Geopressures and Hydrocarbon Generation and Migration Onshore Taranaki

The onshore Taranaki oil and gas fields have been sourced from Paleocene to Eocene fluvio-deltaic coal measure sequences of the Mangahewa and Kaimiro formations. The source sequences lie within regionally continuous, stacked overpressured cells. Migration of the hydrocarbons into stratigraphically-equivalent, and younger, reservoirs is likely to be controlled largely by pressure gradients and episodic breakout along major faults. Definition of the pressure seal using petrophysical data provides a possible predictive technique for determining the likely stratigraphic and areal distribution of oil and gas.

This article has been prepared by Mark Webster of Fletcher Challenge Petroleum Inc. and Stephen Adams of Petrophysical Solutionz Ltd and was presented at the 1996 New Zealand Petroleum Conference.

Introduction

Taranaki crude oils are low sulphur, high wax, 35–44½API gravity oils characterised by high pour points (15–36½C). Numerous geochemical studies (Thompson 1982, Czochanska et al 1988, Johnston et al 1988, 1990, 1991, Cook 1988, Collier & Johnston 1991, Killops et al 1994 amongst others) have established a correlation between the oils and condensates found in the basin and the coal measures of the Kapuni and Pakawau Groups. Notable exceptions are the oils and extracts found in Kora and Tangaroa-1, which are interpreted to have been sourced from a Paleocene marine shale, equivalent to the Waipawa Shale in the East Coast Basin (Reed 1992, Murray et al 1994, Killops et al 1994). Although it has been well established that most Taranaki oils are sourced from coals and non-marine shales, there is still some uncertainty about the level of thermal maturity required for generation and expulsion of hydrocarbons from these sediments.

Waihapa-1, and subsequent sidetracks -1A and -1B, penetrated the thickest Mangahewa Formation coal measure sequence encountered onshore to date and therefore provide an optimum intersection to analyse the potential yield of shales and coals within the Kapuni Group and the level of maturity required for generation and expulsion. The source units lie within an overpressured compartment that extends throughout much of the Eastern Mobile Belt of Taranaki Basin. This paper presents geochemical data from Waihapa-1 (Figure 1) and an assessment of the likely causes of overpressuring and the role that geopressures play in hydrocarbon generation and migration.

Waihapa-1 was drilled in 1985 to test the Kapuni Group sandstones within an overthrust structure at the southern end of the Tarata Thrust Belt (Lock et al 1986). As a result of drilling problems the well was abandoned at 4477 m and sidetracked from 4294 m (Figure 2). The sidetrack, Waihapa-1A, encountered gas-bearing sands below 4890 m which were tentatively identified as Kaimiro Formation on the basis of a lithostratigraphic correlation with offset wells. These sands were tested in an open-hole DST at rates of up to 4 MMSCFD. The test string became stuck during the test and a second sidetrack, Waihapa-1B, was drilled from 4819 m to a depth of 5087 m. This well failed to flow hydrocarbons from the Kaimiro Formation in a cased hole test and the well was suspended until 1988, when the Tikorangi Limestone was tested and the Waihapa oil field discovered. The Waihapa wells penetrated approximately 195 m of coal and 380 m of carbonaceous shale within the Kapuni Group.

Source Quality and Facies

Geochemical analyses were performed on a suite of cuttings samples from Waihapa-1, -1A, and -1B, and a sample of oil from the overlying Tikorangi Limestone reservoir in the Waihapa Field. Twenty nine cuttings samples from between 4030 m and 5085 m were selected from Waihapa-1, -1A and -1B. The cuttings samples were hand-picked to differentiate

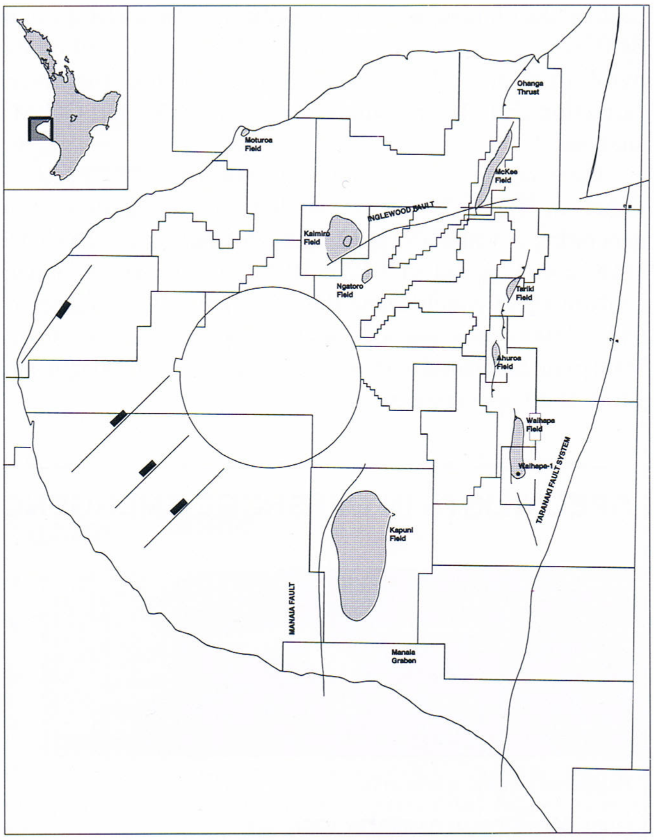

Figure 1: Location map onshore Taranaki Basin fields and structural elements.

