Seal properties, overpressure and stress in the Taranaki and East Coast Basins, New Zealand

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Abstract

The Taranaki and East Coast Basins contain abundant mudstones that are potential seals for hydrocarbon accumulations. However, understanding seal behaviour in New Zealand's complex tectonic and hydrodynamic regime is not straightforward. Analysis of the capillary properties of seals in the region shows that (a) a soil mechanics-based model using a compression coefficient b of 0.36 can predict the decrease in mudstone porosity with increasing stress, allowing recognition of a separate trend for Oligocene-Upper Eocene marls; (b) the Oligocene-Upper Eocene section is high in smectite; (c) seals can retain a 12 m - 700 m gas column, with highest values in diagenetically-cemented Miocene mudstones and lowest values in Eocene siltstones; and (d) calculated permeability based on pore throat size and specific surface area ranges from 10^{-20} to 10^{-23} m^2, with lowest values in smectite-rich Oligocene mudstones. Analysis of the hydraulic properties of seals suggests that fluid pressure, depth and seal composition influence the minimum stress acting in the basin. The high levels of overpressure in some regions of the basins will compromise seal integrity due to hydraulic fracturing of the seal.

Introduction

Mudstones are common within New Zealand's sedimentary basins, and typically form 60-70% of basin fill. The fine grain size and small pore throats of mudstones exert a strong influence on the movement of water and hydrocarbons (Aplin *et al.* 1995), allowing them to form seals to hydrocarbon migration. The abundance of mudstones in New Zealand basins means that seals are often assumed to be a low-risk element of New Zealand's petroleum systems. However, quantification of seal behaviour and risk is not straightforward in a dynamic plate boundary environment, with its attendant complex hydrodynamic and stress regimes. This paper presents initial results of studies of the physical properties of fine-grained sediment in the Taranaki and East Coast Basins, with the aim of making first steps towards quantifying and predicting top seal (caprock) behaviour.

Seals in New Zealand basins are deepwater marine mudstones and limestones. Proven seals in the Taranaki Basin include the Eocene Turi Formation, the Oligocene Otaraoa Formation and Tikorangi Formation, and Miocene-Pliocene basin-floor mudstones in the Moki, Mt Messenger and Giant Foresets Formations. (King & Thrasher 1996). In the East Coast Basin, the Miocene Tangihau Mudstone and Waingaromia Mudstone form seals in the Kauhauroa area (Davies *et al.* 2000). Several previous papers have considered the quantitative properties of Taranaki Basin top seals. McAlpine & O'Connor (1998) considered that the effect of grainsize, compaction, and palaeo-overpressuring could limit seal capacity and integrity in the Taranaki Basin. King & Thrasher (1986) noted that individual reservoirs in Taranaki achieve a maximum column height of 200 m and are generally not filled-to-spill, and suggested that insufficient seal capacity could be one explanation of this phenomenon. Haskell (1991) suggested a control on hydrocarbon column height by seal capacity in the Kapuni and McKee fields, with column height dynamically limited at 220-300 m. Bergmann *et al.* (1992) noted that lack of a good seal formed a major problem in the Kora reservoir. Much less has been published on seal evaluation in other NZ basins. In the East Coast Basin, Davies *et al.* (2000) proposed that thick Miocene mudstones are effective seals, while Field *et al.* (1997) proposed that seals appear to be widespread on the East Coast Basin.

Seal properties and methods for analysing seal behaviour have been reviewed by Watts (1987), Vavra *et al*. (1992), Downey (1994), Dewhurst (1999) and Ingram & Urai (1999), amongst others. This paper follows the general classification of seal behaviour proposed by Watts (1987), who divided top seals into:

(a) *membrane seals*, controlled by capillary properties of the interconnected pore throats

(b) *hydraulic seals* where the capillary pressure is so high that the seal preferentially fails by fracturing.

This paper considers each of these seal types in turn, and analyses their governing factors.

Capillary properties of seals

The capillary fluid flow properties of the rock that govern sealing behaviour include porosity, permeability and capillary entry pressure. These properties are influenced by chemistry (including depositional composition and subsequent diagenetic modifications), and the effective stress acting on the rock (which is a function of depth and fluid pressure). The reduction in porosity of mudstones with increasing stress causes a flow of fluid, and so provides a principal driving mechanism for flow of water and hydrocarbons within a basin. Seals fail by capillary flow if the buoyant pressure of a hydrocarbon column overcomes the threshold capillary pressure (the pressure required for hydrocarbons to enter the largest interconnected pore throat of the seal). Porosity and permeability then dictate the rate of flow through the seal. This section of the paper considers the capillary properties of seals, with emphasis on the Taranaki Basin.

Porosity

The relation between the porosity of fine-grained sediments and depth in the Taranaki Basin is well understood through the empirical curves of Armstrong *et al.* (1998). This “Taranaki Compaction Curve” is widely used for basin modelling studies in the region (e.g. McAlpine & O’Connor 1998). However, the versatile curve of Armstrong *et al.* (1998) suffers two drawbacks for detailed analysis of compaction and seal properties. Firstly, an empirical curve based on depth is inappropriate for analysing porosity in overpressured environments (as porosity depends on effective stress and not depth), and so care must be taken in using it below 3000 m depth, as stated by Armstrong *et al.* (1998). Secondly, it ignores possible small-scale variation in compaction trends that may exist between formations with different compositions (Aplin et al 1995).

