Basin modelling of oil plays northwest of Maui: Results; constraints and calibrations

A McAlpine

Spectrum Exploration Ltd, 25 Maranui Street, New Plymouth, New Zealand, Telephone 0064-6-759 9389,
Fax 0064-6-759 9319, Email spectrum.exploration@xtra.co.nz

Abstract

Petroleum Exploration Permit PEP 38462 is located northwest of the Maui Field and is jointly licensed to Spectrum Exploration Ltd and Fletcher Challenge Energy Taranaki Ltd. Structural mapping and 1-Dimensional maturity modelling shows the permit contains several giant structures and mature, oil-prone source rocks. However, a complex petroleum migration history is revealed using PETROMOD™ finite-element modelling software and by constraining the modelling results with geological, petrophysical, and geophysical parameters.

The modelling shows the importance of correctly defining the detailed structure, stratigraphy and physical properties for the source rocks, carrier beds, reservoirs, and seals. In some cases, additional laboratory data has been obtained to better constrain these parameters.

Determining the compositional kinetics of the various potential source-rock lithologies (coals, shaly-coals and carbonaceous mudstones) was also found to be important. Laboratory data suggests that carbonaceous mudstones are a very significant source-rock component, particularly for oil.

For the overburden, which here comprises the prograding Miocene-Recent “Giant Foresets”, it was found that the chrono-stratigraphy and palaeo-bathymetry were additional critical parameters. The correct chrono-stratigraphy is necessary to properly model the sediment loading rate, which in turn causes compaction-disequilibrium overpressures. An incorrect palaeo-bathymetry can cause erroneous structural tilt in the models.

The modelling strongly indicated the existence of mature, oil-prone kitchens and showed that secondary migration was being complexly affected by hydrodynamic effects set up beneath the prograding “Giant Foresets”. For the modelling results to be considered meaningful it was necessary to constrain the results with available physical data. These include: oil-show properties; petrophysical and geophysical estimates of overpressures; various maturity indices; and fluid-inclusion data. The calibration of the modelled overpressures to seismically-derived overpressures is a particularly novel aspect of this study.

The quantitative modelling approach has led to new insights into the Western Stable Platform region west of Maui. Maturity levels and oil proneness appear to have been previously underestimated. However, oil expulsion, migration and trapping appear to be more complex than might otherwise be thought in this tectonically benign part of the Taranaki Basin.

Introduction

The Taranaki Basin has provided New Zealand’s entire commercial oil and gas production to date. The structurally complex Eastern Mobile Belt (Figures 1 & 2) is considered a fully mature gas and oil province, whereas the tectonically simple Western Stable Platform (WSP) has been regarded as being relatively immature for significant hydrocarbon expulsion and migration (Pilaar & Wakefield, 1984; Beggs, 1996; Armstrong et al., 1996).

Whilst it is recognised the area northwest of Maui contains very large structures, the perceived low maturity and poorly understood migration mechanisms are impediments for explorers. Re-evaluation based upon more advanced modelling and evolving ideas on source-rock characteristics have recently led to a renewal of exploration interest in the area (Wilkinson, 1999). Spectrum Exploration Ltd and joint venture partner Fletcher Challenge Energy Ltd are together exploring this region, in Petroleum Exploration Permit PEP 38462.

This paper describes the computer modelling of potential oil plays northwest of Maui by systematic analysis of: basin-development, thermal history, compaction, pore fluid movement, overpressure generation, seal development and petroleum migration using state of the art PetroMod™ finite-element basin modelling software. The models were constructed with high levels of confidence as they were constrained by much available well and seismic data.

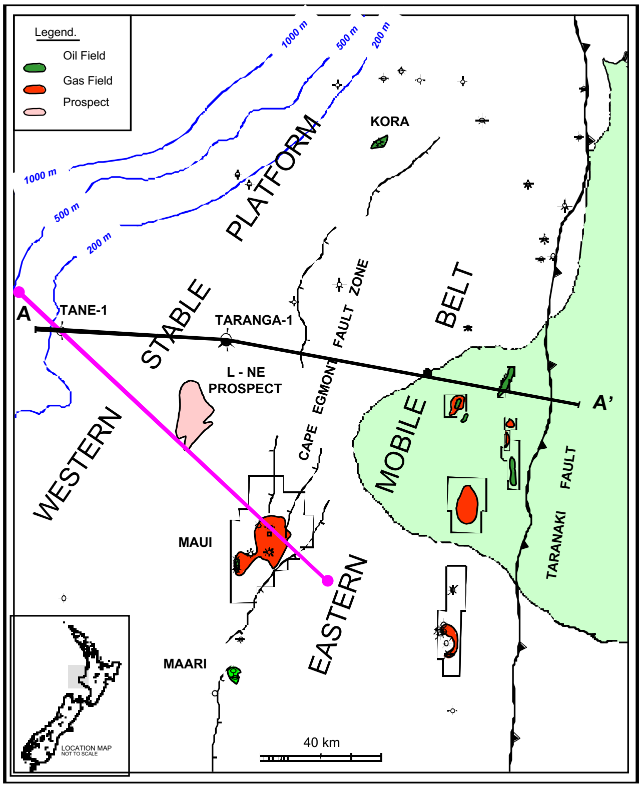

Figure 1: Taranaki Basin location map, structural setting, and location of cross-section and modelling profile discussed in this paper.