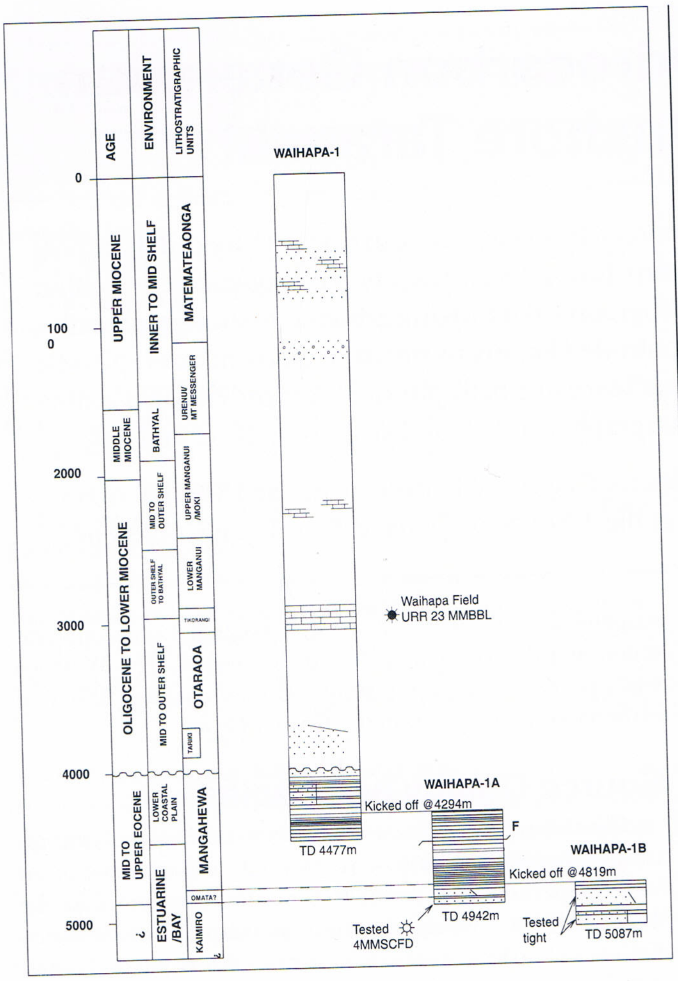

Figure 2: Waihapa-1, -1A, -1B well summaries.

coal and shale lithologies and screened using TOC and Rock-eval pyrolysis; results are summarised as Figure 3. Based on the pyrolysis results, selected samples were submitted for solvent extraction and chromatography, pyrolysis-GC and GC-MS analyses.

The geochemical screening data indicate that the coals are richer in TOC (29–88%) and have higher hydrocarbon generating potential (S1 + S2 = 84–259 mg/g) than the shales (TOC = 4–31% and S1 + S2 = 10–88 mg/g). Extraction data confirm these conclusions; the coals have EOM values of 9444–25000 ppm and total hydrocarbon extracts of 3600–7000 ppm, compared to shale values of 3450–20 100 ppm and 1400–6800 ppm respectively.

The coals and shales plot in a similar position on a modified van Krevelen diagram (Figure 4), with the coals being apparently more oil-prone (HI = 229–348) than the shales (HI = 189–312). High saturates contents (978–4308 ppm in coals and 1072–3956 ppm in shales) indicate excellent liquids potential for both lithologies (Figure 5). This is confirmed by pyrolysis gas-chromatography data which indicate that between 6 and 15% of the hydrocarbon generating potential in the coals consist of C_{15}–C_{31} alkanes and alkenes, and that these compounds constitute 6–8% of the S2 peak in shales; a cutoff of 5% is generally used to discriminate liquids prone source rocks (Geotech pers comm.)

The kerogens comprise predominantly vitrinite in both coals (87–96%) and shales (89–97.5%). Liptinite comprises 3–8% of the coals and 2–6% of shales. The vitrinite comprises detrovitrinite (70–90% of vitrinite in coals and 60–90% in shales) and telovitrinite. Detrovitrinite and telovitrinite are derived from humus but contain higher plant as well as

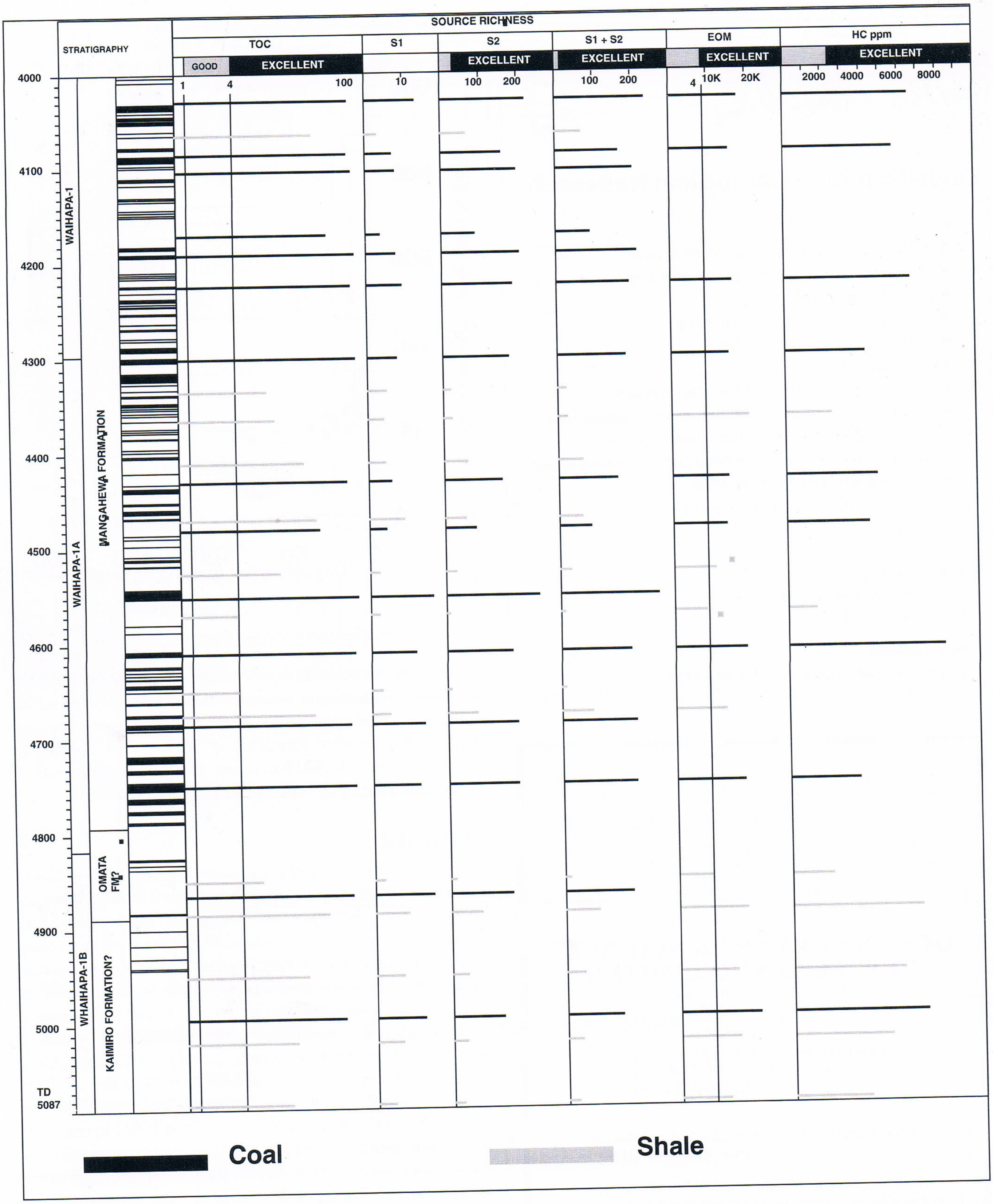

Figure 3: Composite geochemical log, Waihapa-1, -1A, -1B showing source richness parameters.

bacterial and fungal lipids. It is likely that the liptinite, detrovitrinite and telovitrinite all contribute to the high liquids potential of the sediments.

