

Petroleum Potential of an enigma: the Raukumara Sub-basin, East Coast, North Island

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Abstract

The Raukumara Sub-basin is the northernmost part of the East Coast Basin. Sedimentary thickness is thought to be more than 10 km across a large area of the Sub-basin. It is enigmatic because it is largely undeformed, unlike the rest of the East Coast Basin, and no wells have been drilled and no bottom samples are available to constrain its subsurface geology. Seismically-defined units are correlated with onshore geology on the basis of a wedge of chaotically-disrupted sediments which is present across much of the Sub-basin. This chaotic wedge is interpreted to be the offshore extension of the East Coast Allochthon, known from onshore. The Allochthon was emplaced as the modern plate boundary was initiated, around 25 million years ago (Ma). Post-allochthon sediments are commonly channelled and slumped indicating an active tectonic setting, consistent with the modern plate boundary. Pre-allochthon sediments are commonly continuous, gently folded and faulted, suggesting deposition in an extensional environment. The basal three seconds of sedimentary section is likely to be of Paleogene and Cretaceous ages.

Petroleum source rocks are likely to be oil-prone and include correlatives of the Paleocene Waipawa Formation black shale and Cretaceous oil shales. Reservoirs may include Cretaceous and Paleogene turbidite sands deposited into a muddy marine background, so seal is likely to be present. The thick Neogene sedimentary section implies generation and expulsion, primarily of oil. Large structural leads are apparent in the new data.

This basin is not for the faint-hearted as much of the region lies below 2,000 metres water depth and more seismic data is required before prospects can be delineated. Nevertheless, the Raukumara Basin is close to shore and may have trapped very large volumes of oil. We conclude that the Raukumara Basin may be significant for the future New Zealand economy.

Keywords: *New Zealand, East Coast Basin, Raukumara Sub-basin, East Coast Allochthon, Cretaceous Sediments, Petroleum Systems, Direct hydrocarbon indicators.*

Introduction

The East Coast Basin of North Island New Zealand is a large sedimentary accumulation sitting above part of the New Zealand plate boundary (Figure 1). The north end of the East Coast Basin is the Raukumara Sub-basin; the extension to the northeast of the Raukumara Peninsula (Figure 2) The Sub-basin covers an area of at least 25,000 km². It is approximately 300 km long and tapers from a width of around 100 km in the south to less than 50 km in the north. Water depths range from the coast to more than 3000 metres at its northern termination. The eastern margin of the Raukumara Sub-basin is formed by the northeast extension of the East Coast subduction complex, the East Cape Ridge (Lewis et al., 2004), while the western margin of the basin is formed by the Kermadec Ridge (Gillies and Davey, 1986; Davey et al, 1996).

The Raukumara submarine plain was first recognised as the site of a sedimentary basin by Gillies and Davey (1986) following a single-channel seismic survey. In 1990, the first deep penetration 2D

seismic line was acquired from the region revealing 7 seconds two-way time (TWT) of sedimentary fill in the nearshore part of this Sub-basin. Depth conversion using seismic stacking velocities suggested sedimentary thicknesses of up to 13 km (Davey et al., 1996). This was confirmed in 2005 by a second

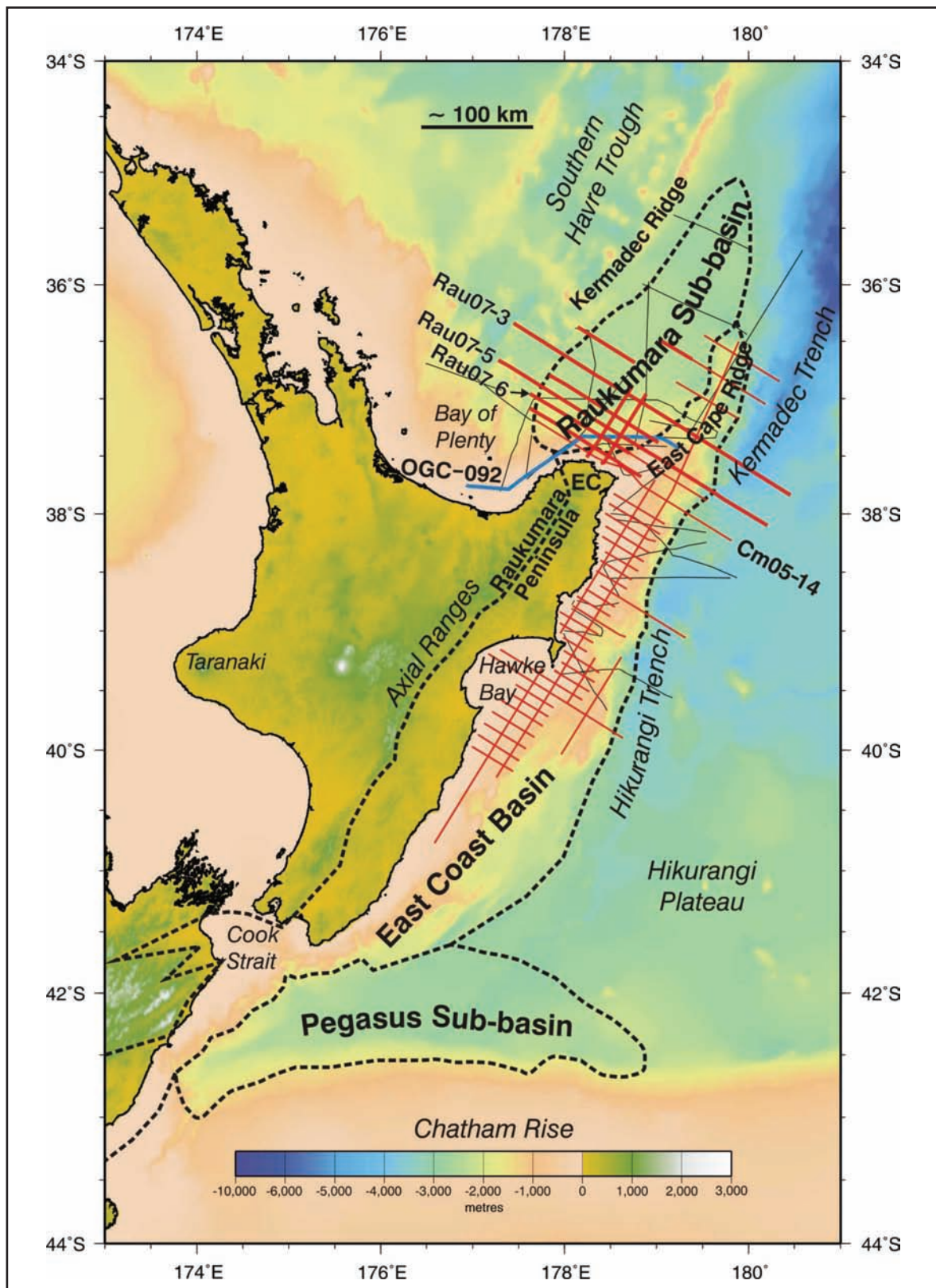


Figure 1. The Raukumara Sub-basin (green polygon - R) is located at the northern end of the East Coast Basin (red polygon). The solid yellow line is the New Zealand EEZ, the dashed yellow line indicates the area claimed by New Zealand as Legal Continental Shelf under the provisions of Article 76 of the United Nations Convention of Law of the Sea. The black box is the location of figure 2. The dashed red line is the present plate boundary, see text for annotations A to E.

deep penetration 2D seismic line (Uruski et al, 2006). In early 2007, the Crown Minerals group of New Zealand's Ministry of Economic Development, the government unit responsible for regulating and promoting the petroleum industry in New Zealand, carried out a seismic survey aimed at delineating the extent of thick sedimentary fill in this basin. The new survey, RAU07, will be made freely available to the industry from mid-2008, probably in conjunction with the announcement of a licencing round. This paper deals with the preliminary results of this survey and highlights the petroleum prospectivity of the basin.

