RESERVOIR POTENTIAL OF MIOCENE SANDSTONES, SOUTHERN EAST COAST BASIN, NEW ZEALAND

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Abstract

Past exploration in the East Coast Basin concentrated on potential reservoir formations of Cretaceous and Pliocene age. This was because of the known occurrence of Cretaceous sandstones with some reservoir potential, and the highly porous Pliocene limestones. It was also believed that Oligocene to Miocene deposits were either mudstones or turbidites with low quality sandstones. More recently, interest in the middle to upper Tertiary strata has increased because of production from turbidites elsewhere, easier resolution of targets, possible shallower drilling depths, and the numerous oil impregnations and seepages associated with beds of this age in the East Coast Basin.

Deposition in a forearc setting, with rapid sedimentation and short transport distances, means that many East Coast Basin sandstones are arkosic with high detrital and authigenic clay content and poor sorting, and consequent poor reservoir qualities. Fewer indications of oil have led to the southern East Coast Basin being considered less prospective than areas further north. However, more oil indications have been discovered recently. The present study discusses the reservoir potential of units such as the Takiritini Sandstone (middle Miocene).

Introduction

The East Coast Basin (figure 1) covers an area of 70 000 km^2, both on and off shore. The present study is concentrated on the onshore central Hawke's Bay to central Wairarapa area. Located on the eastern side of the North Island, the Basin stretches from Marlborough in the northeastern part of the South Island to East Cape in the north. The western boundary is a northeast-trending belt of uplifted Triassic–Jurassic metasediments. In the south the Canterbury Basin forms the southern boundary. The northern and eastern boundaries are defined by the edge of the continental shelf.

The East Coast as a Frontier Petroleum Exploration Province

The East Coast Basin has held interest as a potential petroleum provenance for the last 100 years, but is yet to have a commercial discovery made. The lack of success is due, in part, to the initial petroleum reservoir targets being Cretaceous sandstones (which have been found to be too tight to be potential reservoirs), or Pliocene limestones (a growing feeling exists that the hydrocarbons are not reaching these highly porous limestones). Until recently the limited accessibility, poor geological data, perceived complexity of structure, and the difficulty of producing workable seismic, have all been problems of exploration.

Recently, interest has been growing in the reservoir potential of Miocene sediments. The East Coast Basin's thick Miocene sandstones were previously seen as having poor reservoir potential because of the proximity to the sediment source, resulting in fine-grained immature sandstones with high feldspar and clay contents. Another reason the Miocene sediments were ignored was the belief that the overall sequence largely consisted of mudstone and turbidites. Commercial discoveries from turbidites overseas and in the Taranaki Basin, New Zealand, now show these deposits to have potential as reservoir bodies.

The Miocene sediments are somewhat shallower than previous Cretaceous targets, which enables more workable seismic to be acquired and drilling costs are lower. The Miocene sequence is less deformed than the Cretaceous and has formations present that can act as seals, and is also less exposed than the Pliocene limestones.

Interest in the East Coast Basin, as a potential new source of hydrocarbons to replace New Zealand's dwindling domestic supplies, seems well-founded. The occurrence of up to 250 gas and several oil seeps (predominantly in the north) (Francis, 1992a, 1992b), plus the many oil impregnations throughout the basin are evidence that hydrocarbons have been and are being produced and are migrating.

The intense structural deformation in the area is well suited to the migration and trapping of hydrocarbons, and the presence of many seals throughout the sequence show the basin to be ideally suited as a petroleum province.

The question now must change from "are there hydrocarbons in the East Coast Basin?" to " where are the hydrocarbons in the East Coast Basin?"

