# East Coast Basin Exploration

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## Abstract

Petroleum Exploration Permit 38329 covers 5 550 km² onshore Hawke's Bay on the East Coast of the North Island, New Zealand. Exploration activities have focused on reprocessing existing seismic, acquisition of 375 km new seismic, and geological field studies of Miocene sandstones. Interpretation of the seismic data has revealed the presence of several untested anticlinal closures with potential Miocene and Pliocene reservoirs.

Existing seismic data were reprocessed with special emphasis on refraction statics, surface consistent statics, deconvolution, and spectral whitening. Significant reprocessing improvements provided a regional framework for the northern and western portions of the permit. A 275 km reconnaissance vibroseis survey acquired along existing roads covered areas previously unexplored by seismic. Subsequent acquisition of 100 km of detailed cross-country heliportable dynamite seismic over the highly prospective central third of the permit confirmed structural closures.

Two of the new seismic lines provide a 70 km west to east transect of the East Coast Basin along the northern edge of Hawke Bay. A thick Miocene-Pliocene basin-fill in the west is still poorly resolved seismically. In the central portion, asymmetric anticlines with eastward vergence deform a Pliocene to mid-Miocene succession, which appears to rest unconformably on Paleogene or older strata. The eastern part of the transect contains a thick early to mid-Miocene succession overlying thrust-faulted Paleogene and Cretaceous strata. Starting in the latest-Miocene, this eastern basin was uplifted, while the Wairoa structural high subsided. Basin infilling and uplift in the Wairoa area has occurred within the last 2.6 million years.

The primary reservoir target is the mid-Miocene Makaretu-D sandstone which has been tested in only one well, Ruakituri-1. Core and ditch cuttings indicate the presence of very fine to fine, well to moderately sorted, slightly to moderately consolidated sandstone with variable amounts of coarse fragments of mollusc shells, benthic foraminifera, and shale lithoclasts. Certain intervals exhibit good reservoir parameters with analyses indicating porosities up to 27% and permeabilities up to 238 mD.

The presence of several untested anticlines and the paucity of subsurface data warrant an early drilling programme. The initial drilling phase comprising four exploratory wells is scheduled to commence March 1998.

## Introduction

This paper discusses the exploration status of Petroleum Exploration Permit 38329, which covers 5 550 km² onshore northern Hawke's Bay, North Island, New Zealand (Figures 1, 2). The permit, with offshore PEPs 38325 and 38326, was awarded to Westech Energy New Zealand Limited and Enerco New Zealand Limited in May 1996.

Petroleum exploration has taken place in the East Coast for over 100 years without yielding any commercial discoveries. While only five wells have been drilled in the last 20 years, geological research has intensified in the last few years. The understanding of structural style has been influenced by the seismic interpretation of Uruski (1994, 1996, unpublished 1997) and Field, Uruski et al (in press). Reservoir studies by Francis (1991a, 1993, 1994) have highlighted the potential of Miocene sandstones.

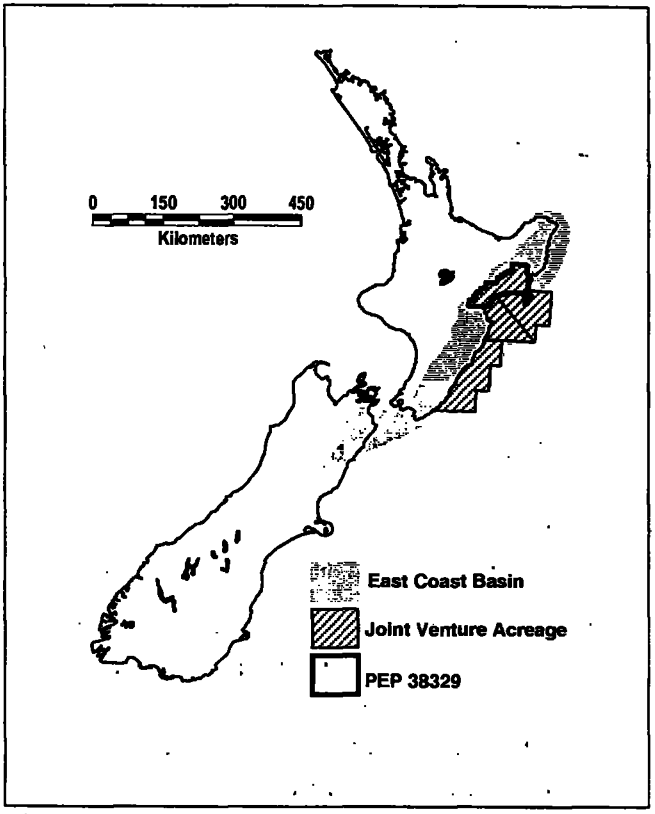


Figure 1. Location of the East Coast Basin in New Zealand, overlain by Westech-Enerco permit areas, including PEP 38329.

Geochemical studies by Rogers (1995), Killops et al (1996) and Francis and Murray (1997) have elucidated biomarker characteristics of potential source rocks, and correlated these with oil and gas seeps. Simpson and Jarvis (1993) and Field, Uruski et al (in press) have provided basin overviews. Collectively, these studies have provided a comprehensive foundation for the current petroleum exploration programme of Westech and Enerco.

## Regional Setting

The East Coast Basin is a complex of Cretaceous to present day sedimentary basins bounded to the west by the axial mountain ranges of the North Island, and extending offshore across the continental shelf and slope to the Kermadec-Hikurangi subduction zone. Strike-slip deformation predominates along the western margin of the basin, as part of a zone that extends south to the Alpine Fault in the South Island. Compressional tectonics with southeast-verging thrust faults dominate the centre and eastern margin of the basin, along with a component of strike-slip deformation.

## Stratigraphy

The basement rocks of the East Coast Basin are Triassic to Early Cretaceous, indurated and strongly deformed sandstone and mudstone of the Torlesse Terrane. These are onlapped by Early Cretaceous shelf sandstone north of the permit area, succeeded by a thick interval of Late Cretaceous deep-water sandstone and mudstone (Figure 3). The tectonic setting for Cretaceous sedimentation is interpreted as a subduction margin similar to the modern environment (Mazengarb and Harris 1994).

From the Late Cretaceous through the Paleogene, a passive margin existed. Siliceous mudstone of the Whangai Formation and organic-rich mudstone of the Waipawa Black Shale succeeded shelf sandstones in the northeast. Bentonitic mudstones of the Eocene Wanstead Formation and fine-grained limestone of the Oligocene Weber Formation completed the passive-margin deposition (Figure 3).

At the beginning of the Miocene, a new plate boundary between the Indian and Pacific Plates propagated through New Zealand, causing renewed subduction along the eastern margin of the country. Earliest Miocene sediments are glauconite-rich, reflecting the redeposition of shelf sediments into newly created deep-water basins (Ballance 1993). Early-Miocene sediments are mud-dominated, but include sandstone formations such as the Rere Sandstone and Whangara Greensand.

The mid- to late-Miocene was a period of rapid sedimentation, dominated by gravity-flow sandstones of the Tunanui and Makaretu formations (Figure 3). The latest Miocene comprises deep-water deposited mudstone, siltstone and tuff beds up to 2000 m thick, which should provide an effective seal over the older sandstone formations.

