CRETACEOUS-CENOZOIC BASIN EVOLUTION AND HYDROCARBON POTENTIAL OF CANTERBURY, NEW ZEALAND

B D Field* and G H Browne**
* New Zealand Geological Survey, DSIR, Lower Hutt, New Zealand
**New Zealand Geological Survey; present address: University of Western Ontario, London, Canada.

Ten petroleum exploration wells have been drilled in Canterbury, with increasingly promising results; the last hole drilled, Galleon-1, warranted onsite testing. The main target zone is the Cretaceous terrestrial-paralic source and reservoir sequence in offshore Canterbury Bight.

Crustal stretching in the Cretaceous, prior to the rifting of New Zealand from Antarctica, led to the formation of numerous half grabens filled with coarse clastics and potentially prospective lacustrine beds. Continued faulting and rapid subsidence in the mid to Late Cretaceous formed a large basin in the Canterbury Bight: the Clipper Basin. Its basal fill, fine grained coal measures of the Clipper Formation, is a promising source and reservoir target.

Faulting virtually ceased in the Paleocene, though subsidence continued as did westward transgression. Renewed tectonism in the Eocene was comparatively mild, resulting in minor basin formation and local uplift. Deformation continued into the Oligocene with increased tempo and reflects a change from extensional to transpressional tectonism in the late Oligocene, as the Alpine Fault plate boundary developed. Uplift in the west, causing a massive influx of sediment to the east, reached a climax in the Pliocene to Recent.

Maturation appears to have been sufficient to have generated significant hydrocarbons only in the Canterbury Bight. Areas further west are not only immature but have also been subject to flushing. The bathymetry of Canterbury Bight could restrict drilling to a belt in the centre of the Bight. To date only some of the structural traps have been drilled. Future targets could include stratigraphic and possibly hydrodynamic traps. The mid Cretaceous half grabens could be evaluated in more detail.

INTRODUCTION

The Canterbury region lies on the eastern side of the South Island of New Zealand (Fig. 1). Ten petroleum exploration wells have been drilled in the Cretaceous-Cenozoic cover rocks of the region though only two, Clipper-1 and Galleon-1, have been drilled in the last ten years. Each of these two later wells produced hydrocarbon shows from Cretaceous source and reservoir rocks, with the most recent well, Galleon-1, warranting onsite testing of gas condensate flows. The prospectivity of the region indicates further evaluation and exploration are warranted.

A major review of the basin evolution of the region has just been completed and this paper is based on extracts from this publication (Field and Browne *et al.*, 1989). Similar reviews have also been completed for two adjacent regions (Fig. 1): the West Coast (Nathan *et al.*, 1986) and Chatham Rise (Wood, Andrews and Herzer *et al.*, 1989).

GEOLOGICAL SETTING

The Canterbury region lies on the western edge of the Pacific plate. About 480 km of right lateral offset, and several kilometres of uplift and shortening occurred along the plate boundary (manifest as the Alpine Fault) in the Neogene. In the Cretaceous-Paleogene the Canterbury region lay much further east and north with respect to western New Zealand (e.g. see Stock and Molnar, 1987).

Major crustal features in the northern half of the region include the Chatham Rise (an east-west-trending Cretaceous-Recent topographic high) and the Hikurangi Trough, an offshore element of the Australian-Pacific plate boundary system that propagated southward to its present position in the Neogene.

Economic basement consists mainly of Permian to Early Cretaceous inter- bedded greywacke and argillite (Torlesse Supergroup), grading into schist in the south (Haast Schist) and far west (Alpine Schist).

The oldest cover rocks are of mid Cretaceous age and overlie basement unconformably. The thickest sequence of Cretaceous-Cenozoic cover rocks (6500 m) lies offshore, in the Canterbury Bight. The structure in the prospective part of the basin is generally simple; most structures developed in the Cretaceous.

