: New Hebrides trench; TK: Tonga-Kermadec trench; NZ: New Zealand; and MOR: mid-ocean ridge. From Coblentz et al. (1995).

considerable resistance to plate motion is likely to be imposed because of the buoyancy of continental lithosphere (Zhou and Sandiford, 1992; Figure 1). Like other forces acting at convergent boundaries, precise quantification is difficult, due to both inadequate knowledge of deep lithospheric density structure, and the lack of measured geoid anomalies over the continents.

Shear stress generated by motion of plates over the underlying asthenosphere acts at the base of the lithosphere (Figure 1). The contribution of this basal drag force to the intraplate stress field is difficult to constrain since the degree of coupling between the lithospheric plates and the underlying asthenosphere is poorly understood. However, there is little correlation between the asthenospheric flow pattern, at least at long wavelengths, and the present-day plate motions (Richards and Hager, 1984), suggesting that basal drag is not a major force acting on the plates. For a more complete discussion of the forces acting on the plates see Richardson et al. (1979) and Turcotte and Schubert (1982).

MODELLING THE INTRAPLATE STRESS FIELD OF THE INDO-AUSTRALIAN PLATE

The stress field of the Australian continent cannot be considered in isolation and must be modelled as part of that of the IAP as a whole. The IAP is the most complex of the Earth's plates on which to undertake stress modelling. The convergent northeastern boundary of the IAP is heterogeneous and the stress field results from contributions from Himalayan continent–continent collision, subduction of oceanic IAP under the Sunda Island Arc, continent–continent collision in New Guinea, and subduction of the Pacific Plate under the IAP at the Tonga–Kermadec Trench (Figure 2). The heterogeneous nature of the northeastern boundary of the IAP, and the variability of its associated stress field contrasts with plates such as North and South America which are characterised by long homogeneous plate boundaries, and exhibit relatively simple intraplate stress fields.

Since the magnitude of intraplate forces is better constrained than those associated with convergent margins and basal drag, the intraplate stress field of the IAP is modelled by varying the convergent boundary and basal drag forces within a reasonable range in four different models. The forces applied in the four different models are summarised in Table 1, and the stress fields predicted by each of the models using an elastic finite element analysis are shown in Figure 3. The modelling procedure was further discussed by Coblentz et al. (1995).

RELIABILITY OF THE MODELLED STRESS FIELD

Two criteria can be used to assess the reliability of the stress field predicted by the four models. First, the models should fit the available in situ stress measurements for the IAP. Second, in areas where there are no available in situ measurements, and the results may be applied to hydrocarbon exploration-related issues, the modelled stress field should be robust with respect to changes in the poorly constrained convergent boundary forces.

In order to test the models against in situ stress measurements for the Australian continent, Coblentz et al. (1995) averaged stress indicators within 3° x 3° bins. The averaged stress indicators are shown on Figure 3. It should be noted that using the previously existing data in the World Stress Map (Zoback, 1992), Coblentz et al. (1995) inferred that the regional maximum horizontal stress (σ_H) orientation in the Carnarvon Basin was approximately north–south