These drawbacks can be improved by using the robust process-based approach to compaction developed within the field of soil mechanics (Aplin *et al.* 1995, Skempton 1970, Darby *et al.* 2000), based on oedometric experiments and the Terzaghi (1943) principle of effective stress:

$$\sigma' = \sigma'^{*} \exp\left(\frac{e^{*} - e}{\beta}\right)$$

where σ' = effective stress, e = void ratio, e^* = void ratio at a reference effective stress σ'^*, and β = compression coefficient The use of a soil mechanics curve allows quantification of compaction in overpressured basins, and furthermore allows use of the Yang & Aplin (1998) methodology for calculation of permeability. The compaction curve of Armstrong *et al.* (1998) in normally-pressured sediments is fitted adequately by a soil mechanics curve with a compression coefficient (b) of 0.36 (Fig 1).

This methodology also highlights data that does not fit the general b = 0.36 compaction curve, allowing high-resolution analysis of mudstone porosity. In Kaimiro-1, the b = 0.36 curve fits the normally-pressured sediments of the Manganui Formation and the underlying, overpressured Kapuni Group (Fig 1), when corrected for uplift following the analysis of Armstrong *et al.* (1998). Marine mudstones clearly separate “cells” of siltier/sandier rocks which show parallel b = 0.36 compaction curves. However, marls and marine mudstones of the upper Turi Formation, Otaraoa Formation and Taimana Formation between 3000 m and 4000 m depth in this well show approximately constant porosity with increasing depth. This effect can be attributed to either:

(a) a different compaction curve for these marly formations, related to a distinct chemical composition. This will be discussed in Section 2.2 below;

(b) the presence of overpressure at 23 MPa km^{-1} within these units, giving constant effective stress with depth; or

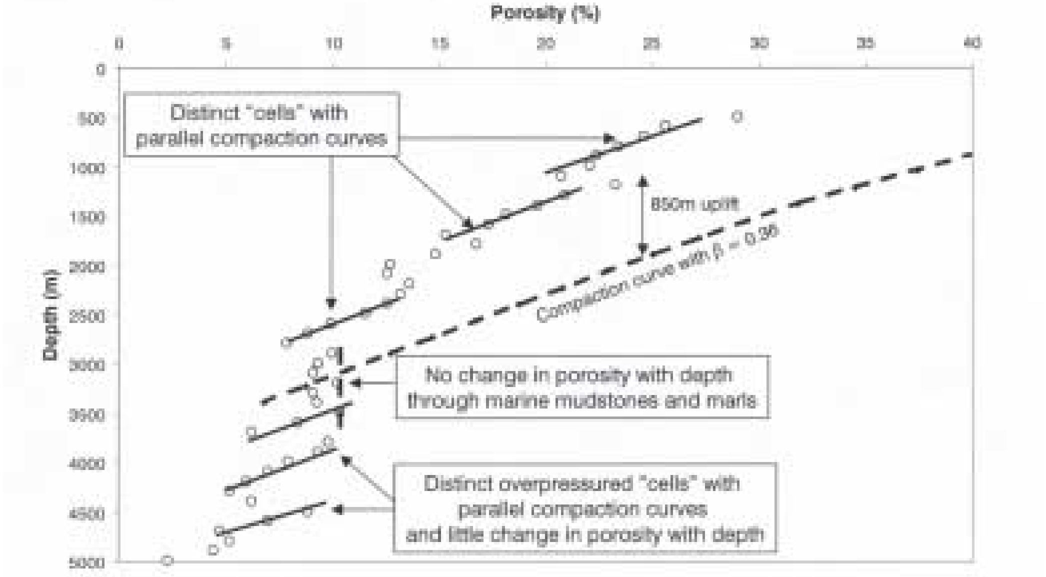

Figure 1: Porosity-depth curve for Kaimiro-1, for log-derived data from Armstrong *et al.* (1998). From 500-2500m depth, the porosity data shows three distinct uplifted “cells” with compaction trends that parallel a soil mechanics curve with b = 0.36. Below 3000m , three further parallel cells can be defined in Kapuni Group sediments. Between the cells, marine mudstones and marls show no decrease in porosity with depth.