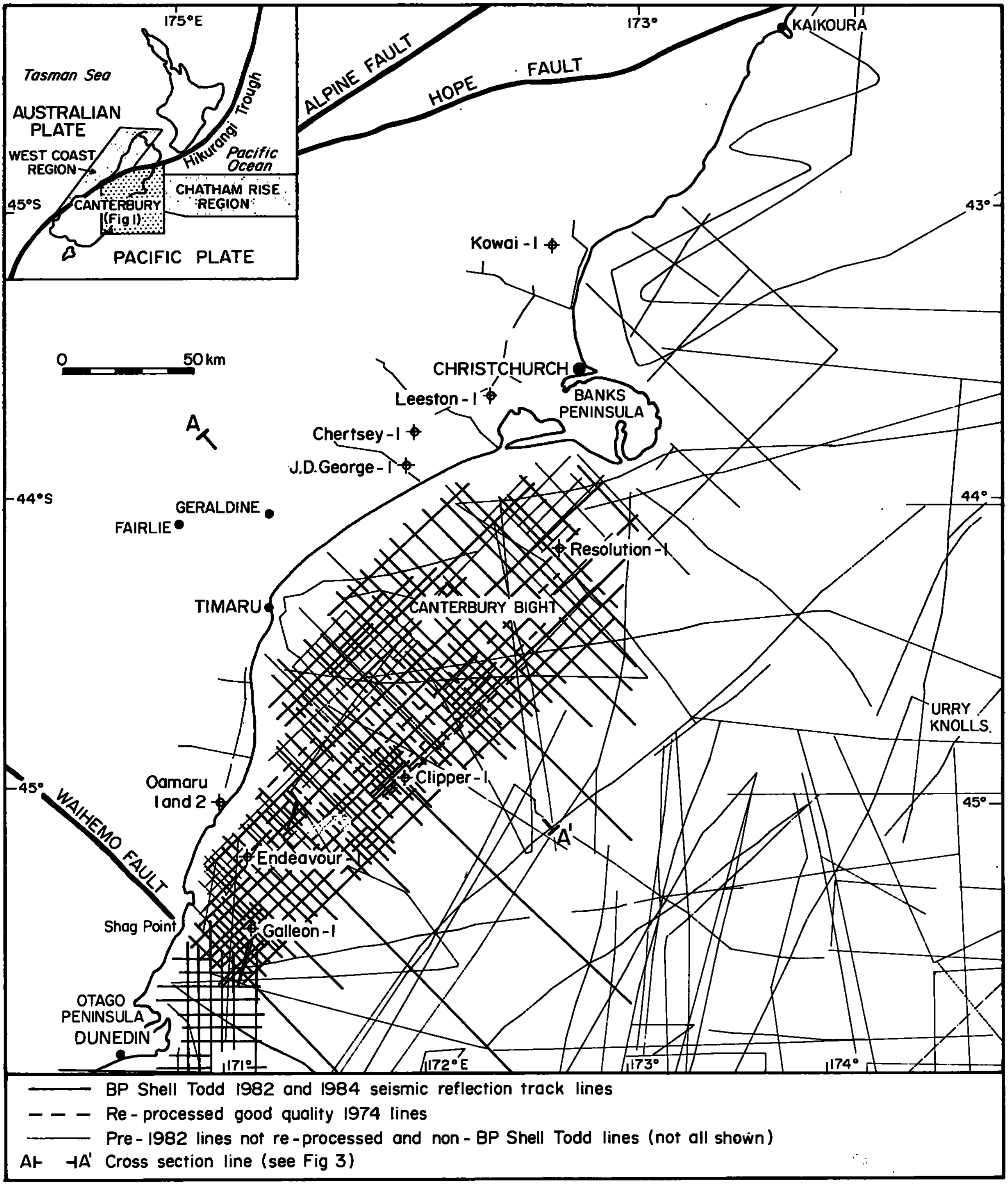

Fig. 1: Locality map, showing petroleum exploration wells and seismic lines.

PREVIOUS WORK

Most of the detailed work onshore has been done by DSIR geologists. The lithostratigraphy of most of the region has recently been reassessed (Browne and Field, 1985; Field and Browne, 1986; Andrews et al., 1987; Field and Browne *et al.*, 1989) and several stratigraphic holes have been drilled (e.g. Field, 1985; Field *et al.*, 1989).

Most of the offshore studies in the Canterbury Bight have been carried out by B.P. Shell Todd (Canterbury). This company, which recently held the two licences in the region, ran 5819 km of new seismic reflection lines, drilled the two most recent wells (see Hawkes *et al.*, 1985; Wilson 1985; Dernie and Mound 1986) and compiled several 1:250 000 and 1:100 000 scale maps of horizons in the offshore part of the region. They also compiled several reports giving their company's interpretation of the prospectivity of the region (see B.P. Shell Todd 1984; Mound and Pratt, 1984). B.P. Shell Todd mapped, locally, up to nine reflectors offshore.