Pliocene sediments exposed onshore are characterised by thick coquina limestones which commonly unconformably overlie Miocene sediments. Seismic profiles show that elsewhere, basinal sedimentation continued uninterrupted into the Pliocene, and this relatively recent thick cover may be a major control on maturation of the Cretaceous to Paleogene source rocks.

## Reservoir Development

The presence and quality of reservoir rocks have been regarded as major exploration risks in the East Coast. Nearly all wells have had pre-Miocene targets, and it is only in the more central portion of the basin that a large thickness of Pliocene to Miocene, with the well-developed mid- to late-Miocene Makaretu and Tunanui sandstones, has been preserved. The Makaretu sands are the primary target of the current exploration programme, and are discussed in a later section. Additional potential reservoirs comprise Pliocene coquina limestones, and early- to mid-Miocene sandstones of the Tunanui, Taumatapoupou and Rere formations. Pliocene limestone exposures around inland Hawke's Bay range up to 100 m thick, and exhibit high porosity and permeability. Lateral facies changes to deepwater mudstone have blighted previous exploration focused on these targets.

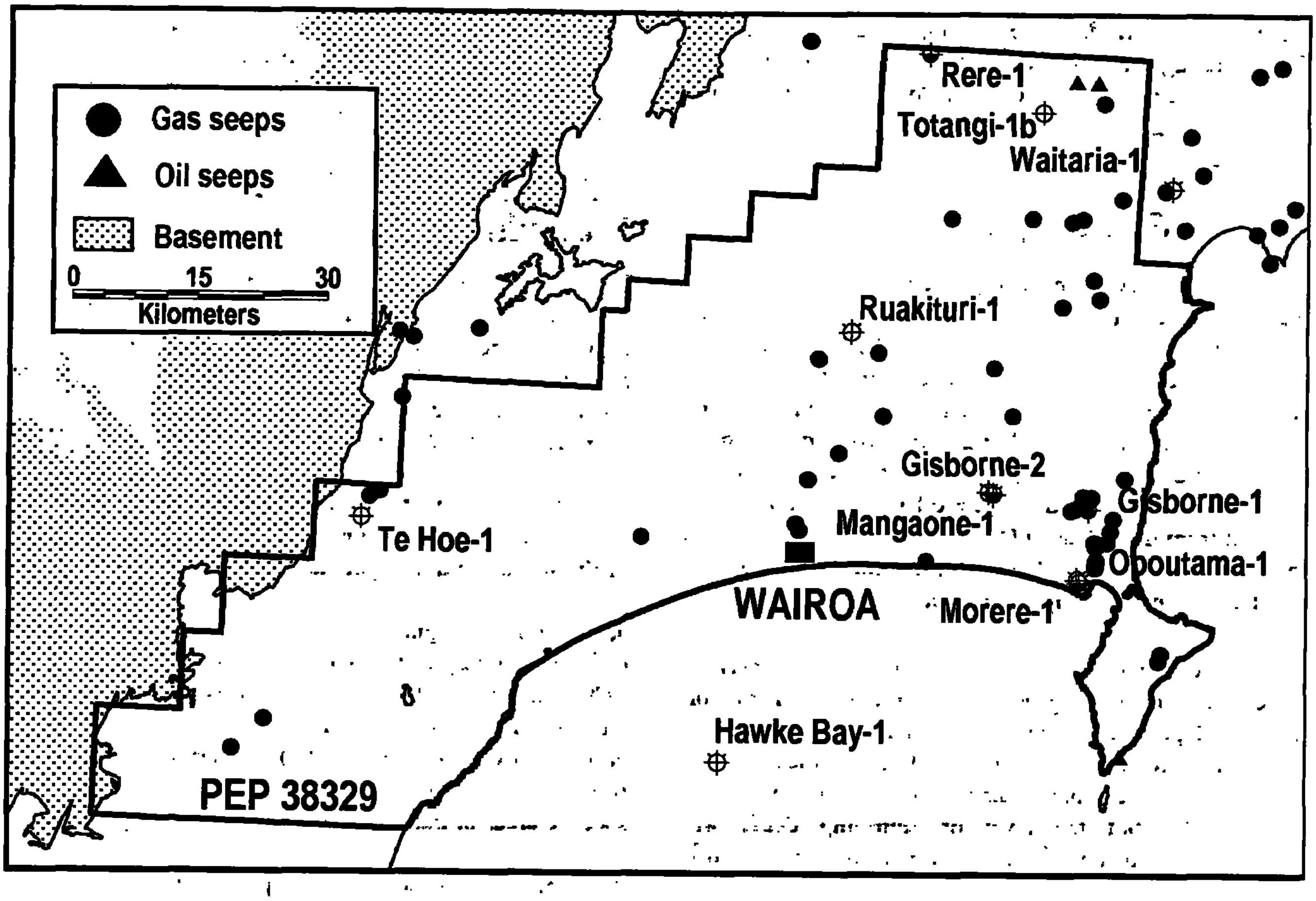


Figure 2. Petroleum wells and hydrocarbon seeps in PEP 38329, East Coast Basin (seep locations in part after Francis 1995).

## Source Rock and Maturity

The most prospective source rock identified is the Waipawa Black Shale of Paleocene age, up to 50 m thick and widespread in the East Coast Basin. Analyses summarised by Leckie et al (1992) indicate 0.59-5.26% TOC. Cross-plots of the Hydrogen Index (HI) and the Oxygen Index indicate a dominance of Type II kerogen (gas and oil prone) with a contribution of Type III (gas prone). High HI and S1/S2 values indicate that oil is likely to be generated.

The Waipawa Black Shale outcrops in several localities on the western margin of the basin, and also to the east in scattered outcrops on Mahia Peninsula and on the coast south of Hawke's Bay (Leckie et al 1992). This provides support for the presence of the formation in large synclinal kitchens ranging to below 5000 m depth within and adjacent to PEP 38329. This depth exceeds the 3000-4500 m oil generation window based on the present-day geothermal gradient of 25°C/km (de Bock et al 1986; Field, Uruski et al in press). Killops et al (1996) postulated an environment of deposition restricted to the top of the continental slope, and this may restrict Waipawa Black Shale distribution in parts of the permit area.

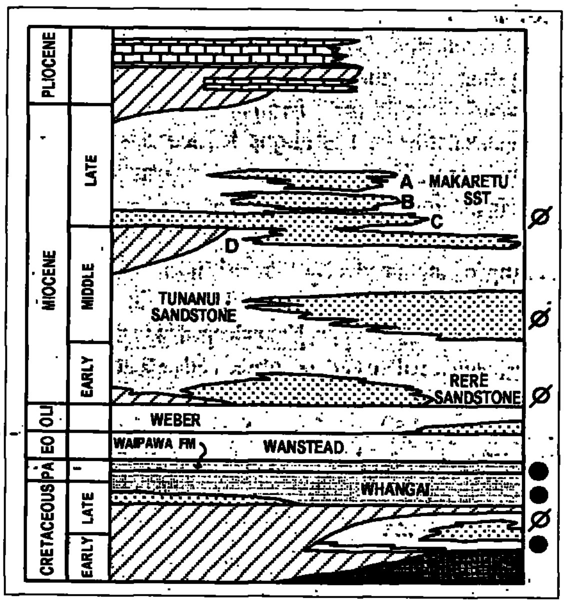


Figure 3. Generalised stratigraphic column of the East Coast Basin in the PEP 38329 area. Hatched intervals are periods of erosion and/or non-deposition. Solid circles in the right hand column indicate potential source rock intervals; open, slashed circles indicate potential reservoirs.

