Structure of the Taranaki Fault from the interpretation of magneto-telluric observations

V Stagpoole[1], S Dravitzki[2], M Ingham[2], S Bennie[1], H Bibby[1]

[1]Institute of Geological & Nuclear Sciences, PO Box 30-368, Lower Hutt, New Zealand. Telephone 64-4 570 4832, Email v.stagpoole@gns.cri.nz [2] Victoria University of Wellington, PO Box 600, Wellington, New Zealand. Telephone 64-4-463 5216, Email Malcolm.ingham@vuw.ac.nz

Abstract

The Taranaki Fault, located along the eastern margin of the Taranaki Basin, is a large thrust fault that juxtaposes Mesozoic metamorphic greywacke against Cretaceous and Cenozoic sediments. Several commercial hydrocarbon discoveries have been made in traps along the fault and it is an important exploration target. Most of our knowledge on the structure of the Taranaki Fault is derived from conventional seismic and gravity surveys. Interpretation of these data has had limited success at delimiting structures beneath the over-thrust block, and accurate determination of the shape of the fault continues to be a challenge to onshore exploration in Taranaki.

Magneto-telluric (MT) studies offer an alternative approach to imaging the structure and hence to produce better definition of the fault geometry, not only in the depth range of immediate interest to the petroleum industry (2 to 5 kilometre), but also at a crustal scale (10 to 30 kilometre). MT surveys are becoming a widely used geophysical method in both petroleum and geothermal exploration where there is a significant resistivity contrast at the target zone. In New Zealand Mesozoic greywacke rocks have high electrical resistivities (up to c. 300 ohm-m) and in contrast, Cretaceous and Cenozoic sedimentary rocks in the Taranaki Basin tend to have low resistivities (c. 3-30 ohm-m). The contrast in the electrical properties of the two rock types, and the essentially 2-D nature of the Taranaki Fault makes it a suitable target for the use of MT data to determine the resistivity structure of the eastern margin of the Taranaki Basin.

After initial forward modelling of the likely resistivity structure to determine the effectiveness of the MT method in Taranaki, a small pilot survey was undertaken along a 35 kilometre east-west transect near Stratford. Results from this survey clearly image the deeper basement structure in the region. These data and the derived 2D models demonstrate the potential of the MT method as an exploration tool to complement existing techniques.

Introduction

The Taranaki Fault is one of the largest known thrust faults in New Zealand. Located at the eastern margin of the Taranaki Basin, its westward displacement has resulted in Mesozoic metamorphic greywacke overlying Cretaceous and Cenozoic sediments. The fault is an important exploration target with several commercial and sub-commercial fields associated with structures along its length.

To date knowledge of the Taranaki Fault has come from exploration drill-holes, seismic and gravity data. Using magneto-telluric (MT) surveying data to determine the resistivity structure of the region provides complementary information on the eastern margin of the Taranaki Basin. The MT surveying technique is a widely used geophysical method, particularly in geothermal exploration and crustal studies (e.g., Ingham and Reeves, 1993; Ingham and Brown, 1998; Wannamaker et al., 2002). A significant resistivity contrast at the target zone is required for clear definition of structure. The basement Mesozoic greywacke rocks at the eastern Margin of the Taranaki Basin have high electrical resistivities (up to c. 300 ohm-m) and in contrast, Cretaceous and Cenozoic sedimentary rocks in the area tend to have low resistivities (c. 3-30 ohm-m). The contrast in the electrical properties of the two rock types indicates that the MT method has potential to delineate the resistivity structure of the eastern margin and add to our knowledge of the region.

The Taranaki Fault

The Taranaki Fault forms the pre-Miocene edge of the Taranaki Basin and is inferred to form one of the fundamental geological boundaries in New Zealand (Mills, 1990; Thrasher, 1990). The fault is part of a system of faults that includes the Waimea, Flaxmore and Manaia faults and the Tarata Thrust (Figure 1). It extends from the Alpine Fault in the South Island to at least offshore Auckland in the north, a distance of over 600 kilometres (Nicol et al., 2004 this volume).

Many exploration wells have intercepted the Taranaki Fault with drilling targets that have been based on seismic reflection data that images the upper 2 - 5 kilometre of the structure. The deeper structure of the fault has been interpreted from the large positive gravity anomaly associated with the up-thrown hanging wall (Mills, 1990; Holt and Stern, 1994). The gravity anomaly, associated with the fault was named the Patea-Tongaporutu High by Acheson (1939), who deduced that its origin was from a large basement fold. Subsequently the term Patea-Tongaporutu High has become the name for the basement structure.