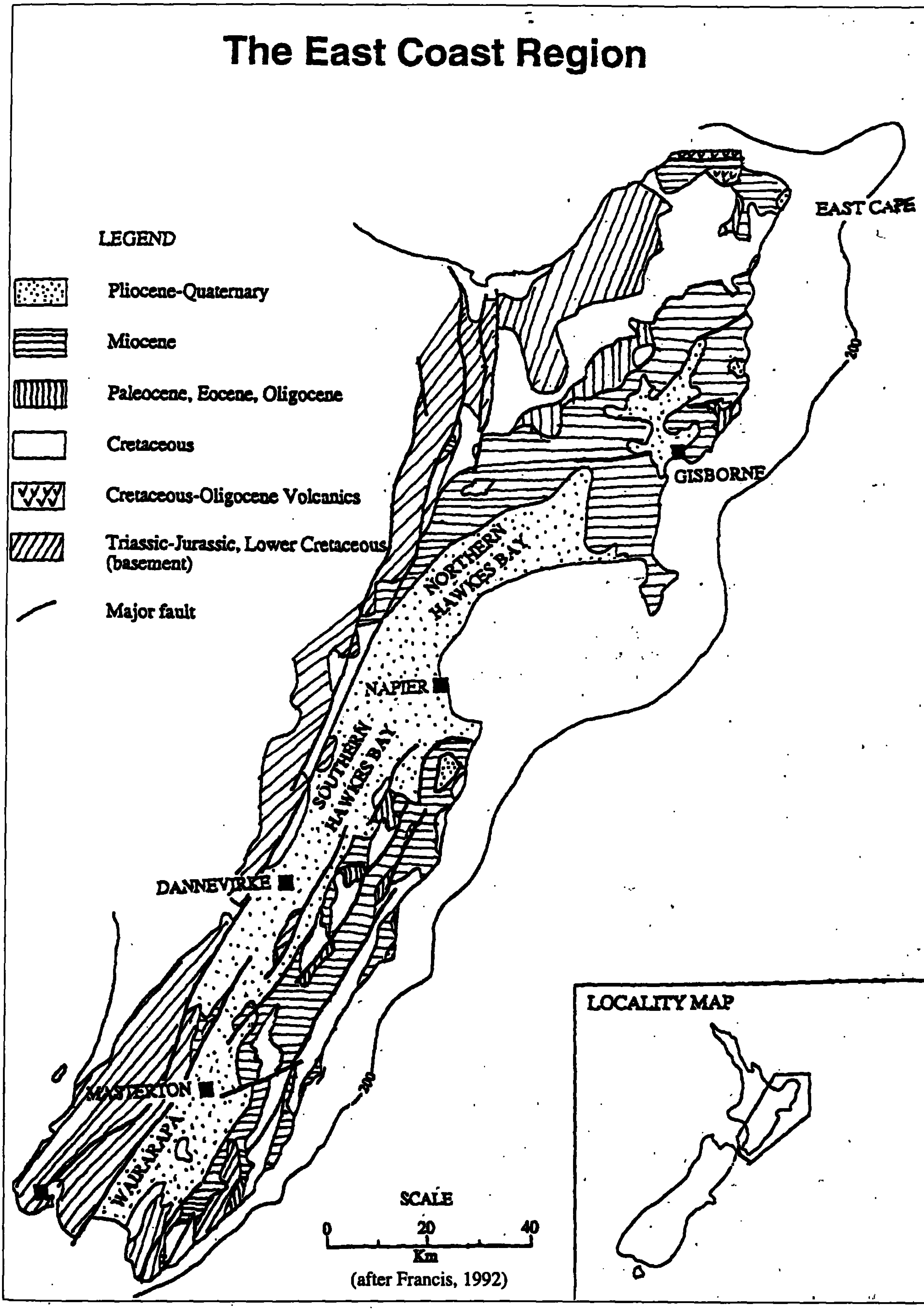

Fig. 1. Map of the East Coast Basin.

Potential Miocene Sandstone Reservoirs

The ongoing study, resulting in this paper, has been to research Miocene sandstones that have been identified by previous workers as having reservoir potential. The study area is from the central Wairarapa to the lower central Hawke's Bay region (figure 1). This area was chosen because there are fewer oil/gas indicators than in the northern part of the basin and less interest has been shown recently, with little published information. At present no onshore licenses are held over the study area while interest in the northern region, especially around Gisborne, is growing.

The aim of the study was to concentrate on a single promising Miocene reservoir. By studying petroleum reports, theses and relevant papers, six formations were found that previous workers considered promising, but these had not been studied with respect to their reservoir characteristics, or confidentiality has not yet expired on the licences (table 1).

Potential Reservoir Units

Westcott Formation

The Westcott Formation of Altonian age was first discussed by Laing (1963) as strata equivalent to the lower section of the Ihungia Formation of McKay (1887). Francis (1990b) divided the Westcott Formation into two, naming the basal section the Waipatiki Sandstone and retaining Westcott Formation for the overlying section. The type section is the Westcott Stream (Laing 1963).

The formation consists of a calcareous siltstone and mudstone sequence. It is shelly in places with interbeds of porous sandstone (Francis, 1990b). The formation is found in the Westcott area on the eastern limb of the Mangatuna Anticline (Francis, 1990b) and crops out further north on the flanks of the Waipatiki Syncline.

Lillie (1953) considered the Ihungia Formation of McKay (1887) as having oil/gas indications, especially at Waipatiki. It is not certain whether this includes the lower section equivalent to the Westcott Formation and Waipatiki Sandstone.

Laing's (1961) description of the Waipatiki facies of the Pareora Series rocks shows a close similarity to the Westcott Formation of Laing (1963) and the Westcott Formation and Waipatiki Sandstone of Francis (1990b); he also mentioned oil impregnations in two parts of this sequence. As these are at or near the top of the formation they may be equivalent to the upper Westcott Formation of Laing (1963) and the Westcott Formation of Francis (1990b).