The underlying Whangai Formation, of Paleocene to Late-Cretaceous age, comprises calcareous, siliceous mudstone with minor sandstone and chert. Two members with a net thickness of 250-500 m are graded as poor to fair source rocks (Leckie et al 1992).

## Oil and Gas Seeps

Numerous gas seeps have been reported from northern Hawke's Bay (Figure 2; Francis 1995). Methane predominates, with traces of higher hydrocarbons. Oil seepages occur at Totangi and Waitangi, 65 and 85 km respectively northeast of Wairoa. The seeps are in Miocene rocks, and the oils are highly paraffinic with low viscosity and gravities of 25°-35° (Francis 1995). Oil typing by Rogers (1995) indicated that the oil seeps were probably sourced from the Whangai Calcareous Member rather than the Waipawa Black Shale, based on the minor quantities of $C_{30}$ steranes and low sulphur content.

The abundance of gas seeps in the permit area may be indicative of deep gas generation or fractionation from oil traps at depth. A reconnaissance Petrex soil-gas survey (Northeast Research Institute, 1995) indicated that prospective geochemical anomalies are present in the permit area, but the level of sampling detail was insufficient to distinguish a gas versus oil accumulation origin.

Gas samples from tests of three separate intervals between 891 m and 1529 m in Ruakituri-1 comprised 99.3-99.6% methane and 0.4-0.7% higher hydrocarbons (Phizackerley and Robinson 1962).

## Seals

Between and above the major Miocene sand units, the section is predominantly massive mudstone, which should form an excellent regional seal. This mudstone dominance persists into the Pliocene. The possibility of breaching of structures by faulting is difficult to quantify with the existing loosely spaced seismic grid, however there does not appear to be a lot of small-scale crestal faulting, and roll-over is observed structurally above fault intersections.

The risk of fresh-water flushing is low, based on analyses of water recovered on drill-stem test from Ruakituri-1. A shallow test at 891-893 m yielded water with 10 850 ppm NaCl (Phizackerley and Robinson 1962).

## Seismic Acquisition and Processing

The quality of previous seismic ranges from very poor to fair (Table 1; locations on Figure 4). The 1982 survey provides good regional coverage in the eastern part of the permit area, with line lengths of 25-65 km. Figure 5a shows part of line GW-1, as lodged with the Ministry of Commerce in 1982.

One of the first methods used to evaluate the permit was the reprocessing of existing seismic control. Using state-of-the-art techniques such as refraction statics, spectral whitening, and surface consistent statics and FX deconvolution, significant improvements were made in producing interpretable sections. The GW, GIS84 and EC91 lines responded well to reprocessing, except on the crests of anticlines or faulted structures, where the signal to noise ratio was poor (Figure 5b). Nevertheless, these lines provided a regional framework and allowed focus on specific areas of interest.

A significant portion of the permit had never been explored with seismic, particularly the area along the coast covered by Plio-Pleistocene sediments. A 275 km reconnaissance vibroseis survey along roads and tracks was carried out in February to March 1997 and it highlighted prospective areas for further evaluation by cross-country heliportable dynamite surveys. A 62 km survey was carried out in June 1997, followed by a 38 km survey completed in January 1998 (Figure 4). All surveys were conducted by GECO-Prakla in association with BTW Surveys and Drillwell Exploration.

A 10 m receiver interval was chosen in order to provide increased spatial sampling in an area involving steep dips and faults. The tight receiver interval provided better trace-to-trace continuity on the seismic records, and a better image of the subsurface. For the vibroseis survey, the geophone array within the receiver group comprised

| Company | Series | Year | No. lines | Km | Quality | Source |
|---|---|---|---|---|---|---|
| Petrocorp | G | 1979 | 4 | 95 | Very poor | vibroseis |
| Petrocorp | GW | 1982 | 6 | 263 | Poor | dynamite |
| Petrocorp | GIS84 | 1984 | 8 | 157 | Fair | dynamite |
| Claremont | CM84 | 1984 | 5 | 47 | Very poor | dynamite |
| Petrocorp | NW88 | 1988 | 23 | 351 | Poor | vibroseis |
| Petrocorp | EC91 | 1991 | 6 | 82 | Fair | dynamite |

Table 1. Previous seismic surveys in the area covered by PEP 38329.

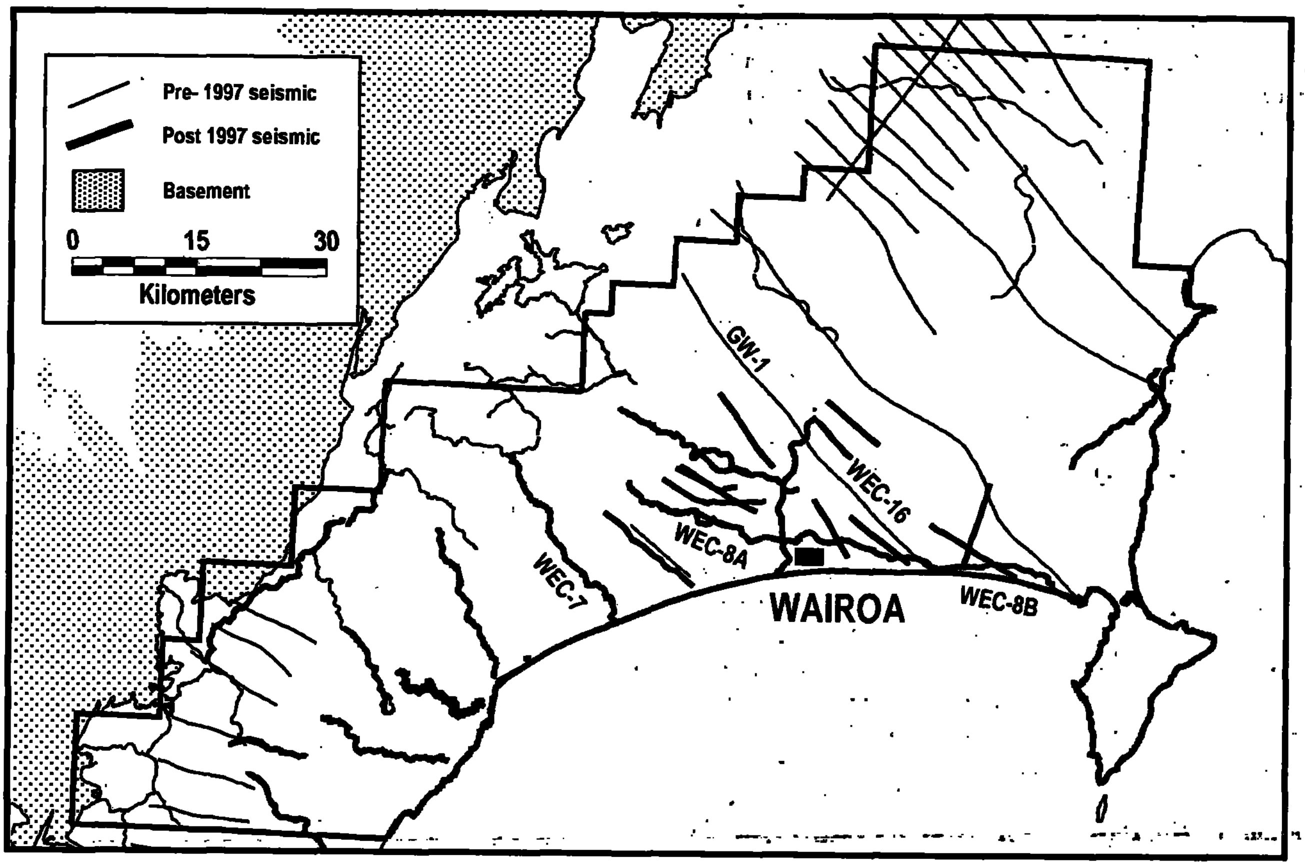


Figure 4: Seismic control in PEP 38329. Lighter lines are previous seismic surveys, as discussed in the text, with GW-1 identified. Wider lines are the WEC lines acquired in 1997-98, with WEC-7, 8 and 16 identified.