Analysis of seismic reflection data indicates that the average dip of the fault is between 25° and 45° with indications that it flattens towards the tip and at crustal depths, between four and five seconds TWT (11 - 15 kilometres). Typically there is over six kilometres of vertical displacement and the observed horizontal displacement is up to 15 kilometres (Nicol et al., 2004 this volume).

Faulting History

The Cretaceous to Eocene history of the Taranaki Fault is inconclusive because sediments older than Eocene in age are not found on the eastern, upthrown side of the fault. Many studies have depicted the fault as normal throughout the Cretaceous and Paleogene, with inversion and thrusting occurring in the Late Oligocene and Early Miocene (e.g. Mills, 1990; King and Thrasher, 1992). However, there is evidence of Late Eocene uplift on the Taranaki Fault and the Manaia Anticline west of the fault (Voggenreiter, 1993; Palmer and Andrews, 1993; Holstege and Bishop, 1998; Nelson et al. 1994; Nicol et al., 2004 this volume) with a significant proportion of uplift occurring before the Oligocene (Nicol et al., 2004 this volume). North of the Taranaki Peninsula most reverse movement on the Taranaki Fault ceased in the Early Miocene about 20 million years ago. South of the peninsula, fault movement continued into the Late Miocene, or possibly later (Nicol et al., 2004 this volume).

Petroleum exploration and prospectivity

In 1959 the Kapuni gas /condensate field was discovered by the Shell BP and Todd consortium in Late Eocene strata on the Manaia Anticline. This was the first major commercial discovery in Taranaki outside the New Plymouth area. Kapuni went into production in 1970. From 1978 the Crown-owned Petroleum Corporation of New Zealand began a strong exploration program onshore. This resulted in the discovery of several petroleum accumulations along the eastern margin of the basin including the McKee and Waihapa/Ngaere oil fields in the Tarata Thrust Zone. In 1986 New Zealand Oil and Gas Ltd discovered hydrocarbons (oil and gas/condensate) in the Kupe South structure on the Manaia Anticline south of the Taranaki peninsula. Swift Energy began development of the Rimu oil field in 1999 after the company's exploration of prospects associated with the fault in the southern Taranaki Peninsula. The Rimu reservoir was discovered beneath the Taranaki Fault overthrust.

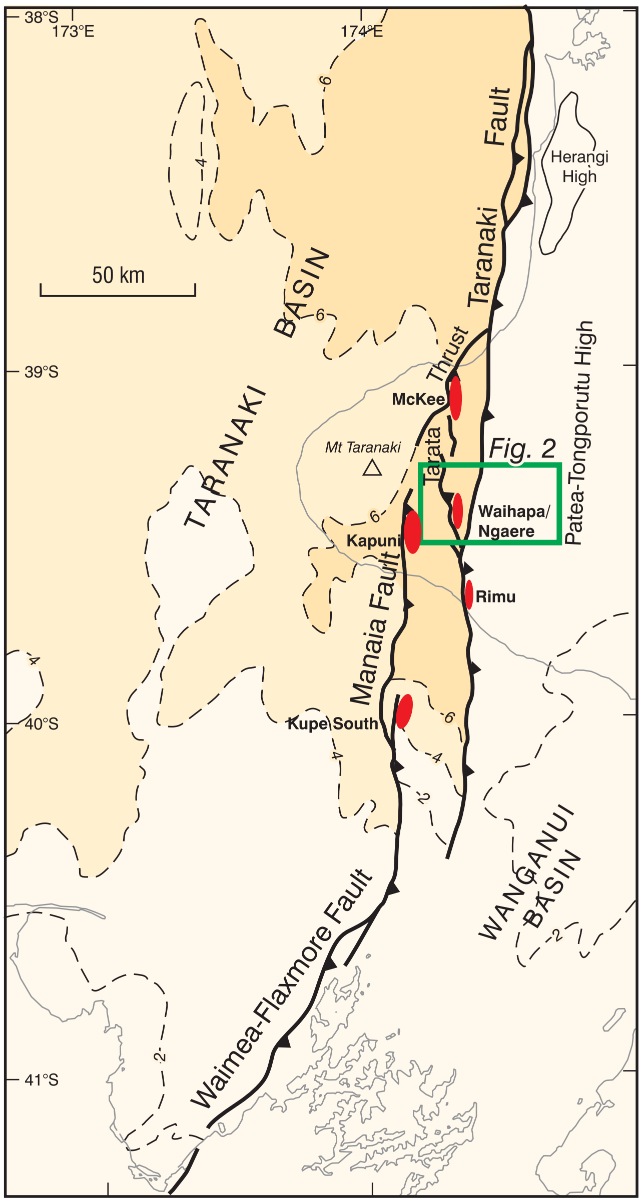

Figure 1. Location diagram showing the smoothed total sediment thickness in the Taranaki Basin, the position of the Taranaki Fault and proximal petroleum fields.