A stratigraphic corehole was drilled into the Westcott Formation for East Coast Petroleum in 1991 (Laing, 1991). The formation was 62.32 m thick and overlaid the Wanstead Formation. The section from 43.40 m below the corehole surface, to the top of the Wanstead Formation is called the "basal section" by Laing and the description closely resembles the Waipatiki Sandstone of Francis (1990b). If it is the Waipatiki Formation then the upper section (0–43.40 m) may correlate with the Westcott Formation of Francis (1990b). Laing described the section from 0–43.40 m as fine- to medium-grained sandy siltstone with poor to fair porosity. A section was analysed between 10 m and 38.84 m and was found to have low permeabilities of 0.04–0.17 mD and porosities of 11.0–21.8%. Strong oil shows were noted down to 39 m from the surface but did not continue. No explanation was given.

Waipatiki Formation

As discussed above, the Waipatiki Sandstone of Francis (1990b) is equivalent to the lower shelly member of the Westcott Formation of Laing (1963), and the lower part of the Ihungia Formation of McKay (1887) as used by Lillie (1953). The type section is the same as that of the Westcott Formation, as is the distribution. The Waipatiki Sandstone has been given an age ranging from Otaian to Altonian (Francis, 1990b), and consists of fine to medium sandstone that is calcareous, shelly and/or conglomeratic in parts, and porous. The shelly sandstone grades to shelly algal limestone.

Laing (1963) considered the basal sandstone of his Westcott Formation, (equivalent to the Waipatiki Sandstone of Francis (1990b)) as being one of the best reservoir beds in the Waipatiki area. Though the permeability is low (plugs cut from two samples gave permeabilities of 42 and 84 mD) the sandstone is known to contain traces of oil (Laing, 1961; 1963, Francis, 1990b).

As mentioned above (see Westcott Formation), a stratigraphic corehole was drilled in 1991. The results of the analysis of the basal section (43.40–63.32 m) showed the hard, calcareous, very fine-grained silty sandstone to have poor porosity; the minor interbeds of fine- to medium-grained sandstone to have fair porosity; and the very fine-grained silty sandstone to have poor porosity. No fluorescence was found but an oil film developed when samples were crushed under water. A sample from 49.80 m gave analyses of 13 mD permeability and 20.5% porosity.

Francis (1990a) considered the sandstone near the base of the Miocene in the Westcott area as being a potential reservoir target; this basal sandstone may be equivalent to his Waipatiki Sandstone (1990b). Francis (1990b) noted strong to weak oil smells in most exposures of Waipatiki Sandstone.

Whakataki Formation

The name Whakataki Formation was first used by Johnston (1975) for a Waitakian to Clifdenian age sequence of graded beds ranging from 25 mm to 1 m in thickness, with a base of thick sandstone that grades laterally northwest into a conglomerate. In the upper Mataikona valley the conglomerate is 90 m thick (Johnston, 1980), and is also exposed at the mouth of the Mataikona River (Crundwell, 1988).

The Whakataki Formation is similar to the eastern facies of Lillie's (1953) definition of the Ihungia Formation of McKay (1887), which is situated on the coastal region of the southern Hawke's Bay. Haskell (1988) called this facies Whakataki Formation. The formation crops out in the Tinui and Whareama valleys, on the coast from Castlepoint (Johnston, 1980; Crundwell, 1988), and to the north of Akitio where it is at least 900 m thick (Neef, 1991). Neef (1992a) noted outcrops of Whakataki Formation to the north between the Mt Cadmus and Te Tumu faults. No complete section was found by Johnston (1975) or Neef (1992a). Johnston designated a base for the section at the head of the Mataikona River and a top in the lower Whareama Valley.

Turnbull (1988), describes Ta-Tb type units (Turnbull zonal nomenclature) as containing thin-bedded alternating medium- and coarse-grained calcite cemented sands, 5 cm to 10 cm in thickness. Calcite cement can be easily dissolved by organic acids to produce secondary porosity and improved permeability.

Table 1. Formations with reservoir potential from central Wairarapa to lower central Hawke's Bay.

NAME	REFERENCE	AGE	LITHOLOGY	DISTRIBUTION	SEAL	SANDSTONE THICKNESS	PORO/PERM	RESERVOIR POTENTIAL	COMMENTS
TAKIRITINI FORMATION	Johnston (1980) Neef (1991b)	Pl-Sc	Shallow marine sandstone	Principally Tinui Valley, extends to Waihoki	Tanawa Fmn turbiditic mudstones	15–1000 m	Never measured	Considered favorable	Thick, well-sorted thought ideal target
WHAKATAKI FORMATION	Johnston (1980) Turnbull (1988) Neef (1992a)	Lw-Sc	Turbidite	Whareama Valley, to southern Hawke's Bay & coastal areas	Whakataki Fmn turbiditic mudstones	5 cm–10 cm	Never measured	Never considered	Contains coarse grained calcite cemented sst
WAIPATIKI FORMATION	Francis (1990b)	Po-Pl	Shallow marine sandstone	Westcott region & flanks of the Waipatiki Syncline	Ihungia Fmn mudstone/ siltstones	3–30 m	20.5% por 13–84mD	Considered best in area of deposition	Traces of oil
WESTCOTT FORMATION	Laing (1963) Francis (1990a)	Pl	Shallow marine interbedded sst	Equivalent to Waipatiki Fmn distribution	Westcott Fmn siltstone/ mudstone	0.3–1 m	0–21.8% por 0.04–0.17mD	Considered fair	Strong oil shows
GREEN-HOLLOWS FORMATION	Neef (1991b)	Pl-Sc	Turbidite	Paripapa Syncline flanks	Tanawa/ Greenhollows turbidites	0.1–1.2 m	Never measured	Considered very good	Believed best turbidite fmn
MAUNSELL/ TANAWA FORMATION	Johnston (1980) Neef (1990)	Sl-Sw	Turbidite	Extensive, from Whareama Valley to northeast of Pongaroa	Tanawa/ Ngarata/ Pakowhai turbidites	cm–15 m	Never measured	Considered fair	With structure believed very well disposed