Pristane/phytane ratios of 4.5–14 in the source rocks indicate an oxidising environment of deposition and show a general increasing trend upsection, indicating increasingly oxic peat-swamp conditions (Figure 6). Waihapa crude has a Pr/Ph ratio = 8.13, consistent with an oxidising source environment. There is a strong correlation in sterane and triterpane biomarker distributions between the Mangahewa Formation samples and the oil found in the shallower Tikorangi reservoir. Both show a predominance of C_{29} steranes over C_{27} steranes, confirming input from terrestrial higher plants. Oleanane is also present in the sediments and in the oil, reflecting input of higher plant matter in the form of angiosperm debris.

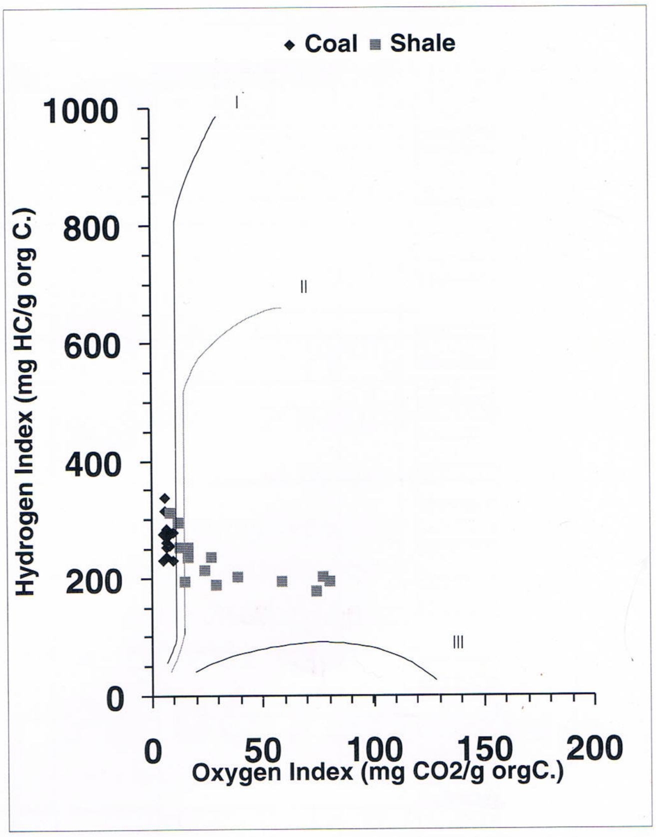

Figure 4: Modified van Krevelen diagram, Waihapa-1,-1A,-1B.

The geochemical data from Waihapa-1 indicate that the oil in the Tikorangi Formation was sourced from the coals and shales of the Mangahewa Formation. The wet gas produced from the sands in the Kaimiro formation in Waihapa-1A appears to have been sourced from Paleocene non-marine sediments of the Kaimiro/Farewell Formations (Killops et al 1994).

Maturity

Biomarker ratios, and particularly the ratios of the 20S to 20R isomer of the C_{27}–C_{29} steranes and the 22S to 22R isomer of the C_{31}–C_{35} hopanes, are commonly used as maturity indicators in oils and source rocks. These ratios are at, or close to, equilibrium point for most Taranaki oils and condensates, suggesting they were generated at similar levels of maturity (Czochanska 1988), but are invariably lower in the source rocks penetrated in wells. The same relationship is evident in Waihapa, where the deepest sample analysed (5020 m) has a C_{29} 20S/20R ratio of 0.7, compared to 0.79 in the oil. This disparity has led many previous authors (Cook 1988, Johnston et al 1988, 1990, 1991, Collier & Johnston 1991) to conclude that mature source rocks have not been penetrated in even the deepest wells and that maturity levels of $R_o = 0.9\%$, equivalent to maximum burial depths in excess of 6 km, are required for expulsion of oil from the Kapuni Group coals.

Pyrolysis data from Waihapa indicate that the coals and shales within the Mangahewa Formation contain high levels of free hydrocarbons, with S1 ranges of 4–16 mg/g and 2–9 mg/g respectively. The GC traces of saturates fractions of coal extracts (Figure 7) exhibit rapid and progressive maturity with depth. The sample at 4030 m exhibits a Pr/nC_{17} ratio of 6.27; this decreases with depth and the sample at 4430 m = 1.49; this trace is more characteristic of Waihapa crude (Figure 8) with a heavy-end bias in the *n*-alkane distribution and a Pr/nC_{17} ratio