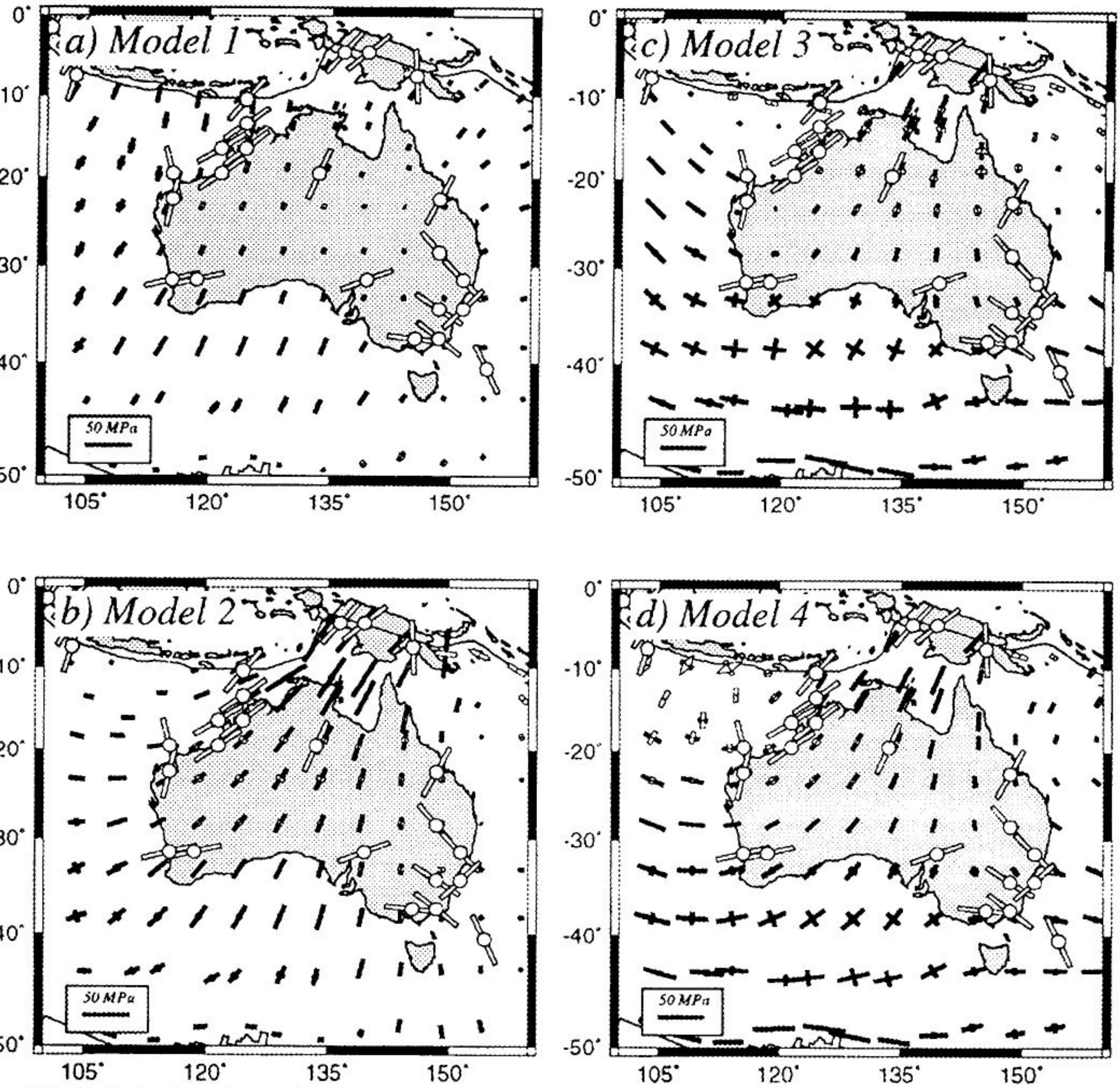

Figure 3. Predicted horizontal tectonic stresses for continental Australia from an elastic finite element analysis for four different models of the plate boundary forces acting on the northeastern margin of the Indo-Australian plate. Solid bars indicate (the direction of maximum) deviatoric compression and open bars indicate deviatoric tension. Average $\sigma_H$max orientations in 3° x 3° bins of data from the World Stress Map (Zoback, 1992b) are indicated by larger open bars centred on open circles. (a) Model 1: entire convergent northeastern boundary balances topographic forces (ridge and continental margin push) acting on the plate equally along its length, regardless of the nature of the convergent boundary, ie, no additional forces generated at the convergent boundaries, only reaction forces. (b) Model 2: only the collisional segments of the convergent boundary balance topographic forces (ie, forces balancing the topographic forces focused at segments of continental collision such as New Guinea, but no forces generated at the convergent boundaries). (c) Model 3: compressive forces generated at the collisional segments incorporated in addition to the topographic forces, with force balance achieved by incorporating the drag force at the base of the lithosphere (no forces generated at subducting boundaries). (d) Model 4: topographic, compressive collisional and tensional subduction forces all act on the plate, with force balance achieved by incorporating the drag force at the base of lithosphere. Table 1 summarises the forces applied in the different models. From Coblentz et al. (1995).

Table 1. Summary of the forces applied in the four models of the stress field.