12 geophones spaced approximately 1.8 m apart in a 20 m linear array. For the off-road dynamite survey, the receiver group consisted of 12 equally spaced geophones laid out over a 10 m interval in a linear array wherever terrain would permit.

The source interval was 30 m for the vibroseis survey, with four vibrators sweeping four times per VP point, and moving across a 10 m distance. This arrangement provided a nominal 110 fold coverage. The dynamite surveys incorporated a single shot of 4 kg per shothole spaced at 30 m, providing a nominal 50 fold. The high fold enabled effective noise cancellation during the stacking process. The high cost of helicopter-supported shot hole drilling precluded a closer shothole spacing.

The 660 channel recording (600 with the dynamite surveys) provided high fold and far trace offset distance greater than 2900 m. It also allowed the elimination of traces during crooked line processing with the retention of the desired fold. The IO System II, with its multi-channel capability and 24 bit recording system, provided good dynamic range and sufficient latitude in determining field parameters.

Dramatic improvement in the resolution achieved by the new seismic is exemplified by line WEC-16 (Figure 5c), which lies parallel to and 2.5 km north of GW-1. Rollover of the anticlinal crest is clearly demonstrated.

Interpretation of the seismic data has yielded several very interesting structural and stratigraphic anomalies. In some cases, the data have verified and further delineated structural features mapped on the surface, and in other cases, previously unmapped structures have been identified. The anomalies exhibit diverse structural styles, ranging from tight folds to broad, low relief structures. The following discussion presents two of the new lines as examples of the seismic resolution achieved, and the geologic interpretation derived from them.

## Seismic Interpretation

Seismic lines WEC-7 and WEC-8 provide a composite transect, 70 km long, across much of the basin (Figure 6). Both lines were shot along roads (Figure 4), using a vibroseis energy source. Line WEC-7 runs from the basal Pliocene contact near the middle reaches of the Waiau River, along Putere Road to the Mohaka River mouth, a total distance of 30 km. Line WEC-8 is a parallel line 11 km to the northeast, and runs along part of Cricklewood Road, through Wairoa township, along State Highway Two to Nuhaka, and finally along the Nuhaka-Opoutama Road. The east end of the line lies within 1 km of the Opoutama-1 well drilled by Aquitaine in 1967.

The west end of line WEC-7 lies 20 km east of the East Coast Basin margin, where a strike-slip fault zone juxtaposes Miocene to Cretaceous strata against indurated low-grade metamorphic basement. The basin-fill ranges from Late Cretaceous shelf sandstone, to Paleogene to Miocene bathyal sediments, with major hiatuses through the Oligocene, much of the mid-Miocene and the latest-Miocene (Moore 1987a; Francis 1991b; Cutten 1994). This succession totals 3500 m up to the base of the Pliocene (Francis 1991b), and dips southeastwards at about 20 degrees.

There is little subsurface information on the pre-Pliocene succession until about halfway along line WEC-7 (Figure 6a). The Pliocene interval reaches 3500 m thickness, probably lying conformably on late-Miocene strata, which are poorly resolved seismically. The deepest consistent reflector is correlated with the top mid-Miocene Makaretu Sandstone.

The Kiakia Anticline (Figure 6a) is the first of a series of thrust-cored anticlines that persist across the remainder of the onshore basin. These are all southwest-northeast trending, eastward verging, commonly with subordinate back-thrusts, eastward verging, commonly with subordinate back-thrusts, soling out at 3-5.4 seconds TWT (ca 7000 m). Kiakia Anticline has been previously mapped at the surface as part of the Makareao Anticline (Quennell 1940; Haw 1959a), but seismic suggests that the latter structure is a separate feature to the northeast.

In the Wairoa valley, the Makareao and Kauhauroa Anticlines are well known from surface mapping dating back to the 1930s (Bremner 1934; Quennell 1939, 1940; Haw 1958, 1959a), but the new seismic is the first to elucidate the structures at depth. On line WEC-8 the southwest continuations of both structures are correlated with a subdued structural plateau (Figure 6a), with the eastern flank of the latter controlled by a major thrust fault.

The Awatere Anticline (Figure 6b) is closed at Miocene level, but has little closure higher in the Pliocene, and is not recognised in surface mapping. The Pliocene succession deepens to a maximum of 2000 m between the Kauhauroa and Awatere structures. These sediments range as young as Nukumaruan age, and therefore possibly into basal Pleistocene, but are all of marine origin, including turbidite facies (cf Hornibrook 1981). The new seismic grid prompts a re-evaluation of the Wairoa Syncline, long regarded as a major basinal axis. The prominent syncline between the Kauhauroa and Awatere anticlines continues northeastwards towards the flank of the basin. The saddle between the Makareao and Kauhauroa anticlines, barely recognisable on this line, deepens northwards into the Wairoa Syncline as mapped in the Wairoa and Hangaroa valleys. En-echelon development of the synclines may indicate a strike-slip component on the Kauhauroa and Awatere bounding faults.