BASIN EVOLUTION

Cretaceous

In the mid Cretaceous, prior to the breakup of New Zealand and Antarctica, crustal stretching and subsidence led to the development of numerous half grabens. In the present onshore area, remnants of these may be found at Banks Peninsula, Hewson River, Kyeburn and near Shag Point. The 4000+ m of sediments that accumulated in the Kyeburn area were mainly conglomeratic, though they include thick, partly carbonaceous lacustrine units (Bishop and Laird, 1976). At both Kyeburn and Shag Point the conglomerates record progressive unroofing of the Haast Schist on the south side of the Waihemo Fault. Probably similar, though generally smaller, half graben structures formed in terrestrial settings under the Canterbury Bight and on the Chatham Rise. Mid Cretaceous volcanism (e.g. Mt Somers Volcanics) was widespread, though is now best exposed in mid Canterbury. By Cenomanian-Santonian times, new regional structures had started to develop (see Field and Browne *et al.*, 1989). In the Canterbury Bight, seismic reflection profiles have provided a good three-dimensional picture of Cretaceous paleotopography. The main basin, Clipper Basin (Fig. 2), appears to have been bounded to the east by a growth fault. Up to 2000 m of mid Cretaceous coal measures and paralic sediments accumulated in the Clipper Basin (Fig. 3). These sediments, known as the Clipper Formation, occur over a large part of the Canterbury Bight and are the most widespread potential source and reservoir rocks to have reached thermal maturity in the region. Clipper-1 and Endeavour-1 are the only wells to have penetrated the formation which, at these two wells, consists mainly of interbedded units of sandstone and mudstone. The formation appears to fine up-sequence, from being pebbly at the base to coaly near the top.

The Caroline Basin, just east of Timaru, was smaller but is inferred to have had a similar history, with similar deposits, as are the numerous small half-grabens recorded by Mound and Pratt (1984). A NE-trending topographic rise, the Canterbury Bight High, dominated the western part of the Canterbury Bight. Other highs existed east and southeast of Clipper Basin (Benreoch and Zapata Highs). The Chatham Rise remain subaerial until the Late Paleocene.

At both Clipper-1 and Endeavour-1 the Clipper Formation is overlain by locally dolomitic, marine, dark mudstone of the Katiki Formation. At Clipper-1 foraminifera indicate that the Katiki Formation (apart from the basal part) was deposited at bathyal depths, and this suggests a rapid relative rise in sea level in the Santonian. This is attributed mainly to increased regional subsidence. The raised base level heralded widespread accumulation of paralic coal measures in the western (present onshore) part of the region in the Campanian-Maastrichtian (e.g. Taratu, Papakaio and Broken River Formations). The Cretaceous sequence in the Clipper Basin is locally over 3000 m thick.

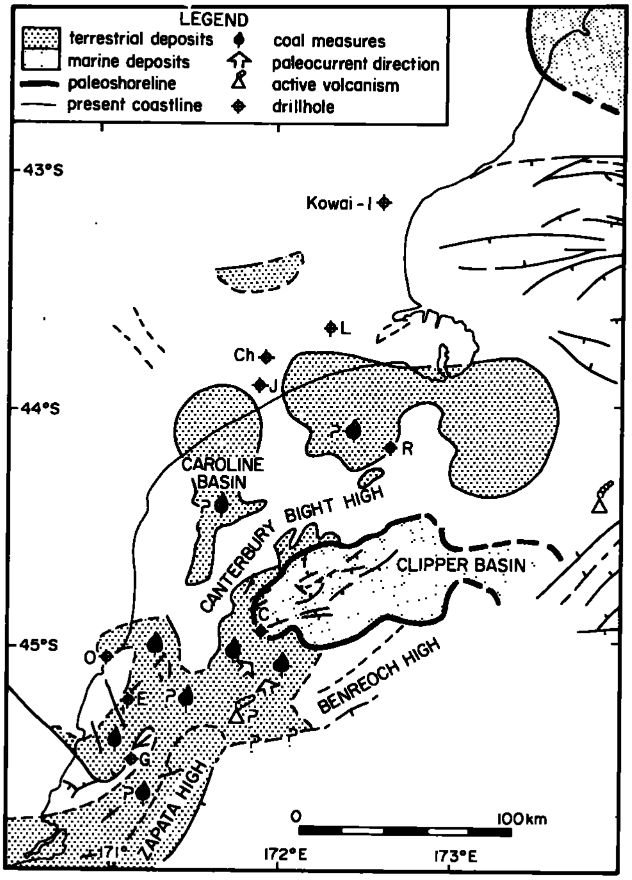

Fig. 2: Late Cretaceous paleogeography.