The East Cape Ridge (Figure 1) is the northeast continuation of the Raukumara Peninsula and shelf. It has a highly complex structure and consequently its sedimentary section can only be poorly imaged. The Ridge plunges to the northeast from East Cape to a saddle at more than 2000 metres water depth. A separate bathymetric high extends above the 1500 metres isobath to the northeast before it joins the Kermadec Ridge. The East Cape Ridge appears to consist of highly deformed sediments or possibly a mix of sediments and volcanic rocks although the latter have not been positively recognised on seismic data, nor have they been modelled with potential field data. The older rocks of the flank of the Raukumara Basin appear to have been involved in the tectonism that deformed the Ridge, but younger rocks onlap the feature. Deformation of Neogene age extends westwards from the East Cape Ridge into the Raukumara Basin inverting older features and gently folding some strata (Uruski et al, 2006). Extensional faults extend to the seabed, where their scarps show up to 130 metres of relief suggesting young extensional tectonics in a back-arc environment (Uruski et al, 2006). The western margin of the basin is characterised by a set of westwards-dipping normal faults some of which also break the seabed (Figure 2).

The new survey, Rau07 (Figure 1), was acquired by the CGG Duke in early 2007 and was processed by Fugro in Perth to pre-stack time migration. A total of 1203 km of a planned 2170 km of 2D seismic data were acquired using a 7.2 km streamer. The 5,280 cubic inch air gun array, pressured to 2000 psi was triggered every 37.5 metres and recording time was 13.3 seconds for most of the survey. The exception was line Rau07-5, which was acquired with a 50 metres shot interval, recorded for 15.35 seconds. Line Rau07-5 was acquired along the line of a previously acquired wide-angle refraction profile. Work is still in progress on this earlier refraction data set. Gravity measurements were also made along Rau07-5 and the initial results of modelling are included in this paper.

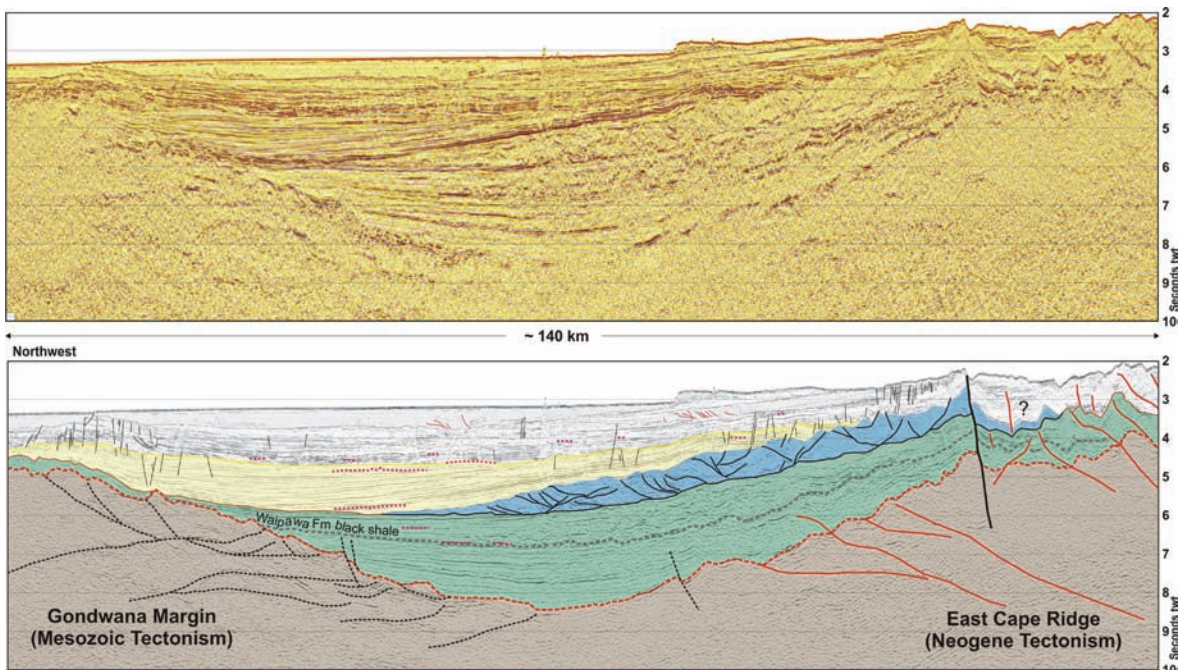


Figure 2. Data defining the Raukumara Sub-basin. Thin black lines are pre-existing low-fold industry and research data. The heavy blue line is OGS-092. The thin red lines are lines of the CM05 seismic survey and the heavy red lines are the new Rau07 data. Line Rau07-5 was modelled using 2D gravity, while Rau07-3 is the subject of figures 3,7 and 8.

The Rau07 data reveal a thick, little-deformed basal succession overlain by an apparently westwards-verging thrust wedge, which is, in turn overlain by a series of sequences or sediment wedges deposited alternately from west and east. The new data raises as many questions as it answers. For example:

- How old is the sedimentary fill?
- How did the sub-basin evolve?
- How can this sedimentary basin have remained virtually undeformed while occupying its position adjacent to such an active plate boundary?
- Does this sub-basin imply constraints on rotation of the plate boundary?
- Does the geometry of the offshore thrust wedge add to understanding of the Raukumara Allochthon?
- What is the geodynamic cause of the large negative gravity anomaly that overlies the sub-basin?
- What is the petroleum potential of this sub-basin?

This paper does not attempt to address all of these questions, but to show that, after making some reasoned assumptions, there is a strong possibility that the basin may have generated, expelled and trapped hydrocarbons.

Components of the East Coast region

Traditionally, the East Coast Basin has been considered to be the sedimentary succession lying between the axial ranges in the west and the Hikurangi Trench to the east including the accretionary prism along the modern plate boundary, onshore regions in a fore-arc location and accumulations within Cook Strait and onshore in northern Marlborough. In recent years, new evidence for thick accumulations to the north of the Raukumara Peninsula and in the deepwater east of Cook Strait (Uruski et al, 2006) extend the definition of the East Coast Basin to include the Raukumara and the Pegasus sub-basins (Figure 1).