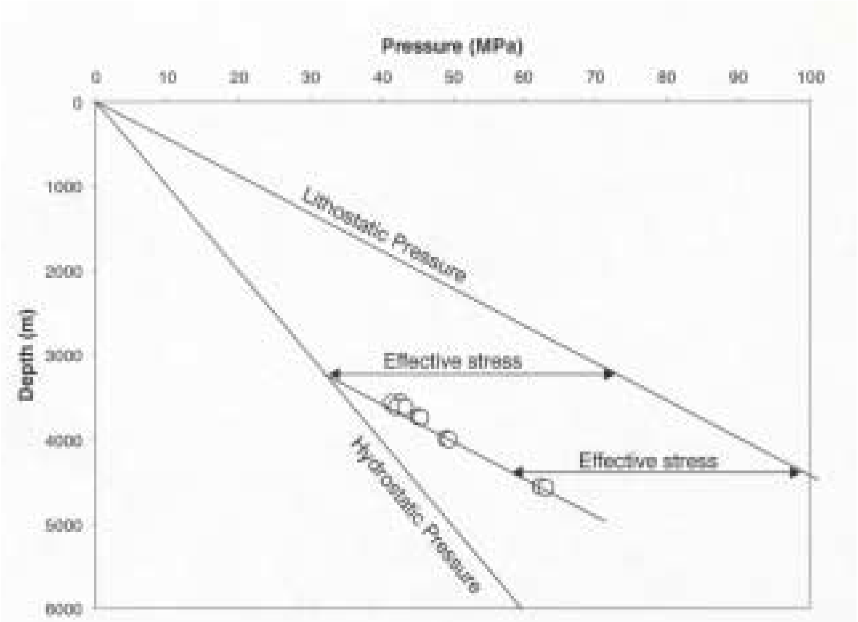

Figure 2: Pressure-depth plot for Kaimiro-1, with pressures from repeat formation tests. Overpressure exists below 3000m at a 23 MPa km^{-1} gradient, leading to constant effective stress with increasing depth.

(c) log interpretation problems due to poor hole quality or inaccurate sonic-porosity transforms in these formations.

Pressure data from repeat formation tests in Kaimiro-1 below 3000 m depth (Fig 2) clearly shows the presence of a 23 MPa km^{-1} pressure gradient, and so this paper proposes that (b) is the most likely explanation.

Seal chemistry

The analysis of compaction trends and associated pressures presented above suggests that they are behaving in a hydrologically distinct manner from the underlying and overlying formations. The hydrological behaviour of the formations will be determined by their capillary properties, which in turn are influenced by sediment composition. It is hypothesised that distinct hydrological behaviour and compaction trends in these formations are related to variation in composition between formations.

Several authors have identified a mineralogical change in mudstone composition immediately above, within and below the Oligocene condensed section (the time period of maximum marine flooding of the New Zealand region). In the Wanganui Basin, Nelson & Hume (1977) show an increase in montmorillonite content through the lower Miocene and Oligocene, reaching a maximum in the Whaingaroan. In the Waikato Coal Measures, King (1978) noted an increase in montmorillonite content from the Turi Formation-equivalent Glen Afton Claystone to the Otaraoa Formation-equivalent Mangakotuku Siltstone. The detailed regional review by Larmer (1998) noted high smectite contents in the Whaingaroan OtaraoaFormation and Abel Head Formation in the Taranaki Basin (Fig 3), with smectite being much less

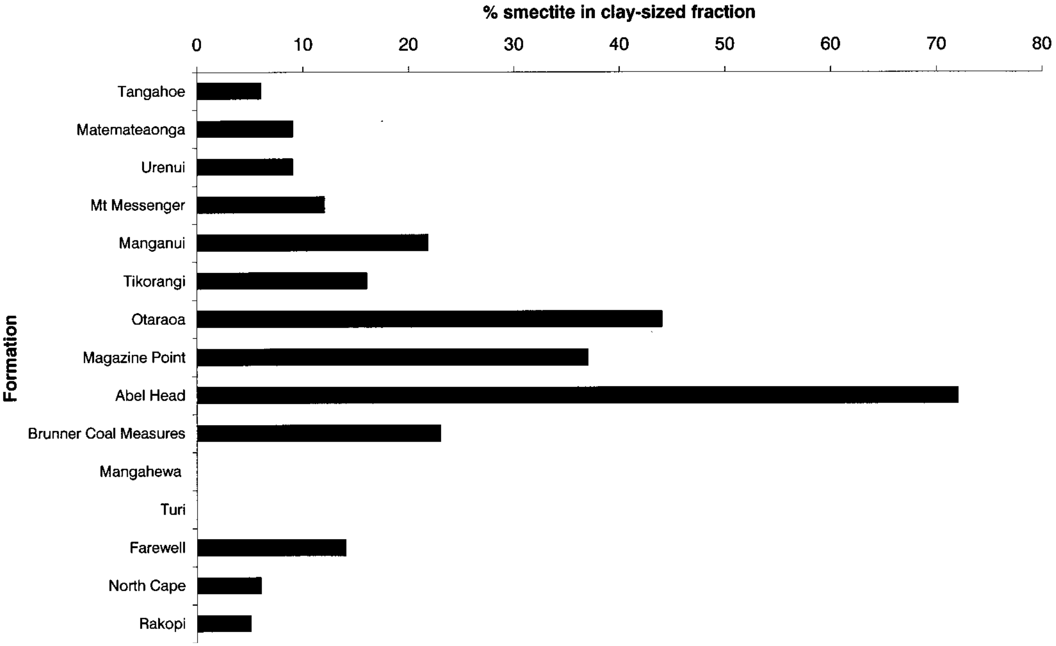

Figure 3: Mixed layer illite/smectite content of various formations in the Taranaki Basin, from Larmer (1998) showing the highly smectitic nature of Oligocene formations (e.g. Otaraoa, Abel Head Fms).