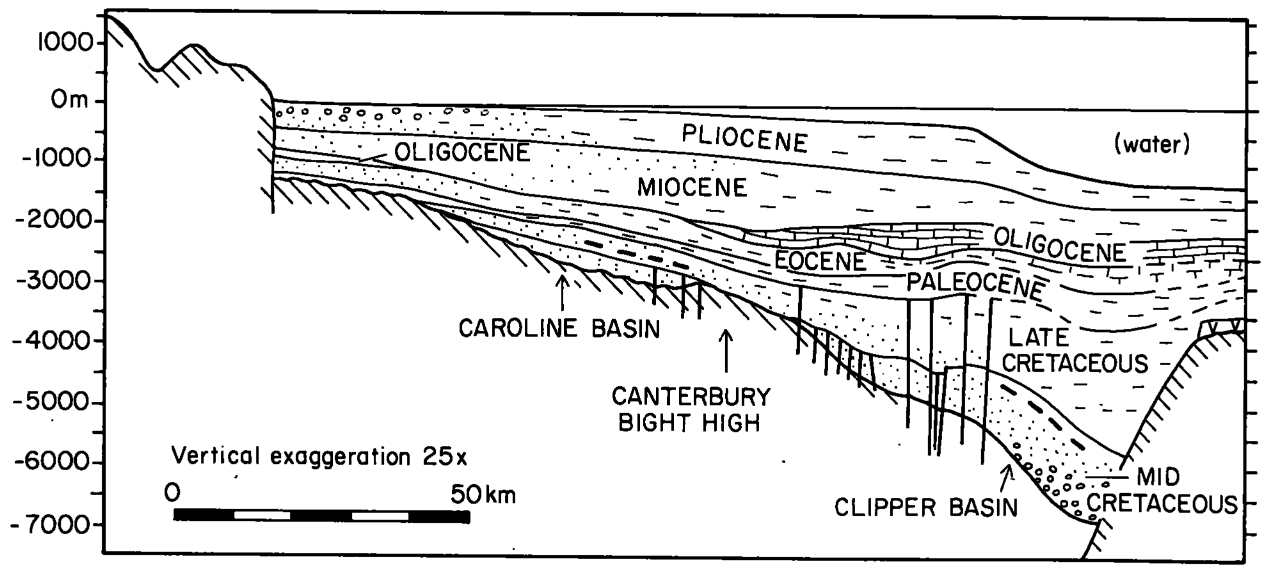

Fig. 3: Cross section (see Fig. 2).

Paleogene

The passive margin drift phase of the Paleocene is characterised by continued, though slightly slower, subsidence and westward transgression. The main sediments deposited in the Canterbury Bight were the dark shales of the Moeraki Formation. In North Canterbury the Paleocene is also marked by dark mudstone (Loburn Formation), with overlying greensand (Waipara Greensand). The Eocene is generally characterised by calcareous mudstones (Ashley and Hampden Formations) that pass up-sequence into Eocene to Early Oligocene micrite (Amuri Limestone). In the west the Eocene sequence is more varied, with influxes of quartzose sand (Homebush, Karetu and Opawa Sandstones).

Mild tectonism started in the Late Eocene, and a basin developed around Fairlie. Faulting and erosion in the northwest of the region was locally sufficient to lead to Oligocene Amuri Limestone resting on Torlesse basement (McLennan and Bradshaw, 1984). These movements may have been precursors to the development of the Alpine Fault plate boundary. The inception of this boundary, accompanied by partly extensional or transtensional tectonism, occurred in the Late Oligocene. This was manifest as sand diapirism and low amplitude regional folding, as well as the development of a low, NE-trending ridge in the Canterbury Bight (Endeavour High, Fig. 4) that was probably subaerial or shallow submarine for much of the Late Oligocene and Early Miocene. Subsidence and marine deposition continued on either side of the high. A record of the effects of the Late Oligocene to Early Miocene deformation is preserved around a widespread unconformity (c.30 Ma age) that was caused by a large relative fall in sea level (cf., the Tejas A/B supercycle set boundary of Haq *et al.*, 1987). The Late Oligocene is characterised by shelfal calcareous greensand (Kokoamu Greensand) and grainstone (e.g. Otekaike Limestone) though, in the deeper water settings in the east of Canterbury Bight, the unconformity and up-sequence lithological change is less marked. Late Oligocene alkalic to tholeiitic volcanism was widespread in the west (e.g. Brothers Basalt, Cookson Volcanics).