A surprising discovery is that rapid sedimentation during Miocene-Pleistocene times caused compaction-disequilibrium overpressures to develop within a thick Eocene shale interval and create a "thermal blanket" which enhanced thermal maturity in the underlying kitchens. Compaction-disequilibrium also caused hydrodynamic effects in the reservoirs and produced a more complex migration history than might otherwise have been thought.

Geological setting

The general geology of the Taranaki Basin is well documented (eg. King & Thrasher, 1996). The Eastern Mobile Belt is structurally complex as a result of Neogene tectonism associated with the modern Pacific-Australian plate boundary (Holt & Stern, 1994). Beyond the outer limit of deformation is the Western Stable Platform which has remained comparatively undeformed since the Palaeocene (Figures 1 & 2).

Late Cretaceous sediments on the Western Stable Platform fill half-grabens and comprise mixed terrestrial/marine coal-bearing and sandy facies, which provide both source-rock and reservoir.

During the Palaeocene, marine transgressions deposited shelfal and coastal sands and siltstones. Subsequently, the entire area was affected by foreland-basin subsidence, and Eocene holomarine shales are overlain by a condensed Oligocene limestones and marls deposited in deep water during a starved basin phase. This interval forms a regional pressure seal by virtue of its lateral continuity and low-permeability lithologies.

Northwesterly prograding marine sediments of Miocene-Pleistocene age (collectively termed the "Giant Foresets") record the rapid influx of terrigenous clastics and the onset of regressive sedimentation.

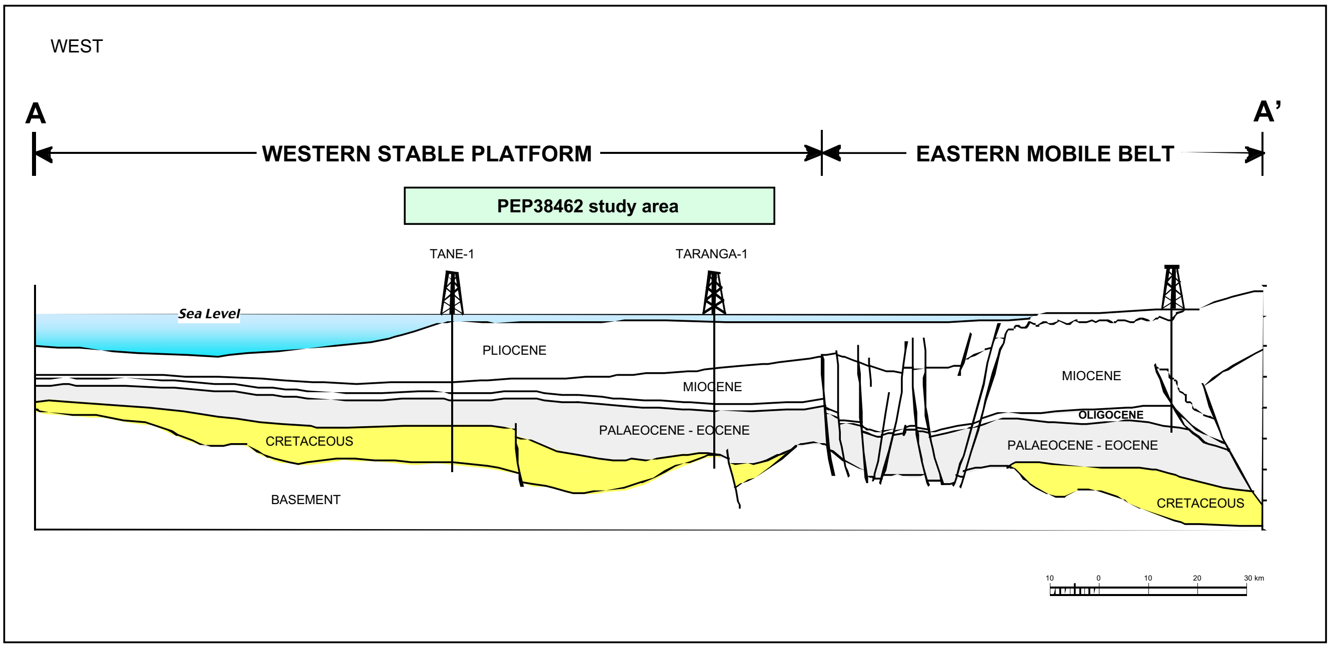

Figure 2: Cross-section (A-A') through the Taranaki Basin.

Basin modelling methods

Basin modelling was performed with the PetroMod™ finite-element simulation package produced by IES in Germany. Ten 2D transects were modelled in the study. These included straight regional transects, as well as “crooked-line” transects running along likely migration routes between the kitchen depocenters and the main prospects.

Model configuration

The profile discussed in this paper runs NW-SE through the Maui oil and gas field, the L-Northeast prospect, and well Tane-1 (Figure 1). The configuration of the important horizons and faults were derived from a regional mapping study. Ages of these horizons were determined from biostratigraphic reports for wells in the region.