There is increasing interest in turbidites as potential reservoir units — Taranaki is producing from thin-bedded sandstone layers within turbidites. It is important to keep the Whakataki Formation in mind for further study as a possible reservoir unit.

Takiritini Formation

The Takiritini Formation (Johnston, 1975) is described as a thick, medium- to coarse-grained shallow water sandstone and algal limestone with interbedded siltstone. Given an age of Altonian to Clifdenian the formation is coeval with the Upper Whakataki Formation (Johnston, 1975) and is principally located in the Tinui–Awatoitoi area with small fault slivers in the Whareama Valley (Johnston, 1975) to the south and east of the Waihoki Syncline (Neef, 1992a).

The maximum exposed thickness of the sandstone is 500 m at Maunsell Trig. The limestone has a maximum thickness of 5 m at Bellis Quarry, Tinui River (Johnston, 1980). The siltstone is only complete at the type section, designated by Johnston as the outcrop of the formation in the Takiritini River, where it is approximately 100 m thick and grades into the overlying sandstone lens of the Takiritini Formation.

In a report for Lakes Oil Ltd, entitled "The structures, oil-bearing formations and recommendations for stratigraphic drillhole sites in PPL 38317" (an area from Weber to Owahanga), Francis (1990b) discussed the Mt York Anticline that lies to the west of Tanawa Trig as a possible site for a stratigraphic drillhole. It was decided that the prospective formations would be at a depth beyond the 120 m reach of the drill and accordingly no hole was drilled. Francis stated that the structure was prospective for exploration in the future, referring in particular to the Takiritini Formation.

Greenhollows Formation

The Greenhollows Formation is described by Neef (1991b) as a poorly graded sandstone-rich turbidite deposit of Altonian age. The formation crops out to the east of the township of Pongaroa and in a north-northeast trending strip following the Tinui Fault in the Owahanga Gorge area. Three kilometres southeast of Pongaroa the formation is approximately 370 m thick and in the Owahanga area the thickness is approximately 200 m.

In discussing five turbidites of the East Coast, including the Tanawa and Whakataki formations, Neef (1992a) described the sand-rich Greenhollows Formation as the best potential Miocene reservoir for oil and/or gas.

Tanawa Formation

The Maunsell Formation was first designated as a name for massive mudstone and siltstone with minor sandstone and pebbly shell limestone beds and concretions by Johnston (1975). The formation grades to a thick sequence of graded beds (called the Tanawa Member by Johnston (1975)) to the northwest of the type section in the Tinui Valley. To the northeast the formation grades into thick sandstone of the Grassendale Member (Johnston, 1975). The formation is found in the Tinui Valley, where at the type section it measures approximately 2800 m thick, and to the south in the Whareama Valley (Johnston 1975).

In 1991 after extensive fieldwork in the Akitio region, Neef (1991b) redefined the formation. Neef replaced Maunsell with Tanawa as the formation name, relegating the Maunsell to member status, while describing the siltstone as the Linside Siltstone Member. The Tanawa Formation was defined as medium- and thin-bedded sandstone and mudstone couplets. The conglomerate and sandstone of the Grassendale Member of Johnston (1980) were renamed the Packspur Conglomerate Member and the Mara Sandstone Member respectively, with the name Grassendale dropped completely. The Benvorlich Member represents another style of graded bedding — very thick to thick-bedded sandstone and mudstone couplets (Neef, 1992a).

While discussing prospectivity for hydrocarbon entrapment in the Tinui–Awatoitoi area, Johnston (1980) named the Maunsell Formation as the most promising prospect, noting that the presence of impermeable mudstone and siltstone overlying coarse porous basal beds in conjunction with faulting or folding might produce a suitable trap. Johnston also pointed to the Mt York Anticline as a prospect, with the Maunsell Formation being folded. Mentioned previously, Francis (1990b) reported to Lakes Oil Ltd the prospectivity of the Mt York Anticline for hydrocarbon exploration.

Potential Miocene Reservoir

From the above list the Takiritini Formation was chosen as worthy of a more detailed study.

The formation is a fine to medium well-sorted sandstone, up to at least 500 m in thickness. It is a shallow marine sandstone as evidenced by the occurrence of echinoid fossils. At depth this facies would be easier to follow on seismic over distance than the individual sandstone beds of the turbidites which are usually unmappable.