Neogene

Tectonism increased throughout the Neogene, as the Southern Alps gradually rose in the west, shedding pre-Neogene cover sediments and eroding great thicknesses of Permian-Cretaceous basement rocks. This detritus built an eastward-prograding sediment wedge that now forms the continental shelf in Canterbury (Fig. 3). In the west, the early sediments (e.g. the Early Miocene Southburn Sand and Caversham Sandstone) invaded settings previously dominated by the calcareous blue-green Tokama Siltstone and its correlative, the Rifle Butts Formation. Subsidence continued in the Fairlie Basin.

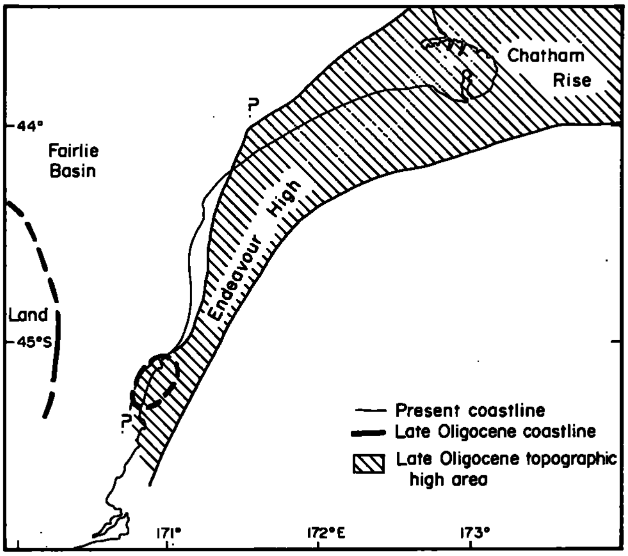

Fig. 4: Major Oligocene structural elements.

By Pliocene times thick sheets of conglomerate (Kowai Formation) were laid down in the west, in an increasingly faulted and folded terrain; faults had locally over 1000 m of reverse throw. Siltstone deposition persisted through to the Recent in the east, where the Neogene sequence is virtually undeformed.

Neogene deformation was most intense in North Canterbury adjacent to the Hikurangi Trough section of the plate boundary which was propagating southward. In the Canterbury Bight there is very little evidence of Neogene deformation apart from regional subsidence, the Cretaceous structures appear to be undisturbed. In the west, however, some earlier faults appear to have been rejuvenated (e.g. Waihemo Fault), with Neogene reverse movements. The four main centres of volcanism in the Neogene were Otago Peninsula (Middle Miocene; Coombs *et al.*, 1986), Banks Peninsula (Late Miocene; Sewell, 1988), Timaru-Geraldine (Pliocene; Duggan and Reay, 1986) and Urry Knolls (Plio-Pleistocene; Herzer *et al.*, 1989), though several smaller eruptions occurred near the foothills of central Canterbury (Sewell and Gibson, 1988).

HYDROCARBON POTENTIAL

Potential hydrocarbon source rocks of various ages are widespread in Canterbury. It is likely, by analogy with the Kyeburn sequence, that some of the mid Cretaceous half graben structures contain carbonaceous units, and it is known that coal beds occur in the Clipper Formation. The Taratu, Pukeiwitahi, Papakaio and Broken River Formations locally contain sufficient carbonaceous material to be considered potential source rocks though, for these units, in the west of the region, maturity may not have been reached. The marine Katiki Formation is in places very carbonaceous and must also be considered a potential source rock. Some of the Paleocene-Eocene units have promising TOC values, but have probably not reached maturity.

No kerogen data is available for the mid Cretaceous rocks. Vitrinite is the dominant kerogen in the Late Cretaceous lithologies, except at Endeavour-1, where inertinite is locally more common, and at Kowai-1, where liptinite is more common. Sapropelic material is slightly dominant over humic material, suggesting good oil-prone potential. Hydrogen index/oxygen index diagrams for Clipper-1 and Galleon-1 (Fig. 5) generally show poor discrimination, but with a predominance of type II and III organic matter, consistent with the inferred paralic to non-marine paleoenvironments. Organic material in the Clipper Formation has a predominance of C_{27} and C_{28} hydrocarbons with long-chain n-alkanes and high pristane/phytane ratios. The single gas sample analysed from the Clipper Formation had 57% methane, 15% higher alkanes and 28% incombust-ables. Gibbons and Herridge (1984) concluded that the gas was derived from an oil-prone source of quite high maturity. The