Petroleum accumulations (oil and gas/condensate) associated with the Taranaki Fault occur at several levels from Cretaceous Farewell Formation to Eocene Tariki Sands and Miocene Tikorangi Limestone targets. Most prospects are structural traps at greater than three kilometres depth. McKee, the largest oil field so far discovered, had recoverable reserves of 45 MMbbl of oil and 160 BCF gas (King and Thrasher, 1996).

Magnetotelluric Survey

The MT geophysical method uses natural fluctuations in the earth's magnetic field to determine the resistivity structure beneath the ground surface. At each MT site, simultaneous observations are made of the earth's magnetic and electric fields for up to two days. Together, these data are analysed in the frequency domain. The lower frequency data sense the resistivity of more distant and generally deeper layers. The MT method offers an alternative and complementary exploration tool to seismic and gravity surveying. It is particularly appropriate as a deep penetration reconnaissance tool used for delineating large scale conductive zones within sedimentary basins and the crust.

Before undertaking the survey, analysis of borehole resistivity logs indicated that the resistivity of Cretaceous and Cenozoic sediments generally range between 3 ohm-m and 30 ohm-m, but can be greater than 500 ohm-m for coal seams. The basement resistivity ranges from 30 to 300 ohm-m. Forward models of possible Taranaki Fault structures suggested that to resolve the basement overthrust wedge a resistivity contrast of about 10:1 (that is a basement resistivity ten times that of the Cretaceous and Cenozoic sediments) would be required (Dravitzki, 2003).

Survey observations and data processing

Four and five component MT data were recorded at 13 sites along a 35 kilometre profile perpendicular to the Taranaki Fault near Stratford (Figure 2). Instrumentation consisted of 3 Phoenix MTU-2000 systems synchronised by GPS clocks (GNS instruments) and a single 4-component system belonging to Victoria University of Wellington. Field observations were made between the 3rd and 12th of February 2003. Data were recorded at each site for about 40 hours (i.e. for two nights). Calibration data for the magnetic field sensors (coils) and recording electronics were also collected during this period. The site located at the eastern end of the profile was used as a remote reference for cross-correlation with the data from some of the other sites to reduce electric fence and other cultural noise that contaminate the records (Gamble et al., 1979).

Most sites were contaminated by electric fence noise to some degree. This noise is characterised by pulses at about 1 s intervals and is not able to be removed by the remote reference signal processing for periods less than about twice the pulse rate of the electric fence, i.e. less than about 2 s. The effect of the electric fence noise is to override the natural signals, causing uncertainty in calculated apparent resistivity and phase values in the period range between 0.07 and 2 seconds. At one site (EMT010) the level of cultural noise contamination from electric fences and nearby power lines was so great that data from this site could not be used in modelling and interpretation.

Data were processed using robust analysis techniques, which minimize the effect of data outliers, to give estimates of MT impedance tensor at discrete period values. Apparent resistivity and phase values were determined from the impedance tensor, as a function of period. At a number of sites where electric fence noise caused significant distortion of apparent resistivity and phase curves, rational function interpolation (Nonweiler, 1984) was used to smooth the curves across the affected period range. Examples of measured apparent resistivity and phase data from sites to