Model	Ridge and Continental Margin Push	Collisional Boundaries	Subduction Boundaries	Other Boundaries	Basal Drag
1	force applied	pinned	pinned	pinned	not applied
2	force applied	pinned	free	free	not applied
3	force applied	force applied	free	free	force applied
4	force applied	force applied	force applied	force applied	force applied

Ridge and continental margin push were calculated as described by Coblentz et al. (1994). When applied, a force of 2 x 10^{12} Nm^{-1} was assumed at the collisional boundaries of the Himalayas, New Guinea and New Zealand. The subduction boundaries (and, when applied, the forces at these boundaries) are those of Sumatra (-2 x 10^{12} Nm^{-1}), Java (-2 x 10^{12} Nm^{-1}), Solomon (-1 x 10^{12} Nm^{-1}) and New Hebrides (-1 x 10^{12} Nm^{-1}). The other boundaries, the Banda arc, which is in an early stage of collision, and the Tonga-Kermadec trench, where the Pacific plate subducts under the IAP, were considered to generate compression with respect to the IAP, and when applied, a force of 1 x 10^{12} Nm^{-1} was used at those boundaries. Positive forces indicate compression directed towards the interior of the plate. Negative forces indicate tension due to slab pull.

(Figure 3). The regional σ_H orientation in the Carnarvon Basin can now be shown to be east–west (Hillis et al., in press).

In model 1 the resultant intraplate stress field is oriented approximately 020° N throughout the IAP, which is clearly inconsistent with the observed stress field. Hence a homogeneous northeastern margin condition cannot account for the regional heterogeneity of stress field of the IAP. Models 2, 3 and 4 all show broad agreement with the observed stress field of the Australian continent (and indeed with that of the IAP). Significantly, regional horizontal stress orientations predicted by models 2, 3 and 4 are broadly consistent over much of Australian continent, despite the widely differing plate boundary forces that they assume (Table 1). Where consistent, the regional stress orientations predicted by models 2, 3 and 4 are considered reasonably robust. The horizontal stress orientations predicted by models 2, 3 and 4 are generally consistent with those of Cloetingh and Wortel (1986), who used a markedly different approach to the modelling, and argued that all the forces acting on the plates can be constrained. Thus it is reasonable to conclude that, at a regional scale, the modelled stresses are reasonably robust.

Although horizontal stress orientations are consistent, stress magnitudes predicted herein and those of Cloetingh and Wortel (1986) vary by an order of magnitude. Indeed there is considerable difference between the magnitudes predicted by models 2, 3 and 4. Hence, while modelled stress orientations may be applied to hydrocarbon exploration-related issues, there is still significant debate regarding the magnitudes of modelled intraplate stresses.

Stress orientations derived from theoretical modelling are averaged over the entire thickness of the lithosphere. Furthermore, modelled stress orientations can only match regional-scale (approximately 100 km and greater) trends. They cannot match local stress field effects due, for example, to stress reorientation around a fault. However, such effects could be incorporated in more local models, the boundary conditions of which would be derived from the plate-scale modelling presented here.

When available, in situ stress measurements, such as those from hydraulic fracture tests and borehole breakouts, are more reliable than the modelled data presented here, largely because of the scale effects discussed above. Hence, modelled data should not be applied to issues such as the stability of deviated wellbores and hydraulic fracturing which should be planned with reference to in situ stress measurements. Nonetheless, modelled stress orientations can provide information prior to drilling, and associated testing in frontier/wildcat areas, and is inexpensive. The following section of the paper discusses the application of modelled stress orientations to exploration-related issues.

MODELLED STRESS ORIENTATIONS AND HYDROCARBON EXPLORATION

Implications for fault reactivation

The orientation of horizontal stresses, as modelled above, can be used to predict the fault orientations most prone to reactivation within the contemporary stress field, and the sense of that contemporary reactivation (Figure 4). Planes inclined at 45° to the maximum principal stress are subject to the maximum shear stress. However, failure often occurs on planes at a somewhat lower angle to the principal stress, typically 30°. Pre-existing vertical faults striking at 30° to 45° to the σ_H direction are thus the most prone to a component of strike-slip motion. Faults oriented 30° to 45° anticlockwise from the σ_H direction are prone to dextral movement, and those oriented 30° to 45° clockwise from the σ_H direction are prone to sinistral movement (Figure 4). Vertical planes oriented parallel and orthogonal to the σ_H direction are subject to the least horizontal shear stress, and are the least prone to a component of strike-slip motion. Planes dipping in the minimum horizontal stress (σ_h) direction are the most suitably oriented to be reactivated in extension, and planes dipping in the σ_H direction are the most suitably oriented to be reactivated in compression (Figure 4). These observations have significant implications for the structural interpretation of seismic reflection records in areas like the Timor Sea where there has been debate on the style of recent tectonism (cf. Woods, 1988; Nelson, 1989).