The axial ranges form the “back-stop” to much deformation at the margin, although margin-related deformation continues westwards into the Taranaki and Northland basins (Figure 3). The axial ranges were uplifted approximately 1000 metres only 1 million years ago, possibly because the anomalously thick ocean crust of the Hikurangi Plateau collided with their root at that time (Uruski et al, 2006).

The Hikurangi Plateau is a large block of thickened buoyant oceanic crust occupying a roughly triangular area to the east of the East Coast Basin and to the north of the Chatham Rise (Figure 3). The Plateau has a crustal thickness of between 15 and 20 km (Davy and Wood, 1993) and covers an area of some 350,000 km² or about the same as the land area of New Zealand. It is believed to have originated as a Large Igneous Province (LIP) or part of one (Mahoney and Coffin, 1997).

It is not known how much of the Hikurangi Plateau was subducted before subduction ceased nor whether the collision was a contributory cause in that cessation (Davey et al, in press).

The East Coast subduction trench is subdivided into two sectors; the Kermadec Trench extends about 1200 km to the north of New Zealand where water depths exceed 8000 metres. The Kermadec Trench results from an ocean to ocean plate collision. The foot of the accretionary prism is marked by the southward continuation of the Kermadec Trench, the Hikurangi Trench. This sector is considerably shallower than the Kermadec sector. In the north, the Hikurangi Trench rises from around 5000 metres to about 3000 metres to the east of Hawke Bay and 2000 metres off Cook Strait. The Hikurangi Trench is the site of collision between thick oceanic and continental crust.

The East Coast Basin itself lies between the backstop of the axial ranges and the subduction trench (Field et al, 1997). It includes what has been described as a fore-arc component running from Cook Strait through Hawkes Bay, an uplifted and deformed coastal block and the accretionary prism

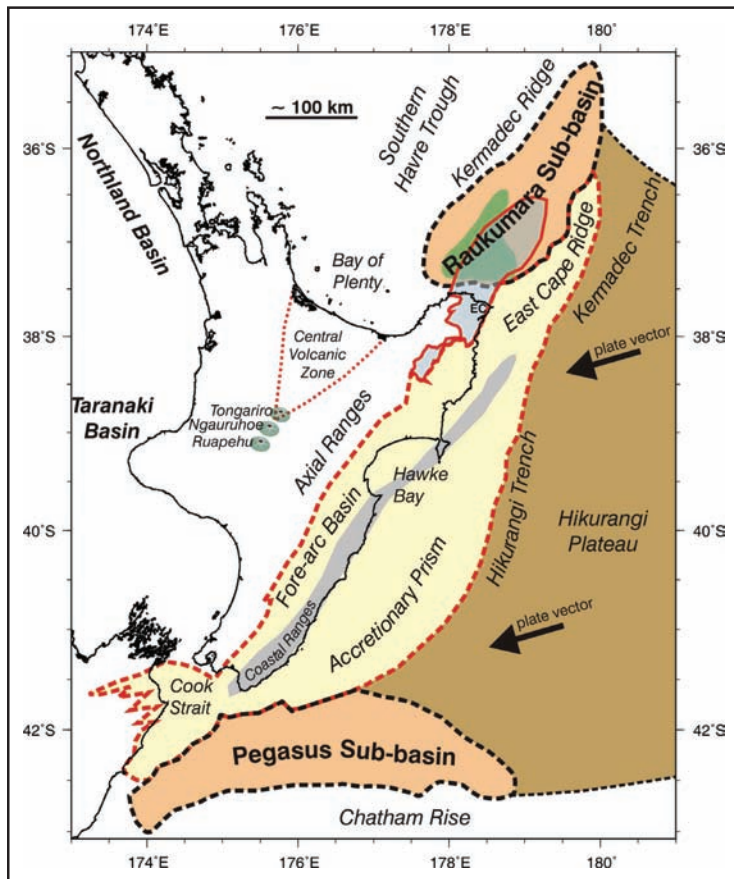


Figure 3. Panel from seismic line Rau07-3 across the centre of the Raukumara Sub-basin. The green mega-sequence is the syn- and post-tectonic basin fill, blue is the Allochthon, Yellow is Miocene and uncoloured is Late Miocene to Recent. Grey bodies within this youngest unit represent mass transport units, some less chaotic zones appear to have been thrust and folded during movement. The location of the Waipawa Formation is shown as a grey dashed horizon. Dotted magenta curves show locations of amplitude anomalies. See Figure 2 for location.

may be that the East Coast Basin would all look like the Raukumara Sub-basin without the severe deformation that affects much of it.

Geology of Raukumara Peninsula

The Raukumara Peninsula is the most rugged part of the East Coast Basin, with peaks up to 1750 metres. It is extensively incised by a number of large rivers, including the Waipoua which carries the largest sediment load of any river in New Zealand and flows into the East Coast Basin to the east of Gisborne (Figure 4).

Economic basement in the Raukumara Peninsula is considered to be the Torlesse Supergroup (Figure 4). The Torlesse forms the axial ranges of North Island as well as much of the Eastern part of South Island and ranges in age from Carboniferous to Early Cretaceous (~ 350 to 120 Ma). The Torlesse consists for the most part of lightly metamorphosed alternating sand and mudstone facies and includes massive mudstones and sandstones as well as conglomerates with volcanic clasts. In the Raukumara Peninsula, the Torlesse Supergroup (Figure 4) ranges from Late Jurassic to Early Cretaceous in age (~ 150 to 120 Ma), is thought to underlie much of the East Coast Basin (Mortimer et al, 1999) and outcrops extensively in the Raukumara Peninsula (Mazengarb and Speden, 2000).

As in other parts of New Zealand, Cretaceous and Paleogene sediments record overall transgression across basement terranes, but unlike the rest of New Zealand, terrestrial rocks are unknown in the East

(Figure 3). The “fore-arc” basin is characterised by a broad, flat valley floor to the east of the axial ranges, however, seismic data show it to be complex in the subsurface, with structures dominated by thrust faults and compressional anticlines. As the volcanic arc lies a large distance away and in fact consists of only three andesitic volcanoes, its designation as a fore-arc basin is dubious. The Coastal ranges consist of highly deformed Cretaceous and Neogene sedimentary rocks with some Torlesse basement at the surface. Many of the structures may be mapped from surface outcrops unlike those of the fore-arc basin, which rarely have a surface expression. The Accretionary prism (Figure 3) is characterised by a series of northeast-trending, arcuate thrust ridges with intervening piggy-back basins. Thick sediments continue onto the Hikurangi Plateau portion of the Pacific plate.