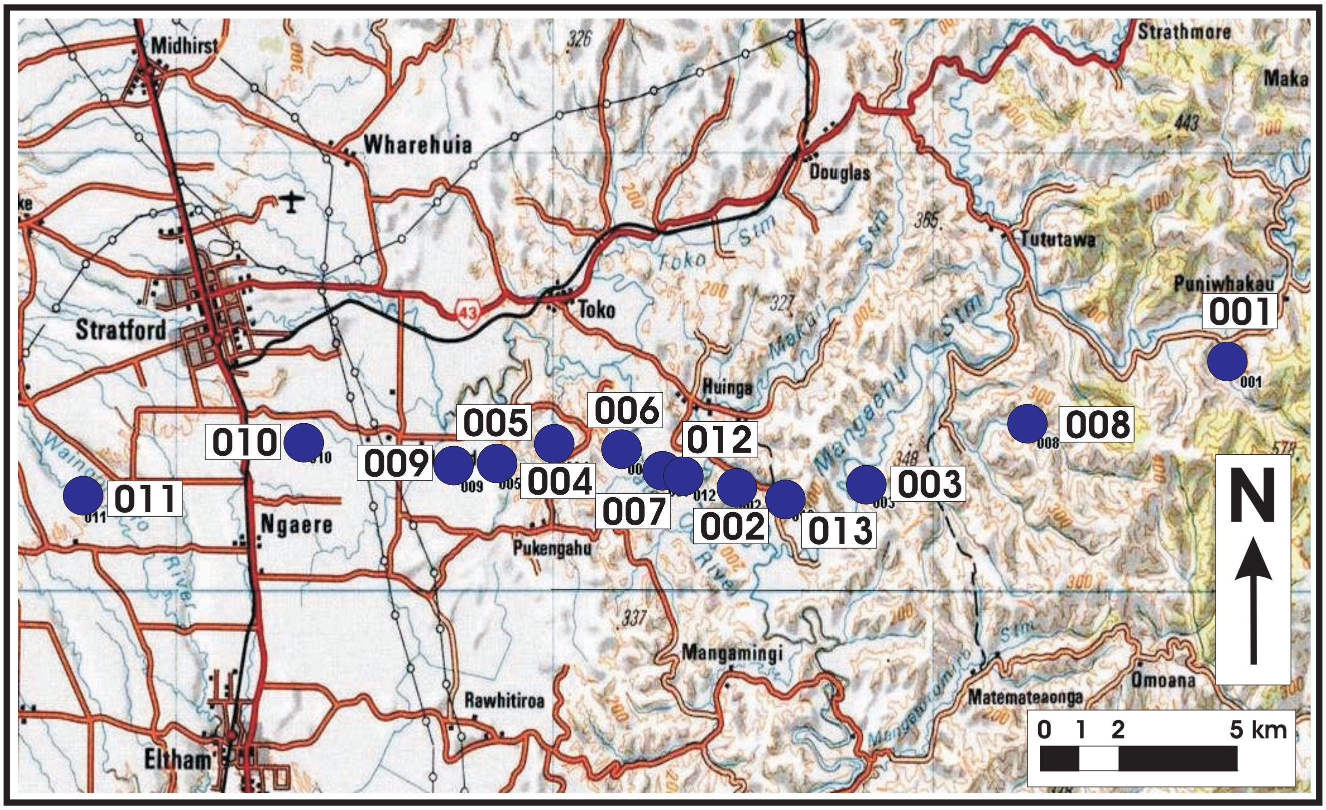

Figure 2. Location and station numbers of the MT sites (background map from LINZ).

