Preliminary results of exploration in the onshore Canterbury Basin

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Abstract

The Canterbury Plains cover the onshore portion of a large but lightly explored late Mesozoic/Cenozoic basin. The onshore area has all the prerequisites for hydrocarbon discovery, in the form of excellent reservoirs, good seals and source rocks. However, until the grant of PEP 38256 in mid 1997, there had been no exploration since the mid 1980s, and no modern exploration seismic had ever been acquired in the onshore area. None of the five onshore wells had been placed on a valid structure, while two out of four offshore wells were hydrocarbon discoveries.

Since 1997, three separate vibroseis surveys have established a high quality seismo-stratigraphic and structural framework for the onshore area. Several structural prospects and leads have been identified, and outcrop and laboratory studies have identified excellent Eocene and Miocene reservoirs, and potential source rocks in Late Jurassic and Cretaceous sediments.

The main focus has been on structures adjacent to areas where prominent gravity ‘lows’ and a thick reflective seismic section beneath a regional Late Cretaceous unconformity, indicate that source is most likely to be present and generative. In the south near the Rangitata River, a large fault bounded closure has been mapped on the south flank of the Hinds Trough. In the north, adjacent to the Rangiora Trough, high relief pop-up structures on transcurrent fault splays from the Alpine Fault have been mapped as closed structural traps, with the Arcadia structure having surface expression and covering some 30 sq km. The onshore basin is now mature for drilling, which is planned for later in 2000.

Introduction

The Canterbury Plains cover an area of approximately 12,000 sq km, which comprises about a quarter of the total area of the onshore/offshore Canterbury Basin (Figure 1). Both onshore and offshore areas of this large Late Mesozoic/ Cenozoic basin remain very lightly explored; despite the obvious presence of hydrocarbons, as demonstrated by the gas-condensate test flows and RFT recoveries at the offshore Galleon-1 and Clipper-1 wells (BPST 1984 & 1986) This lack of interest probably relates to the early refocussing of exploration attention to the Taranaki Basin, following the commencement of the modern exploration era in the 1950s. In addition, the thick (~500 m) cover of Quaternary outwash gravels, eroded from the rapidly rising Southern Alps to the west, have built out the plains eastwards across the underlying sedimentary basin, concealing the geology.

The Canterbury Plains, however, offer an excellent setting in which to conduct an exploration campaign. The generally flat and open terrain, and the extensive network of roads, provide the means to acquire good quality seismic data in a very cost effective manner. These logistic advantages also extend to drilling, and to the ease and economics of development including pipelining. The city of Christchurch, with a population of 320,000, offers a nearby market for gas, especially given its air pollution problems; while the major port of Lyttelton provides a convenient means of oil export. The local forestry industry is also a potentially large market for gas for use in timber processing.

Exploration history

Exploration dates back to 1917, when the Chertsey-1 well was drilled through the base of the gravels and reported globules of oil beneath the underlying mudstones. Samples of these were reported as lodged at the Canterbury Museum, and a recent search found the original sample bottles in the old oil collection, but having only a residual petroliferous

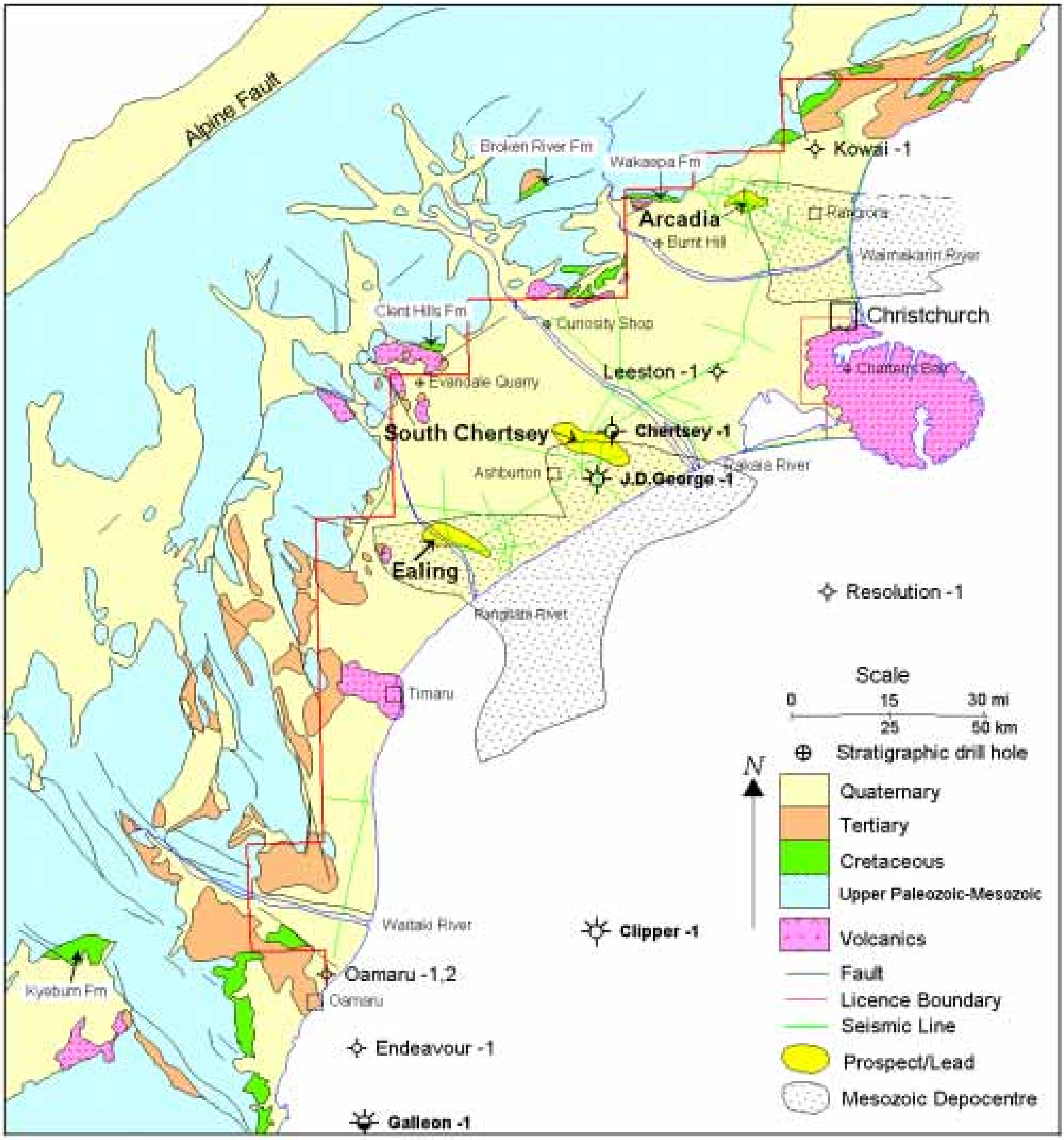

Figure 1: Location of Canterbury Basin with main geological features, wells, leads, seismic lines and outline of onshore permit PEP 38256.

odour. The Oamaru-1&2 wells, drilled by a diviner in the 1950s, provided little useful information.