It is important to note that we are not saying that the exposed Takiritini Formation itself is a potential reservoir; quite obviously it is not, as the formation is exposed sporadically throughout its area of distribution, but the facies that the Takiritini Formation represents — shallow marine sands — may be promising. If the reservoir characteristics of the Takiritini Formation were found to be good, the next step would be to look for this facies at depth.

Takiritini Formation

The Takiritini Formation consists of a thick shallow marine sandstone (indicated by the presence of echinoids) that grades from very fine-grained sandstone in the northeast to medium- to coarse-grained sandstone in the southwest. Algal limestone is found at the base of the formation and thickens to the south. A massive siltstone is interbedded with thick sandstone lenses to the north. Given an age of Altonian to Clifdenian the formation unconformably overlies the lower Whakataki Formation, and is coeval with the upper Whakataki Formation in the south. The formation follows a north-northeast direction straddling the Tinui Fault from the Maunsell Trig at the Tinui township to Te Mai Station in the north (Johnston, 1975). Neef (1992a) noted the northernmost extent of the formation to be approximately 4 km southwest of the Owahanga Gorge. To the south, Crundwell (1987) described a fault sliver of the Takiritini Formation on the west side of the Whareama Valley.

The sandstone is massive, with slight bedding in the north and 10–15 m bedding in the south. Sedimentary structures are lacking but trace fossils including burrows are common throughout. Concretions are evident in some parts of the sandstone. The sandstone varies in thickness from 15 m in the Takiritini River, to approximately 500 m at the Tinui Taipos. The name taipo is usually synonymous in the East

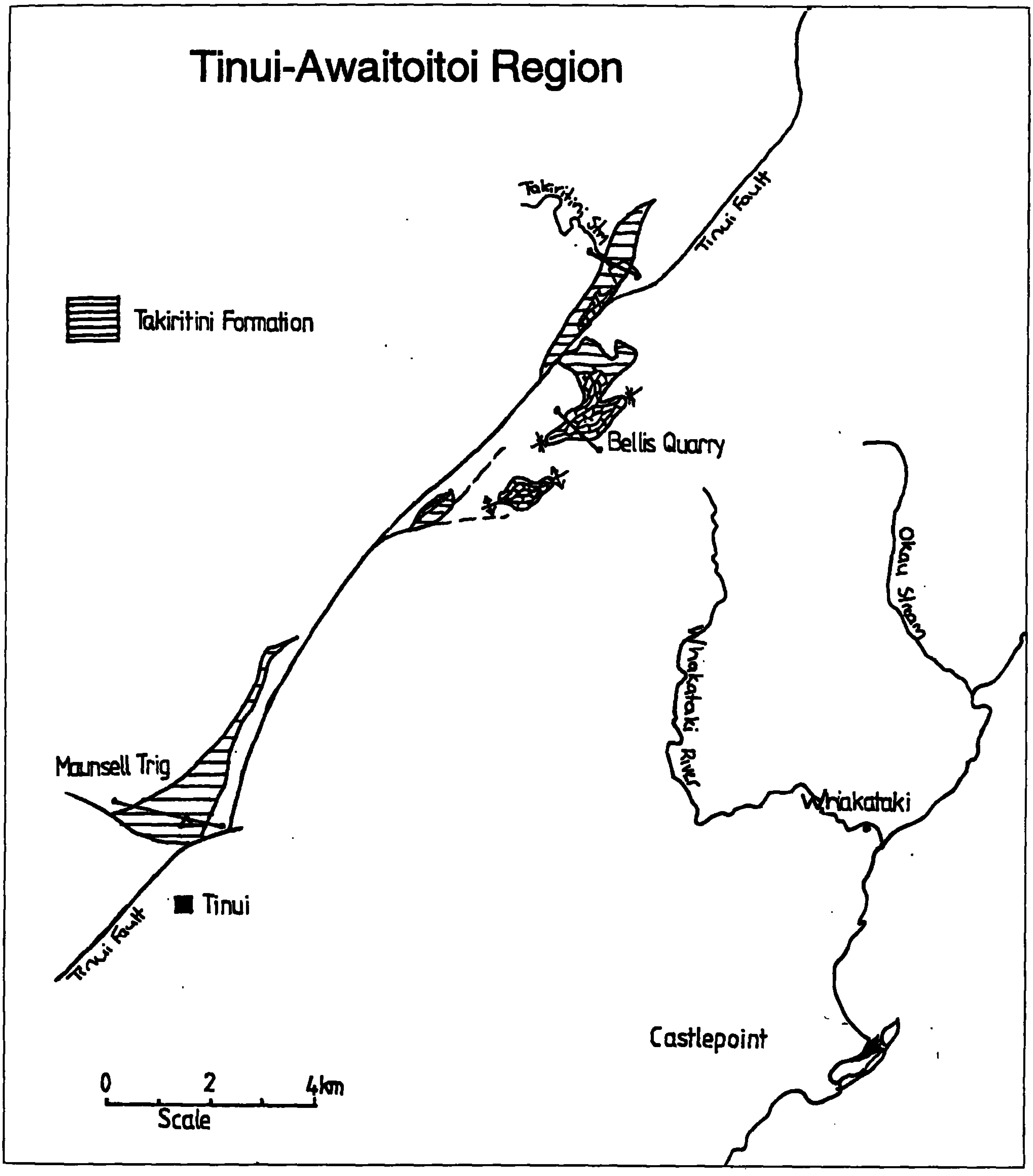

Fig. 2. Location map of Tinui–Awaitoitoi area, indicating section sites.