Formation lithologies were determined from a petrophysical study, supplemented by sequence stratigraphy and general seismic and geological interpretations. Default PetroMod™ rock parameters were used wherever they were similar to specific Taranaki Basin rock properties described by Funnell et al. (1996). However, the parameters for the important source, carrier-bed, reservoir and seal units required refinement to better match available pressure, temperature and geochemical data. For example, the default PetroMod™ values of permeability for limestone and marl are too high for this area and do not result in significant overpressure development.

Thermal conditions

Surface heat-flow in the northwestern Western Platform is lower than in other parts of the Taranaki Basin. Funnell et al., (1996) modelled this area using present-day heat-flows which increase from 50mW/m^2 at top basement to 56mW/m^2 at seabed, although higher heat-flows were used for the Late-Cretaceous to Eocene post-rift phase. Our study initially used a heat-flow which increased vertically from c.50mW/m^2 at top basement to c.56mW/m^2 at seabed. Later, a constant vertical heat-flow (53mW/m^2) was found to give essentially identical results and was subsequently adopted. A slight increase in the input heat-flow from the western area (53mW/m^2) towards the Maui field area (56mW/m^2) was required in order to match observed bottom hole well temperatures. Funnell et al.(1966) also noted an increase in basin heat-flow in this direction.

The final heat-flow in the models was significantly influenced by groundwater flow. Migrating deep groundwaters carry heat towards structual highs and towards potentiometric “lows” such as the Maui Field (Figure 3). This mechanism has previously been cited as the probable cause of anomalously high geothermal gradients (c. 3.2°C/100m) at Maui.

Source-rock characteristics & kinetics

Source unit characteristics are reasonably constrained from well penetrations, seismic facies mapping, and oil shows characteristics. Wells show variations in organic facies and source-rock characteristics within the stratigraphic thickness of each source unit. Moreover, marine-influenced source intervals appear to be more perhydrous and oil-prone than their terrestrial equivalents (Bal, 1994; Newman et al., 1998; Sykes & Dow, 2000). In this respect, the marine influenced types belong to the Type III (DE) organofacies of Pepper & Corvi (1995).

Source-rock coals are vitrinite-rich, yet have hydrogen indices that average around 300 mg/g (with maximum values in the 400-500 mg/g range), clearly sufficient to have sourced substantial amounts of oil and gas (Wood et al., 1998).

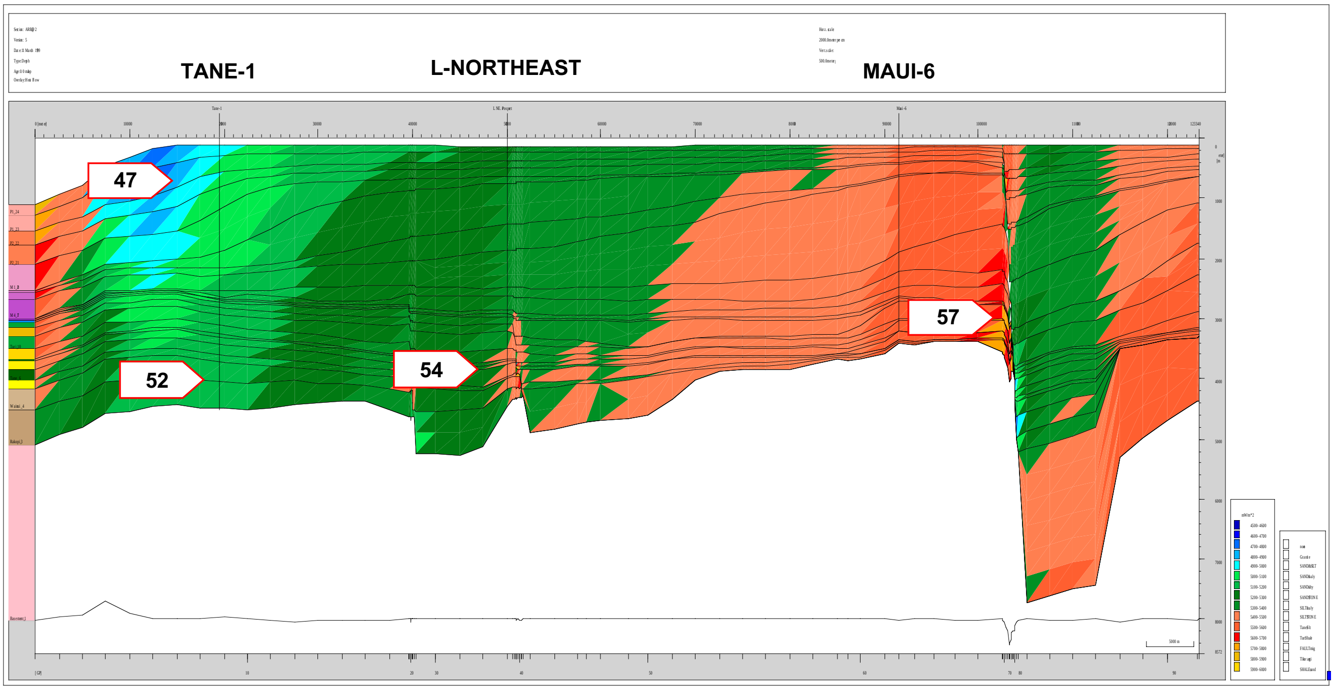

Figure 3: Modelled present-day heat-flow (mW/m^2) showing elevated heatflow in Maui area due to heat transfer from deep migrating groundwater.