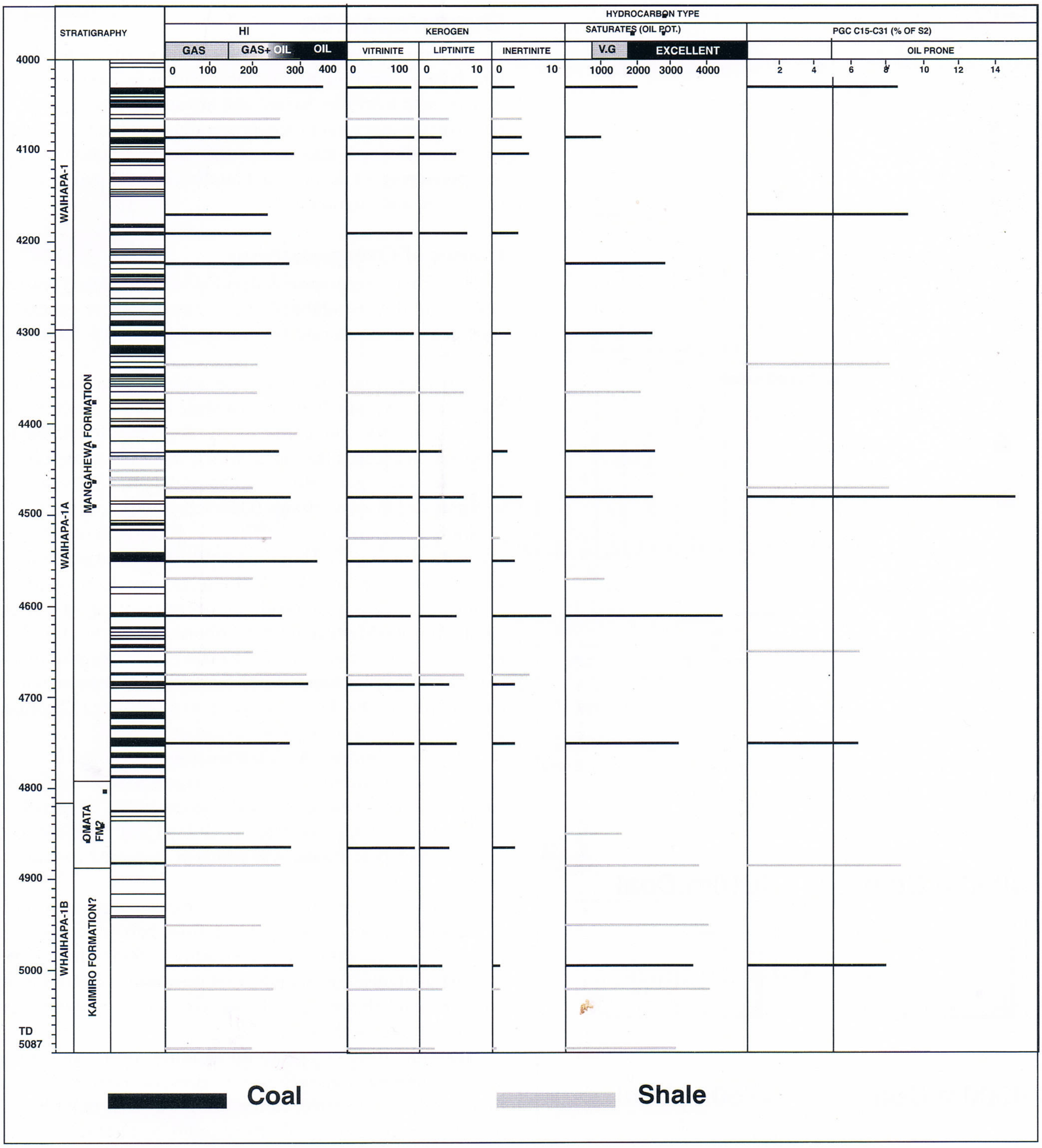

Figure 5: Composite geochemical log, Waihapa-1, -1A, -1B showing hydrocarbon type parameters.

of 1.08. The trace from 4995 m shows a light-end bias in the *n*-alkane distribution, suggesting cracking of the longer chain molecules, consistent with the wet gas tested in Waihapa-1A. T_{max} values in the Kapuni Group range from 423–449 ½C.

Figure 9 illustrates the vitrinite reflectance profile for Waihapa-1. An offset is evident at the top Kapuni unconformity; this is possibly due either to different kerogen macerals in the non-marine and marine sequences, or a real offset in maturity above and below the unconformity. R_o ranges from 0.56% at the top of the Kapuni Group to 0.9% at 4995 m. The best geochemical correlation with the Tikorangi oil, on the basis of biomarker distributions and overall character, is with a coal at 4430 m, which has an $R_o = 0.78\%$.

The data from Waihapa-1 suggest that maturity levels equivalent to $R_o = 0.75–0.8\%$ are sufficient for generation and expulsion and that the onset of generation occurs rapidly. This is in agreement with Killops et al (1994), who concluded that expulsion from coals occurs at maturity levels of $R_o = 0.8\%$. Primary migration of oil from coals is likely to be aided by the generation of large volumes of carbon dioxide (Killops et al 1994) and the development of extensive microfracture networks, which develop preferentially in vitrinite-rich coals (Paterson et al 1992).

The contrast in maturity from biomarker ratios could be due to delayed sterane isomerisation in coals (Grantham 1986) or fractionation as hydrocarbons are expelled from the source rock.

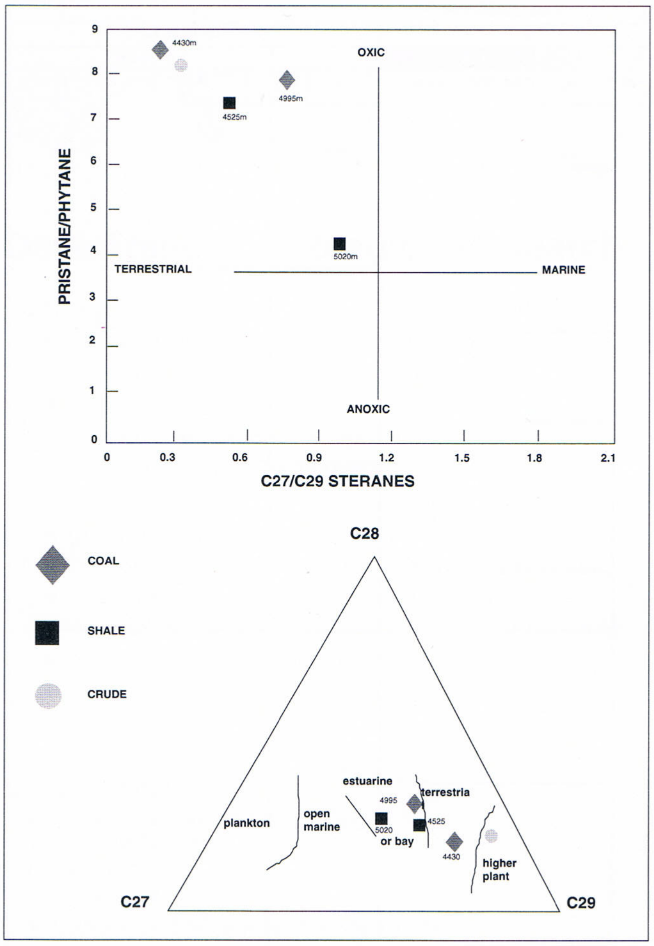

Figure 6: Waihapa-1, -1A, -1B source rock depositional environments inferred from biomarker data.