The East Coast Basin components do not have an obvious extension into the Raukumara Sub-basin, which appears to overlie at least three zones; the fore-arc, the backstop of the Axial Ranges and a possible “back-arc” position to the west of the Axial Ranges. It

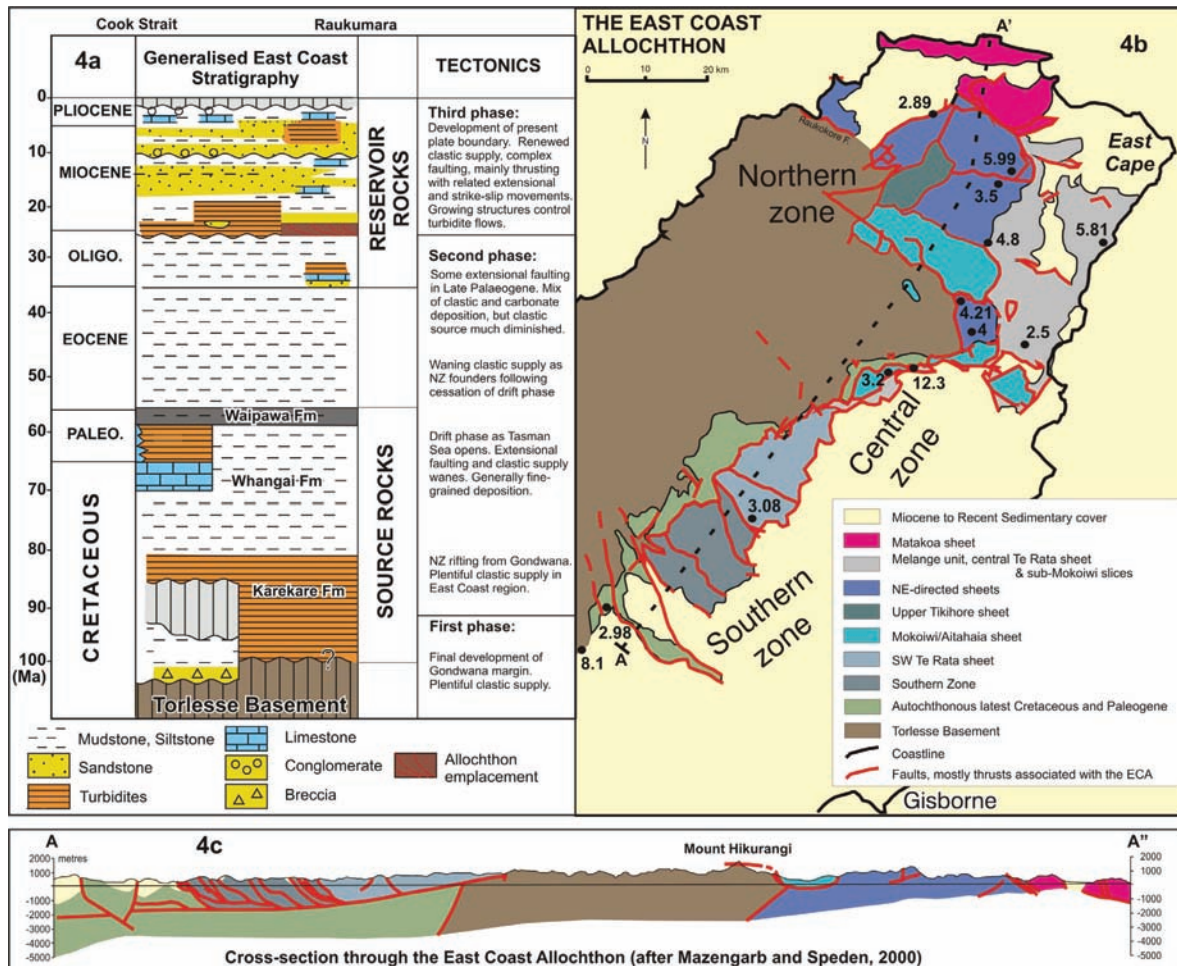


Figure 4. Components of the East Coast region. The green area within the Raukumara Sub-basin is the region below which the interpreted Waipawa Formation source rock is deep enough to be expelling oil today. The light blue polygon with heavy red boundary is the East Coast Allochthon (ECA: see Figure 5 for details)

Coast Basin and all units are of marine origin. Early Cretaceous sediments generally overlie the Torlesse Supergroup unconformably although the age of the basal sediments varies from place to place.

Soft sediment deformation is common in some regions and the youngest Torlesse rocks appear to be younger than the oldest cover sediments. These factors together suggest that an actively deforming topography was gradually inundated by later sediments. Analogies are widespread in the Neogene of the region, which is currently deforming due to subduction (Uruski et al, 2005, 2006). Early Cretaceous units were deposited in marine environments ranging from shelf depths to around 500 or 1000 metres water depth. The earlier units are coarse grained and later units are fine grained clastic sediments but punctuated with sandy intervals. Near the top of the Early Cretaceous, channel systems and submarine fans are recorded. Latest Cretaceous and Paleocene units are generally fine-grained deep-water deposits and include units containing significant organic carbon. One such unit is the Waipawa Formation black shale with an average Total Organic Carbon (TOC) content of around 5% (Figure 4), but varying from 2.5% to 12% in the Rakumara Peninsula, where most outcrops are parts of the Allochthon.

The East Coast Allochthon consists of a series of thrust sheets which appear to have been obducted onto the Raukumara Peninsula. It occupies much of the Raukumara Peninsula and was first recognised by Stoneley (1968) who mapped 15 south-southwest directed thrust sheets in a large area to the northwest of Gisborne. The Allochthon consists mainly of Cretaceous and Paleogene sedimentary rocks with some volcanic and Torlesse Supergroup rocks. The Allochthon was emplaced during the Early Miocene (Figure 4), contemporaneously with the Northland Allochthon (Ballance and Sporli, 1979, Isaac et al., 1994). Timing of emplacement is constrained by relationships between the Allochthon units and syn-tectonic deposits (Field et al., 1997). The basal detachment commonly developed at, or near the

top of the Paleocene Waipawa Formation black shale, or the underlying Latest Cretaceous Whangai Formation, probably exploiting Eocene smectitic mudstone as a glide plane. The Allochthon exhibits 50% overall shortening with increasing deformation to the north-northeast. Although the most southerly sheets have moved only 2.7 km, the most northerly units have an estimated displacement of 235 km (Rait 1995). South-southwest directed thrusting caused foreland effects with small basins formed ahead of imbricate thrust ridges. Near the end of the Early Miocene, the western region, now occupied by the axial ranges of North Island, was uplifted and large volumes of allochthonous and Torlesse basement rocks were eroded and re-deposited to the east. The Allochthon is covered to the east by up to 5000 m of late Neogene sedimentary rocks and its eastwards extent offshore remains unknown.

Cretaceous and Paleogene rocks emplaced by the Allochthon are generally comparable with their autochthonous correlatives, but one unit records a relative sealevel drop, contains more plant and carbonaceous material and is of Coniacian to Campanian age (~ 90 to 75 Ma), comparable in age to the Taranaki Delta (Uruski et al, 2002) as well as with other deltas in the region, such as the Emperor Group of Gippsland and the Great Australian Bight deltas (Norvick et al, 2001; Bernecker and Partridge, 2001; Totterdell et al, 2000). The relative sealevel fall which allowed outbuilding of deltas throughout the region may have resulted in deposition of large volumes of coaly source rocks at that time.