Associated carbonaceous mudstones are also excellent source-rocks (Sykes & Dow, 2000 - *this volume*).

An average source-rock composition was used for the modelling, based on petrophysically derived proportions of source-rock and non-source rock lithologies in wells, and average coal and mudstone properties (Table 1). Whereas this approach indicated the average source-unit TOC was 7.1%, a more conservative figure of 4.5% TOC was used in the modelling.

Newly acquired compositional kinetics for coals and mudstones were used. These were similar to those for the BP Type III (DE) organofacies of Pepper & Corvi (1995), but differed in that they indicated oil was expelled almost contemporaneously with lesser proportions of gas.

Model calibration

Models were calibrated against a number of measured parameters including: bottom hole temperatures; vitrinite reflectance; reservoir pressures; shale overpressures; oil geochemistry; and fluid-inclusion homogenisation temperatures.

Temperature

Bullard-corrected bottom hole temperatures were provided for key wells by the New Zealand Institute of Geological Sciences (Funnell, pers. com.). Corrected temperatures were as much as ten degrees centigrade higher than uncorrected temperatures which, if used for model calibration, would result in pessimistic estimates of thermal maturity. Matching the model to well temperatures is shown in Figure 4.

Vitrinite reflectance

Vitrinite reflectance is an imprecise maturity indicator for New Zealand coals and other perhydrous coals generally, because of reflectance suppression (Suggate & Lowery, 1982). Notwithstanding, a selection of vitrinite reflectance data (Lowery, 1988) were used to provide a comparison with the vitrinite reflectance modelled using the method of Burnham & Sweeney (1989).

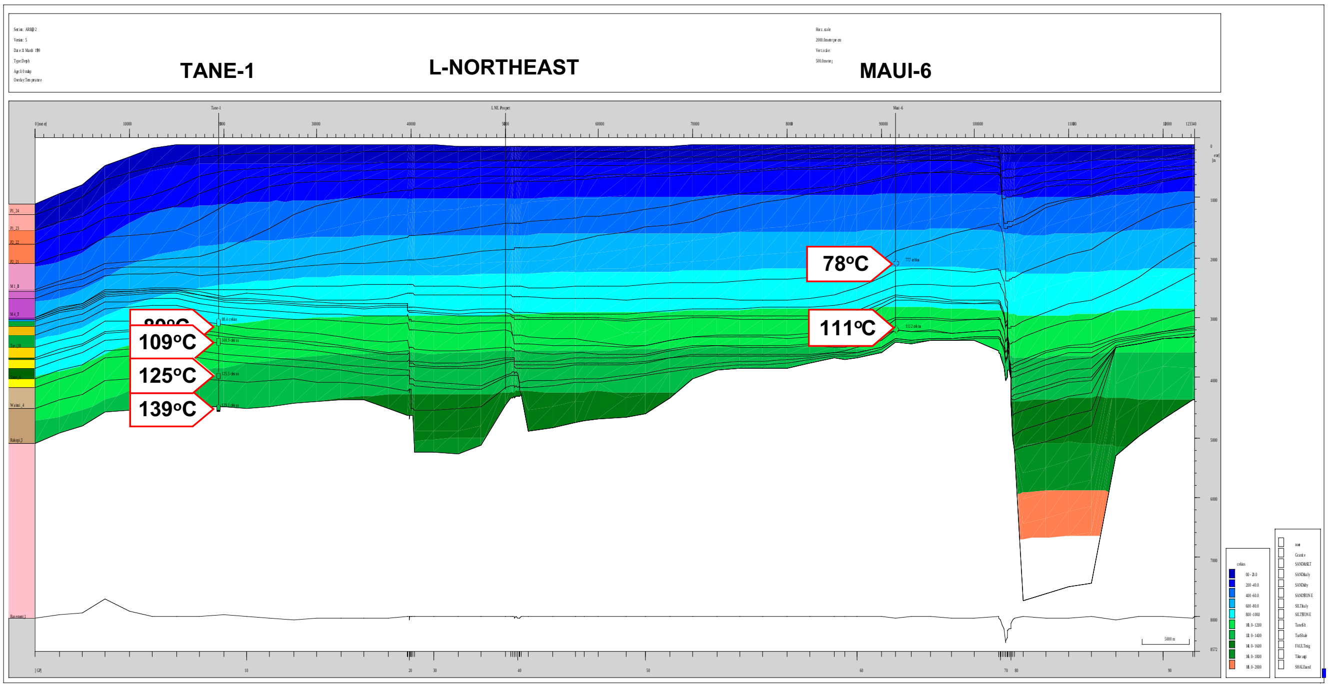

Figure 4: Modelled present-day temperature (°C) matched to Bullard-corrected bottom-hole temperatures.

Lithology	Average Proportion	TOC%	HI	S1/TOC	HI*(S1/TOC)
Coal	8%	68.25	258	0.15	38.7
Carb. Mdst.	19%	8.55	302	0.12	36.2
Sand/silt	73%	-	-	-	-
Average		7.1*	289	0.13	37.6

*A more conservative figure of 4.5% average TOC was actually used in all modelling.