Coast Basin with Cretaceous age units so we will refer to them as the Maunsell Trig to avoid confusion.

Using the classification of Pettijohn (1987), the sandstone is an arkosic arenite. Grain size ranges from very fine to coarse with a sub-angular to sub-rounded grain shape. The sandstone is well-sorted to very well-sorted.

By plotting major-element data on Harker variation diagrams with data for New Zealand terranes included (Roser & Korsch, 1988), it is found that all data points plot tightly in the Torlesse provenance group. This indicates a source from the ranges to the west.

The limestone was formed from the deposition of detrital material from the erosion of shallow water algal reefs or banks. Benthic and planktonic foraminifera as well as shallow water molluscan shell fragments are also present. Fine-grained sub-angular terrigenous material is found scattered throughout. The limestone is cream in colour and weathers to pink, thinning from cm scale at the type section in the north to approximately 5 m in Bellis Quarry on the Tinui River. There is no evidence of the limestone at Maunsell Trig.

The siltstone is only complete at the type section where it separates two sandstone lenses. The siltstone is found at Bellis Quarry where it is incomplete. It is not found at Maunsell Trig. Fossil lenses are found throughout the siltstone with *Tropicolpus* cf. *milleri* Marwick dominating. The

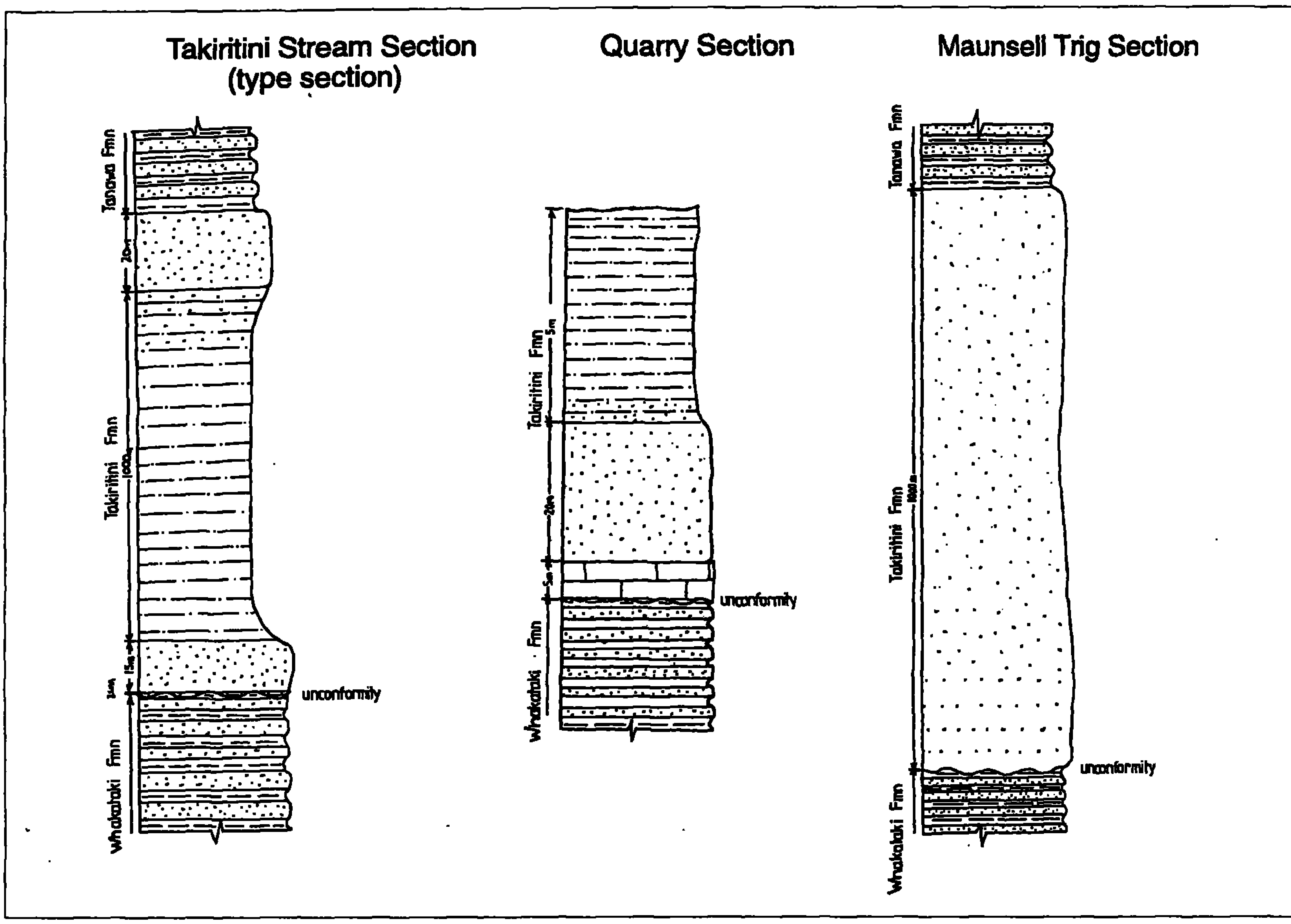

Fig. 3. Stratigraphic columns of studied sections.

siltstone is massive with no recognisable sedimentary structures.

Three sections through the Takiritini Formation were studied (figure 2).

Takiritini Stream Section The Takiritini Stream is the type section for the formation (figures 2 and 3). The sandstone is massive with no observable structure. The formation dips to the west at 40°. The basal sandstone lens of the type section is approximately 15 m thick. A 2 cm thick limestone is found at the base of the sandstone and is in unconformable contact with turbidites of the Whakataki Formation below. This indicates a relative sea-level rise to expose the turbidites, then a fall to shallower depths to deposit the limestone and the shallow marine sandstone (as indicated by the presence of shallow water echinoid remains). Less than a stage is missing at the unconformity (Johnston, 1980). Massive siltstone lies above the basal sandstone lens in sharp contact indicating a rapid change to a deep-water environment. The siltstone is approximately 100 m thick and grades into the upper sandstone lens following a more gentle decrease in water depth. The upper lens is about 20 m thick and is similar in lithology to the basal lens. Conformably overlying the upper lens are deep water turbidites of the Tanawa Formation which indicate another rapid increase in water depth and mark the end of the deposition of the Takiritini Formation. The Tanawa Formation, initially called the Maunsell Formation by Johnston (1980), has been redefined by Neef (1991b) who promoted the Tanawa member to formation status.