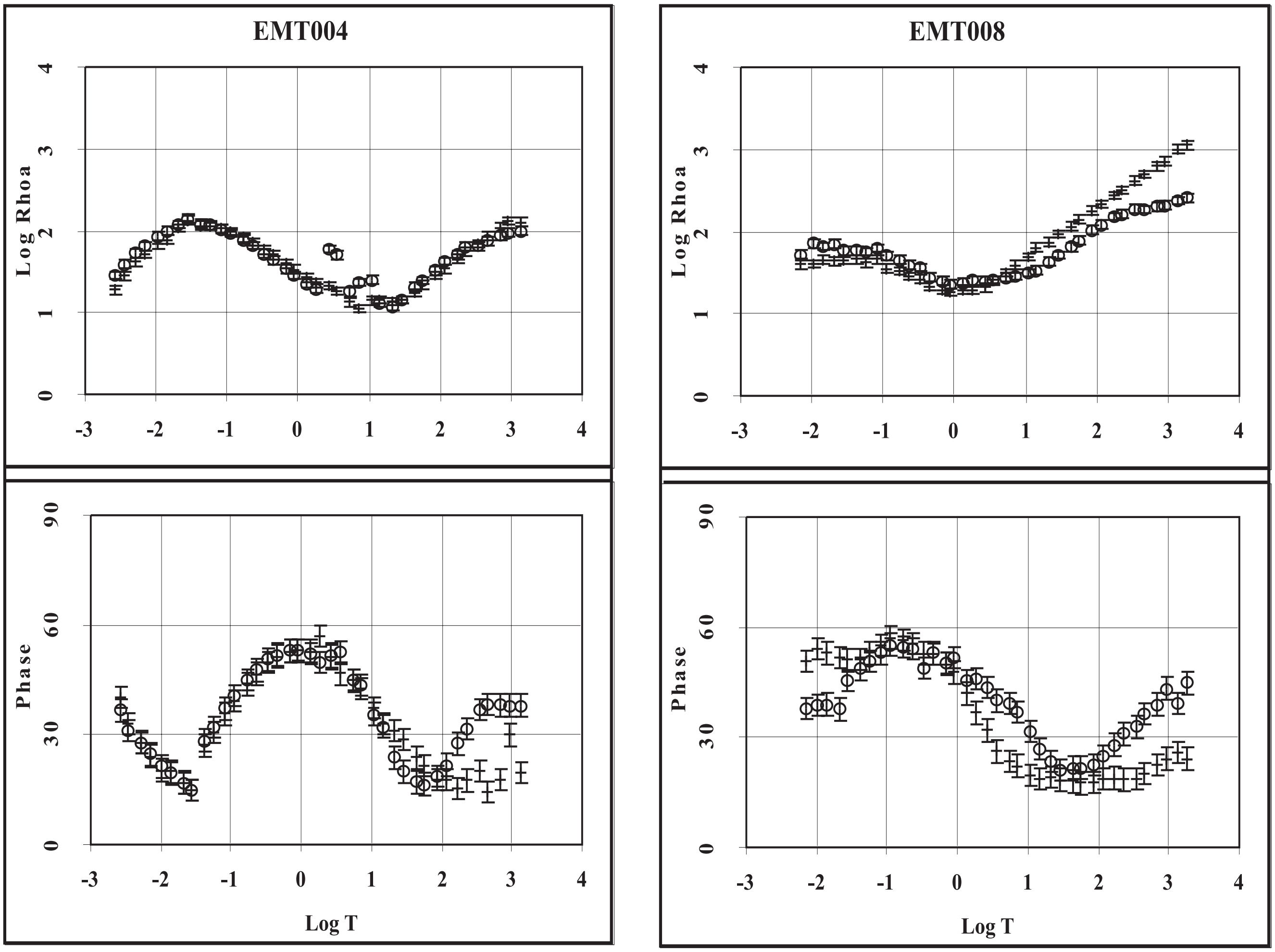

Figure 3. Examples of measured apparent resistivity and phase data from sites to the west (EMT004) and east (EMT008) of the Taranaki Fault. Note that data from station EMT004 has been smoothed.

the west and east of the Taranaki Fault are shown in Figure 3. The basic shapes of the curves are typical of all the measurement sites and indicate the existence of a conductive layer lying between two more resistive layers. As can be seen from Figure 3, the curves for the two polarisations are infer generally isotropic conditions over much of the measured period range, diverging in both apparent resistivity and phase only at the longest periods where the data are sensitive to structure that is both deeper and more laterally distant.

A broad interpretation of the data indicates that the basement resistivity is between 100 and 500 ohm-m. The Cretaceous and Cenozoic sedimentary cover, although it contains high resistivity beds, has a bulk resistivity that ranges between 3 and 50 ohm-m. The resistivity of the basement overthrust wedge also appears to be low (about 30 ohm-m) and so its structure will be difficult to determine from the adjacent Cretaceous and Cenozoic sediments. However, the high resistivity contrast between Cretaceous and Cenozoic sediments and the deeper basement can be modeled using a 2D inversion program.

Two dimensional models

Data inversion and modelling was carried out in the measurement axes (magnetic NS-EW). This axial system is very close to parallel and perpendicular to the assumed fault strike and the off-diagonal elements of the impedance tensor may therefore be treated as being the TE and TM mode data. Prior to inversion and modelling, apparent resistivity data were manually corrected for static-shift by raising or lowering apparent resistivity values to match curves in the period range 0.01 - 0.1 s.

Two dimensional (2D) numerical inversion of the MT data was undertaken using the Rapid Relaxation Inversion program of Smith and Booker (1991). The program produced a number of inversions with varying parameters. Smoothing iterations allow a trade-off of quality of fit with smoothness of structure and often produces a structure that is more geologically reasonable. Results from a smoothed 2D inversion are shown in Figure 4 for the upper 10 kilometres of the profile with interpreted basement depth from seismic reflection data. The inversion uses smoothed parameters, so that regions of rapid resistivity change, such as may occur at faults, are suppressed and seen as a smooth gradient in resistivity.