Table 1: Average source-rock properties, based on end-member proportions and compositions.

Reservoir and aquifer pressures

Several direct measurements of reservoir or aquifer pressures were available from wells. The Cretaceous to Palaeocene section in the Western Platform is only slightly overpressured (less than 150psi) and overpressures generally decrease in a southeasterly direction towards the Maui Field (around 60psi).

Shale overpressures

In contrast to the sandy Cretaceous to Palaeocene interval, the overlying Eocene shales exhibit characteristics of being severely overpressured. Qualitative measures of shale overpressures include: drilling mudweight data, shale cuttings density; and "d" exponent measurements. Quantitative measures include those derived from the sonic logs (using a modified approach of Hottman & Johnson, 1965) and from seismic interval velocities (using the approach of Pennebaker, 1968). The derivation of seismic interval velocities for this study is described in a separate paper (Humphris & Ravens, 2000 - *this volume*).

The modelled permeabilities of the Oligocene marls and the Eocene shales were adjusted in order to match these qualitative overpressure measurements (Figure 5).

Fluid-Inclusions and homogenisation temperatures

Oil-filled fluid inclusions in several wells confirmed the presence of migrated oil, though it was not always possible to determine meaningful homogenisation temperatures to constrain migration timing.

The deep oil reservoir in the Maui Field, however, yielded fluid inclusion homogenisation temperatures consistent with oil entrapment dating from end-Miocene times (5.6 MaBP) onwards. The results are shown in Figure 6, together with the modelled temperature history of the reservoir. The Maui Field area has experienced around 350 m of late Pliocene uplift and erosion (Sykes et al., 1992) which is not fully reflected in this basin modelling study. Consequently, the present-day temperature of the reservoir (c. 112^{o}C) might be approximately 12 degrees lower than the maximum temperature attained in the past.

Oils and oil shows

The only proven accumulation to help calibrate the migration timing for the "West of Maui" oil expulsion model is the Maui F-Sands pool. The pinch-out of the F-Sands onto the Maui basement high (shown in Young, 1996 - for example) makes it unlikely these could be charged from the east or northeast – the suggested direction of charge for the Maui C- & D-Sands. New Zealand Oil & Gas Ltd. (Matthews et al., 1998) believe that the Late Cretaceous Rakopi Formation source rocks on the western flank of the Taranaki Basin are in the oil maturation window rather than gas. They, too, suggest that the oil found in the Maui-B "F" sands below the field's gas reservoirs has been sourced from the west and claim to have identified migration fairways from the west at the 'F' sand horizon, but not from the east (Wilkinson, 1999).

Oils or oil shows occur in several wells and in the nearby Maui Field. Oil biomarkers and C^{13} and S^{34} isotopes are consistent with marine-influence in the Late Cretaceous source units of the Western Platform. Oil maturity indices