Neogene successions in the Raukumara Peninsula record renewed voluminous clastic deposition sourced from the collision zone of the developing plate boundary. Sediments were typically deposited by turbidite currents into a mud-rich marine environment. Geometries of basins tended to control flow and therefore locations of turbidites and many are preserved in the axes of synclines rather than across the crests of the syn-depositionally rising anticlines.

Origin of the gravity anomaly

The East Coast Basin trends north-northeast and extends from the Raukumara Sub-basin in the north to Marlborough in the northern part of South Island. The basin is gravitationally complex as a variety of processes is in operation today. Prominent among these processes are;

- Subduction, which creates the regional gravity trends
- Back-arc extension in the Havre trough, which impinges on North Island through the Bay of Plenty to create the Central Volcanic Zone (Figures 3,5)
- Uplift due to the affects of subduction of the Hikurangi Plateau
- Subsidence of the “fore-arc” basin through the onshore Hawke Bay region and;
- Rapid erosion, transport and deposition of sediments, which fills lows, helps drive subsidence and redistributes mass from onshore to the offshore accretionary prism, increasing its gravity high.

Some components of the East Coast region are well-imaged by the gravity field and others less so (Uruski et al, 2006). Anomalies generally trend to the northeast (Figure 5a) and are dominated by the Southern Havre Trough, a broad high averaging around 60 milligals and the Kermadec trench to the east of the Raukumara Sub-basin is a large gravity low extending to around -150 milliseconds. The Raukumara sub-basin occupies the region between these northwards-converging features.

Much of the onshore Raukumara region is overlain by a neutral or slightly negative gravity field (Figure 5a). In contrast with the onshore gravity low, the offshore accretionary prism is characterised by a gravity high, suggesting that it has been uplifted above isostatic equilibrium. The Hikurangi Plateau gives rise to a gravity high of similar magnitude to that of the accretionary prism and is separated from it by a narrow gravity low marking the position of the Hikurangi trench.

The southern part of the Raukumara Sub-basin gives rise to a -150 milligal free air gravity low. This large, almost circular low is in contrast to the background anomaly which, over the Raukumara Peninsula and the northern part of the Raukumara Sub-basin is a neutral or slightly positive anomaly.

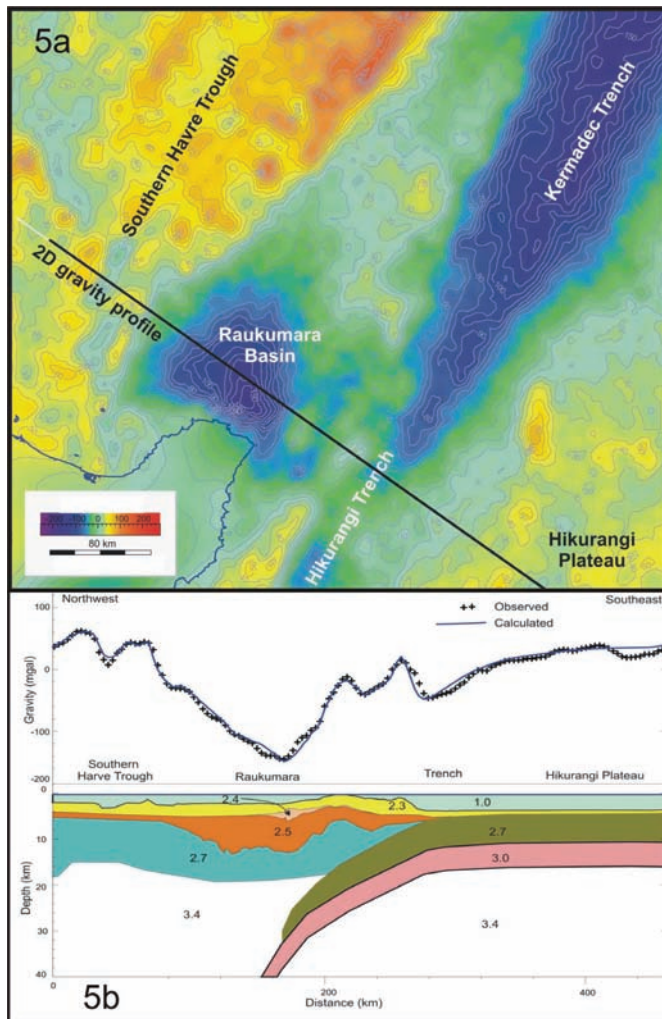


Figure 5. 5a is a generalised stratigraphy for the East Coast Basin showing the relative stratigraphic positions of source and reservoir facies. 5b is a generalised outcrop geology map of the Raukumara Peninsula, A-A' is the location of 5c. The black dots are the locations of Waipawa Formation samples and the numbers are measured values of TOC.

with subduction related earthquakes (Reyners et al., 1999) to a depth of 50 km, the assumed basalt to eclogite transition. Models also incorporate a mass anomaly associated with the main body of the subducted plate comprising a 100 km thick body between 100 and 300 km depth with a density contrast of 0.04 Mg/m^3 (not shown in models). Although the nature of the crust beneath the Raukumara Basin is uncertain, it is assumed to be Mesozoic metasediments of the Torlesse Supergroup with a density of 2.7 Mg/m^3 .

The model (Figure 5b) shows the base of the metasedimentary crust beneath the Raukumara basin extends to about 20 km depth, and the edge of the Hikurangi Plateau thins to the west beneath the eastern part of the basin. The observed gravity anomaly can be adequately explained by the assumed crustal thickness, the associated water depth and the sedimentary succession in the Raukumara Basin, which together accounts for about -100 mgal of the observed anomaly. The remaining -50 mgal arises from the low-density of the subducted oceanic crust of the Pacific Plate relative to mantle densities.

Gravity model

Satellite altimetry-derived gravity data from the region are shown in Figure 5a. The free air gravity anomaly data are dominated by southwest-northeast trending anomalies: the gravity high in the northwest is the result of crustal thinning in the southern Havre Trough and lows in the east are associated with the deep water in the southern Kermadec and Hikurangi trenches. A -150 milligal (mgal) free air gravity anomaly is centred on the Raukumara Basin.

A provisional 2D gravity model of profile perpendicular to the strike of the major structures and coincident with seismic line Rau7-05 is shown in Figure 5b. The model is based on a preliminary seismic interpretation of this line and is consistent with previous models of the Raukumara Basin (Davey et al. 1996) and the adjacent Hikurangi Plateau (Davy and Wood, 1993; Davy et al in press). The model was generated using Encom ModelVision-Pro (www.encom.com.au). It has four major layers; water, sediment, crust and mantle. The sedimentary section is subdivided into three units of increasing density with depth. Density of the sedimentary layer varies from 2.3 to 2.5 Mg/m^3 . Hikurangi Plateau crust is assumed to consist of a basaltic upper crust with a density of 2.7 Mg/m^3 , underlain by oceanic gabbro and metagabbro with a density of 3.0 Mg/m^3 .