The modern exploration era commenced in the late 1950s when the BP-Shell-Todd consortium (Haw 1961) collected a total of 336 km of single fold dynamite seismic by 1963 (Kirkaldy & Thomas 1963). These reconnaissance data were of generally poor quality, and neither of the subsequent 1969 wells at Leeston-1, TD 1159 mBKB (Wood 1969a) and J. D. George-1, TD 1650 mBKB (Wood 1969b) can be considered to have been drilled in a structurally proven setting (modern seismic indicates they were not). Leeston-1 encountered Late Cretaceous coal measures above Torlesse basement, while J.D. George-1 bottomed in Late Cretaceous volcanics (Mt Somers), with minor methane shows in the overlying basal Miocene. Bounty Oil acquired 86 km of seismic near Oamaru in 1970; while AAR in the mid 1970s (Brown 1975) and Cue Energy in the early 1980s, completed geological reviews without acquiring new seismic or drilling data (GGS 1981). The Kowai-1 well (Hoolihan 1978) was drilled to 1419 mBKB, significantly off structure on a surface anticline (Katz 1982), and encountered a Late Cretaceous section with good quality reservoir and source rocks lying on Mesozoic metasediments at TD.

The extensive gravity coverage has been modelled (Hicks 1989, Brown 1975) to demonstrate the existence of substantial sedimentary "deeps'' beneath the plains; as also indicated by research magnetotelluric data in the Rakaia River area (Ingham 1995). In the deep crust/upper mantle SIGHT seismic experiment, which placed shot and receiver points along the Rangitata River and across the South Island (Davey et al. 1995, Taylor 1997), seismic reflection events are clearly visible around 3 seconds, particularly on data from SP3, between Ealing and Carew; also indicating deep sedimentary section. Teleseism studies from the same SIGHT experiment indicate significant thickening of the sedimentary section beneath the plains in this same area (Stern et al., 2000 in press).

Exploration post 1997 has been conducted under the present Petroleum Exploration Permit PEP 38256. This has principally consisted of three separate vibroseis seismic surveys totalling 667 km, the most recent of which was acquired in March 2000. Field sampling has also been conducted on various outlying sections exposed in the adjacent foothills northwest of the range front fault system, together with laboratory analyses for source and reservoir potential; and the gravity data base has been augmented with additional observations.

Regional geology

The Canterbury Basin is one of series of sedimentary basins which developed during the mid-Cretaceous as part of the fragmentation of eastern Gondwana (Field & Browne 1989, Laird 1993) Prior to breakup, the Australasian margin had been a convergent plate boundary, with westward subduction of the Phoenix Plate along an extensive trench system which accumulated a great (c.20 km) thickness of Permian to Late Jurassic sediments (Balance 1992). The folding, uplift and erosion of this trench sequence during the Rangitata Orogeny created metasediments of the Torlesse which constituted basement for subsequent basin formation.

Throughout most of its vast thickness and age range the Torlesse is composed of a monotonous series of interbedded mud-rich sandstone turbidites (greywacke) and claystones (argillites) which have been folded and metamorphosed to low-grade zeolite or prehnite/pumpellyite facies (NZGS 1978). The maximum degree of metemorphism is attained however in the west adjacent to the Alpine Fault.

The Canterbury Basin has developed exclusively upon a Torlesse basement whose depositional age extends from Permo-Triassic in the south to Late Jurassic in the north. Division between an older Rakaia and younger Pahau terrane is marked by the Esk Head Melange which formed at a period of regional diastrophism (Rangitata 1) in the mid-Jurassic (Bradshaw 1989). Following this uplift several grabens developed with the accumulation of coarse clastic fanglomerates and interbedded coal measure sequences of the Clent Hills and Wakaepa Formations (Speight 1928). These are distinct from the underlying Torlesse in terms of their depositional environment (terrestrial versus deep marine) and degree of induration and deformation and must be considered apart from the Torlesse basement since they still possess source rock and reservoir potential. Their presence within faulted half-grabens within the Canterbury Basin is discussed later in this paper.

The present Canterbury Basin covers parts of two mid-Cretaceous depocentres, being the northern extension of the Great South Basin, (with orthogonal cross-cutting relation to the underlying basement; Bradshaw et al. 1996)), and southern extension of the Marlborough Basin, (with minor break in sedimentation between Torlesse and overlying mid Cretaceous Coverham group). The intervening region is the westward arm of the Chatham Rise Basement high (Haskell 1993).

Syn-rift deposits are found in the Kyeburn, Horse Range, Hewson and Clipper depocentres and are mostly composed of terrestrial conglomerates, sandstones and coal measures. Maximum thickness for the Kyeburn Formation (Bishop & Laird 1976) is estimated at 4000 m within an outcrop area of some 80 sq km. Offshore, the equivalent succession has been mapped by Wylie & Haskell (1997) as the "Kawau Seismic Interval' within the Clipper sub-basin.

An angular unconformity separates earlier syn-rift ('Kawau') from later similar rift fill successions ('Clipper Seismic Interval') and coincides with the extrusion of calc-alkaline volcanics of the Mount Somers Group, dated at 89 +/-2 Ma. This composite suite of rhyolitic lava domes, ignimbrite sheets and massive tuffs is exposed along the western margin of the Canterbury Basin and is mapped extensively on seismic away from its intersection in the J.D.George-1 well (1430-1650 mBKB).

The later rift sequence was deposited throughout the Late Cretaceous and is represented onshore by the Monro Conglomerate and Broken River (Mathews 1989). Following the commencement of seafloor spreading in the Tasman and South Pacific at c.85 Ma, subsequent thermal decline of the continental lithoshere heralded the onset of marine incursion into rift-basins as encountered in the Katiki Formation of the offshore Clipper-1 well (BPST 1984). This marine transgression persisted throughout the Paleocene and Eocene with coastal and shelfal sequences (e.g. Moeraki and Hampden formations) generally thinning and younging towards the margins of the basin in the west (Field & Browne 1990).

Following a lengthy period of hinterland erosion, clastic input of to the basin became severely limited and by Eocene times sedimentation was dominated by quartz and glauconite rich sands (Homebush Sandstone). This clastic starvation culminated in the Oligocene with the widespread deposition of predominantly bioclastic, shallow marine limestones (Amuri, Amberley Limestones).

Renewed clastic sedimentation followed inception of movement along the Alpine Fault in the Early Miocene at c.25 Ma and thereafter accompanied the progressive eastwards progradation of the shoreline and shelf. Considerable variation is seen in thickness and lithofacies across the outcrop in north Canterbury (Andrews et al.1987, Browne & Field 1985) and may be ascribed to local tectonics along fault zones which formed subsidiary to the main Alpine Fault.

Volcanism has been active within the Dunedin and Akaroa Centres since the Late Miocene (13-8 Ma) but is not obviously related to any significant tectonic event. Increased vertical movement on the Alpine Fault, principally during the past 5 Ma is responsible for the uplift of the Southern Alps and the outbuilding of piedmont fans which have coalesced to form the thick (<500 m) Late Cenozoic gravels of the Canterbury Plains. Recent tectonism associated with movement on the Alpine Fault results in continued uplift and faulting along the Southern Alps range-front with Torlesse basement overthrusting Holocene gravels.

As shown in the summary stratigraphic column of Figure 2 the principle targets for hydrocarbon exploration lies within the Late Cretaceous and early Tertiary sequences where there is a close association of source, reservoir and seal. These are disussed below, together with other secondary objectives which have been recognized from outcrop, well intersections or on recent seismic.

Reservoir and associated seals

Good to excellent reservoir properties have been measured from cored stratigraphic drillholes and outcrops in the onshore Canterbury Basin.

Units with the best reservoir properties are sandstones of Late Cretaceous and Eocene age, and limestone of Early Miocene age, although there is also some reservoir potential in older Cretaceous and possibly Jurassic sandstones (Figure 3).

The Late Cretaceous Broken River Formation includes intervals of friable quartzose sandstones in outcrops around the margins of the Canterbury Plains which are generally too friable to obtain core plugs. Excellent visual porosity suggests permeabilities in the 1-5 Darcy range, and a single porosity value of 35.9% (with no permeability measurement possible) has been obtained from outcrop.