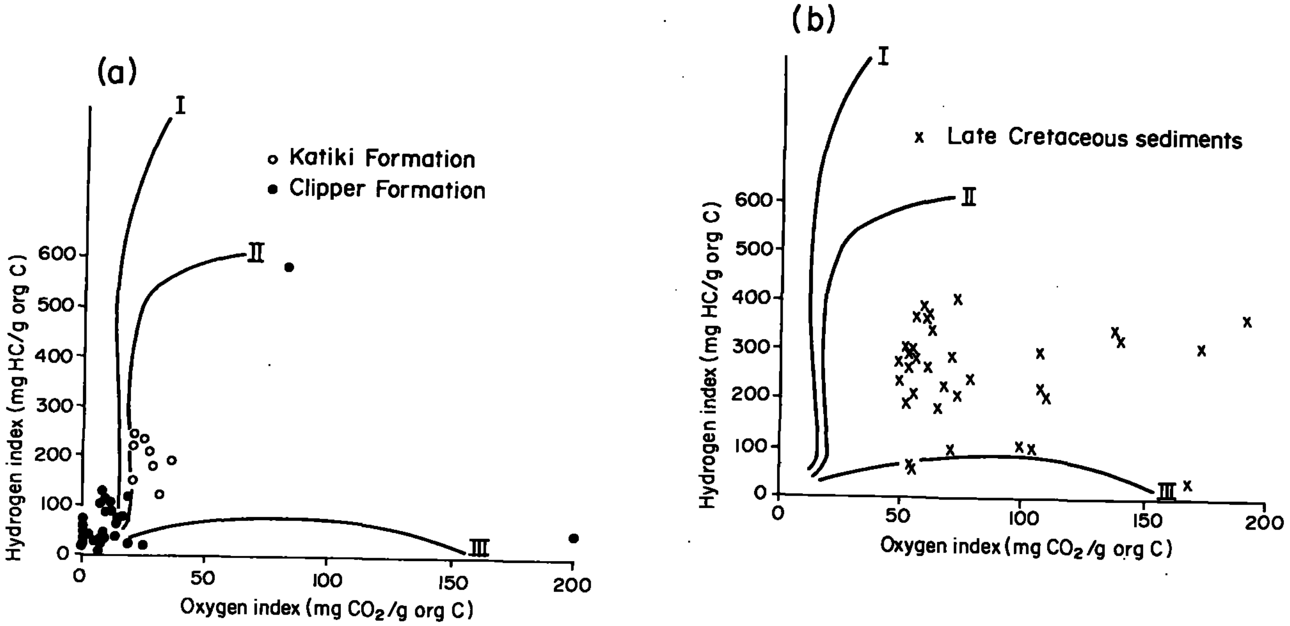

Fig. 5: Hydrogen index vs oxygen index diagrams. (a) Clipper-1 and (b) Galleon-1.

test oil/condensate from Galleon-1 (between 2753-2763 m) was a light (51° API) paraffinic-aromatic crude with low sulphur, nickel and vanadium (Gibbons and Fry, 1986). There was a good C_{15}+ solvent-extractable bitumen content in samples from Kowai-1, and Thompson *et al.*, (1978) concluded that the Late Cretaceous sediments were a good potential oil and associated gas source.

Vitrinite reflectance is not a reliable guide to maturation level (Newman and Newman, 1982; Suggate and Lowery, 1982). Nevertheless, reflectance data is available for many Canterbury samples and, in the absence of large numbers of chemical analyses, is used here as a very approximate guide to maturation levels. The generation window is taken as 0.6-1.3% Ro (max). Data from Kowai-1, Resolution-1 and Endeavour-1 suggest that the sequences there are unlikely to have reached maturity, though Torlesse basement was not reached at Resolution-1 and greater maturity could be expected below the base of the drill hole. The basal 175 m of the sequence at Galleon-1 has probably reached maturity, and at Clipper-1 the oil floor apparently lies about 500 m above basement. Effectively, the reflectance data suggest that the oil window lies beneath the regional Late Cretaceous (Haumurian) seismic reflector, and that the central Canterbury Bight (especially the Clipper Basin) is the most prospective part of the region (Fig. 6).

Potential reservoir units include the Clipper, Pukeiwitahi, Herbert and Katiki Formations. The porosity of the Clipper Formation varies with both lithofacies and degree of diagenetic clay formation. More favourable porosities have been recorded for the other three formations.