Implications for the orientation of open natural fractures

As discussed below, there is a link between open natural fracture orientation and contemporary stress orientation. Knowledge of the orientation of open natural fractures is critical to the successful application of deviated drilling to the exploitation of naturally fractured reservoirs, and in the absence of in situ stress measurements, modelled stress orientations can be used to help plan deviated well trajectories. Regional fractures in relatively tectonically undisturbed hydrocarbon reservoirs tend to be vertical, or steeply dipping (Lorenz et al., 1991). Hence deviated wells oriented at a high angle to the predominant trend of open, natural fractures can intersect many more fractures than vertical wells, thus demonstrating the deliverability of a fractured reservoir. Conversely, wells oriented at a low angle to the predominant trend of the open natural fractures may not provide any improvement in fracture intersection over vertical wells and may lead to fractured reservoir potential being overlooked.

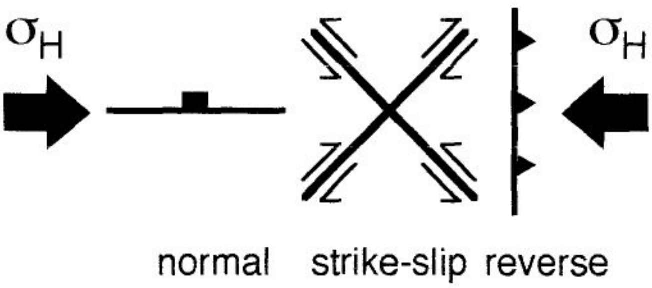

Figure 4. Preferred fault reactivation orientations for a modelled maximum horizontal tectonic stress orientation (σ_H).

Several fractured reservoirs indicate that fractures oriented normal to the σ_h direction are more likely to be open and productive than fractures normal to the σ_H direction. Corbett et al. (1987) reported an orthogonal fracture set at outcrop in the Cretaceous Austin Chalk. However, drilling experience suggests that in the subsurface most open natural fractures trend normal to σ_h (Horn, 1991). Orthogonal sub-vertical natural fracture sets are also present in the Cretaceous Niobrara Chalk of the Silo Field, Wyoming. However, only the fracture set normal to σ_h is productive (Martin and Davis, 1987).

It is often suggested that extensive, approximately vertical, fluid-filled fractures generate the anisotropy which causes seismic shear-wave splitting (Winterstein and Meadows, 1991). To the extent that the recognition of shear-wave splitting and determination of the faster polarised direction is indicative of open natural fracture orientation, seismic shear wave splitting suggests that there are many more reservoirs where open natural fractures are normal to the σ_h direction (Queen and Rizer, 1990; Winterstein and Meadows, 1991; Bush and Crampin, 1991; Lefeuvre et al., 1993).

Not all open natural fracture orientations are controlled by the contemporary stress field. In the Auburn Geothermal Well (New York), steeply dipping fractures in the lower half of the Palaeozoic section of the well (which comprises salts, carbonates, shales and sandstones) are normal to the σ_h direction. However, at the base of the well, in Precambrian marbles, fractures exhibit no strongly preferred orientation (Hickman et al., 1985). In the Palm Valley Field of central Australia, open fractures in Ordovician quartzites are orthogonal to the σ_H direction. Mineralisation in the fractures at Palm Valley may prop them open against σ_H (Berry et al., 1996). In general it seems that contemporary stresses control open natural fracture orientation in softer rocks such as chalks, but in harder rocks such as marbles and quartzites, fractures are stiffer and pre-existing fracture orientation is the dominant control. Hillis (in press) presents a methodology for combining information on the contemporary stress field with that on the stiffness of natural fractures in order to ascertain the orientation of open natural fractures. Nonetheless, in the absence of evidence of stiff natural fractures normal to the σ_H direction, open, natural fractures are most likely to be oriented normal to σ_h. Hence in the absence of in situ stress measurements, deviated wells should be oriented in the modelled σ_h direction.