Eocene Homebush and Iron Creek sandstones, sampled from cored stratigraphic drillholes towards the west of the plains, produced porosities ranging from 30 to 38% (average of 8: 33.0%), with permeabilities of 163 to 6410 mD (average of 7: 3233 mD).

The Early Miocene Mt Brown Limestone sampled from outcrop in the north of the Canterbury Basin has a single measurement of porosity of 43.6% and permeability of 3105 mD.

Data from Cretaceous sandstones at 2750-2780 m the offshore Galleon-1 well (Figure 3) give core porosity of up to 19.9% and permeabilities averaging 650 mD (BPST 1986), although most permeabilities were less than 100 mD.

The Jurassic Wakaepa Formation sampled from strongly tectonised outcrops to the west of the plains includes intervals of sandstone; however the reservoir properties of these sandstones are poor, with a maximum porosity values of 3% and permeability of 8.1 mD. In areas with less intense tectonism these sandstones could be much better reservoirs.

No separate study of the seal potential of claystone formations has bee carried out, but as shown in Figure 2, most of the Late Cretaceous and early Tertiary potential reservoirs are closely associated with regionally extensive claystone caprocks. By contrast, intraformational shales within the mid-Cretaceous terrestrial sequences are generally lenticular and involve a greater risk for sealing any hydrocarbon accumulation.

Source and maturation

The main source intervals in the onshore Canterbury Basin (as in Figure 4) are within the coal-rich Jurassic Wakaepa Formation, mid-Cretaceous Kyeburn and Horse Range Formations and equivalents, and Late Cretaceous Broken River Formation (Field & Browne 1989, Duff 1986). Marine source rocks assigned to the Waipawa Black Shale and Whangai Formation as seen in the East Coast Basin in the North Island occur in offshore Canterbury (Killops et al. 1996), but it is uncertain if they occur in the onshore Canterbury Basin.

The Jurassic Wakaepa Formation includes intervals of carbonaceous shale and coaly beds, and recent work shows them to have TOCs of between 3.9 and 38.8%, with hydrogen indices of up to 163 (Figure 5). Thickness of the formation is at least 300 m, with about 25% of it consisting of carbonaceous beds. Outcrops sampled west of the Canterbury Plains produced Tmax values of 430-436°C, suggesting the formation has reached but not exceeded peak hydrocarbon generation.

The higher ranks (low-volatile bituminous to semi- anthracite) in coals sampled from the Clent Hills Formation, are reported by Suggate (1990) to have resulted from increased levels of tectonism close to a major Torlesse basement overthrust.

Outcrop samples from coaly lenses and carbonaceous shales from the Mid-Cretaceous Kyeburn and Horse Range formations to the south of the onshore Canterbury Basin gave TOCs of up to 15.0%, with Tmax of between 418 and 429°C. One sample collected from coaly mudstone in the Upper Cretaceous Broken River Formation in North Canterbury gave a TOC value of 5.4%, Tmax of 426°C and hydrogen index of 194, suggesting that the formation has good generative potential but is immature in this locality.

Offshore, samples of the Late Cretaceous Pukeiwitawaitahi and Katiki formations in Galleon-1 well give excellent hydrogen indices from coals and associated carbonaceous shales (BPST 1986). The mid-Cretaceous Clipper Formation in Clipper-1 well also has good source potential (Gibbons & Herridge 1984).

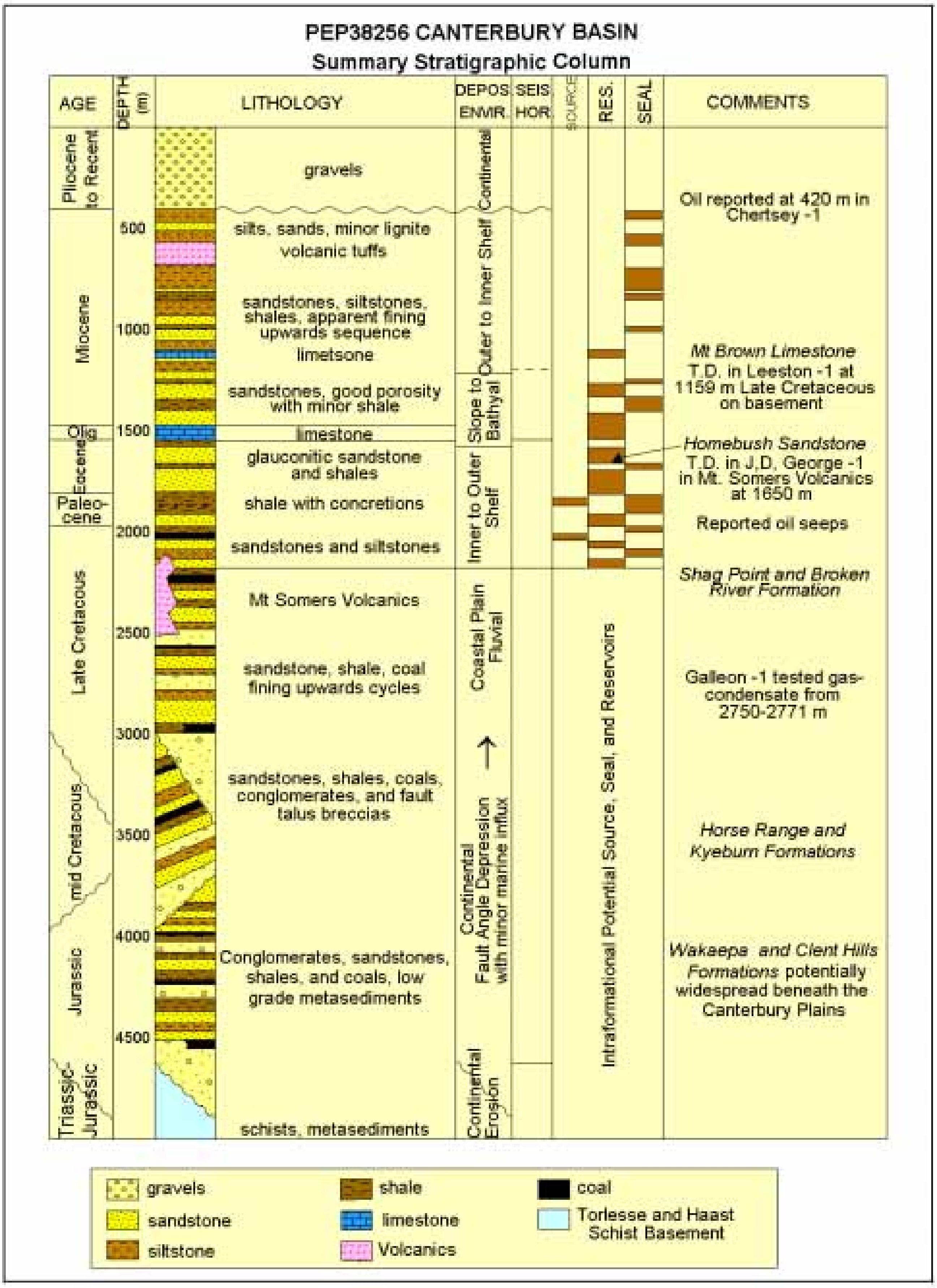

Figure 2: Summary stratigraphic column for onshore Canterbury area.