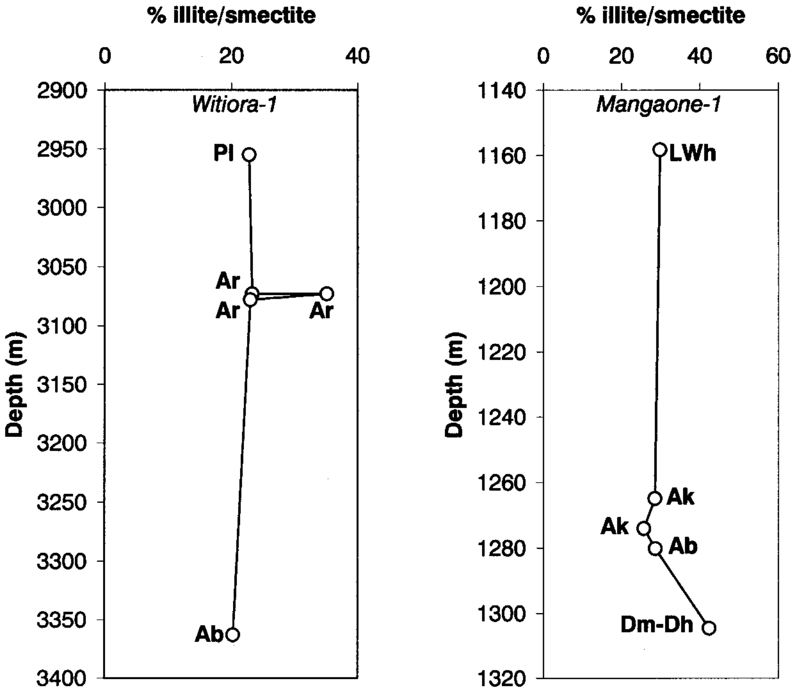

Figure 4: Mixed layer illite/smectite content of Witiora-1 and Mangaone-1 showing high smectite contents in Eocene formations.

abundant or absent in underlying and overlying formations. In the East Coast Basin, Fergusson (1985) described high smectite contents in marls in the Eocene-Oligocene Amuri Limestone and the Wanstead Formation . Bentonites (smectite-rich mudstones) are often described in drilling reports in the East Coast, occurring in the lower Whaingaroan – Eocene section in Morere-1 and Mangaone-1, and in the Middle Eocene (cross-fault) in Opoutama-1.

Whole-rock XRD (Fig 4 and Table 1) confirms that high values of interlayer illite-smectite exist in the Oligocene-Eocene section in both Taranaki and East Coast basins, in wells Mangaone-1, Witoria-1 and Onaero-1. The XRD results also indicate compositional differences between the clay minerals in the two basins: Mangaone-1 in the East Coast Basin contains a smectite-rich mixed-layer clay mineral, while the mixed-layer clay in Witiora-1 is equally rich in smectite and illite. These results confirm that the deepwater marine marls and mudstones deposited during maximum marine flooding of the New Zealand region have a distinct, high-smectite composition. The presence of abundant smectite is significant for the hydrological behaviour of the formations, as smectite-rich mudstones generally have very low permeability (Dewhurst *et al.* 1999) and are thus more likely to become overpressured. Additionally, the presence of smectite (with high surface area) has a major effect on the physical and engineering properties of mudstones, such as friction angle. The smectite-rich mineralogy of the upper Turi Formation (Kaitian-Runangan) in the Taranaki Basin and the Wanstead Formation in the East Coast Basin, as well as possible overpressuring as discussed above, are potential contributing factors to the significant wellbore stability problems that have been encountered.

Capillary entry pressure

The entry pressure of a non-wetting phase into a rock can be measured by mercury injection capillary porosimetry (MICP), where mercury is injected at high pressure into an air-filled rock sample. The measured capillary pressures can be converted to subsurface brine-oil or brine-gas capillary pressures by translating the contact angle and interfacial tension (IFT). The MICP values in this paper have been converted to subsurface conditions using standard values of IFT, contact angle, and gas/oil/water densities (e.g. Vavra *et al.* 1992). Capillary pressure is a function of the pore throat size distribution, and increases as pore throat size decreases. MICP delivers much useful information about a seal, including a calculation of pore throat size, a displacement pressure (the first entry of non-wetting phase into the sample, which is important for determining free water level in an underlying reservoir), and the threshold pressure (corresponding to the initial breakthrough of non-wetting phase through the sample). The threshold pressure determines seal capacity.

A total of 15 data points from Petroleum Reports on Taranaki caprocks have been collated together with the results of analyses of six new samples from Oligocene and Eocene mudstones. Gas column heights have been calculated from capillary pressures measured on the new samples using the same parameters as within existing Petroleum Reports, so datasets are comparable. Calculated gas column heights are shown in Fig 5, and range from a maximum of 711 m (Miocene distal-fan Moki Formation. in Kaimiro-2) to a minimum of 12 m (Eocene Tane Member. of Turi Formation, in Tane-1). The average supportable column height is 185 m.

The data is currently inadequate for detailed understanding and prediction of column height. Many more analyses are required, and in particular an understanding of the lateral and vertical variability of caprock properties is needed. The current dataset is biased due to use of conventional cores, and it is likely that the finest-grained regional seals (e.g. upper Eocene/Oligocene mudstones) have not been adequately sampled. There is also likely to be a bias in the sampling by previous workers, as capillary pressure measurements have typically been conducted where seal is already perceived as a risk.