The resistivity contrast between the basement and sediments is most clearly observed at the eastern end of Figure 4, where up to four kilometres of low resistivity sediment is interpreted to overlie the basement. At the Taranaki Fault the high resistivity basement steps down to over six kilometres depth, in good agreement with seismic reflection data. The deep basement has a generally lower resistivity west of the fault than to the east, possibly reflecting different rock types.

A resistivity contrast between the basement overthrust wedge and Cretaceous and Cenozoic sediments is not apparent in Figure 4. These MT data indicate that the overthrust block has different physical properties to Mesozoic greywacke in the eastern part of the cross-section and elsewhere in New Zealand (Wannamaker et al., 2002). Possible reasons for the low resistivity basement in this zone include; joints and fractures filled with low resistivity pore fluids, or the presence of significant alteration products and clays within the overthrust block, resulting in the basement rock having anomalously low resistivity.

Both the 2D inversion and forward models of the data indicate that the basement resistivity east of the fault is between two and five times the basement resistivity in the west. The boundary between these zones correlates with the predicted Brook Street – Murihiku terrane boundary of Mortimer (2002) and the resistivity contrast suggests that the two terranes have different electrical properties.

Discussion

Results from the survey indicate that the resistivity signature of the basement overthrust wedge is subtle. There appears to be little contrast between the overthrust and adjacent Cretaceous and Cenozoic sediments. In this situation it is important for MT data to be of the highest quality. Unfortunately man-made noise (particularly from electric fences) contaminated the the pilot survey data in the critical time period (between 0.07 and 2 seconds). Further work is required to filter out this electrical interference in order to precisely determine the resistivity contact and hence overcome the impediments for resolving the overthrust structure.

The most likely causes for the small contrast in resistivity between the basement overthrust wedge and Cretaceous and Cenozoic sediments are conductive fluids in basement fractures, and the presence of clays in basement produced by weathering and faulting of the overthrust block. Given the large total displacement on the Taranaki Fault (>10-12 km) the overthrust basement wedge may well have been intensely weathered and pervasively deformed by brittle faulting and jointing. This hypothesis is supported the anomalously low velocities observed within the basement wedge (Maslan pers. comm., 2003) and by the apparent imbrication and reordering of strata in wells that penetrate the thrust wedge. The MT method may, therefore, be of some use for accessing the competency of basement rock above the fault, and to determine the extent to which this rock is deformed.

The MT data can be used to determine the depth to basement over most of the profile, although there is a low station density at each end of the line, and the uncertainty in depth from the 2D inversion is quite large in these areas. The data are useful for estimating the depth to basement beneath the overthrust wedge, which is an important factor in determining extent and maturity of potential source rock close to the fault. In addition, the resistivity contrast between basement rocks on either side of the fault appears to correlate with a predicted terrane boundary (Mortimer, 2002). The MT method may provide a means for mapping these terranes in other areas, however more work has to be determine the MT methods applicability.

Conclusions

The main features of the derived models are consistent with previous geophysical investigations. West of the Taranaki fault the conductive sediments of the Taranaki Basin are at least seven kilometres thick, while to the east they are between two and four kilometres thick. The basement