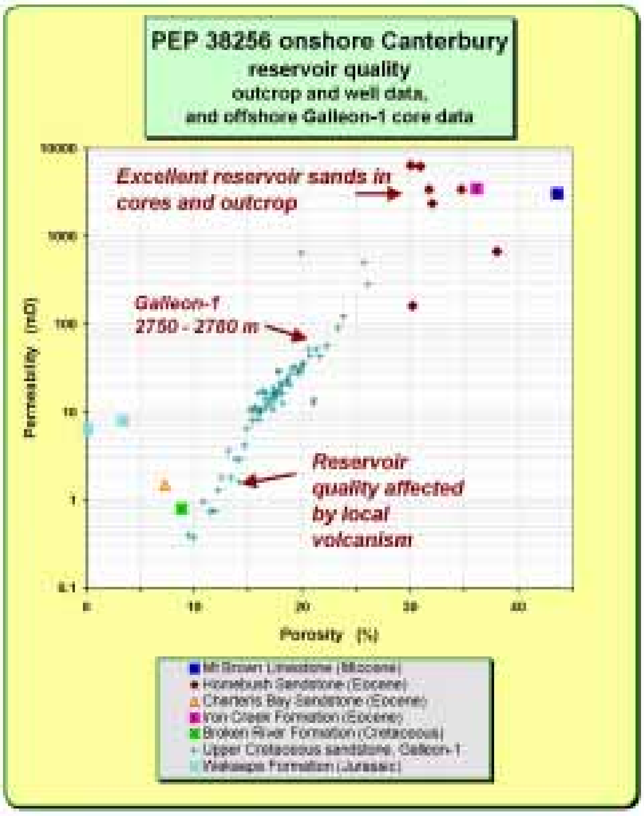

Figure 3: Canterbury Basin reservoir quality from outcrop, well data and the offshore Galleon-1 core data.

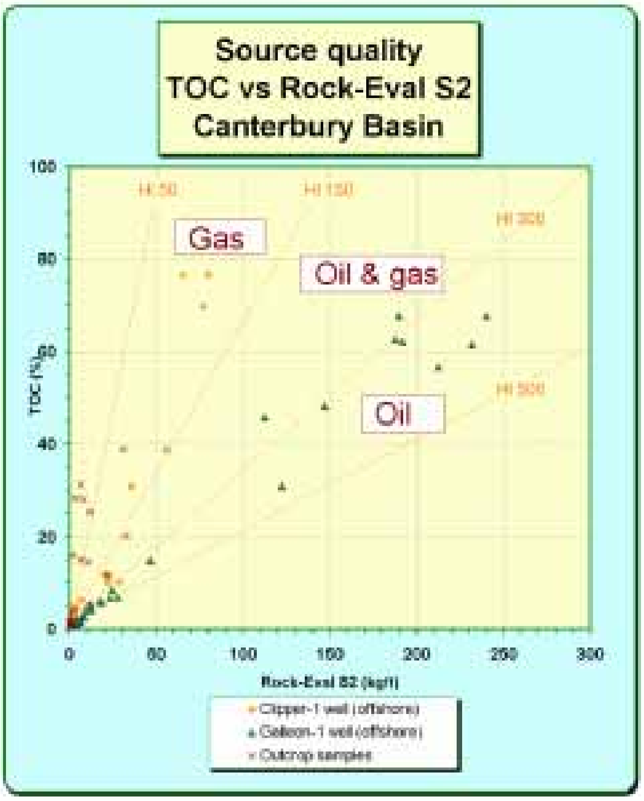

Figure 4: Source rock TOC v S2 for Canterbury Basin well and outcrop Mesozoic samples.

Most of the source and potential source formations analysed from outcrops onshore and offshore are type III kerogens, although some plot closer to the Type II curve (Figure 5).

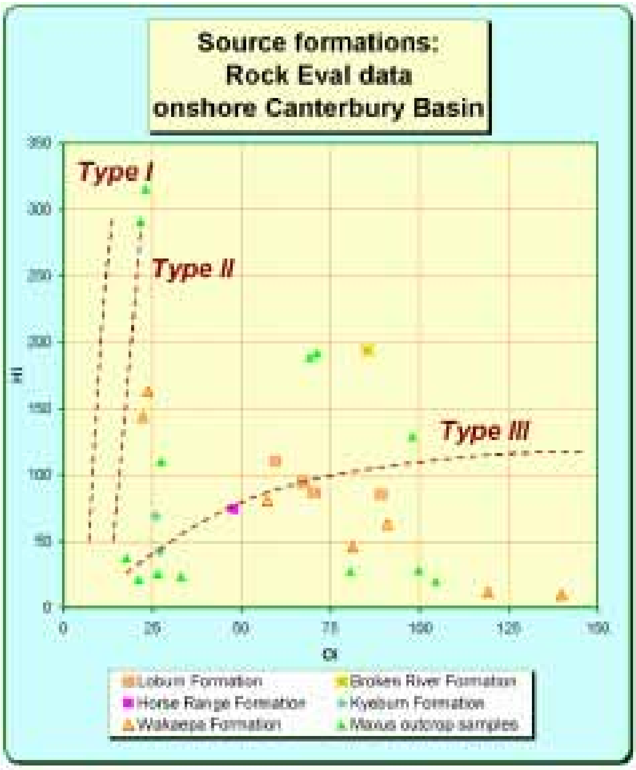

Figure 5: Van Krevelen plot: Hydrogen Index v Oxygen Index for Canterbury Basin Mesozoic outcrop samples.

Vitrinite reflectivity versus depth plots from the offshore Canterbury Basin wells, as shown in Haskell and Wyllie (1998) suggest a top of oil window (Rv=0.6%) at c.3600 m, with peak generation at 4000 m. However shallower depths of burial for maturation (OGT at 2800 m) are experienced in Galleon-1 and further south where increased heat flow is associated with the emplacement of Dunedin Volcanics in the Late Miocene (Funnell & Allis 1996).

It is possible that the source rocks mentioned above of both Jurassic and Cretaceous ages will have reached maturity and expelled hydrocarbons in areas of onshore Canterbury where the deep half-grabens have been mapped on seismic below 2 seconds TWT (e.g. Hinds Trough) and also where pronounced gravity lows suggest thick sedimentary accumulations occur above basement (e.g. Rakaia Trough).

Hydrocarbon indications

The Quaternary alluvial cover of the Canterbury Plains is an extensively fresh water flushed aquifer system, and is not a good area in which to find oil or gas seeps. There is, however, some evidence on seismic for gas chimneys and gas 'flags' within the gravels along the major fault on the south side of the Hinds Trough.

A 'strong kerosene odour' was reported (Gage 1968) in a shelly limestone directly overlying the Broken Hill coal measures in the Castle Hill Basin, in the ranges to the west (Figure 1); while Wilson (1963) reported petroleum odours in an oyster bed at a similar level in the geological section at the Waipara River, to the north. The reported oil indications from below the base of the gravels in Chertsey-1 are of uncertain status. Other oil indications are reported from Waiho Downs and Moeraki to the south, and Cass and Cheviot to the north, while gas emanations at Hanmer Springs are high in ethane (McLernon, 1978).

However, the best evidence for hydrocarbon generation in the basin comes from the offshore wells Galleon-1, where a stable flow rate of 10.6 MMCFD gas/2240BCFD condensate was recorded from a 21 m Cretaceous sand; and Clipper-1, where gas-condensate was recovered by RFT (McManamon & Bennett 1993).

Seismic mapping and prospect delineation

The pre-existing seismic data, acquired between 1957 and 1963 by the BP/Shell/Todd consortium, was scanned in to the workstation. Reprocessing of the scanned data was attempted, with little success, and these data are only useful in mapping as a general backup to the modern vibroseis data. This has been acquired in three separate surveys between 1998 and March 2000 by Schlumberger-Geco-Prakla using an IO System Two and four VVCA-A 19,000 pound peak force vibroseis units as source. The flat terrain and long straight stretches of road lend themselves to quick and good quality acquisition, and after some experimentation in the first survey, acquisition parameters have settled on a group and source interval of 20 m, with 400 groups in a split-spread mode. This has allowed good quality seismic to be acquired in a cost-effective manner, with production rates frequently averaging 15 km per day. The only drawback has been that the light impact weight of the source units, coupled with the attenuating effect of the gravels, has meant that in places the seismic data has had insufficient energy to image reflections down to basement.