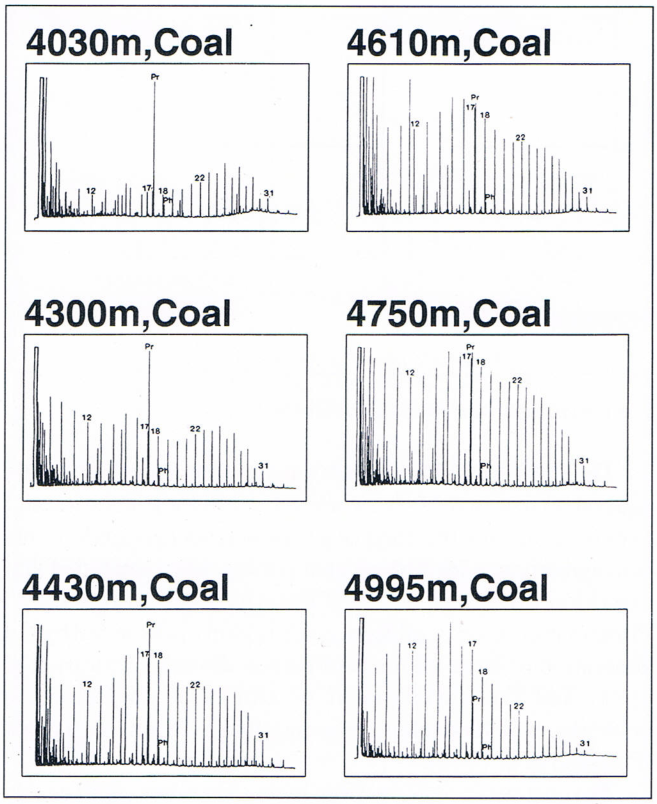

Figure 7: Waihapa-1, -1A, -1B coal C_{12+} chromatograms, saturates fraction.

Overpressures

Abnormally high formation pressures (overpressures) have long been recognised in Taranaki Basin, principally because they present a drilling hazard and are an important factor in reservoir management in deeper producing fields. Little study has been directed into the causes or distribution of the overpressuring, or the potential implications for hydrocarbon generation and migration.

Causes of Overpressuring

Abnormal overpressures develop in sedimentary basins when fluid flow is inhibited or prevented, and are generally considered to be caused by one or more of the following phenomenon:

Disequilibrium compaction (or undercompaction): This occurs in thick, rapidly deposited shale sequences where the rate of porosity and permeability degradation related to compaction exceeds the rate at which water can escape from the shale, and is generally regarded as the principal cause of overpressure in many basins (Gaarnenstroom et al 1993).

Kerogen transformation (hydrocarbon generation and cracking of oil to gas): The process of hydrocarbon generation, and the subsequent cracking of oil to gas, results in net fluid volume increases that result in overpressuring in sealed compartments (Martinsen 1994, Osborne & Swarbrick 1995). Hydrocarbon generation also reduces the relative permeabilities to water and to petroleum, thereby creating effective seals and contributing to the development of overpressure (Chapman 1994, Iverson et al 1994, MacGowan et al 1994).

Clay dehydration: At a temperature of about 105 ½C, smectite begins altering to illite and expels a large volume of structural water in the process (Martinsen 1994). If the rock is sealed, this volume increase, combined with the thermal expansion of pore fluids, will result in increased formation pressure.

Aquathermal expansion: Water expands when heated and, if prevented from escaping by a flow barrier, causes an increase in pressure (Osborne & Swarbrick 1995). The volume expansion involved in aquathermal pressuring is very small, however, and this process is not considered a significant overpressuring mechanism.

Tectonic forces: Tectonic compression can cause overpressures by exerting horizontal stress on sediments where fluid escape is inhibited, in the same way that rapid burial imposes vertical stress. Tectonic uplift is another possible mechanism by which overpressures can develop, if internal pressures are preserved within the uplifted sequence. Tectonic uplift is not regarded as a common mechanism for overpressuring, as uplift and erosion removes the hydrostatic and lithostatic load acting on a formation and also results in a temperature, and hence pressure, decrease; tectonic uplift more commonly results in underpressuring (Powley 1990).

Osmosis: The mass transfer of waters with different salinities across a semi permeable membrane can cause abnormally high pressures in isolated zones (Martinsen 1994), although pressure differences across shale membranes are likely to be small (Osborne & Swarbrick 1995).

Topographically induced: The hydraulic head resulting from elevation of a water table in highland regions exerts a pressure in the subsurface if the aquifer is overlain by a seal. Such a process is apparent in the onshore Taranaki basin as a