The paucity of data also leads to ambiguity in interpretation and application of these results to exploration. If a high entry pressure seal is likely to extend over an entire structure, risking a prospect based on the high end of the results in Fig 5 might be justified. Alternatively, low capillary pressure zones may exist throughout heterogeneous seals, in which case risking based on average values may be more appropriate. However, Downey (1994) suggested that average seal properties are meaningless and that the lowest randomly-sampled value of capillary pressure should be considered when risking a seal. Downey (1994) particularly emphasised the importance of this viewpoint for stratigraphic traps and thin seals.

Despite these limitations, the capillary pressure data are valuable in defining initial trends in seal properties:

- Present-day depth of burial is not a basin-scale control on capillary pressure, and so depth of seal during charge should be carefully assessed. It is apparent that depositional variation (i.e. between Turi mudstones in Maui-6 and Tangaroa-1) is a more important control than depth of burial. However, capillary pressure increases with depth within single formations in individual wells.

- The presence of low capillary pressure zones within the regional seal will compromise sealing capacity, particularly at the base of the regional Eocene flooding surface where there is higher quartz content. It is likely that significant "waste zones" (where hydrocarbons saturate the mudstones, but cannot be extracted on a production timescale) will occur in stratigraphically-lower seals and along migration paths, leading to large-scale migration losses.

- The highest capillary pressure yet measured in the Taranaki Basin comes from the relatively shallow Miocene Moki Formation in Kaimiro-2. However, this sample has undergone significant diagenetic cementation by calcite. Uncemented Moki Formation from the same well have far lower capillary pressures, and so the likely presence and extent of cemented zones within the seal must be assessed before upside predictions of seal capacity can be used.

Permeability

Although capillary entry pressure determines seal capacity, permeability is useful for modelling rates of leakage through seals, and for predicting fluid pressure. Permeability of a mudstone is time-consuming and expensive to measure. However, Yang & Aplin (1998) have proposed that pore throat size distribution (from MICP) can be linked to specific surface area measurement to calculate permeability. Their results show excellent agreement to measured permeability values. This paper follows their methodology to calculate permeability for 6 samples in the Taranaki Basin. Results are shown in Table 1 and described below.

- Permeability of the mudstones ranges from 10^{-20} to 10^{-23} m^2. The lowest calculated permeability comes from the Otaraoa Formation in Onaero-1, while the highest value comes from the 3899.0 m sample in Tangaroa-1. This highest value of permeability comes from the deepest, oldest sample, and so permeability is not a simple uniform function of depth. Values agree well with permeabilities measured on other datasets from deeply-buried mudstones (e.g. Yang & Aplin 1998). Extrapolation of these initial results to large-scale fluid flow simulations requires further understanding of the spatial variability of rock properties.
- The sample from the Otaraoa Formation has a much higher surface area than the Turi Formation samples. It has a large microporous (<2 nm diameter) component indicative of significant intra-particular porosity. This is expected, given the smectite-rich mineralogy of this sample. However, the surface area analysis also indicates the presence of irregular inter-particular pores such as those formed by a "house-of-cards" structure, which are an order of magnitude larger than the intra-particular porosity, and should be thought of as a typical mudstone pore geometry. The very low permeability calculated for this sample does not fit well with the low capillary pressure measured. This can be attributed to macroscopic effects (such as the presence of fractures or silt layers) that affect the larger sample volume used for the MICP analysis.
- The Turi Formation samples from Maui-6 have lower surface areas, and suggest similar "house-of-cards" pore structures to the Otaraoa Fm, but lack significant intra-particular porosity. This can be attributed to the absence of smectite clays. Surface area and pore volume decrease steadily from 3023.6 m to 3035.0 m, suggesting diagenetic modification of the samples. This result parallels the increase in capillary threshold pressure for these samples (Fig 5).
- Surface areas from Tangaroa-1 are low and result from coverage of relatively large individual particles. Analysis is indicative of totally non-porous particles (unlike that of the smectite clays in Onaero-1). This matches well with the XRD analysis (Section 2.2) that shows high quartz content in these samples.

Hydraulic properties of seals

Seals can fracture due to tectonic movements, the buoyant action of long hydrocarbon columns (Watts 1987), or the effect of overpressure. Tectonically-driven seal fracturing may occur during deformation. Ingram & Urai (1999) have shown that dilatant fracture of top seals is favoured by significant uplift prior to deformation (overconsolidation), although dilatant fracturing is difficult to achieve in ductile, smectite-rich mudstones. The smectite-rich Upper Eocene layers discussed above may be critical in preserving trap integrity during polyphase basin evolution. This process may be of major importance in controlling trap integrity in New Zealand's dynamic basins. However, it is currently difficult to quantitatively simulate and predict tectonically-driven fracturing, although this remains a long-term research goal. Accordingly, this section is confined to a consideration