A total of 667 km of vibroseis seismic has been acquired in the three surveys. These have been concentrated, from south to north, adjacent to the Hinds, Rakaia and Rangiora gravity 'lows' (Figure 6), which were considered to be the likeliest places to contain sediment buried sufficiently deeply to generate hydrocarbons.

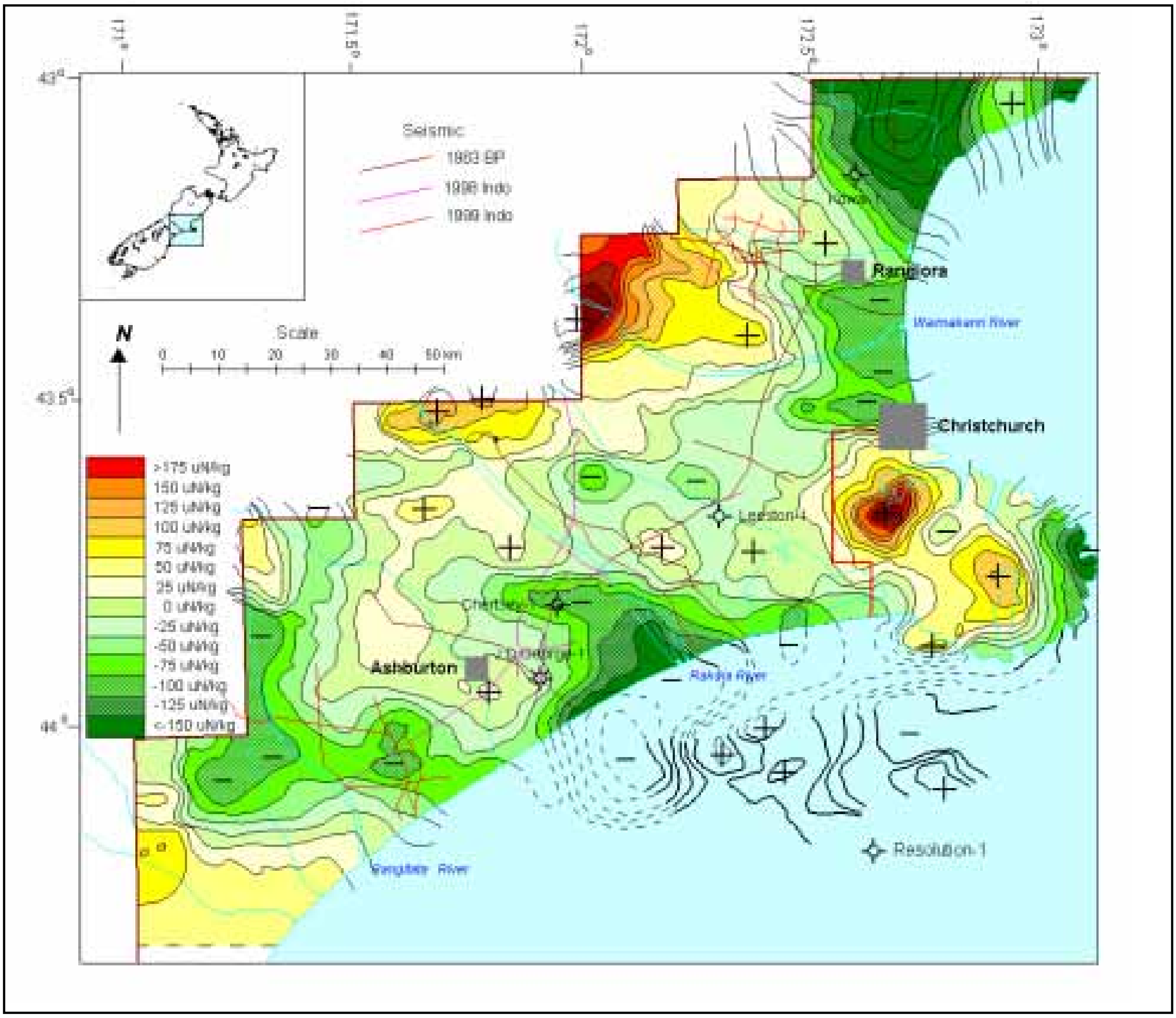

Figure 6: Basement corrected residual Bouguer gravity field of the Canterbury Basin.

Hinds and Rakaia troughs

A composite regional line from Torlesse greywacke outcrop in the west, to the coastline near the mouth of the Rangitata River in the east (Figure 7) shows the main structural details of this part of the basin. The Torlesse greywacke steps down in a series of high angle reverse fault steps across the range front into the basin. Beneath the gravels (in the top 300-500 msec range), which have muted seismic response, the Tertiary section is relatively unstructured, and cannot be invoked as the cause of the prominent east-west gravity 'low'. The mass deficit which creates this gravity anomaly is considered to lie below the base Tertiary unconformity. A major fault is situated near the northern margin of the gravity low. On the north side of this fault, a very strong top Torlesse seismic event is evident; whereas the steeply dipping section to the south has a much lesser reflective contrast with the overlying Tertiary at the unconformity contact. This section could be aged between mid-Jurassic (Clent Hills Formation) and mid Cretaceous (Kyeburn Formation) further north. The strong banded reflective package in the upper part of this dipping sequence, suggestive of a terrestrial coal measures sequence is underlain by a more bland (possibly marine) reflective section, visible down to at least 2.5 seconds TWT (c. 4000 m), with an apparent open folding of this section on a wavelength of some tens of kilometres. This extent of deformation is similar to that experienced by the Murihiku in the Southland Syncline in Otago which may still retain source rock potential (Cook et al. 1999).

On the south side of the Hinds Trough, drape over paleotopography, augmented by flexure over a reactivated basement fault on its northern margin (Figure 8) has created a large, low relief closure extending over some 30 sq km (~7,500 acres) at Lower Tertiary levels (Figure 9). This provides an Eocene Homebush Sands exploration objective at a depth near 1400 m, with underlying secondary objectives in Late Cretaceous sandstones within the Broken River Formation above the unconformity, and Clent Hills equivalent beneath (Figure 10). The trap would be charged from the underlying pre-unconformity section, and potentially also by lateral migration from the Hinds Trough to the north, or even possibly updip from the offshore basin to the southeast (Galleon subgraben).

The Rakaia Trough is considered to link offshore with the Hinds Trough, with the intervening Ashburton High plunging to southeast. The J.D. George-1 well on the high intersected Late Cretaceous volcanics at TD, and seismic in this region is of lesser quality. However, a tilted fault block lead can be recognised immediately south of the Chertsey-1 well; and this has been pursued with a series of seismic lines acquired in March 2000, which have yet to be processed.

Rangiora Trough

The prominent gravity low extending westwards from Pegasus Bay, north of Christchurch (Figure 6) is the expression of the Rangiora Trough, an onshore/offshore sedimentary deep. On the north flank of this feature, active deformation is occurring, both onshore and offshore, on the right lateral splay fault system linking along the plate boundary from the Alpine Fault to the Hikurangi Trench (Barnes 1996).