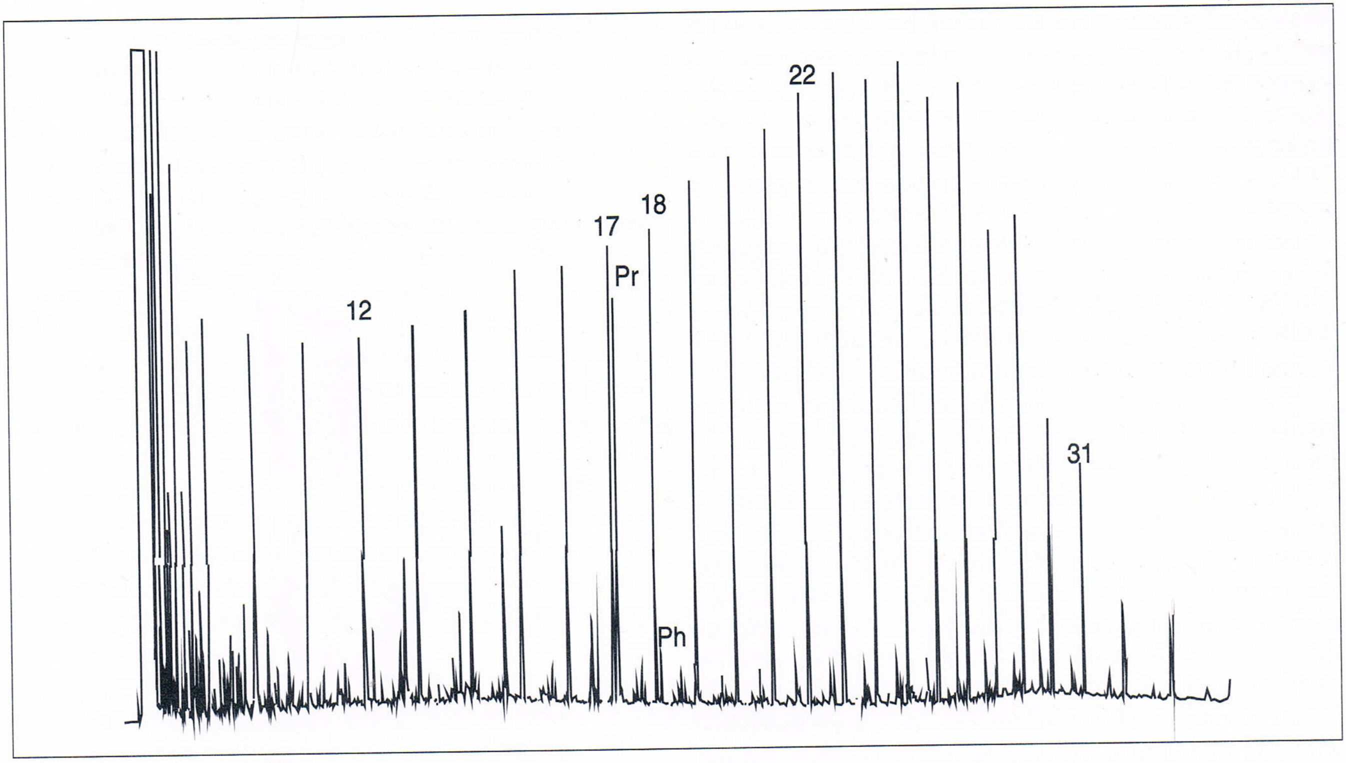

Figure 8: Waihapa Crude, C_{12+} GLC saturates fraction.

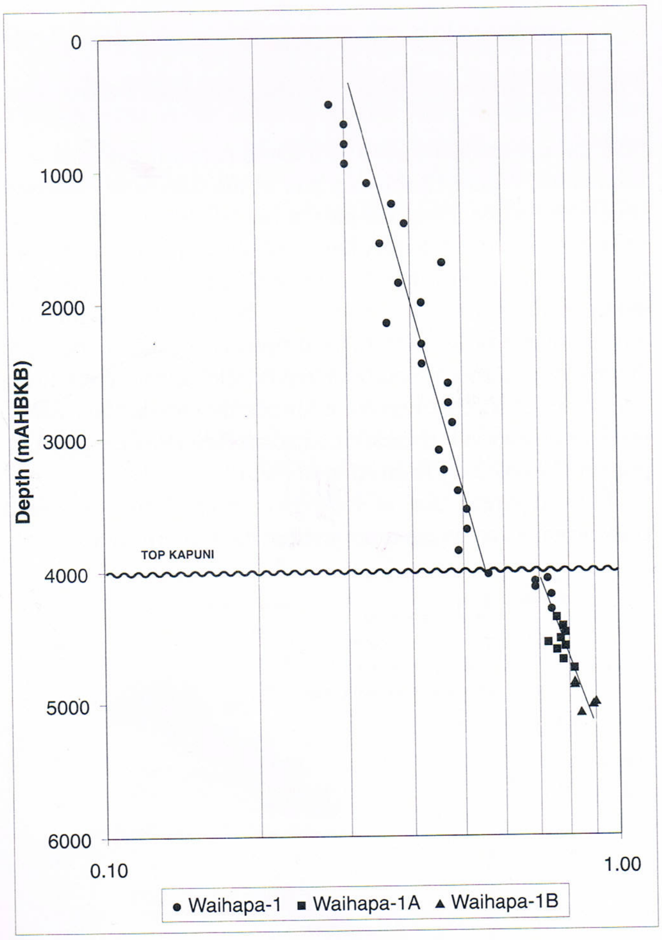

Figure 9: Waihapa-1,-1A,-1B vitrinite reflectance data.

result of the groundwater flow patterns generated by Mt Taranaki (Allis et al in press).

Disequilibrium compaction, kerogen transformation and hydraulic head are generally considered the main causes of overpressuring (Martinsen 1994, Osborne & Swarbrick 1995).

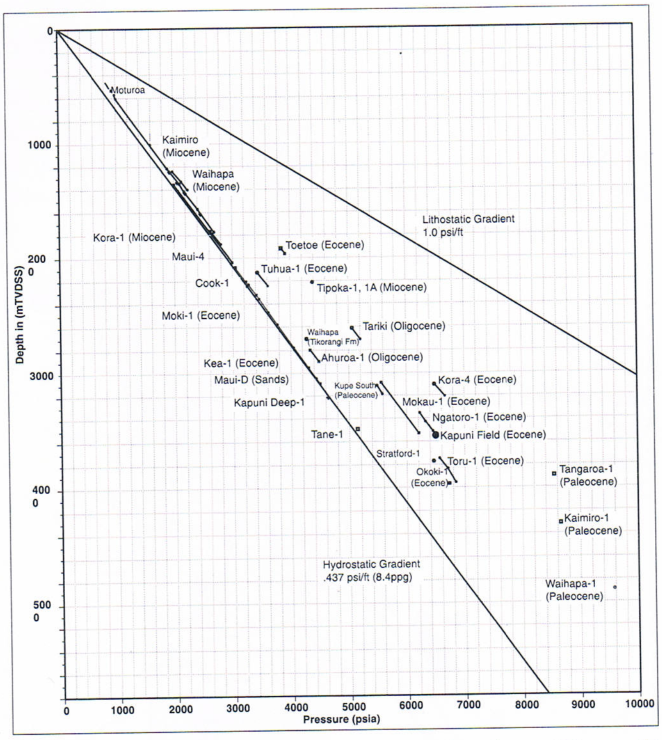

Figure 10: Original formation pressures in selected Taranaki Basin wells.

Distribution of Overpressures in Taranaki

Overpressures are most accurately defined by direct pressure measurements in permeable units. Figure 10 shows original reservoir pressures from RFT and DST data from a selection of Taranaki Basin wells. A hydrostatic gradient of 0.437 psi/ft, equivalent to a fluid with density of 8.4 ppg, and a lithostatic gradient of 1 psi/ft are displayed for reference. All data are referenced to a sea level datum. Several trends are evident: wells on the Western Platform, including Maui Field, and in the Southern Inversion Zone, all plot on a normal pressure gradient.

Three overpressure trends are evident for other wells in the eastern Mobile Belt: the first is a relatively small degree of overpressure in shallow reservoirs onshore, caused by topographic effects (Allis et al in press) or, in some cases, depleted overpressures. The second trend exhibits overpressures of up to 1100 psi relative to the hydrostatic gradient and includes deep reservoirs at Kapuni, Kupe South, Kaimiro, the Mangahewa Formation in McKee, Tariki sands in Tariki Field, Miocene sands in Tipoka-1 and Eocene reservoirs in the North Taranaki Graben at Okoki-1 and Mokau-1. The third trend, with overpressures of 2200+ psi, has been encountered in Paleocene sands at Waihapa-1A and Kaimiro-1 and offshore at Tangaroa-1 and Kora.