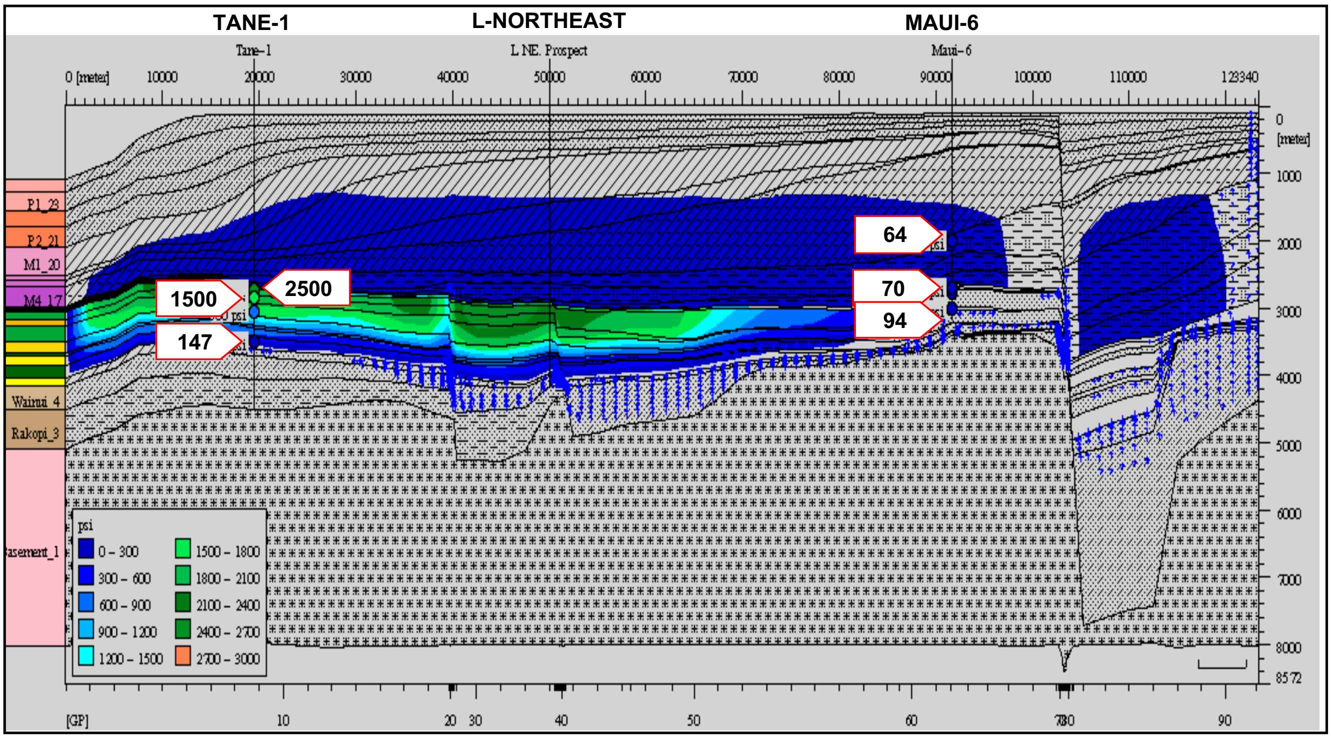

Figure 5: Modelled present-day overpressures (psi) matched to aquifer pressures measured by RFT/FIT tools, and to petrophysically and seismically derived shale overpressures.

also suggest the oils were expelled at maturity levels corresponding with vitrinite reflectance levels of 0.8% - 0.9%, which is consistent with the modelling results.

The model outputs were finally calibrated to all available well and seismic data, and alternative source-rock models were run in order to test the sensitivity to source-rock kinetics.

Model results

The profile discussed in this paper, and shown in Figure 1, runs NW-SE through the Maui oil and gas field, the L-Northeast prospect, and well Tane-1. The purpose of this profile was to illustrate the general effects of sediment loading, overpressures and hydrodynamics on maturation and petroleum migration. The profile does not run through the main kitchen areas, so hydrocarbon generation and charge are underestimated. Originally the profile was extended a further 50 km to the NW into the deepwater part of the basin to investigate possible edge-effects in the model, but these were found to be minimal.

Figure 7 summarises the main features of the basin modelling. The distribution of present-day overpressures is shown by the solid colours. Gas and oil migration vectors are shown as red and green arrows, respectively. Significant