Data from some of the older exploration wells have indicated extensive flushing has occurred in the west of the region. Trap evaluation should allow for this, and also allow for the presence of hydrodynamic traps. Fourteen potential trap structures, with potential reserves ranging from 28 to 503 million barrels, at various risks, have been delineated by B.P. Shell Todd, but only two of these (Clipper and Galleon, both structural) have been drilled. No stratigraphic play has been drilled.

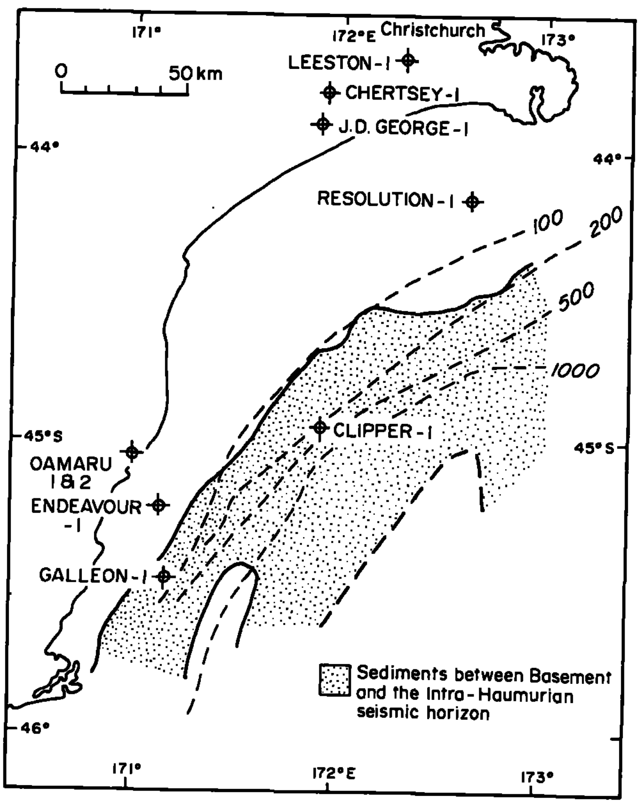

Fig. 6: Distribution of sediments between basement and the Late Cretaceous (Haumurian) seismic reflector; this corresponds approximately to the distribution of sediments that have reached sufficient maturity to have generated hydrocarbons. Bathymetry (in metres) is also shown.

CONCLUSIONS

There is good quality, modern seismic reflection coverage for the most prospective part of the Canterbury region, and the two most recent wells have demonstrated that hydrocarbons have been generated. The search for a productive trap should include a reassessment of the early half graben features, stratigraphic traps, and hydrodynamic effects.

ACKNOWLEDGEMENTS

We thank NZ Geological Survey, Geophysics Division and B.P. Shell Todd (Canterbury) staff for information contributed to the project that is summarised briefly in this paper. We also thank Malcolm Laird, David Smale and Chris Uruski for their helpful comments on this paper; Lee Leonard for drafting and Chris Johnstone for typing the manuscript.

REFERENCES

ANDREWS, P. B., FIELD, B. D., BROWNE, G. H., AND McLENNAN, J.M., 1987: Lithostratigraphic nomenclature for the Upper Cretaceous and Tertiary sequence of central Canterbury, South Island. *New Zealand Geological Survey Record 24.*

BISHOP, D.G., AND LAIRD, M.G., 1976: Stratigraphy and depositional environment of the Kyeburn Formation (Cretaceous): a wedge of coarse terrestrial sediments in Central Otago. *Journal of the Royal Society of New Zealand, 6:* 55-71.

B.P. SHELL TODD, 1984: Interpretation and prospectivity of PPL 38203, Canterbury basin, New Zealand. *Petroleum Report 1046.* New Zealand Geological Survey Library.

BROWNE, G.H., AND FIELD, B.D., 1985: The lithostratigraphy of Late Cretaceous to Early Pleistocene rocks of northern Canterbury, New Zealand. *New Zealand Geological Survey Record 6.*

COOMBS, D.S., CAS, R.A., KAWACHI, Y., LANDIS, C.A., McDONOUGH, W.F, AND REAY, A., 1986: Cenozoic volcanism in north, east and central Otago. In: SMITH, I.E.M. (Ed), Late Cenozoic volcanism in New Zealand. *Royal Society of New Zealand Bulletin 23,* 278-312.

DERNIE, P.J. AND MOUND, D.G., 1986: A review of the Galleon North and South structures PPL 38203. *Petroleum Report 1154.* New Zealand Geological Survey Library.