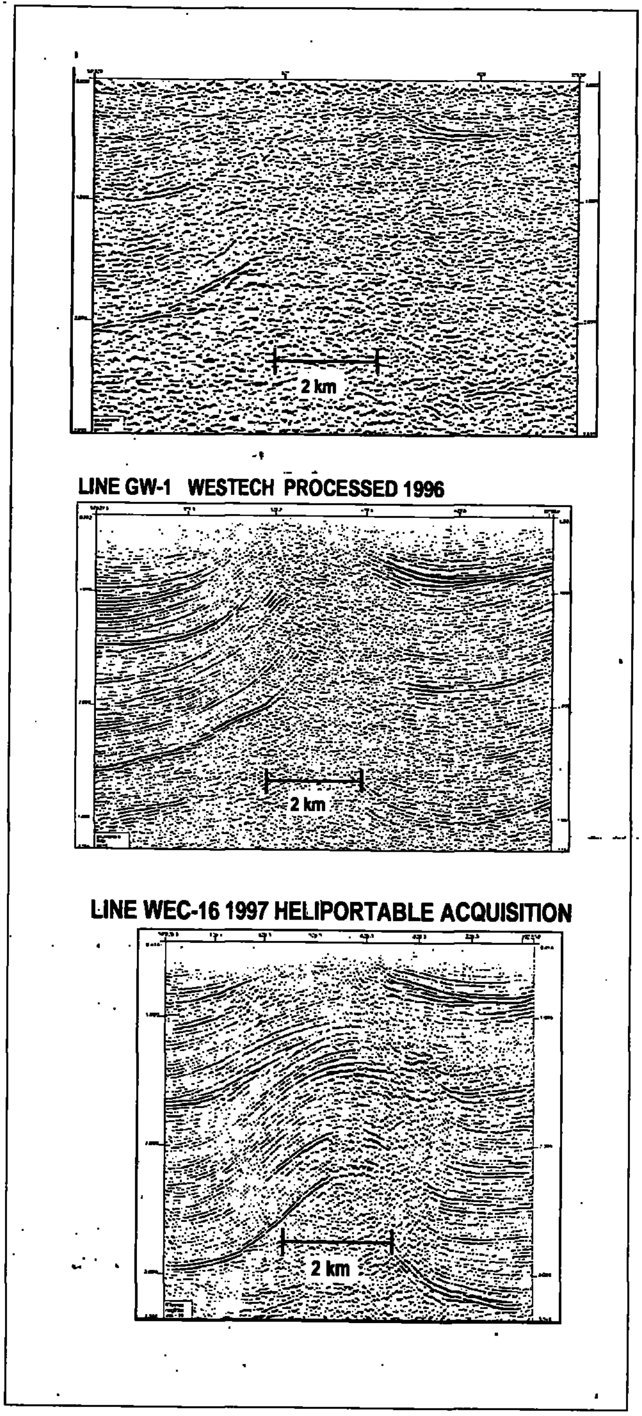


Figure 5. (a) Part of GW-1, a stacked, non-migrated line as lodged with Ministry of Commerce in 1982. (b) The same portion of GW-1 after re-processing and migration in 1996. (c) The equivalent structure, 2.5 km farther north, in new line WEC-16. Line locations shown on Figure 4. All displays are GeoQuest screen dumps.

East of Wairoa, an eastwards down-stepping of depocentres commences: the early-Pliocene (Opoitian) basin centred between Awatere and Tuhara (Figure 6b), the late-Miocene (Tongaporutuan) basin centred between Tuhara and Opoho; and the mid-Miocene (Waiauan-Clifdenian) basin centred near the east end of the line. The early-Miocene (Altonian) basin forms a possible half-graben centred between Tuhara and Opoho. Onlap occurs at sequence boundaries at the base of the early-Miocene, the base of the mid-Miocene, the top of the mid-Miocene, and within the late-Miocene. The mid-Miocene to lower-

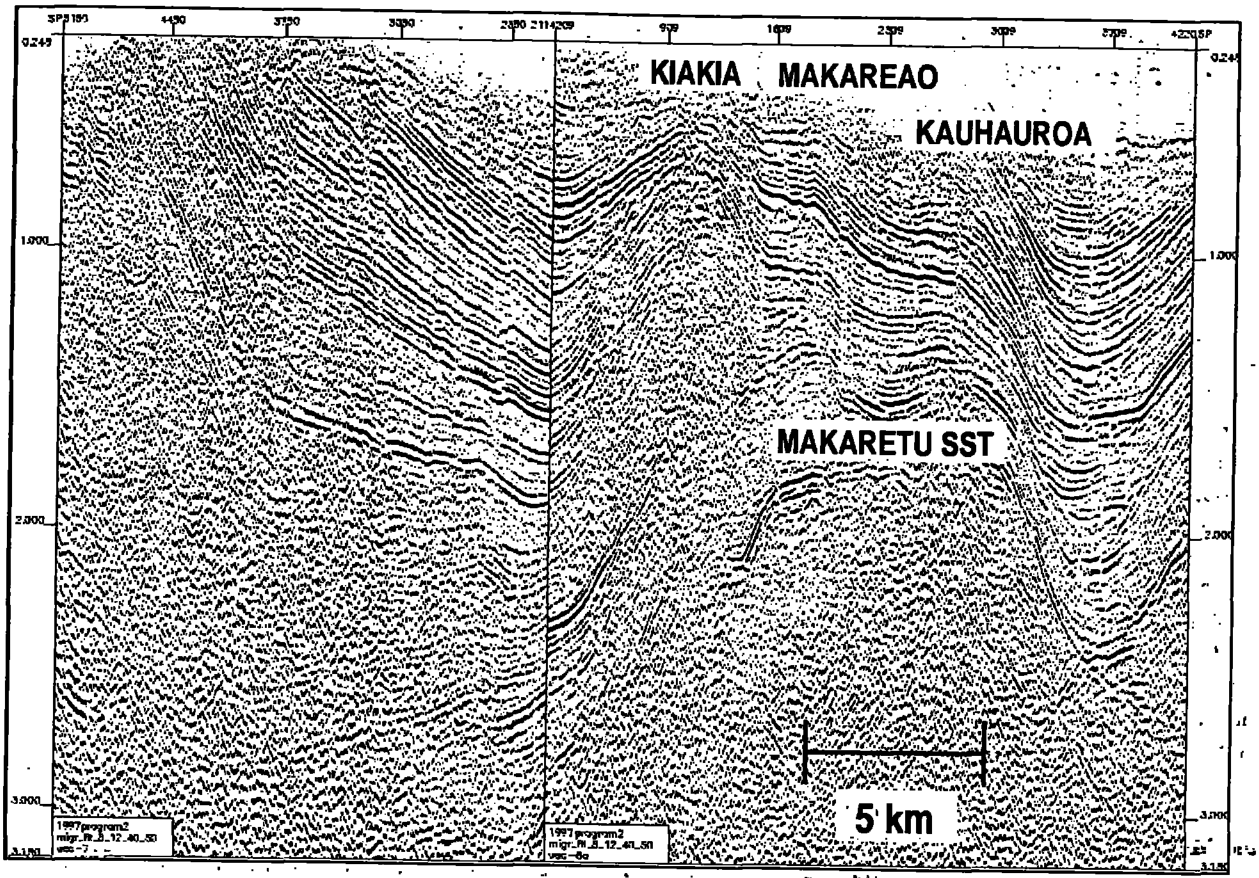


Figure 6a. Composite of seismic lines WEC-7 and WEC-8. A) Western half (WEC-7 and part WEC-8A). Displays are GeoQuest screen dumps.