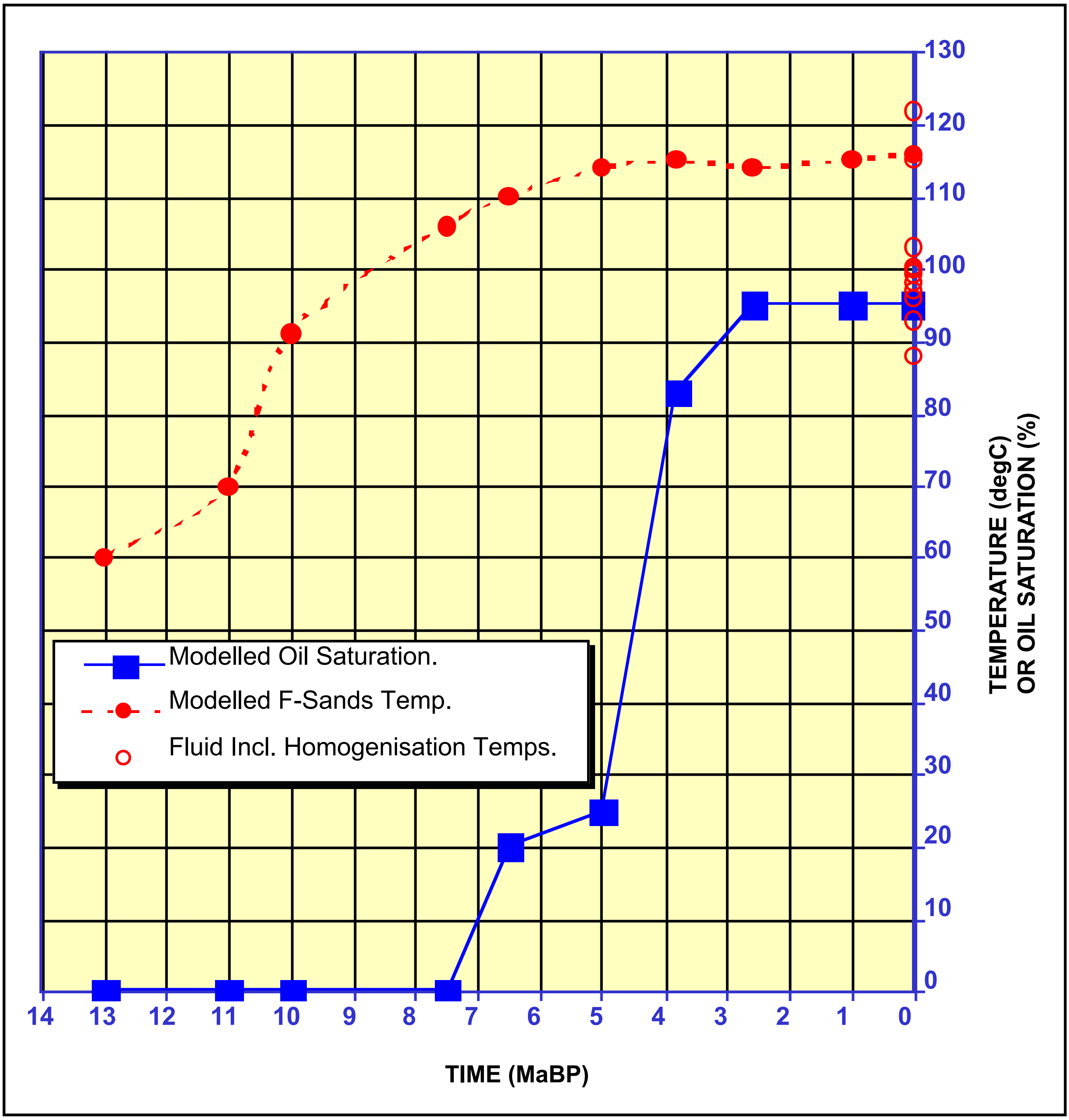

Figure 6: Maui "F-Sands" oil saturation and reservoir temperature modelled through time. Comparison of fluid inclusion homogenisation temperatures (open circles) with predicted reservoir temperatures (closed circles) suggest oil emplacement commenced from c.10 MaBP onwards. Modelled oil saturation (squares) shows emplacement commencing from 7.5 MaBP.

overpressures occur within the Eocene shale interval northwest of Maui but virtually disappear in the Maui area itself due to the thinner Oligocene limestone seal in this area and the more proximal, sandy character of the Eocene interval. The Cape Egmont Fault zone allows vertical leakage of overpressures and creates a potentiometric low in the Maui area. Some minor overpressuring of the Miocene interval also exists throughout the profile, including the area east of the Cape Egmont Fault. The overpressures do not exceed the fracture limit, so hydrocarbons are retained beneath the regional seal except where the Cape Egmont Fault Zone provides an escape zone for some of the hydrocarbons generated from the Maui east kitchen. A prominent gas chimney is seen on seismic in this area and supports the modelling result.

Compaction-related overpressures cause lateral flow of deep groundwaters within the Cretaceous carrier beds. This assists migration from the Tane-east kitchen towards the L-Northeast prospect (where modelled oil charge arrives at 6.5 MaBP), and also from the Maui-west kitchen towards the Maui F-Sands (where oil charge arrives at 2.6 MaBP – though modelled profiles running through the deepest part of the Maui-west kitchen suggest much earlier oil charge). Most hydrocarbons generated from the Maui-east kitchen are modelled to migrate up-dip away from Maui and are assisted by hydrodynamic flow in this direction. Modelled oil saturation at the present day is shown in Figure 7.

Discussion

This study has produced a number of new insights into the maturity and migration behaviour in the Western Platform area. Modelling of 1D pseudo-wells, or 2D profiles through the deepest parts of the kitchens, predicts the onset of oil expulsion to be much earlier than suggested by some earlier studies that only modelled wells located in relatively high structural positions (eg. Killops et al., 1994).

Compositional kinetics show the onset of oil generation from marine-influenced paralic source rocks occurs earlier than from their terrestrial counterparts. This result is consistent with findings from other research on New Zealand source-rocks. Comparisons have been made between the source-rocks of the Taranaki Basin and the Gippsland Basin, Australia (Curry et al., 1994). Johnson & Veevers (1984) suggest the Gippsland and Taranaki Basins occupied similar palaeolatitudes and had similar though opposite palaeogeographic positions with respect to the proto-Tasman Sea, and Ward (1997) notes similarities between their palynofloras. The oil-prone region of the Gippsland Basin contains fields with undersaturated oils of gymnospermous (Late Cretaceous) character and coincides with that part of the basin where the Late Cretaceous source rocks have mixed marine/terrestrial character (Megallaa, 1993). This observation suggests the more distal NW Taranaki Basin could also be more oil prone than the SE part of the basin.

The late burial and inferred late maturation of the Western Platform is partly offset by the development of compaction-disequilibrium overpressured Eocene shales which act as a “thermal blanket”. The undercompacted Eocene shales are 500 m-1500 m thick, though much thinner in the Maui region. Modelling suggests the onset of overpressures developed early in the basin history after as little as 1500 m of burial.