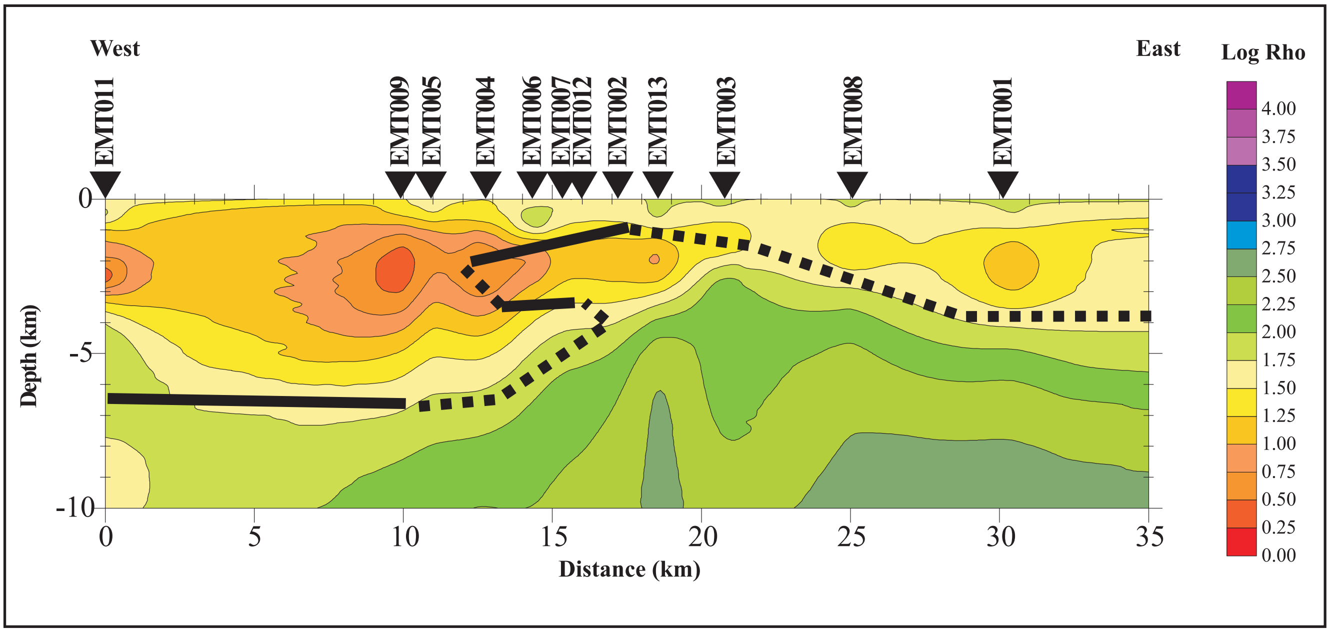

Figure 4. A static-shifted and smoothed 2D model of the upper 10 kilometre of the profile. The overlying lines indicate the depth of basement interpreted from seismic reflection data (bold) and the possible extent of basement derived from interpretation of the MT data (dashed). Note the over-thrust section of the fault has low resistivity compared to other parts of the model.

overthrust wedge, however, has low resistivity, unlike rocks of similar composition in the eastern part of the cross-section and elsewhere in New Zealand. Conductive pore fluids in joints and fractures, and/or the presence of alteration products and clays is suggested as a possible cause for the anomalously low resistivity of the basement overthrust wedge.

2D inversion of the MT data indicates Mesozoic basement has resistivities that range from 50 to 500 ohm-m and adjacent Cretaceous and Cenozoic sediments generally have resistivities of less than 50 ohm-m. Models show that basement west of the Taranaki Fault has a lower resistivity (typically < 100 ohm-m) than basement to the east. This resistivity boundary coincides with a predicted basement terrane boundary.

Although MT observations are easily contaminated by man-made noise, particularly from electric fences, careful site selection enables acquisition of good quality data. The results of the pilot survey presented here suggest that the MT method could be a useful geophysical tool that provides information to enhance our knowledge and hence help to evaluate the petroleum prospectivity of the eastern margin of the Taranaki Basin.

References

Acheson, V.A., 1939. Final report on Gravimetric survey of portions of Taranaki and Wellington land districts. Unpublished open-file *Petroleum Report* 141. Ministry of Economic Development, New Zealand.

Dravitzki, S.M., 2003. A magnetotelluric investigation of the Taranaki Fault. Unpublished *BSc Honours thesis*, Victoria University of Wellington, New Zealand

Gamble, Goubou, W.M. and Clarke, J., 1979. Magnetotellurics with a remote reference. *Geophysics*, 44, 53-68.

Holstege, G.C.J., Bishop, D.J., 1998. Structural evolution of the Kapuni Field, New Zealand. 223-232 In: *1998 New Zealand Petroleum Conference Proceedings*. Ministry of Economic Development, New Zealand.

Holt W.E and Stern T.A., 1994. Subduction, platform subsidence, and foreland thrust loading: the late Tertiary development of Taranaki Basin New Zealand. *Tectonics,* 13, 1068-1092.

Ingham, M., Brown,C., 1998. A magnetotelluric study of the Alpine Fault, New Zealand. *Geophysical Journal International*, 135(2), 542-552

Ingham, M.R., Reeves, R., 1993. Magnetotelluric soundings and structure of the Tokaanu geothermal field, New Zealand. *Journal of Geomagnetism and Geoelectricity*, 45(9), 729-740

King P.R. and Thrasher G.P., 1992. Post-Eocene development of the Taranaki Basin, New Zealand. Convergent overprint of a passive margin. In Watkins J. F. et al. (eds), Geology and Geophysics of continental margins. *American Association of Petroleum Geologists Memoir,* 53, 93-118.

King P.R. and Thrasher G.P., 1996. Cretaceous and Cenozoic geology and petroleum systems of the Taranaki Basin, New Zealand. *Institute of Geological and Nuclear Sciences Monograph* 13. Institute of Geological and Nuclear Sciences Ltd, Lower Hutt, New Zealand.