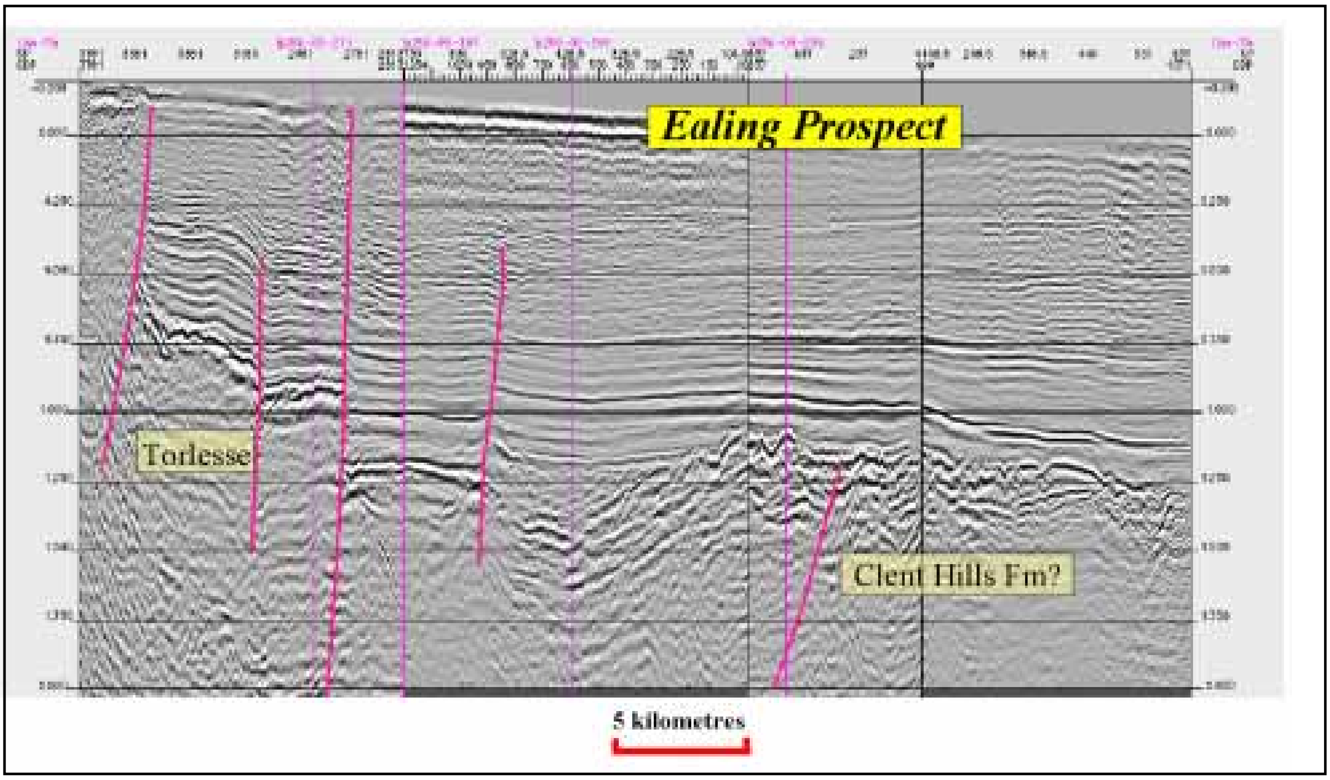

Figure 7: Regional north-south composite seismic line over the Ealing structure ; seismic lines Ip256-99-101, Ip256-00-207, Ip256-99-102, Ip256-00-208; location shown in Figure 9.

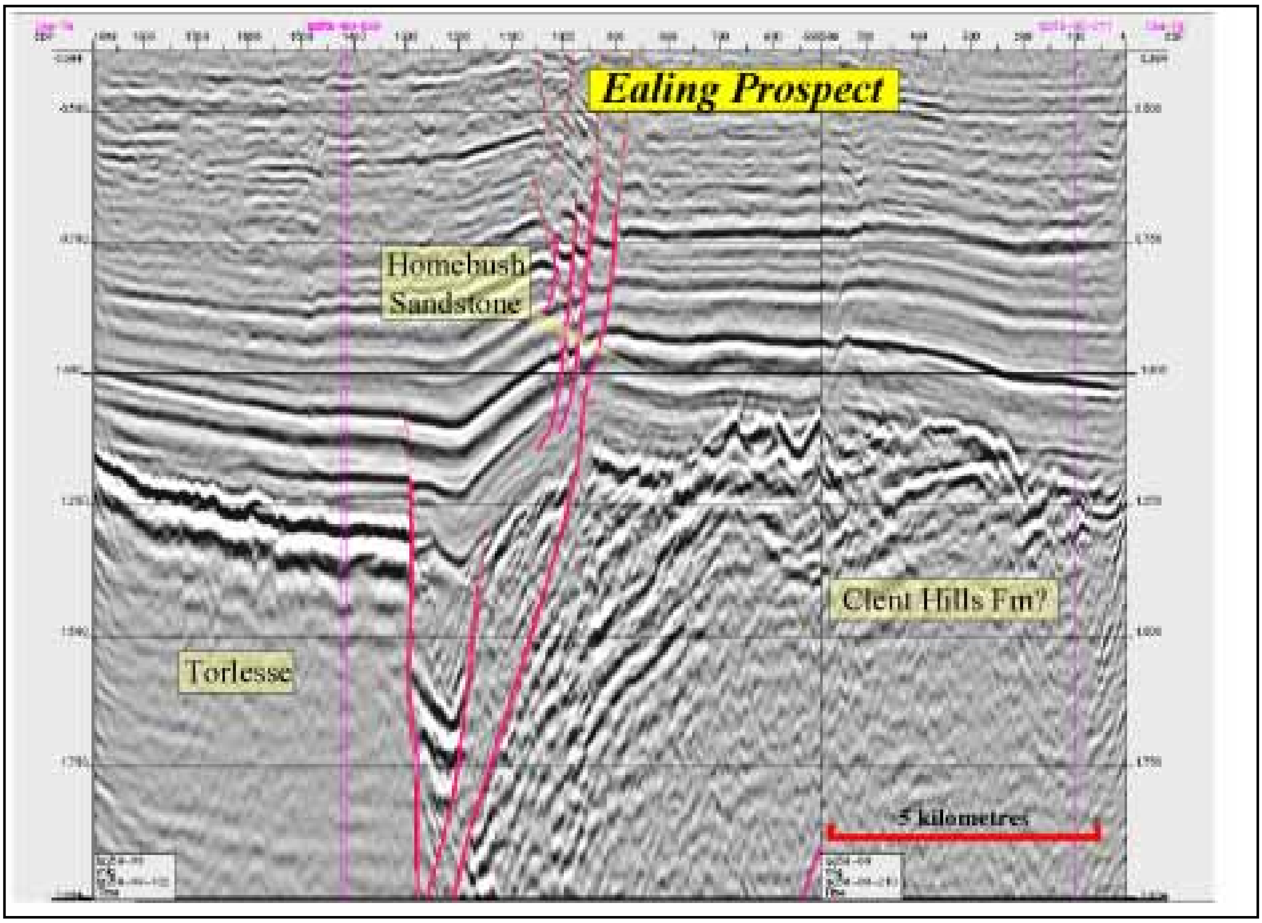

Figure 8: Detailed seismic composite line over the Ealing Prospect and adjacent Ealing Fault; seismic lines Ip256-99-102, Ip256-00-210.