In thin-section the very fine-grained nature of the sandstone can be seen. The grains are sub-angular to sub-rounded and mostly quartz and K feldspar. Abundant clay is evident. Some visible porosity is observed, but micro porosity predominates. The results of samples (table 2) from the Takiritini Stream section (TS) sent to "Core Laboratories" reflect the nature of the formation at this section. Thin-sections also show replacement of foraminifera. Small remnant porosity is seen in fossil cavities. Due to clays, squeezed lithics and glauconite grains there is no visible porosity. SEM analysis reflects the same character showing micro porosity of 1 micron on average and quite a significant amount of clay material. XRD analysis has indicated that the clays present are smectite, chlorite, mica and kaolinite.

Bellis Quarry Section This section is through a small syncline of the Takiritini Formation on the Tinui River (figures 2 and 3). The outcrop shows common trace fossils and abundant macrofossils. The limestone is well exposed forming a small waterfall at the upstream end of the Quarry. The limestone is still unconformable with the underlying Whakataki Formation and is 5 m thick at this section forming a prominent ridge in the northeast of the syncline. Overlying the limestone is the first appearance of the sandstone showing interbedded cemented and uncemented layers. The sandstone is approximately 20 m thick and grades into siltstone. This may indicate a slower rate of increase in water depth than shown at the type section. The siltstone is incomplete and has a minimum thickness of about 5 m.

In thin-section the sandstone shows slightly better porosity, but over much of the sample no porosity is observed. Remnant porosity is seen in patches. Laboratory results show poor porosity (table 2, QS). Again the thin-sections show abundant clay. XRD analysis shows smectite, chlorite, mica and kaolinite to be present. The grain shape is sub-angular to angular and squeezed lithic and glauconite grains are seen. In SEM analysis a lot of grain-coating clays are evident.

The sandstone at the downstream end of the syncline thins and calcite-cemented lenses dominate. In thin-section (plate 1) the sandstone is fully calcite-cemented with grains comprising mostly quartz and K feldspar. Calcite is infilling all pore space both as cement and as a replacement mineral. There is clear evidence of replacement of framework grains shown by highly corroded grain boundaries, replacement between grains, and floating isolated grains. These features are all too fragile to survive transportation and therefore indicate post-burial diagenesis. This is significant in that at greater depths of burial, kerogens releasing organic acids ahead of oil migration will dissolve the observed calcite, producing secondary porosity and increasing permeability. The presence of calcite cement is regarded as a favourable sign as a precursor to good reservoir development. The algal limestone in thin-section is fully cemented and is unlikely to have intergranular porosity, but may well form fracture porosity in the appropriate setting.