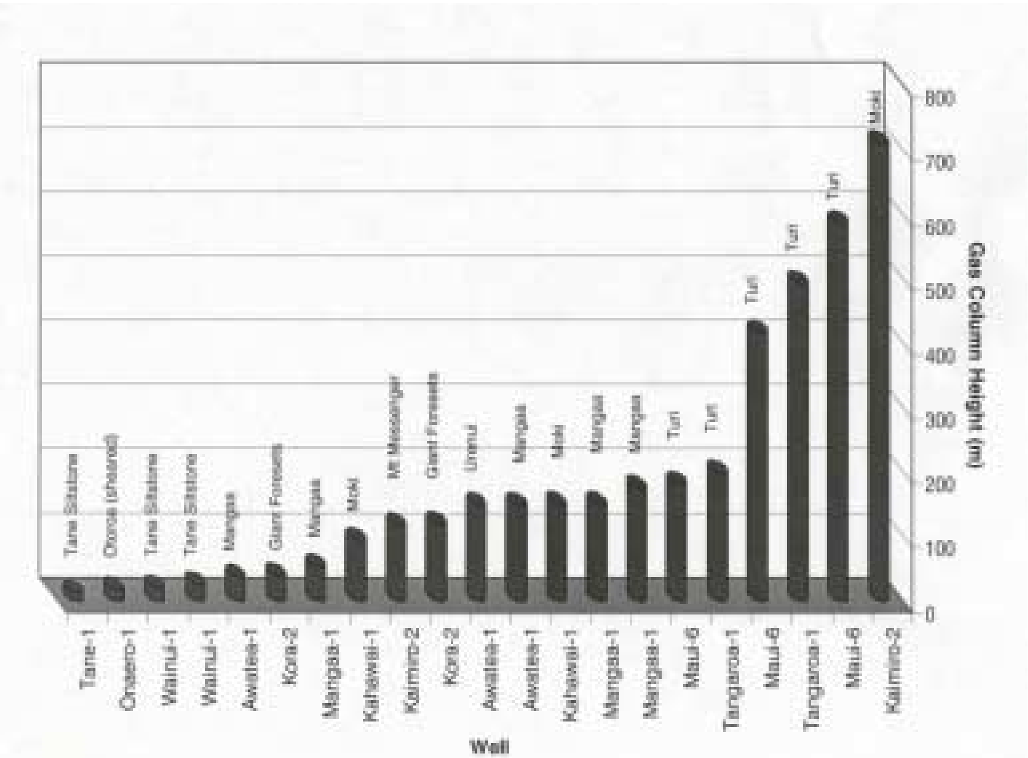

Figure 5: Calculated gas column that can be retained by seals in Taranaki Basin wells based on MICP measurement.

of seal fracturing by fluid pressure, also termed hydraulic fracturing.

State of stress

Hydraulic fractures form when the minimum effective stress is reduced to the tensile strength of the rock. To evaluate the risk of seal hydraulic fracturing, it is necessary to know the pore pressure and the minimum stress acting in the basin. Lithostatic pressure (S_v, or S_1 in extensional basins) can be approximated by integration of the compaction curves presented in Armstrong *et al.* (1998). Minimum stress (S_3, or minimum horizontal stress S_h in extensional basins) is approximated by leak-off tests (LOTs). Interpretation is made more complex by the fact that LOTs frequently overestimate the minimum stress acting on a rock (Breckels & van Eekelen 1982). Fig 6 shows a collation of LOT and fluid pressures from the Taranaki Basin. There is a considerable variation in LOT pressure for any given depth. The third component of the stress tensor, S_2 (or maximum horizontal stress S_H in extensional basins), is more difficult to quantify (Hillis 2000). Directions of S_H and S_h can be defined for Taranaki and East Coast basins from the orientation of borehole breakouts and drilling-induced tensile fractures (Darby, in prep.).

S_h, S_v and pore fluid pressure P are linked through poroelastic theory (Biot 1941, Engelder & Fischer 1994, Hillis 2000)

$$S_h = k(S_v - P) + P$$

where $k = \frac{\upsilon}{1-\upsilon}$ and u is Poisson's Ratio.

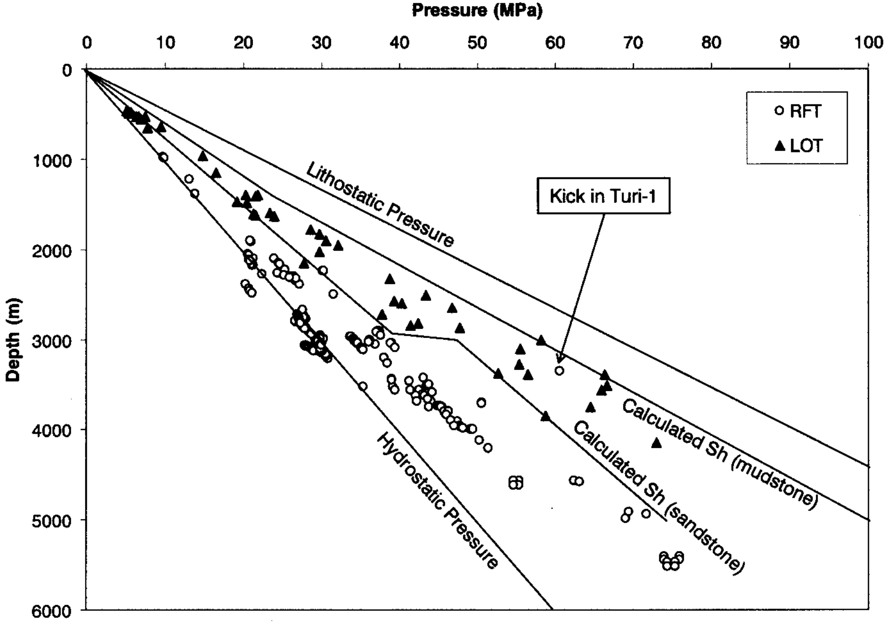

Figure 6: Repeat formation test fluid pressures and minimum stress measured by leak-off tests in the Taranaki Basin. The spread of LOT values can be matched by calculated minimum stresses based on a poroelastic model. The value of pressure for Turi-1 (indicated by arrow) is based on a kick.