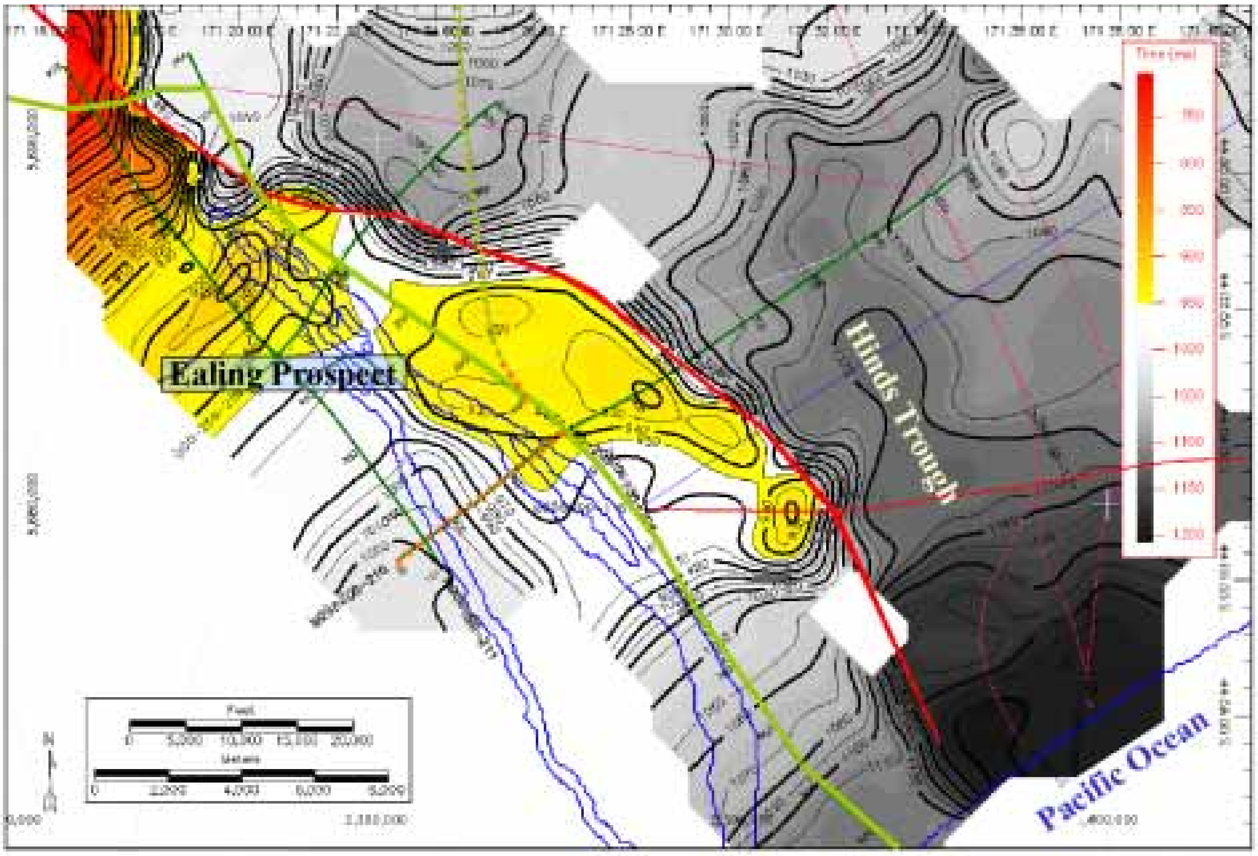

Figure 9: Time structure map at intra-Miocene event (Altonian) of the Ealing Prospect and Hinds Trough area. Contour interval 10 msec TWT.

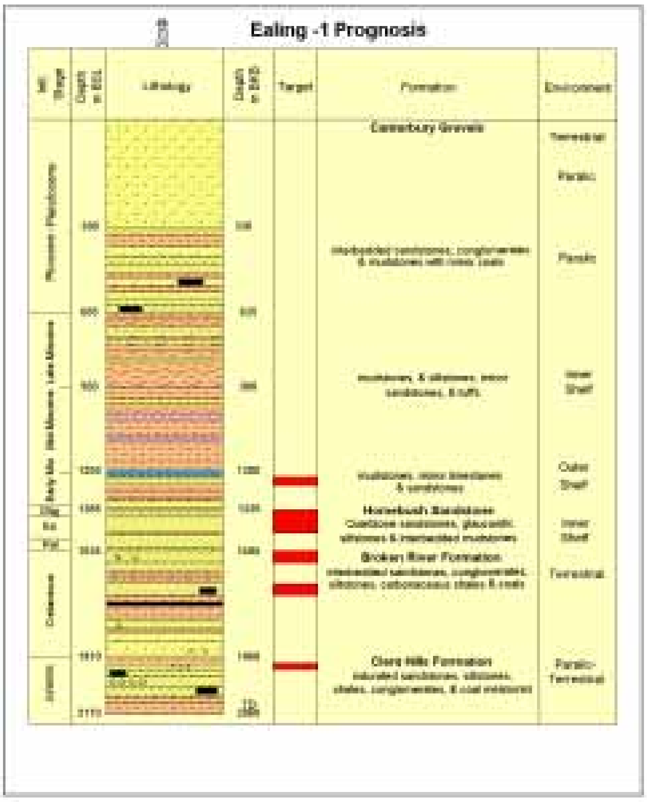

Figure 10: Ealing Prospect well prognosis showing main target horizons.

The Cust Anticline near Oxford is an example of an actively deforming 'pop-up' structure, considered to be associated with restraining bend compression along the Ashley Fault system. An elongate topographically high feature, the Mairangi High, rises out of the Canterbury Plains as the surface expression of this anticline. Seismic crossing Mairangi clearly shows the compressional nature of the structure (Figure 11). The axis of the structure at depth conforms closely to the surface feature, and a large closure can be mapped at Miocene and deeper levels (Figure 12). The fish shaped form of this closure is very typical of such restraining bend 'pop-ups'; and indeed the Arcadia Prospect (as this closure is named) bears similarities of scale and form to the Mt Oxford High, a 'pop-up' mapped in detail in outcrop about 20 km to the west in the Torlesse ranges, on a restraining bend in the Porter's Pass Fault (Cowan 1992)

The Arcadia Prospect is considered to have a primary reservoir objective in the Eocene Homebush Sands, with the mid-Miocene Mt Brown Limestones and Late Cretaceous Broken River Formation sandstones providing secondary objectives. A dipping sequence is visible below the Broken River unconformity, but the seismic has too little energy to define the base of this sequence. As is the case further south, this sequence could be of mid-Cretaceous to mid Jurassic age. Arcadia reservoirs can be charged from this underlying deeper section or laterally from the Broken River Formation