Maunsell Trig Section The final section studied is the impressive Maunsell Trig (figures 2 and 3, and plate 2). Large 10–15 m sandstone beds, forming the Taipos, dip between 50–60° to the west and are massive, medium- to coarse-grained, showing no sedimentary structures. Crawling trail traces can be seen on the underside of the base of the beds. The section is approximately 500 m thick.

In thin-section (plate 3) well preserved primary porosity can be seen. Oversized pores may be caused by the dissolution of framework grains. The results from laboratory analysis show the greatly improved porosity and permeability (table 2, M). Mechanical compaction of grains can be seen in thin-section, and may have reduced porosity where there are lithic and glauconite grains, however glauconite grains are less common in this section than the previous sections. The character of the sandstone is shown (in thin-section and SEM) to be well-rounded to sub-angular, well-sorted with little clay, good pore throat size, and intergranular porosity. Where clays are present the sandstone is similar in composition to the finer-grained sandstone, but because the rock is more porous the clays are able to grow into better developed authigenic forms. XRD analysis indicates that hydroxy interlayered vermiculite, mica and kaolinite are present in the sandstone at this location.

Conclusion

Some Miocene sandstones have reservoir potential. The very promising results of porosity and permeability from the Maunsell section, and the potential for good secondary porosity and improved permeability of the sandstone at the Quarry section show that the shallow marine facies

Table 2. Porosity and permeability results from samples from the studied sections, analysed by Core Laboratories.

Plug	Air Perm Horz (mD)	He Inj Por (%)
TS1	11.0	13.4
TS2	0.15	10.1
TS3	0.12	11.4
TS4	Damaged core, no results	
QS1	0.15	8.6
QS2	1.5	12.2
M1	81.0	21.4
M4	46.0	23.8
M5	61.0	21.0
M10	218.0	26.2

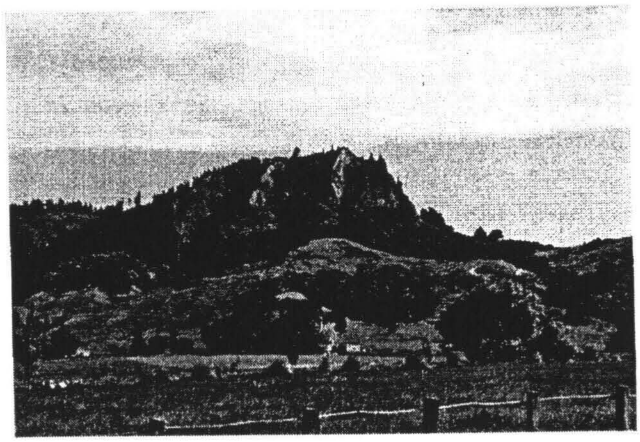

Plate 2. Maunsell Trig, western dipping Takiritini Formation sandstone beds.

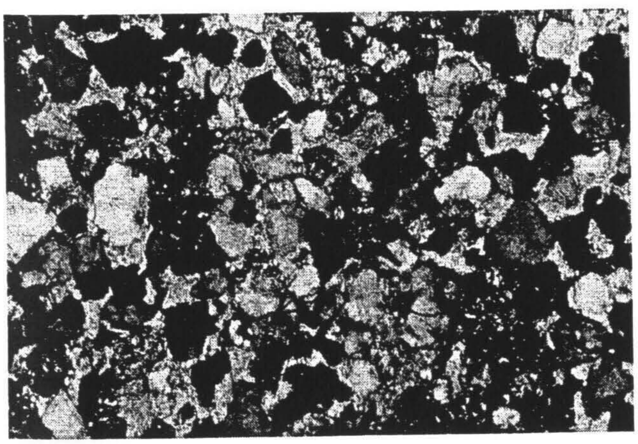

Plate 1. Photomicrograph of calcite cemented Takiritini Formation sandstone, Bellis Quarry Section (cross polarised light).

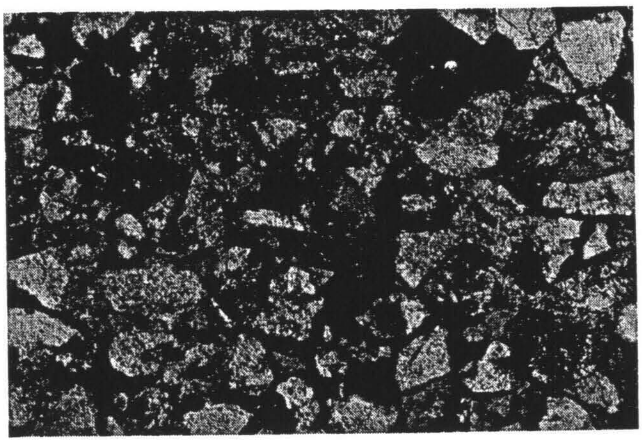

Plate 3. Photomicrocraph of Takiritini Formation sandstone, Maunsell Trig Section (plane polarised light).

represented by the Takiritini Formation would have the potential to act as a reservoir in the right setting. Where this facies exists in the subsurface it would be expected to have potential as a hydrocarbon reservoir.

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