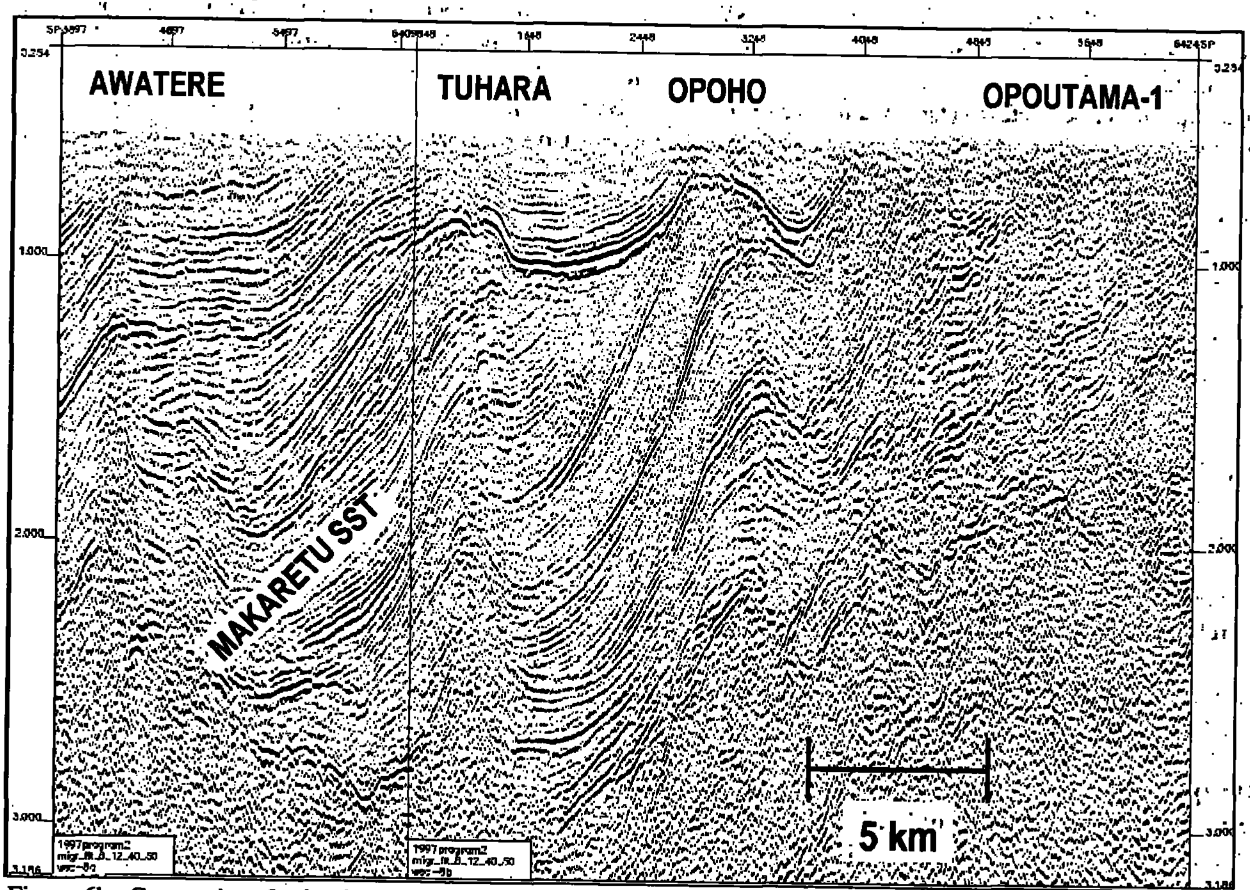


Figure 6b. Composite of seismic lines WEC-7 and WEC-8. B) Eastern half (part WEC-8A and WEC-8B). Displays are GeoQuest screen dumps.

Pliocene succession is truncated by the regionally prominent mid-Pliocene Waipipian unconformity.

Much of the onlap takes place on the eastern flank of the Tuhara Anticline (Figure 6b). This structure is known from surface mapping as a southwest plunging nose, but it extends offshore as a major anticline with crestal grabens. Steeply dipping faults in the crest suggest that it may be a flower structure resulting from strike-slip movement, and there is supporting evidence elsewhere onshore and offshore. Onshore, the structure is along strike from the Tahaenui Fault Zone mapped initially by Haw (1959b), and later interpreted as having strike-slip motion by Francis (1993). It is possible that this fault zone transfers compressional displacement from a thrust system offshore (cf. Uruski, 1997 unpublished) to the Mangaone thrust system to the north.

The Opoho Anticline (Figure 6b) is another anticline controlled by a deep thrust, readily correlated offshore on Aquitaine and Conquest seismic lines. There is marked discordance between the Miocene succession and unconformably overlying mid-Pliocene strata, which are folded into a syncline above the Miocene anticline, and the corresponding Pliocene anticline is considerably offset from the Miocene crest. Flattening the section at the base of the Pliocene shows that the Opoho structure developed in the late-Miocene to early-Pliocene, and since then has subsided slightly. The structure trends northward into the Mangaone Anticline, the crest of which is offset by NW-SE faulting (Villanova 1966). Thrust faulting developed around the SE flank of the Mangaone structure (Francis 1993) may delimit Opoho as a separate structure, and further seismic has been recently acquired to ascertain this.

The remainder of line WEC-8 east of Opoho shows a westwards dipping succession, with mid- to late-Miocene strata exposed at the surface. Low-angle eastward verging thrusts occur across the section, commonly with major back-thrusts, but without creating significant areas of closure. Surface mapping to the north (Haw 1959c, Villanova 1966, Francis 1993) shows the Morere-Opoutama area to be a major anticlinorium with a crest close to the end of the line. Diapiric inliers of Paleogene bentonites outcrop along part of the crest, but have not been reliably identified on seismic.

The Opoutama-1 well, close to the end of the transect, is a valuable reference for the line. The well spudded in mid-Miocene Tunanui Sandstone, continued through early-Miocene and Oligocene strata, then passed through a zone of mixed Oligocene to Paleocene microfauna, variously interpreted as a seafloor slump deposit (Zimmermann and Faber 1967) or tectonic melange (Smith 1982; Strong et al 1993). Seismic quality on this part of line WEC-8B, or the adjacent line GW-2, is poor, but an eastward verging thrust system can be identified. Lower in the well, repetition by thrust-faulting of the Paleogene to Late Cretaceous interval, as proposed by Smith (1982) and Moore (1987b), can be interpreted on seismic.

East of Tuhara, Tunanui Sandstone is exposed in the crests of the Mangaone and Opoutama-Morere anticlinoria, where thicknesses up to 2560 m have been estimated (Haw 1959c). In the Opoho structure, a package of strong reflectors 700 m thick is correlated with the formation; it onlaps the inferred basal mid-Miocene unconformity a few kilometres to the west. To the east, on Mahia Peninsula, the mid-Miocene interval is very thin, indicating rapid thinning on the basin flank (or juxtaposition of different successions by strike-slip faulting).

Underlying the mid-Miocene is a thick development of early-Miocene strata, with indications of deep-water fan complexes. Sandstones of this age (Altonian Stage) were encountered in the Mangaone-1 well, 8 km to the north, in packages 10-30 m thick (Brown 1961). Farther east in the Opoutama-1 well, however, the early-Miocene is sand-poor (Zimmermann and Faber 1967) with internal unconformities (Strong et al 1993).

## Basin Evolution

Studies elsewhere in the East Coast Basin (Rait et al 1991; Field, Uruski et al in press) have documented the tectonic response to propagation of the Indo-Pacific Plate boundary through New Zealand in earliest Miocene time. Emplacement of the East Coast Allochthon from the north did not extend as far as the seismic line transect discussed above. Interpretation of offshore seismic, with superior resolution of deeper stratigraphy than the onshore lines, shows extensive low-angle thrusting and back-thrusting through the Cretaceous and Paleogene interval which predated Miocene sedimentation (Uruski 1994, 1996; Field, Uruski et al in press). Line WEC-8 gives little resolution of the pre-Miocene succession except at the eastern end where thrusting inferred in Opoutama-1 can be supported.