In the model, subducted crust coincides

Seismic stratigraphy

The origin and stratigraphy of this Sub-basin remain enigmatic. Using the single seismic line from the CM05 survey that crosses the southwest part of the Raukumara Sub-basin, CM05-14 (Figure 1), Uruski et al (2006) showed that its seismic stratigraphy may be considered as three mega-sequences; an older “syn-rift” succession, a prograding mega-sequence and a tectonic mega-sequence. By comparison with known onshore geology, it was suggested that the oldest units may be of Cretaceous age, the prograding unit may represent a Paleogene passive margin and the youngest unit, the Neogene, was deposited in a tectonically active environment.

The new data (Figures 1, 2) confirms the existence of the three mega-sequences, but introduces the additional factor of approximately westwards-verging thrust sheets which are tentatively correlated with the East Coast Allochthon emplaced around 25 Ma. The “allochthon” lies above the oldest succession and below the prograding unit, which suggests that the prograding unit may be of Miocene age. This is consistent with other parts of the East Coast Basin, where a major tectonic event is seen to start about the end of the Middle Miocene (Uruski et al, 2005), but, if this interpretation is correct, it is surprising that little tectonism appears to have affected the Raukumara Sub-basin for a period of approximately 15 My following emplacement of the allochthon.

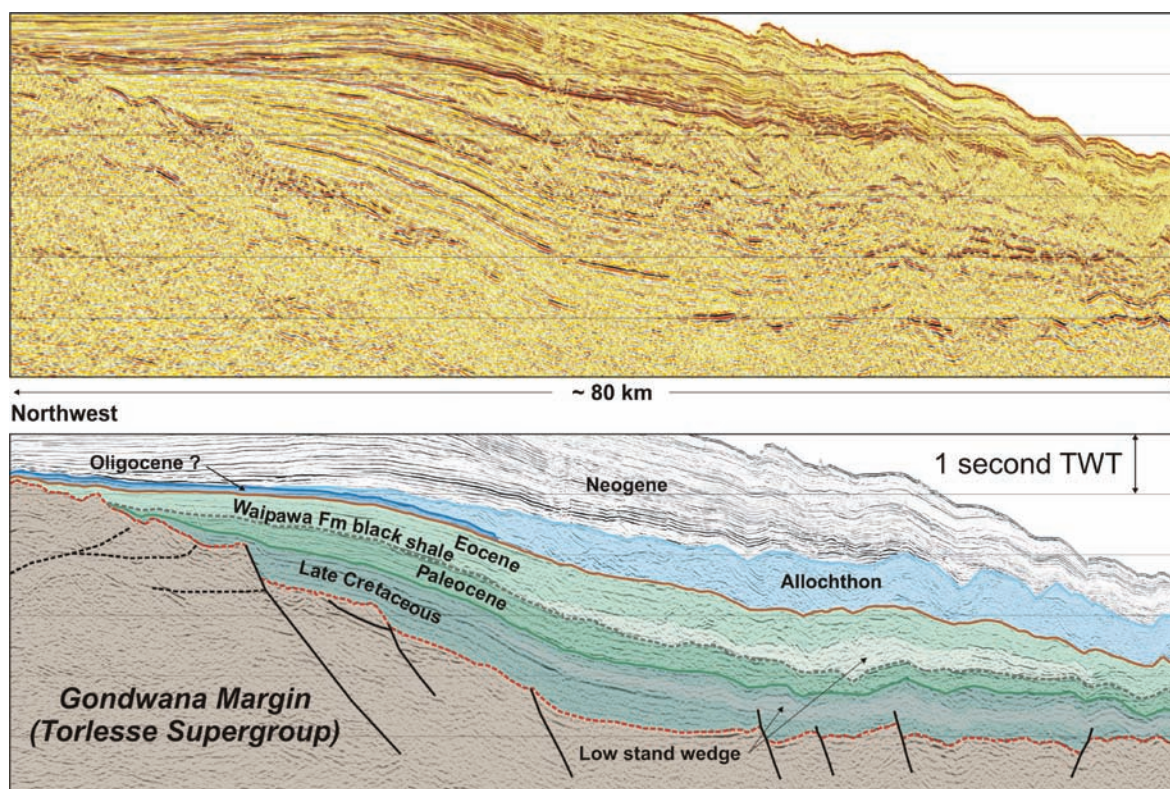


Figure 6. Free air gravity map of the Raukumara Sub-basin (4a) showing main gravity trends discussed in the text and the line of section used for the model (4b). Number associated with the coloured polygons are densities in grams per cubic centimetre. Light blue polygon (1.0) is the water layer, the yellow (2.3) is Neogene sediments, pink (2.4) is the Allochthon, orange (2.5) is Paleogene and Cretaceous sediment layer. The green layer (2.7) to the west of the trench is the Torlesse basement, olive green (2.7) is the Hikurangi Plateau, pink (3.0) is oceanic crust of the Pacific plate and white (3.4) is mantle.

Figure 6 is a panel from Figure 2 (Rau07-03) which has been flattened to show how the interpreted Cretaceous and Paleogene successions may have been deposited as a series of prograding clinoforms across a shelf, slope and basin floor topography. A series of highstand systems tracts appear to have built upwards and outwards into the basin probably in response to subsidence of the ancient Gondwana margin. Two lowstand systems tracts are interpreted from units onlapping the “slope” regions and these

may be indications of reservoir development in lowstand basin-floor fans. The interpreted Cretaceous and Paleogene succession appears to be relatively thin at around 2 seconds TWT, however, depth conversion using seismic stacking velocities gives a maximum thickness of nearly 5000 metres which represents approximately 60% of the basin's sedimentary fill at this point.

Following deposition of the thin Oligocene beds (Figure 6), the eastern part of the basin was uplifted and the Allochthon was emplaced. A westwards-prograding succession similar to the prograding mega-sequence of Uruski et al (2006) was deposited on top and to the west of the Allochthon. It is likely that much of at least the lower part of this prograding wedge was reworked from the Allochthon and the uplifted East Cape Ridge.

The final mega-sequence consists of a series of alternating westwards and eastwards thinning sediment wedges suggesting tilting back and forth. Many of these wedges contain slumped and channeled units and large-scale mass transport units are particularly common in the upper part of this succession.

Petroleum systems and direct hydrocarbon indicators

Although no commercial hydrocarbons have been discovered in the East Coast Basin since the late nineteenth century (Francis, 1993), a large number of gas and oil seeps have been mapped onshore (Uruski et al, 2005; Uruski et al, 2006). In addition many wells have reported shows of oil and gas and a small sub-commercial gas discovery were made by Westech in 1998. Many of the gas and oil samples have been geochemically typed to potential source rocks (eg. Rogers et al, 1999), of which the three generally recognised are the Paleocene Waipawa Formation black shale, the much thicker Late Cretaceous and Paleocene Whangai Formation and older Cretaceous units such as the Karekare Formation mudstone (Figure 4). Source rocks in the Raukumara Sub-basin are likely to include all three formations.

The absence of diagnostic age criteria, the broadly spaced seismic lines with few tie lines and the present early stages of interpretation, makes thermal modelling of the Raukumara Basin difficult. Some of the influences on heat flow include the cool subducting slab of the Hikurangi Plateau from the east, the presence of the Central Volcanic Zone to the west of the basin (Figure 5a) and the modelled relatively shallow mantle below the western part of the basin (Figure 5b). These three factors suggest that heat flow may increase westwards. However, applying a conservative geothermal gradient of 24°C/km (Uruski et al, 2006) allows rough estimates of expelled volumes to be made. The water bottom temperature at 2000 metres in the Raukumara Basin region is approximately 2°C (Ridgway, 1969).