Implications for the integrity of hydraulic reservoir seals

Seals to hydrocarbon reservoirs can be classified as membrane seals or hydraulic seals (Watts, 1987). The dominant trapping mechanism of membrane seals is the capillary properties of the cap rock, where the minimum displacement (or breakthrough) pressure of the cap rock equates to the pressure required for hydrocarbons to enter the largest interconnected pore throat of the seal. A membrane seal will trap a hydrocarbon column until the net buoyancy pressure (related to the difference between the hydrocarbon and water densities) of the hydrocarbons exceeds the capillary breakthrough pressure of the seal. An alternative type of cap rock seal, known as a hydraulic seal, is that where the capillary breakthrough pressure is so high (some tight shales, and various evaporites), that seal failure occurs by natural hydraulic fracturing of the cap rock. Natural hydraulic fractures occur where the effective minimum principal stress is reduced to, or close to, zero, and is often focused on pre-existing faults. The integrity of hydraulic seals is thus controlled by the contemporary stress field, and knowledge of the contemporary stress field can be used to help assess hydraulic seal integrity.

Fault-related hydraulic seals tend to be sealing if the effective normal stress acting on the fault is greater than zero, ie, if the normal stress is greater than the pore pressure. If the effective normal stress acting on the fault is less than zero, then natural hydraulic fracturing may breach the trap. The propensity for open natural fractures in the plane of the fault increases as the effective normal stress on that plane decreases. For a vertical fault in a horizontally anisotropic stress field, the effective normal stress will be maximised if σ_H is normal to the fault. Faults oriented normal to σ_h have the least potential for hydraulic sealing. These hypotheses are supported by observations from the Snorre Field of the North Sea where one fault set (normal to σ_H) is largely sealing, whilst a second, near-orthogonal set (normal to σ_h) is non-sealing (Caillet, 1993). Similarly, faults following the regional northeast–southwest structural trend in the Timor Sea may be poorly oriented to be hydraulically sealing because they are orthogonal to the modelled, and observed (Hillis et al., in press), σ_h direction in the area. Structures controlled by faults with other orientations have been targeted in the Timor Sea (Lowry, 1995), and the Elang Field is located in a structure controlled by east–west oriented faults (Young et al., 1995). In the absence of in situ stress measurements, theoretically modelled stress orientations, determined as outlined above, can be used as an input to predicting hydraulic seal integrity prior to drilling.

SUMMARY AND CONCLUSIONS

Intraplate forces acting on the Earth's lithospheric plates (mid-ocean ridge and continental margin push) can be quantified. However, the magnitudes of stresses imposed at convergent margins (slab pull and collisional resistance), and the drag at the base of the plate are poorly understood. Four different models have been calculated for the stress field of the IAP by combining the known intraplate forces with a reasonable range of convergent boundary and basal drag forces. The regional stress orientations predicted by all three models that recognise the heterogeneity of forces acting along the convergent northeastern boundary of the IAP (models 2, 3 and 4, Figure 3) are considered reliable because they show broad agreement with the available in situ stress measurements for the Australian continent and they are consistent with each over much of the continent, despite the widely differing forces they assume acting on convergent boundaries and on the base of the plate.

Information on the contemporary stress field impacts on a number of issues related to hydrocarbon exploration and development. In situ stress measurements are more reliable than the modelled data presented here and, where available, in situ measurements should be used in assessing development-related issues such as the stability of horizontal wells and hydraulic fracturing. However, modelled stress orientations can provide information prior to drilling, and associated in situ stress measurements in frontier/wildcat areas. Modelled stress orientations can be used to help analyse the nature of recent tectonism. Pre-existing vertical faults striking at 30° to 45° to the σ_H direction are thus the most prone to at least a component of strike-slip motion. Planes dipping in the σ_h direction are the most suitably oriented to be reactivated in extension, and planes dipping in the σ_H direction are the most suitably oriented to be reactivated in compression. Modelled stress orientations can also be used to predict open natural fracture orientation, with the preferred orientation being normal to σ_h, and to assess the hydraulic integrity of reservoir seals, with faults and fractures normal to σ_h less likely to be sealing.

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