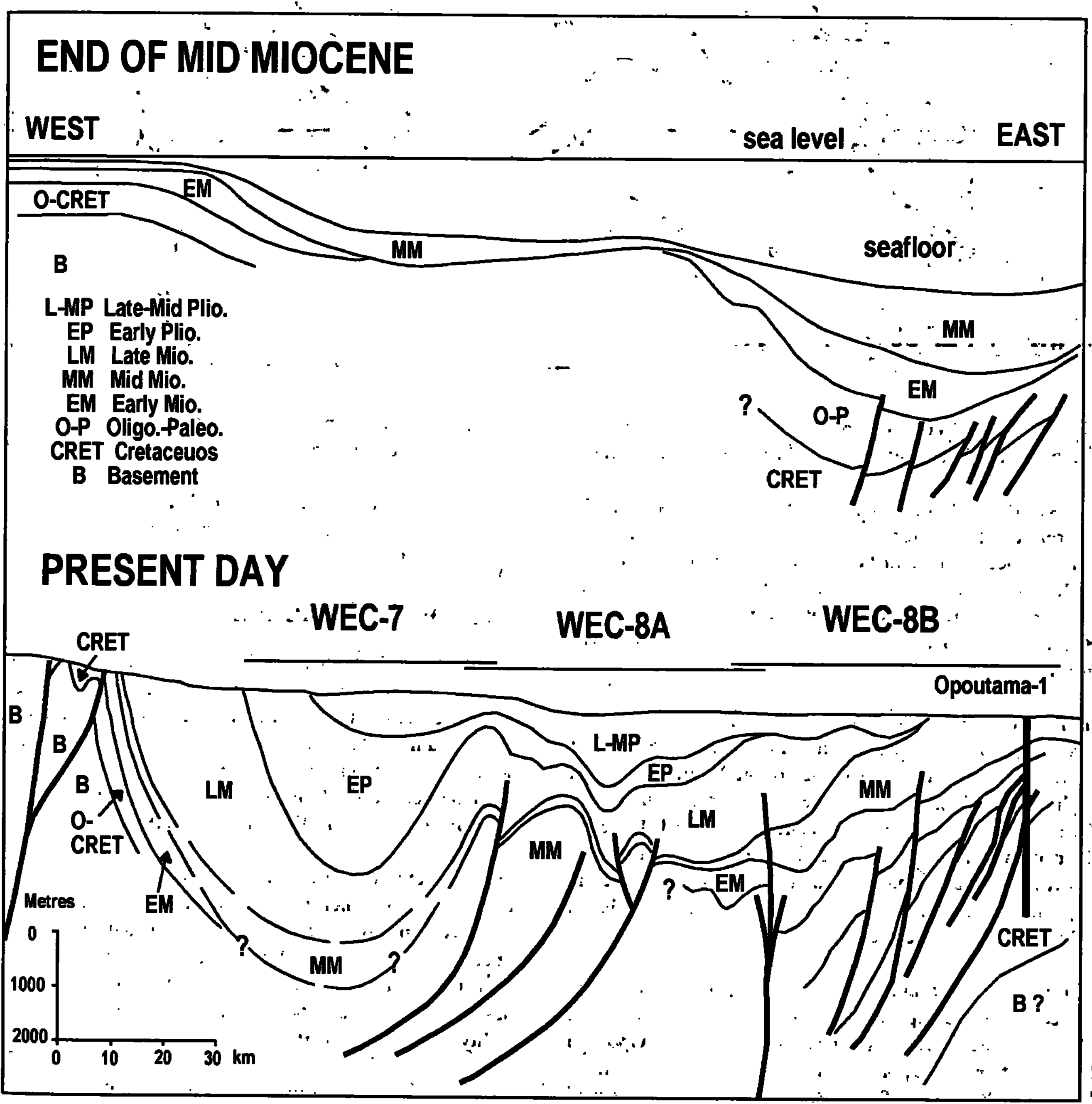
Early- and mid-Miocene strata may be absent from a 30 km wide zone through the Wairoa area, roughly equivalent to the area covered by thick Pliocene sediments (Figure 7). This is inferred from the bland seismic character of the interval beneath the uppermost mid-Miocene horizons, the clear onlap of early to mid-Miocene strata to the east in the Tuhara area, and less evident onlap of the same interval farther west. The implication that this area was a structural high through the early-to mid-Miocene is a working hypothesis to be tested by drilling.

Early-Miocene strata fill an asymmetric basin east of Tuhara, with the west flank probably controlled by normal faulting (Figure 7a). Sandstone facies characterise the western margin.

Mid-Miocene strata reached their thickest development in the eastern part of the transect, coincident with the main development of thick-bedded and amalgamated sandstones (Tunanui Sandstone). In the latest mid-Miocene (Waiauan Stage), the Makaretu-D Sandstone accumulated in the central part of the transect. As with the Tunanui Sandstone, the thickest development of the formation coincided with sand-rich facies, which occur west of the equivalent Tunanui facies. For both formations, the dominant transport direction was from the north.

In the late-Miocene, sandstone deposition (Makaretu A-C sandstones) continued, but from a west or northwest source (the shelf edge beyond the present-day basin margin). Younger strata are mud-dominated with appreciable tuffaceous content. Thick late-Miocene successions accumulated to both the west and east of the Wairoa area (Figure 7b). The western basin (between Kiakia and the basin margin) is poorly known because of poor seismic resolution and thick Pliocene cover. Tectonic loading at the basin margin may have been a primary control on subsidence.

The thickness of all Miocene strata in the eastern basin, between Wairoa and Mahia, ranges up to 3500 m. There is some evidence for normal faulting controlling deposition, particularly in the early-to mid-Miocene and Latest Miocene. The style and timing of basin-filling is similar to that inferred for the offshore Lachlan Basin


END OF MID MIOCENE

PRESENT DAY

Figure 7. Schematic basin cross section: (a) at the top of the mid-Miocene. Seafloor bathymetry is hypothetical. Section is not to scale, and makes no allowance for crustal shortening relative to the present day. (b) at present-day. Vertical exaggeration x 10. Western margin after Moore (1987a), Francis (1991b) and Cutten (1994).