DUGGAN, M.B. AND REAY, A., 1986: The Timaru Basalt. In: SMITH, I.E.M. (Ed), Late Cenozoic volcanism in New Zealand. *Royal Society of New Zealand Bulletin 23,* 264-277.

FIELD, B.D., 1985: Stratigraphic drill holes at Charteris Bay, Lyttelton Harbour, Christchurch. *New Zealand Geological Survey Report SL11.*

FIELD, B.D. AND BROWNE, G.H., 1986: Lithostratigraphy of Cretaceous and Tertiary sediments, South Canterbury, New Zealand. *New Zealand Geological Survey Record 14.*

FIELD, B.D., BROWNE, G.H., AND OTHERS, 1989: Cretaceous and Cenozoic sedimentary basins and geological evolution of the Canterbury Region, South Island, New Zealand. *New Zealand Geological Survey Basin Studies 2.*

GIBBONS, M.J., AND FRY, S., 1986: A geochemical study of the Galleon-1 well, Canterbury basin, New Zealand. *Petroleum Report 1146.* New Zealand Geological Survey Library.

GIBBONS, M.J., AND HERRIDGE, K.J., 1984: Maturity and source potential of Clipper-1, Canterbury basin, offshore New Zealand. *Petroleum Report 1044.* New Zealand Geological Survey Library.

HAQ, B.U., HARDENBOL, J., AND VAIL, P.R., 1987: Chronology of fluctuating sea levels since the Triassic (250 million years ago to present). *Science, 235,* 1156-1167.

HAWKES, P.W., MOUND, D.G., AND SPICER, P.J., 1985: Clipper-1 evaluation report, PPL 38022. *Petroleum Report 1078.* New Zealand Geological Survey Library.

HERZER, R.H., CHALLIS, G.A., CHRISTIE, R.H., SCOTT, G.H., AND WATTERS, W.A. 1989: Urry Knolls, Late Neogene alkaline basalt extrusives on south-western Chatham Rise. *Journal of the Royal Society of New Zealand, 19,* 181-183.

McLENNAN, J.M., AND BRADSHAW, J.D., 1984: Angular unconformity between Oligocene and older Cenozoic rocks at Avoca, Canterbury. *New Zealand Journal of Geology and Geophysics, 27,* 299-303.

MOUND, D.G., AND PRATT, D.N., 1984: Interpretation and prospectivity of PPL 38202, Canterbury basin, New Zealand. *Petroleum Report 1021.* New Zealand Geological Survey Library.

NATHAN, S., AND OTHERS 1986: Cretaceous and Cenozoic sedimentary basins of the West Coast Region, South Island, New Zealand. *New Zealand Geological Survey Basin Studies 1.*

NEWMAN, J., AND NEWMAN, N.A., 1982: Reflectance anomalies in Pike River coals: evidence of variability in vitrinite type, with implications for maturation studies and "Suggate rank". *New Zealand Journal of geology and geophysics, 25,* 233-243.

SEWELL, R.J., 1988: Late Miocene volcanic stratigraphy of central Banks Peninsula, Canterbury, New Zealand. *New Zealand Journal of geology and geophysics, 31,* 41-64.

SEWELL, R.J., AND GIBSON, I.L. 1988: Petrology and geochemistry of Tertiary volcanic rocks from central inland and South Canterbury, South Island, New Zealand. *New Zealand Journal of geology and geophysics, 31,* 477-492.

STOCK, J. AND MOLNAR, P., 1987: Revised history of early Tertiary plate motion in the south-west Pacific. *Nature 325,* 495-499.

SUGGATE, R.P. AND LOWERY, J.H., 1982: The influence of moisture content on vitrinite reflectance and the assessment of maturation of coal. New Zealand Journal of geology and geophysics, 25, 227-231.

THOMPSON, S., DARLINGTON, C., NG, K.H., AND HASELDONCKX, P., 1978: A petroleum geochemical evaluation of the interval 95-1376 metres of the Kowai No. 1 well, South Island, New Zealand. Appendix 6 of *Petroleum Report 633.* New Zealand Geological Survey Library.

WILSON, I.R., 1985: Galleon-1 geological completion report. *Petroleum Report 1146.* New Zealand Geological Survey Library.

WOOD, R.A., ANDREWS, P.B., HERZER, R.H. AND OTHERS, 1989: Cretaceous and Cenozoic geology of the Chatham Rise region, South Island, New Zealand. *New Zealand Geological Survey Basin Studies 3*.