The Waipawa Formation is generally quite thin, averaging about 50 metres in thickness although the wavelet interpreted as the Waipawa Formation (Figure 2) suggests that it could be much thicker. Measurements of its total organic carbon content (TOC) average 5% with maximum values of more than 12%. Hydrogen indices for the Waipawa Formation vary from 200 to more than 400 and it therefore has a mixed oil and gas potential. This rich source rock is seen in many of New Zealand's petroleum basins. It is recognised along the length of the onshore East Coast Basin (Hollis and Manzano-Kareah, 2005) and has been identified in Northland, both onshore (Isaac et al, 1994) and in the Waka Nui-1 well (Milne and Quick, 1999). Its geochemical signature has been recognised in oil from the sub-commercial Kora discovery of northern Taranaki (Killops et al, 1994) and it was drilled by most of the wells in the Great South Basin, where it averaged 47 metres thickness (Cook et al, 1999). Although relatively thin where it has been drilled across highs, the Waipawa Formation reflector commonly becomes broader and its amplitude increases away from highs and into the depocentres so it is likely to be thicker within the deeper parts of basins (Uruski et al, 2004).

The Waipawa Formation is interpreted at a depth of approximately 7.4 km, or 5000 metres below the seabed. Using the assumed geothermal gradient, the Waipawa Formation would be at a temperature of 122°C. A 50 metres thick marine source rock with type II kinetics (Pepper and Corvi, 1995) in the early stages of oil expulsion may expel approximately 5 million barrels of oil per square kilometre (Funnell and Benchilla, 2005). The Waipawa Formation black shale appears to be at a similar maturity across an area of approximately 10,000 km² (Figure 3). Total expulsion from this unit may have been around 50 billion barrels of oil and very little gas.

The Whangai Formation (Figure 4) averages around 500 metres thickness and about 1% TOC. It too has potential for mixed oil and gas, is buried more deeply than the Waipawa Formation and may be capable of expelling some 100 billion barrels of oil equivalent. This figure is based on slightly deeper burial and temperatures of approximately 130°C, but assumes similar kinetics and a similar area of maturity. A small volume of gas is also expected.

The Karekare Formation (Figure 4) is generally lean, but TOC values of 4% have been measured. This mudstone unit is up to 3000 metres thick and may cover an area of 2,500 km². Assuming an average depth of burial of 8 km, the formation would be at a temperature of approximately 194°C which would suggest that is close to peak maturity. The Karekare Formation may therefore be expelling large volumes of gas at present and gas flushing may be a risk to the oil potential of the Sub-basin.

Seeps are well-documented from onshore Raukumara, from south to north are the Totangi, Waitangi and Rotokautuku oil seeps (eg Francis, 1998). Several wells record oil and gas seeps and one well, Waingaromia (Francis, 1993) produced around 50 barrels of oil a day for several years in the late 1880s. Recently a satellite seep study has been conducted by NPA for Crown Minerals (NPA, 2008). A number of slicks were interpreted, particularly from the western margin of the Raukumara Sub-basin. Five slicks were repeated on different satellite images, suggesting that they may have originated from seafloor seeps. However, these are still to be confirmed.

Reservoirs are likely to be shelf and turbidite sandstones. The presence of turbidites is suggested by the lowstand systems tracts of Figure 6 and by mounded facies within the post-allochthon successions. High amplitude reflectors of the lateral equivalents of the prograding mega-sequence are interpreted as shelf sands (Uruski et al, 2006, Figures 2, 7).

Structural traps may be present, as large-scale rollovers, possibly controlled by extensional faults (Figure 9). The western margin of the basin Compressional anticlines are present along the eastern margin of the basin, probably due to back-thrusts to modern convergent tectonics. It is likely that older “Allochthon” structures were reactivated later in the Neogene. The western margin contains a number of leads which are manifest as anticlines in Cretaceous and younger strata. Lateral equivalents of the Waipawa Formation appear to onlap the top Cretaceous surface (Figure 8) suggesting that a late Paleocene or Eocene transgressive sand may have been deposited across the Cretaceous surface. Additionally, at least one structure shows Neogene turbidite sequences draped across underlying structure. The folding event forming the three anticlines and illustrated on figure 9 appears to have taken place by reactivation of older faults about the same time that the Allochthon was emplaced.

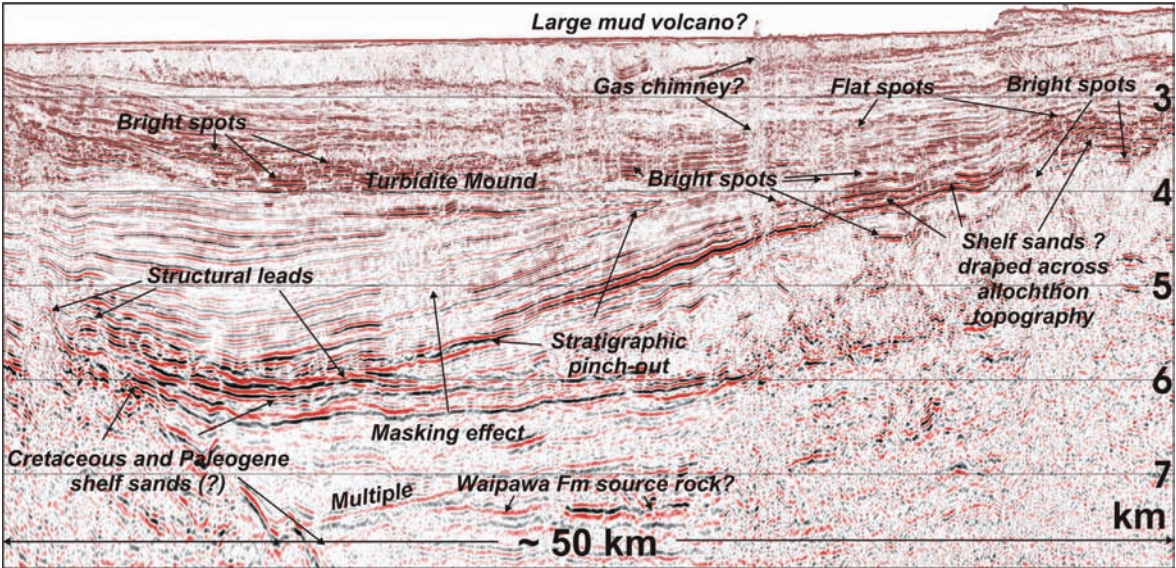


Figure 7. Panel from seismic line Rau07-03 flattened on a surface designed to show the Cretaceous and Paleogene successions as prograding units. The thin, darker blue unit above the Eocene succession is interpreted as an Oligocene unit, perhaps a limestone.