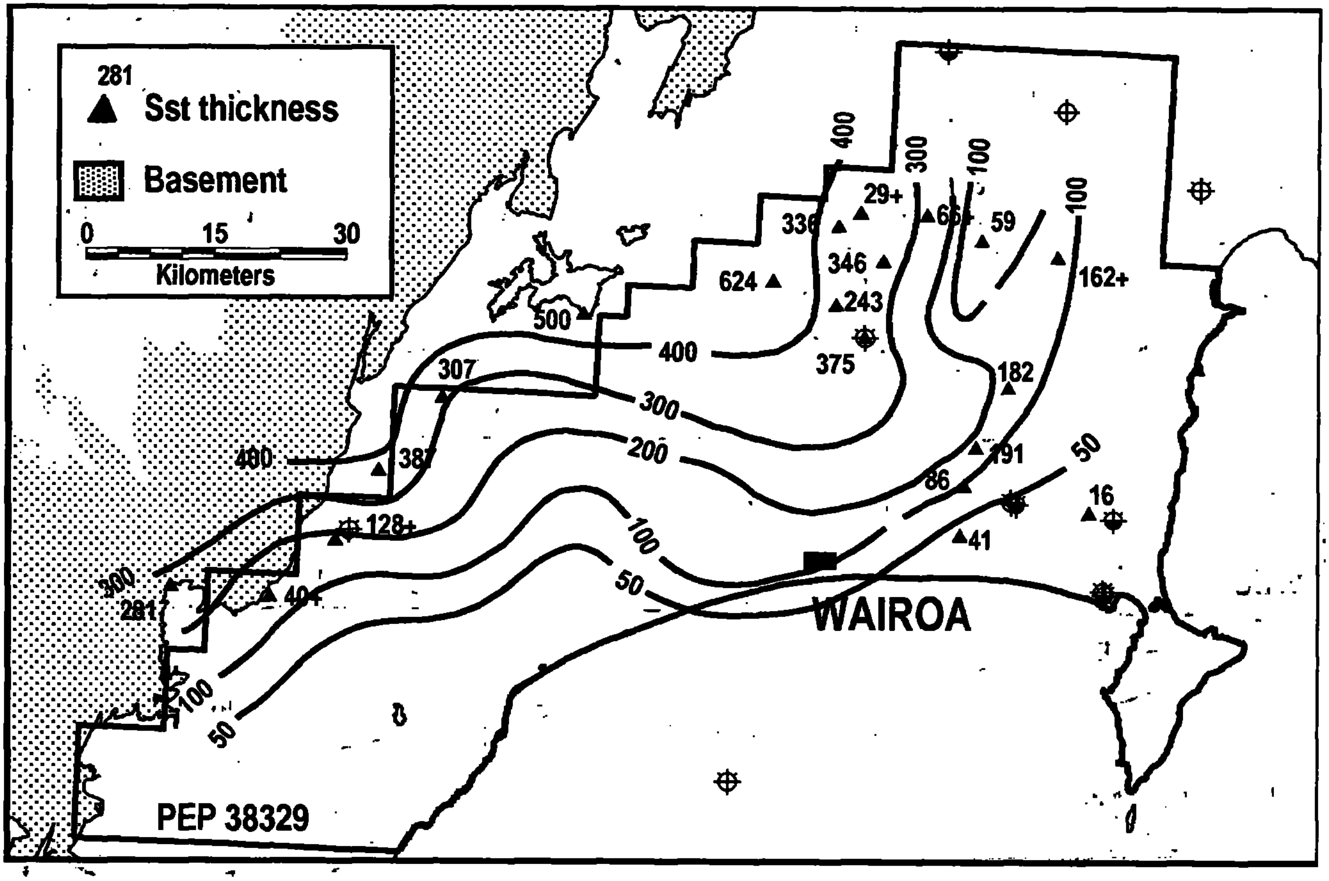


Figure 8. Isopachs of combined net thicknesses of the Makaretu A-D sandstones. Triangles are stratigraphic column locations. Thickness data compiled from our field studies plus Haw (1959a, b, c) and Francis (1991a, 1994).

(Uruski 1994, 1996; Field, Uruski et al in press). Uruski interpreted the latter as a pull-apart basin situated between deep-seated strike-slip faults, with listric normal faults active in the mid-Miocene and late-Miocene. Flower structures along the western side of Hawke's Bay have also been inferred by Field, Uruski et al (in press).

In the latest Miocene or early-Pliocene, regional tilt, about a roughly north-south axis, uplifted the Miocene basin east of Wairoa, and caused subsidence of the Wairoa structural high (Figure 7b). Eastwards-verging thrusting began to form the anticlines in the Wairoa area, and Pliocene deposition was partly controlled by these features. However, in a regional context, the bulk of Pliocene deposition took place west of Kiakia, with the basin subsidence possibly driven by tectonic loading.

Multiple unconformities in the Pliocene succession indicate a complex tectonic history. Regional unconformities occur at the base of the Pliocene Opoitian Stage, within the Opoitian, and at the base of the mid-Pliocene Waipipian Stage (cf. Wright 1986). Local unconformities and packages of sediment occur, for example above the Kiakia-Awatere structures, suggesting the transfer of compression between their controlling faults at different times.

The presence of deep-water strata of Nukumaruan age near Wairoa indicates substantial basin infilling and uplift within the last 2.6 million years.

## Reservoir Objectives

For the initial exploration drilling phase, the most prospective sandstone reservoirs are in the Makaretu Sandstone. This mid- to late-Miocene unit is subdivided into four units, Makaretu-A, B, C and D from youngest to oldest (Figure 3; Haw 1959a). The following discussion is based on recent field studies, with additional data from Simpson and Jarvis (1993) and Francis (1994).

The Makaretu-A sandstone ranges from a thin (40 m), fine sand-dominated inner fan deposit in the east, to a thick (possibly up to 500 m) mud-dominated outer fan succession in the west. Porosity and permeability range from 17 to 28% and 40 to 180 mD respectively. The Makaretu-B unit is not expected to contain reservoir quality sands in the Wairoa area.

The Makaretu-C sandstone is a massive or thick-bedded, fine sandstone with variable silt content, which extends over 90 km along strike. Net sandstone thicknesses of 120-400 m in outcrop are likely to diminish to the southeast, but may still reach 50 m in the Wairoa area.

Poroperm characteristics are highest in the southwest, where outcrop permeabilities range up to 250 mD. Further north, outcrop permeabilities range up to 30-50 mD.

The Makaretu-D sandstone outcrops continuously from the north to the east of the permit area. In the north, the formation ranges up to 170 m net thickness. Medium-thick beds of fine to very fine sandstone are interbedded with subordinate siltstone, and have outcrop permeabilities of up to 40 mD. To the east, a tongue of 100-200 m thick net sandstone is inferred to extend into the Wairoa area. It comprises thick-bedded, locally amalgamated bedded, fine sandstone, with outcrop permeabilities typically 30-100 mD but ranging up to 620 mD.

The Ruakituri-1 well, drilled in 1961-62, penetrated the complete Makaretu succession, although the section dipped at 30-70° (Phizackerley and Robinson 1962). The depth-corrected section is 525 m thick, with 70% net sandstone. Differentiation of the C and D sandstone intervals may coincide with an inferred sequence boundary at 1542 m.

Core and ditch cuttings from this well indicate that the Makaretu C and D sandstones consist of very fine to fine, well to moderately sorted, slightly to moderately consolidated sandstone with variable amounts of coarse fragments of mollusc shells, benthic foraminifera, and shale lithoclasts. Sandstones containing large portions of abraded shell material appear to be preferentially cemented by calcite spar. Certain intervals exhibit very good porosity at both macroscopic and microscopic scales, confirmed by analyses indicating porosities up to 27% and permeabilities up to 238 mD. Destructive diagenetic effects have been relatively minimal given the lithic-rich composition of the sands (J C Webb 1998 unpublished).

The overall distribution of the Makaretu Sandstone (as a combination of the A, B, C and D units) is interpreted as a thick base-of-slope accumulation, with a series of thick lobes extending southwestwards towards Wairoa (Figure 8). The high concentration of shelf-derived material in a Ruakituri-1 core does appear to contradict this interpretation, and suggests deposition on, or derivation from, possible local paleo-highs.

## Conclusions

Overviews of the East Coast have formulated a petroleum framework for the basin. The source rock definition, maturation history, and reservoir identification have perhaps progressed as far as they can with the present data set. The new seismic lines acquired in PEP 38329 have addressed other components of the system such as trap integrity and timing of structural development. Remaining uncertainties, however, warrant better subsurface definition of the Miocene to Pliocene. In addition to testing several prospective large anticlines, the initial drilling programme will provide additional key data such as:

1. Sandstone reservoir extent and quality, defined by modern logging tools;
2. Pliocene limestone extent and reservoir quality;
3. Present-day geothermal gradient, heat-flow; and vitrinite reflectance data;
4. Identification of regionally significant unconformities; and
5. Distribution of source rocks.

A four-well continuous drilling programme is scheduled to commence in March 1998.

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