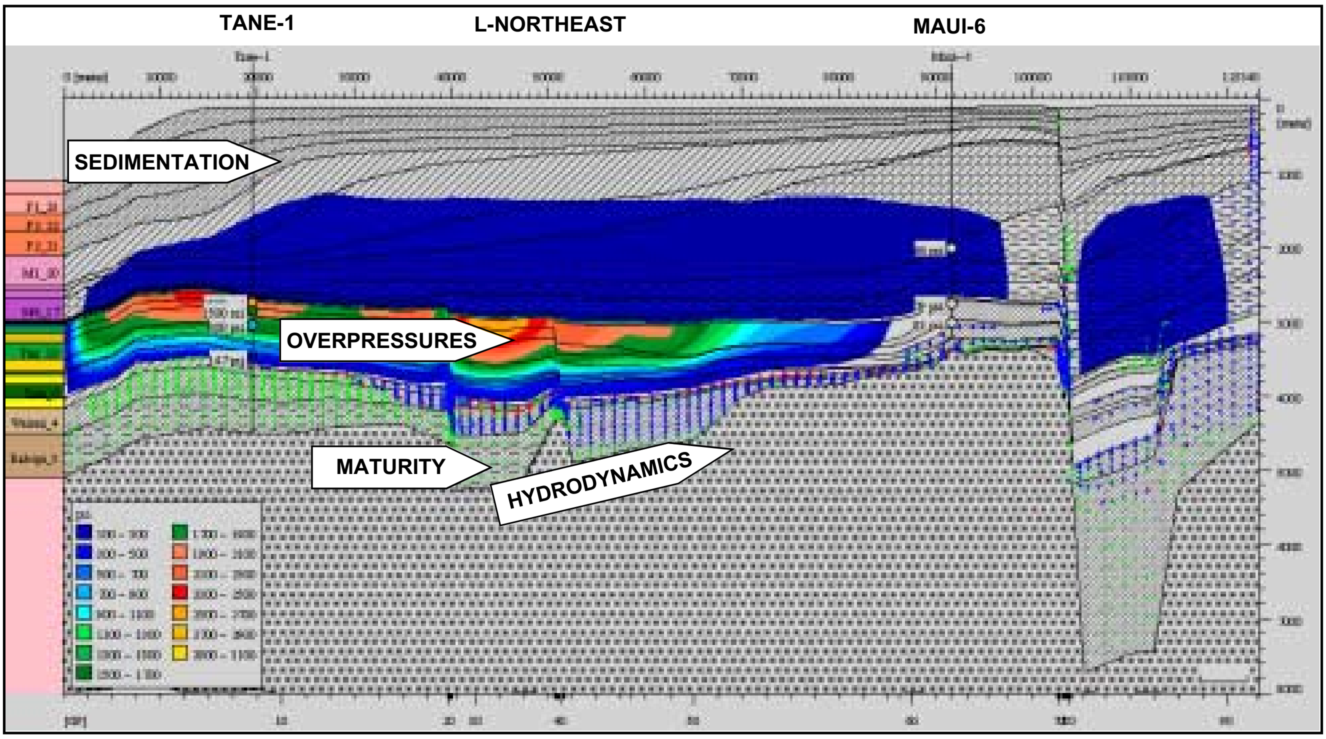

Figure 7: Basin modelling summary. Rapid sedimentation of “Giant Foresets” creates overpressures in Eocene shales beneath regional Oligocene seal. This creates a “thermal blanket” which enhances source-rock maturity. Downward de-watering of overpressured Eocene shales sets up hydrodynamic conditions in the Cretaceous reservoirs which tend to migrate hydrocarbons to the east.

Beneath the Eocene shales, the more sandy Late Cretaceous and Palaeocene intervals are not strongly overpressured and are interpreted to have acted as carrier beds for long distance migration of groundwaters. Hydrodynamic flow in these units is modelled to have had a significant impact on petroleum migration. Only recently is the mechanism and importance of compaction disequilibrium overpressures in the Taranaki Basin becoming understood (Allis et al., 1997). Preliminary modelling of compaction-related fluid-flow by the IGNS (Stagpoole et al., 1998) shows similar results to ours. The IGNS modelling indicates that the deepest sediments achieve a maturity sufficient to generate and expel oil following the deposition of the prograding foresets. Hydrocarbons generated in the Late Miocene initially migrate in a northwesterly direction towards the Western Platform, but with the change in the direction of fluid flow in the late Pliocene, hydrocarbons would then migrate in a southeasterly direction towards the Taranaki Peninsula.

Overpressures in the Eocene shales also complicate the seismic depth conversion (Humphris & Ravens, 2000 - *this volume*).

The overpressures formed beneath a regional seal of Oligocene limestone & marls and have largely prevented vertical migration of hydrocarbons, except up the Cape Egmont Fault Zone. The sandy Late Cretaceous interval is modelled to have experienced strong hydrodynamic flow of compaction-driven groundwaters which assist migration into some prospects, but not others.

Migration out of the kitchens is assisted by hydrodynamic flow of groundwaters in response to sediment loading beneath the prograding “Giant Foresets”. Groundwater flow is predominantly directed towards the east, which inhibits migration into prospects located immediately to the west of down-faulted kitchens.

The Maui-west kitchen is modelled as providing an oil charge to the Maui F-Sands in the Maui-B area, and the timing of this charge appears to agree reasonably well with measured fluid-inclusion homogenisation temperatures. The Maui-west kitchen does not appear to provide any significant charge to the L-Northeast prospect, which is charged from farther west.

The overall conclusion of this study is that several prospects located to the east of the kitchen areas have a high probability of receiving an oil charge. The main remaining uncertainty affecting charge is whether fine-scale stratigraphic discontinuities in the carrier beds, which are necessarily simplified in the modelling, prevent long distance migration. This risk is considered to be small in view that existing fields such as Maui and Kupe prove that long distance migration is possible in the Taranaki Basin.

The basin modelling results have been constrained to give a good match to much of the well and seismic data within the study area. This improves confidence in the modelling results. However, as with any simulation study, the results are not a unique solution, but do give a valuable insight into the likely behaviour of the petroleum system.

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Author

ALEX MCALPINE is founder and Technical Director of Spectrum Exploration Ltd, a company with particular interest in quantitative methods in petroleum exploration, including basin modelling. Alex worked as a geologist with Shell International for 13 years which included assignments in geophysical research and a loan assignment to the U.K. Department of Energy. From 1992 - 1997 he worked with Fletcher Challenge Energy Taranaki Ltd on a number of development and exploration projects. Alex holds a PhD from the University of Newcastle Upon Tyne in the United Kingdom.