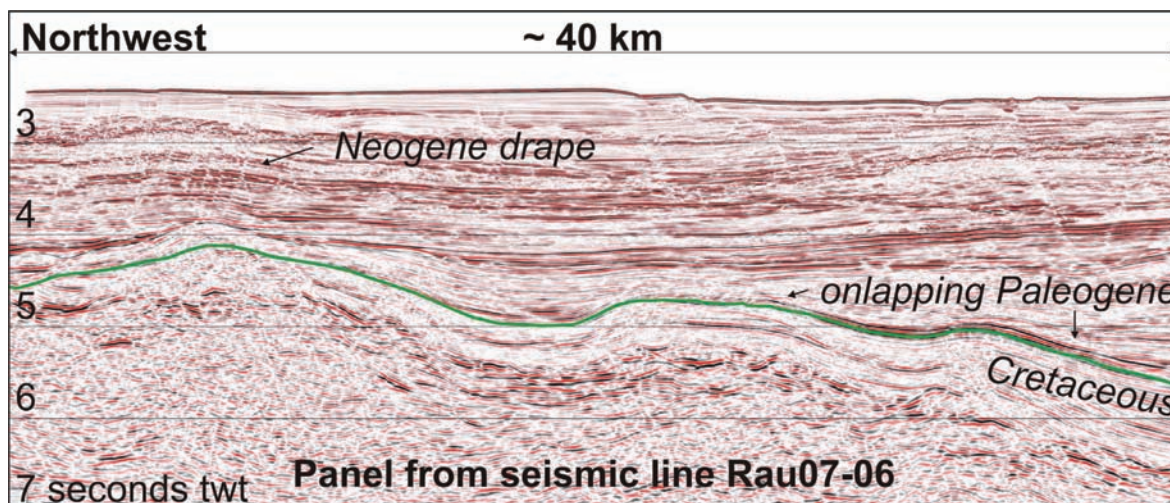


Figure 8. Panel from depth-converted seismic line Rau07-03 showing elements of petroleum systems.

The Raukumara Sub-basin may have significant untapped potential. Many high-amplitude reflectors are present, some of which may be direct hydrocarbon indicators (DHIs). Figure 8 is a depth converted migrated section showing a variety of possible DHIs and trapping styles. The Waipawa Formation lies approximately 5 km below the seabed and the Allochthon terminates about mid-way across the section at a depth of 6 km. The Allochthon appears to be an imperfect migration barrier to hydrocarbons migrating from depth. Just to the northwest of the termination of the Allochthon, a turbidite mound at around 4.1 km depth exhibits a high amplitude signature which masks reflectivity below. This may be a hydrocarbon-charged body about 10 km across. A rough, but conservative estimate of the potential reserves of the feature may be made by assuming porosity of 25%, with 50% pay and 50% saturation. If it is circular in plan, it would cover an area of 78.5 km² and would be capable of containing more than 1 billion barrels of oil or 2.5 TCF of gas. Structural leads associated with faults are visible along the western part of the basin and in drape anticlines across the top of the Allochthon. One possible gas chimney appears to originate within the Allochthon, travelling through the overburden to the seabed where it may have formed a very large mud volcano. Possible flat spots and bright spots are common throughout the basin, particularly in the younger units, but also associated with the interpreted Waipawa Formation.

In summary, onshore geology suggests the presence of voluminous source rocks of varying richness. The Waipawa Formation is at a depth where it should be expelling oil today. A variety of leads has been imaged by all of the lines acquired so far and there are reasonable grounds for the existence of good reservoir facies in the basin. Seismic anomalies may prove to be DHIs, and large oil and gas accumulations may be present. Considering the effect that the modest 42 MMBBL Tui field is currently exerting on the New Zealand economy, this newly-discovered sedimentary basin, together with a number of poorly explored and totally unexplored basins in the New Zealand EEZ, has the potential to make a significant contribution.

Conclusions

The new RAU07 2D seismic data set confirms the presence of an extensive, relatively undeformed and thick accumulation of sedimentary rocks below the offshore Raukumara Plain.

Comparisons with onshore geology allow the erection of a tentative seismic stratigraphy based on the emplacement around 25 Ma of a widespread set of thrust sheets or slides, correlated with the East Coast Allochthon.

The thick sequences below the offshore Allochthon include syn-tectonic units of Paleogene, Late Cretaceous, and possibly Early Cretaceous ages, deposited in an extending basement likely to be composed of Torlesse Supergroup metasediments.

The allochthonous wedge, by analogy with the onshore Allochthon, is likely to consist of Late Cretaceous and Paleogene rocks similar to those of the syn-and post-rift succession.

Post-Allochthon sequences are characterised by alternating westwards- and eastwards-thinning wedges, channelled and slump units. All of these features together tell a tale of a disturbed tectonic regime with crustal-scale tilting and instabilities that would be expected from the location of the basin adjacent to the modern compressional plate boundary. The post-Allochthon succession is therefore likely to be of Neogene age.

The Raukumara Sub-basin is an analogy for the East Coast Basin minus the severe tectonism seen in its sedimentary succession today.

By analogy with onshore geology, the pre-Allochthon Cretaceous and Paleogene succession is likely to consist entirely of marine sediments. As such, petroleum source rocks are likely to be present. Biomarker geochemistry of onshore oil seeps suggests a mix of source rocks including the Paleocene Waipawa Formation black shale, the leaner Whangai Formation and an older marine source rock, probably equivalent of the Karekare Formation mudstone, but possibly as old as Aptian to Albian age.

The depth of burial of the Paleocene Waipawa Formation is around 5000 metres, which, with a geothermal gradient of 24°/km, places it firmly in the oil expulsion window for marine source rock. Older Cretaceous source rocks are likely to be expelling gas at present.

Reservoir facies are present in repeated transgressive and turbidite sands of Cretaceous ages and in probable turbidite sands of Neogene age.

Most lines show several possible anticlinal traps and a number of stratigraphic features. Although a large number of leads is present, this reconnaissance survey cannot define prospects and further data is needed.

One lead on line RAU07-03 shows a mounded, high-amplitude feature at around 1800 metres below the seabed sited above the toe of the Allochthon. Between this inferred turbidite mound and the Allochthon, the section appears to be masked and a little disrupted. The implication is that the inferred turbidite reservoir is charged with hydrocarbons expelled from the Waipawa Formation, which migrated around the relatively impervious Allochthon and up wards into the reservoir. Other high amplitude reflector packages are also seen to either side of the inferred turbidite mound and a little higher in the section.

If this feature were circular, it would cover an area of 78 km² and could contain more than 1 billion barrels of oil assuming porosity of 25%. If the inferred turbidite mound is filled with gas, it may contain 2.5 TCF.

The potential of the basin is ultimately dependant on the volume and richness of the source rock present. Assuming that the Waipawa Formation black shale is 50 metres thick and is mature across half the area of the basin, it is capable of generating around 200 billion barrels of oil. In addition, other source rocks may have generated around 1,500 billion barrels of oil equivalent.

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As well as conducting government-funded research, Chris has worked on contract for many, if not most of the exploration companies in New Zealand and he believes that our deepwater sedimentary basins contain large volumes of oil and gas.