The top of overpressuring is not consistent with one stratigraphic boundary or a consistent depth. Figure 11 illustrates the areal extent of the overpressured compartment.

Wireline logs can be used as indirect indicators of overpressure. The most common methods used are shale resistivity and transit time, plotted on log scales against depth. Such a plot for Ahuroa-1 is shown as Figure 12, with only the data for shale and silt intervals displayed. The plot indicates that the onset of overpressuring occurs at ~2250 m, at the top of the Otaraoa Formation.

The occurrence of overpressures is more clearly understood if the data from each log type are used to estimate a shale porosity. A normal compaction trend (Armstrong et al 1994) can then be fitted through the data to assist with determination of overpressured formations. Figure 13 shows a plot of the data from Ahuroa-1 using this format. From the plot, it can be clearly seen that the resistivity, sonic and density logs are consistent and confirm that the onset of overpressuring occurs near 2250 m. The equivalent depth method (Bigelow 1994a) can be used to quantify the amount of overpressure from the difference in porosity between the observed and normal porosity trends. Although overpressuring is indicated by wireline log data at Ahuroa, the measured formation pressures are not as high as in the adjacent Tariki Field, suggesting pressure has bled off from Ahuroa Field.

It is apparent that at least two stacked overpressured compartments are present throughout the Eastern Mobile Belt,

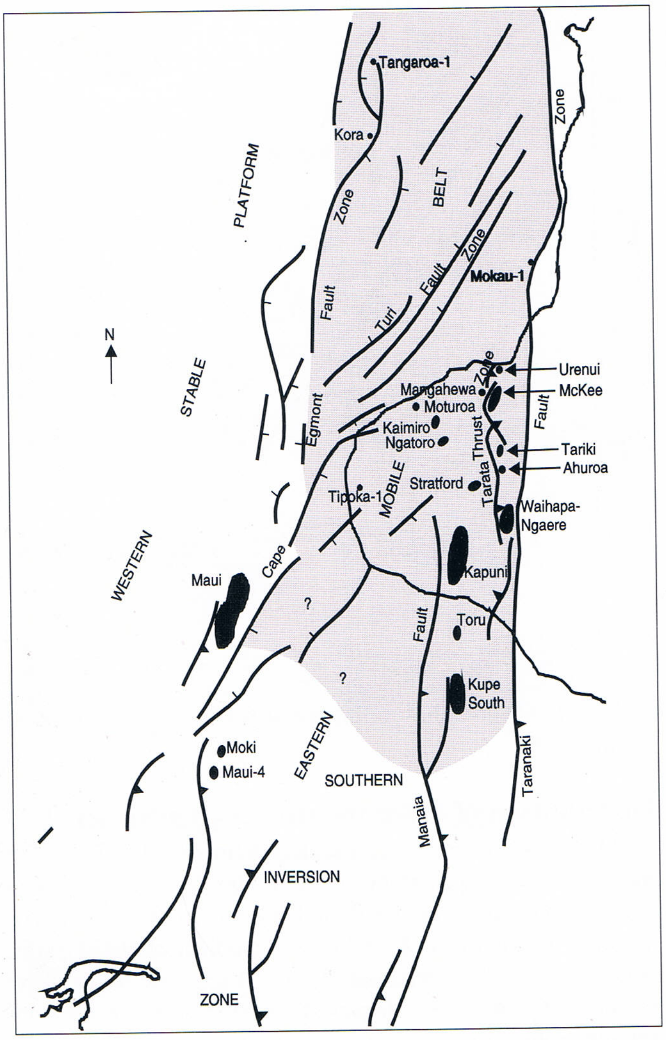

Figure 11: Taranaki Basin — structural features, fields and distribution of overpressures.

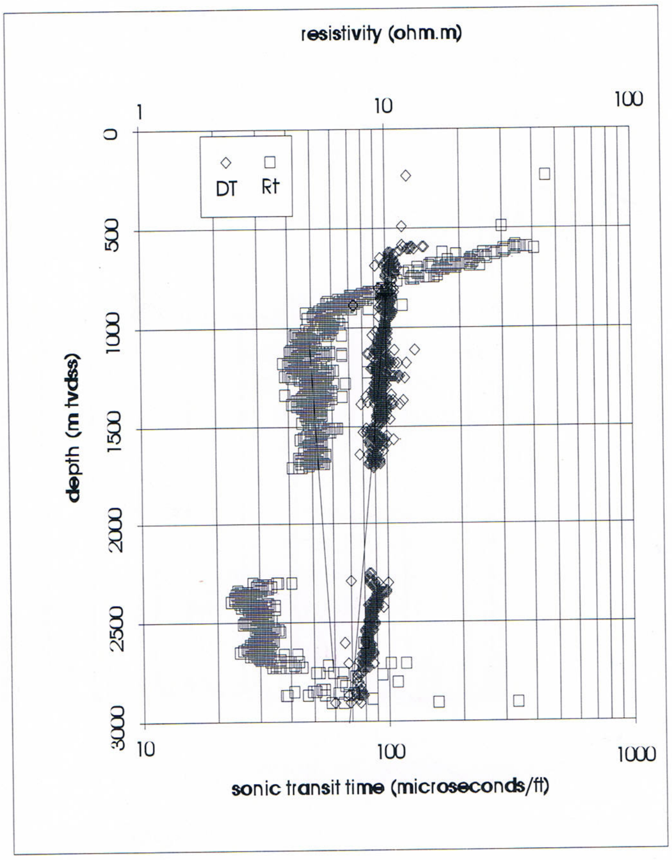

Figure 12: Ahuroa-1 shale resistivity and sonic transit times.