It is possible to simulate the measured variability in S_h from LOT pressures by considering the potential variation of u with lithology, and the variation of S_3 with pore pressure. The lower bound to S_h can be approximated by considering u of 0.25 and a transition from hydrostatic pressures to 1.32 SG (13 MPa km^{-1}) overpressure at 3000 m depth. The upper bound to the measured S_h can be approximated by u of 0.4 and a highly-overpressured 2.3 SG (23 MPa km^{-1}) pressure trend. The highest S_h is measured by LOT in deeply-buried, ductile Upper Eocene mudstones. These rocks may be expected to have high u, and this 23 MPa km^{-1} pressure gradient is consistent with the compaction analysis presented above. Further measurement of rock properties will constrain this envelope more closely. However, Fig 6 suggests that the stress state of the Taranaki Basin can support hydrocarbon columns in excess of 500 m before hydraulic failure of the top seal occurs, and hydraulic seal capacity increases with depth – except where overpressure compromises seal integrity.

Overpressure-driven caprock leakage

Overpressure can significantly reduce seal capacity (Gaarenstroom *et al.* 1993, Darby *et al.* 1996). It can lead to a dynamic control on hydrocarbon column height, although this role is debated (Bjorkum *et al.* 1998). Conditions for overpressure-driven caprock failure are met at specific locations in both Taranaki and East Coast basins.

Titihaoa-1, East Coast Basin

The well encountered high pressures in Middle Miocene turbidites, equivalent to 0.83 S_v (Fig 7). A leak-off test above the top of hard overpressure recorded a minimum stress gradient of 0.85 S_v, while a leak-off test in the overpressured turbidites was higher, at 0.95 S_v. At first glance, this suggests that a significant margin exists between fluid pressure and fracture pressure.

The well has been drilled significantly off the crest of the structure, as noted by Uruski *et al.* (1998). Drilling away from the crest is common practice in overpressured environments, and ensures a safe margin between minimum stress, formation pressure and mudweight. However, mudweights suggest that the seal is not as highly pressured as the underlying turbidites (Darby & Funnell 2001). As stress and pressure are linked, as discussed above, then use of the minimum stress gradient derived from the LOT in the overlying seal may be more appropriate than using the reservoir LOT. Extrapolation of a hydrostatic-parallel gradient from the reservoir suggests that the fluid pressure gradient and seal fracture gradient are equal at the crest of the structure. Accordingly, seal capacity in this structure is close to zero. It appears that Titihaoa-1 is a regional leak point (Darby *et al.* 1996), where formation pressure at top structure is at the maximum sustainable limit. High levels of overpressure have been reported in other areas of the East Coast Basin (Davies *et al.* 2000, Darby & Funnell 2001, Darby & Ellis 2001) and so this mode of seal failure may occur elsewhere in the basin.

Turi-1, Taranaki Basin

In contrast to the East Coast Basin, overpressure within the Taranaki Basin is generally safely below the minimum stress gradient at the present day, especially considering the interrelationship between S_h and pore pressure. Seal failure by overpressure-driven hydraulic fracturing is unlikely to be a significant risk across much of the basin. However, a