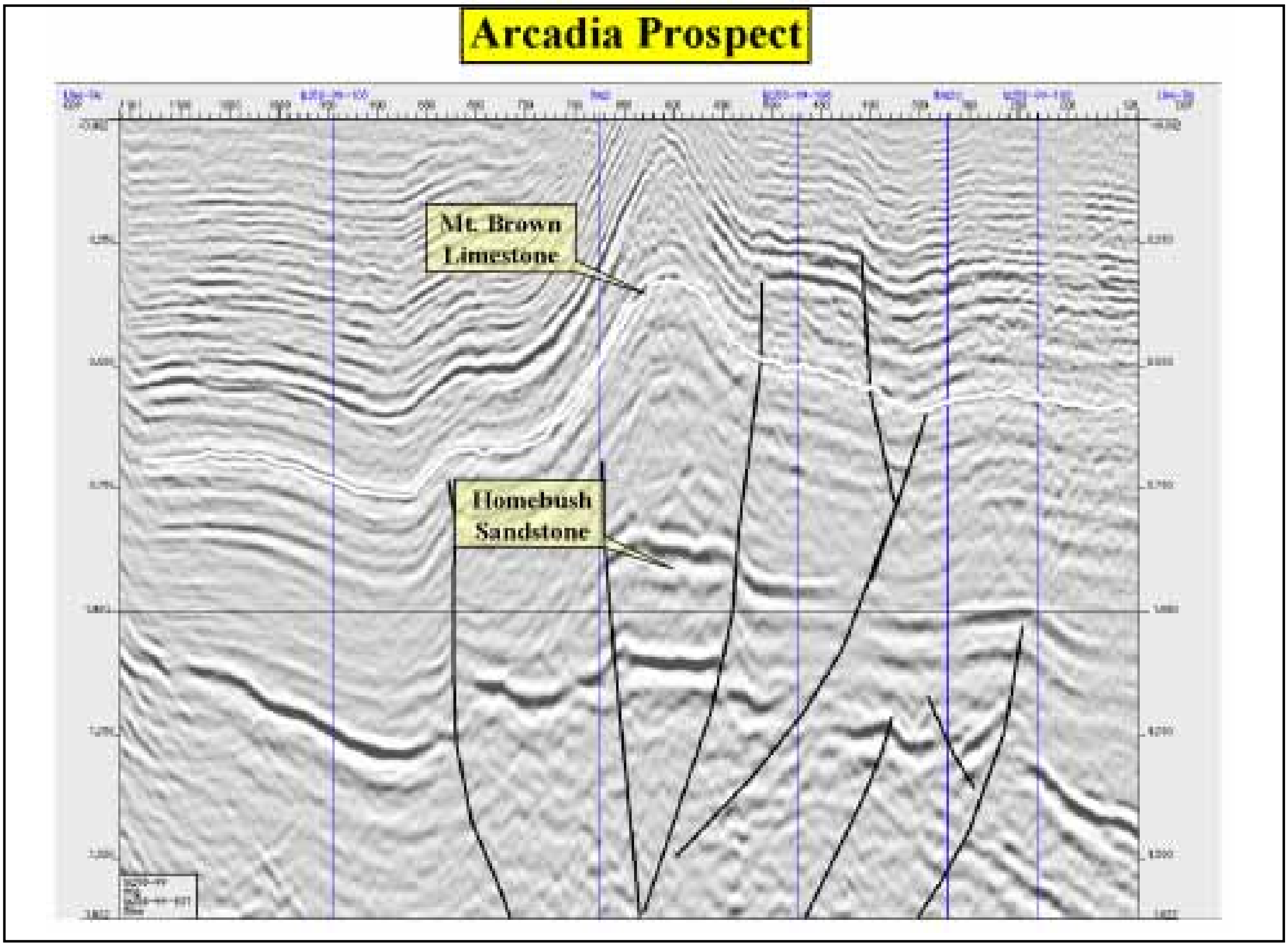

Figure 11: Details of seismic line Ip256-99-107 over the Cust Anticline, showing the culmination in the Arcadia prospect; location shown in Figure 12.

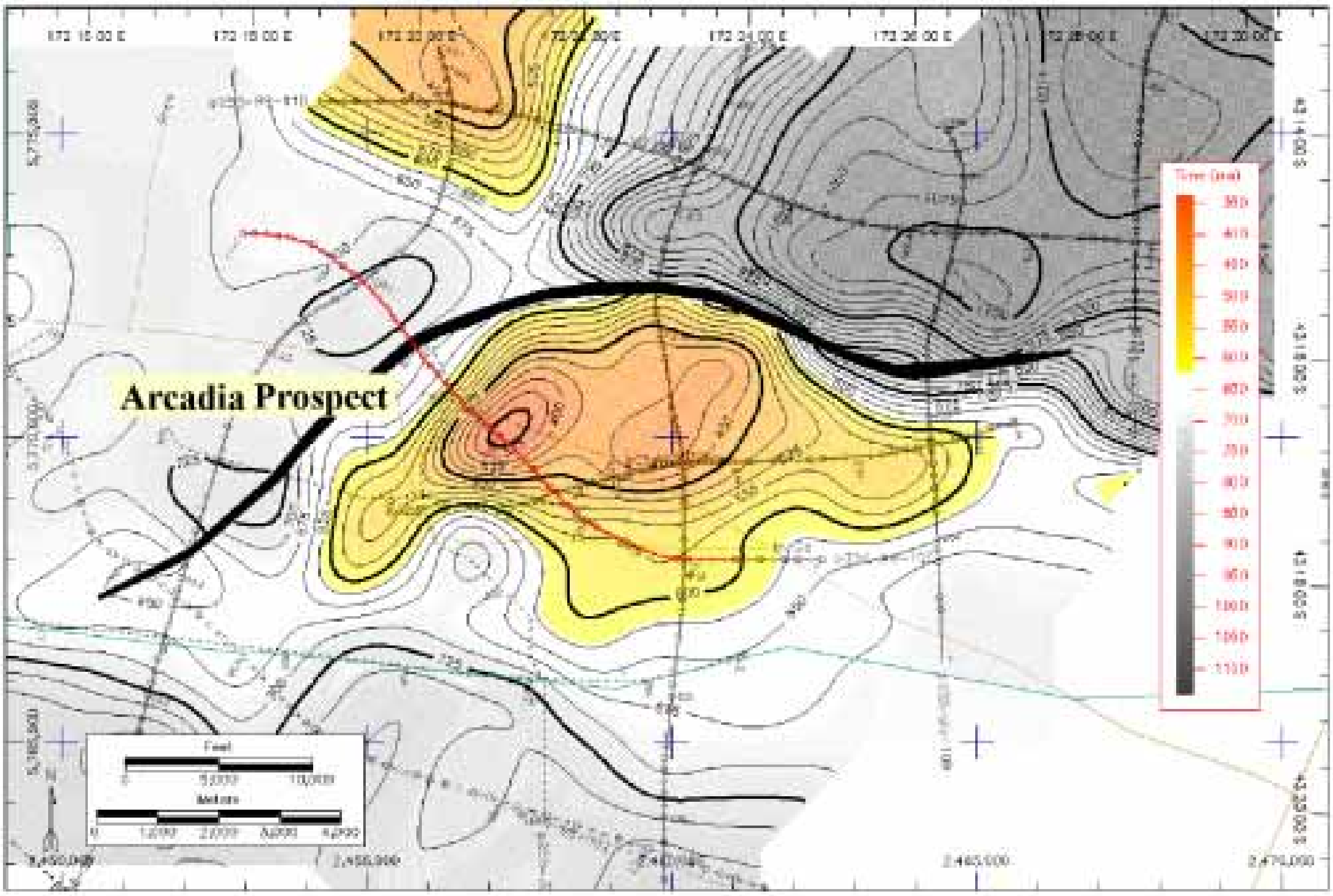

Figure 12: Time structure map at intra-Miocene event (Altonian = Mt Brown Limestone) of the Cust Anticline and Arcadia Prospect. Contour interval 25 msec TWT.

coal measures situated downdip to east in the Rangiora Trough. Following incorporation of the 2000 seismic data, it is expected that Arcadia will be mature for drilling, with a well to 2000m TD testing all objectives.

Conclusions

1. Modern seismic of good quality has been cost-effectively acquired. This has enabled the mapping of the late Mesozoic/early Cenozoic section beneath the outwash gravels which have built out the Canterbury Plains eastwards across the Canterbury Basin.
2. Field studies have determined the presence of good reservoir rock sequences in outcrop and in stratigraphic drill holes around the edge of the Plains
3. Source rock studies, combined with seismic mapping of deeper section demonstrate that mature and generative source rocks may reasonably be expected to be present beneath the plains.
4. The structural styles and geological evolution of the areas to north and to south of Banks Peninsula are quite different. The north reflects present day active deformation adjacent to the plate boundary, while the southern area has experienced relatively minor late phase deformation.
5. Large closed structures have been identified on seismic in both north and south areas, which are prognosed to contain good quality reservoir objectives.
6. All the prerequisites for hydrocarbon generation and entrapment appear to be present in the onshore Canterbury Basin, and drilling of prospects in both north and south areas is technically justified.

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