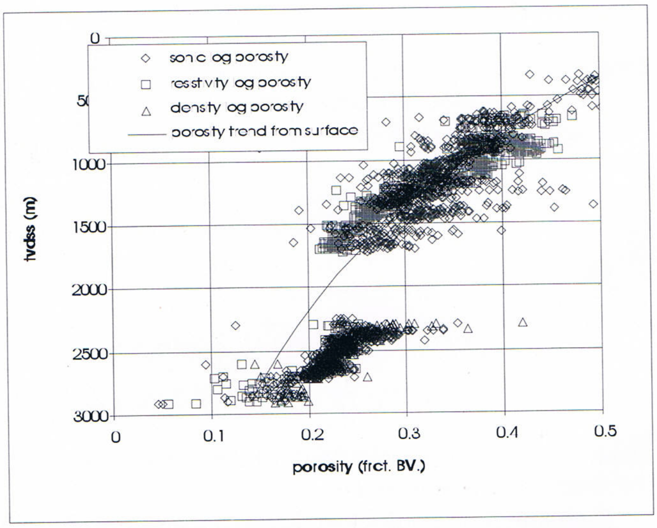

Figure 13: Ahuroa-1, shale porosity and overpressure detection from wireline logs

north of and including Kupe South. The overpressure cells correlate with areas of hydrocarbon generation from either Cretaceous and/or Paleocene to Eocene coal measures and, in the North Taranaki Graben, a Paleocene marine shale. Hydrocarbon generation and conversion of oil to gas are considered the likely cause of the overpressure, although undercompaction resulting from rapid Pliocene sedimentation may also be a contributing factor in some areas of the basin. The hydraulic seals separating pressure cells are most likely to develop with the onset of hydrocarbon generation, when lithologies that were previously permeable to single phase fluid flow (water) become impermeable to dual phase fluid flow (water plus hydrocarbons), due to relative permeability effects. Stacked cells would therefore be expected in basins such as Taranaki where multiple, stacked source units are present that have sequentially entered the generation window. Recent tectonic uplift onshore Taranaki (Allis et al in press) appears to have elevated the top of the upper overpressured cell and in some areas, such as Tariki Field, allowed overpressures to migrate up from the Kapuni Group, where they originated, into shallower reservoirs.

Similar examples of regionally extensive and stacked overpressure compartments have been documented in numerous sedimentary basins worldwide (Bigelow 1994b, Bradley & Powley 1994).

Role of geopressure in migration

As the mature source rocks lie within the overpressured compartments in the Eastern Mobile Belt, migration of the hydrocarbons into stratigraphically-equivalent, and younger, reservoirs is likely to be controlled largely by pressure gradients and episodic breakout, either along major faults, which would act as pressure release valves (Sibson 1992), or through ruptured seals when formation pressures exceed the fracture pressure of the seal. Significant discoveries to date in the Eastern Mobile Belt have been associated with reverse faults (Figure 11).

In the Norwegian Central Graben the largest hydrocarbon accumulations are found in the first reservoir overlying or updip of the transition zone between the second and third pressure compartments in the basin (Leonard 1993). Similarly, in the Tertiary sands of the Louisiana Gulf Coast (Leach 1994) the major oil reserves are in reservoirs overlying the pressure seal, while gas reserves are symmetrically distributed around the pressure transition. A similar distribution of in place volumes is evident in the Eastern Mobile Belt of Taranaki Basin (Figure 14), suggesting oil pools accumulate in reservoirs above the seal as the result of episodic charge.

Conclusions

Geochemical data from Waihapa-1 indicate that the Eocene coal measures of the Mangahewa Formation are actively generating oil and gas at Waihapa and are the source of the oil found in the Tikorangi limestone reservoir. Coals are richer in TOC, have higher generative potential and are more liquids-prone than shales. Data from Waihapa indicate that the onset of generation and expulsion occurs rapidly at thermal maturity levels equivalent to vitrinite reflectance of 0.75–0.8%; Waihapa-1A penetrated the entire oil window and tested in situ gas from within the gas window, in the Kaimiro Formation.

The source sequences lie within regionally continuous, stacked overpressured compartments, which develop when the rate of pressure generation exceeds the rate of diffusion through seals. The coincidence of overpressured areas and active hydrocarbon generation strongly suggests that generation is the main cause of overpressuring; the top of the overpressured cells have been uplifted, and in places breached, in onshore areas as the result of recent tectonic uplift.

Migration of hydrocarbons from the source units within the overpressured compartments into overlying reservoirs is likely to be an episodic process and to occur via faults and fractured seals.

Integrated analysis of pressure data and wireline logs provide a means of identifying preferential migration pathways and discriminating oil and gas prospects in exploration.

Acknowledgment

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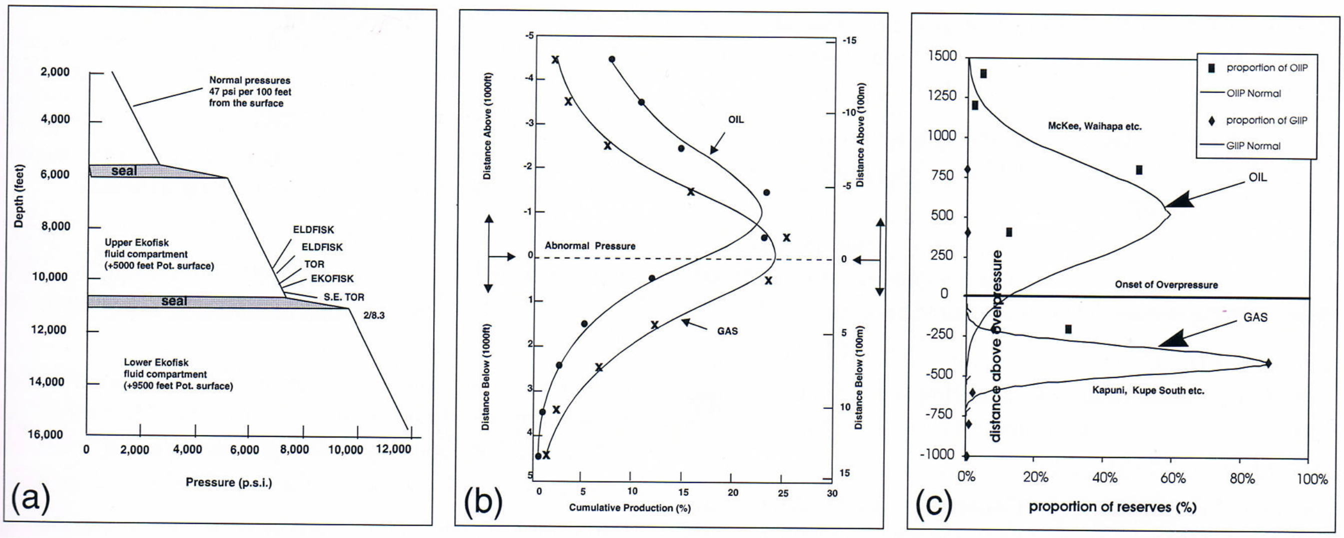

Figure 14: Reserves distribution relative to pressure seals in (a) Central Graben of the North Sea (from Hunt 1990), (b) Louisiana Gulf Coast (from Leach 1994, based on oil production from 25,204 wells), and (c) Eastern Mobile Belt of Taranaki Basin (excludes Maui & Moki).

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