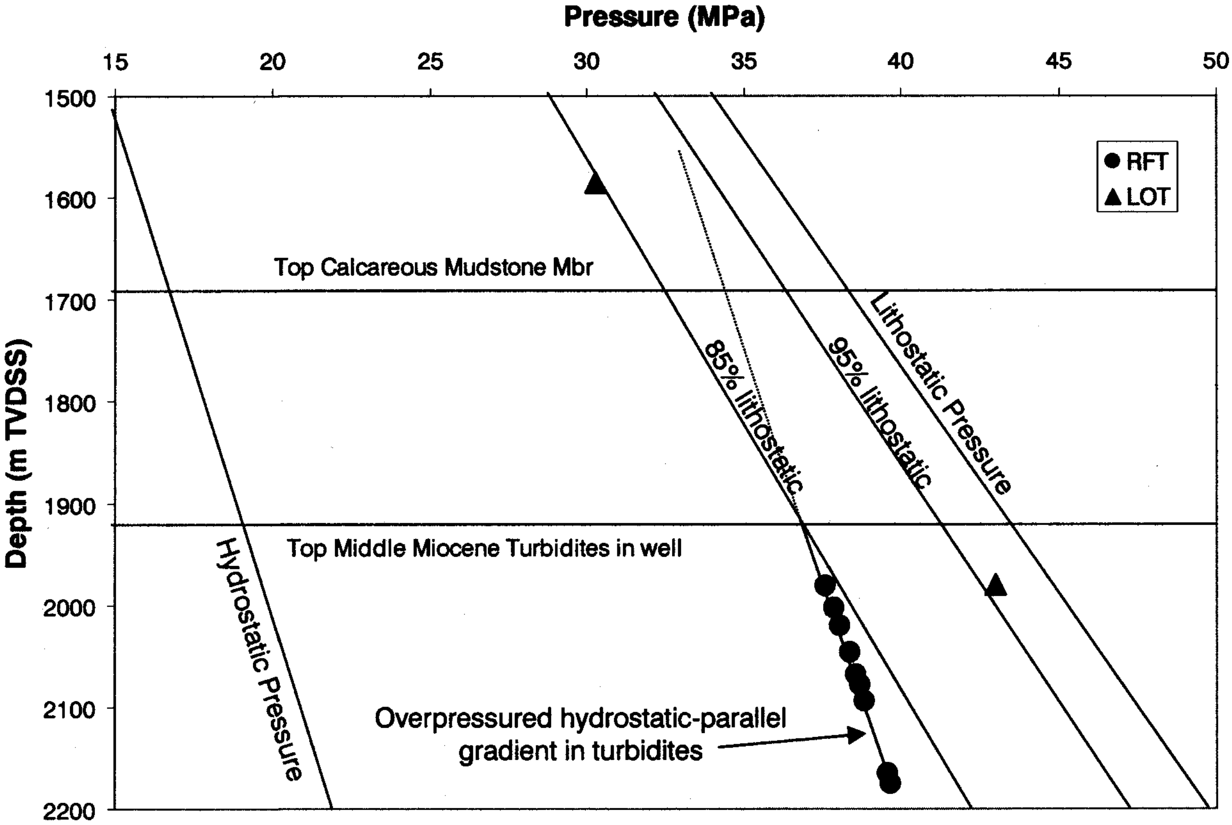

Figure 7: Repeat formation test fluid pressures and minimum stress measured by leak-off tests in Titihaoa-1. Fluid pressure is equal to minimum stress at the base of the seal, leading to hydraulic failure of the seal, and low seal integrity.

significant exception to this is posed by the well Turi-1 (Fig 6), which encountered a kick with fluid pressure of 0.8 S_v in thin Upper Eocene sandstones. Leak-off pressure is 0.87 S_v. RFTs from this interval of Turi-1 are judged to be unreliable, and so direct verification of the fluid pressure magnitude is not possible. However, it would appear that fluid pressure in the Upper Eocene sandstones in Turi-1 is at, or close to, minimum stress. Data is suggestive that dynamic regulation by seal fracturing is controlling overpressure. Such a mechanism may be important for facilitating hydrocarbon migration from the deep Northern Graben.

Conclusions

This paper has presented initial results from a continuing study on the properties of seals in the Taranaki and East Coast basins. It has shown that capillary and hydraulic properties of seals in these basins are highly variable, and may be related to variations in composition between different mudstone formations. There is a need for a much larger database of seal properties before seal risk can be rigorously quantified for prospects in New Zealand basins. In conclusion:

1. A soil mechanics compaction curve with a compression coefficient b of 0.36 can describe the decrease in porosity with increasing stress in the Taranaki Basin. Departures from this curve suggest that Oligocene - Upper Eocene marine mudstones have a separate compaction trend, and are overpressured.
2. Capillary pressure measurements show that seal capacity in Taranaki is highly variable, ranging from 12 m for an Eocene siltstone, to 700 m for a cemented Miocene mudstone. Depositional composition, and subsequent diagenetic modification, are the main influences on seal capacity. The presence of silty low capillary pressure zones in the regional seal is an important influence on seal capacity.
3. Calculation of mudstone permeability using the method of Yang & Aplin (1998) shows that Eocene mudstones have very low permeabilities, ranging from 10^{-20} to 10^{-23} m^2, with lowest permeabilities calculated for the smectite-rich Oligocene Otaraoa Formation.
4. Minimum stress measured in the Taranaki basin is highly variable for a given depth, and is a function of fluid pressure and seal chemistry.
5. Overpressure-driven hydraulic failure of seals has occurred in East Coast and Taranaki basins, and seal integrity is compromised in highly-overpressured regions of the basins.

Acknowledgements

This project has been funded by the Foundation for Research and Technology under contract No. CO5806. Ray Soong is thanked for XRD analysis, Steven Bagshawe of IRL is thanked for surface area measurement, John Kaldi and Ric Daniels of the NCPGG are thanked for MICP work, and Dave Dewhurst of CSIRO is thanked for many useful comments.

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Table 1. *Calculated permeability for Taranaki Basin mudstones*

Well	Onaero-1	Maui-6	Maui-6	Maui-6	Tangaroa-1	Tangaroa-1
Measured Depth (m)	3029	3023.6	3032	3035	3896	3899
Formation	Otaraoa	Turi	Turi	Turi	Turi	Turi
Mineralogy	I/S, Q, PF	K, Q, M	K, Q, M	K, Q, M	Q, K, M	Q, K, M
e_{100}	3	2.2	2.2	2.2	2.2	2.2
Void Ratio	0.125	0.11	0.11	0.11	0.11	0.125
Grain density	2.6	2.6	2.6	2.6	2.6	2.6
Mean pore throat size (nm)	6	60	9	9	90	30
Surface area (m^2g^{-1})	26	5	4	1.5	4.5	4
Calculated vertical permeability(m^2)	3×10^{-23}	1×10^{-20}	2×10^{-21}	2×10^{-21}	2×10^{-20}	1×10^{-20}

Table 1: Calculated permeability for Taranaki Basin mudstones, using the methodology of Yang & Aplin (1998). Mineralogy is determined by XRD and is in order of abundance: I/S illite/smectite; Q quartz; PF plagioclase feldspar; K kaolinite; M mica.

Author

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