Mills, C., 1990. Gravity expression of the Patea-Tongaporutu High and subsequent model for the Taranaki Basin margin. In: *1989 New Zealand Oil Exploration Conference Proceedings* 191-200. Ministry of Economic Development, New Zealand.

Nelson C.S., Kamp P.J.J., Harvey R.Y., 1994. Sedimentology and petrography of mass-emplaced limestone (Orahiri Limestone) on a late Oligocene shelf, western North Island, and tectonic implications for eastern margin development of Taranaki Basin. *New Zealand Journal of Geology and Geophysics*, 37, 269-285.

Nicol A., Stagpoole, V.M. and Maslen G., 2004 (*this volume*). Structure and Petroleum Potential of the Taranaki Fault play . In: *2004 New Zealand Oil Exploration Conference Proceedings*. Ministry of Economic Development, New Zealand.

Nonweiler, T.R.F., 1984. Computational mathematics : an introduction to numerical approximation. p. 119-128. Ellis Horwood ltd, Great Britain.

Palmer J.A. and Andrews P.B., 1993. Cretaceous-Tertiary sedimentation and implied tectonic controls on the structural evolution of Taranaki Basin, New Zealand. In: Ballance P.F. (ed), *South Pacific Sedimentary Basins. Sedimentary Basins of the World* 2, 309-328. Elsevier, Amsterdam

Smith, J.T. and Booker, J.R., 1991. Rapid inversion of two- and three-dimensional magnetotelluric data. *Journal of Geophysical Research*, 96, 1168-1171.

Thrasher G.P., 1990. Tectonics of the Taranaki Rift. In: *1989 New Zealand Oil Exploration Conference Proceedings*, 124-133. Ministry of Economic Development, New Zealand.

Voggenreiter W.R., 1993. Structure and evolution of the Kapuni Antcline, Taranaki Basin, New Zealand: evidence from the Kapuni 3D seismic Survey. *New Zealand Journal of Geology and Geophysics*, 36, 77-94.

Wannamaker, P.E., Jiracek, G.R., Stodt, J.A., Caldwell, T.G., Gonzalez, V.M., McKnight, J.D., Porter, A.D., 2002, Fluid generation and pathways beneath an active compressional orogen, the New Zealand Southern Alps, inferred from magnetotelluric data. *Journal of Geophysical Research., 10,* doi:10.1029/2001JB000186.

Acknowledgements

The authors thank Nick Cozens for helping with the fieldwork and Indo-Pacific Energy for providing well and seismic data and useful discussions on the project. We thank the many farmers and property owners in the Stratford and Toko area for allowing us to make MT measurements on their land. This manuscript has benefited from reviews by Rob Funnell and Terry Russell. The project has been funded by the Foundation for Research, Science and Technology contracts CO5X0302 (GNS) and VICX0204 (VUW).

Authors

VAUGHAN STAGPOOLE is a geophysicist with the Institute of Geological & Nuclear Sciences Limited. He is an Objective leader in the Institutes Hydrocarbons Section and specialises in research on the formation and development of sedimentary basins. Vaughan has a BSc (Honours) and PhD from Victoria University of Wellington.

MALCOLM INGHAM is a Senior Lecturer in the School of Chemical & Physical Sciences at Victoria University of Wellington. He has over 25 years experience in the application of the magnetotelluric method in structural, tectonic and geothermal studies. Malcolm has an MA from Cambridge University and PhD from the University of Edinburgh.

STACEY DRAVITZKI has a BSc (Honours) degree in Geophysics from Victoria University of Wellington. She is currently enrolled as an MSc student at Victoria using MT to study the deep structure of Mt. Ruapehu.

STEWART BENNIE is a geophysicist at Institute of Geological & Nuclear Sciences Limited. He specialises in geophysical investigation of geothermal resources and epithermal mineral deposits, monitoring of mine waste sites and measurement of the geomagnetic field in the New Zealand region. Stewart has a BSc (geophysics) and Diploma of Energy Technology (geothermal) from Auckland University.

HUGH BIBBY is a geophysicist at the Institute of Geological & Nuclear Sciences Limited who specialises in the use of electrical techniques to study volcanoes and geothermal processes. Hugh has published widely on the theory and application of tensor methods in electrical surveying and earth deformation studies. He has a PhD from the University of Manchester and is a Fellow of the Royal Society of New Zealand.