Sedimentary systems of northwest New Zealand

C.I. Uruski

GNS Science, Lower Hutt, New Zealand. Email C.Uruski@gns.cri.nz

Abstract

Recent exploration has blurred the accepted boundaries of the Taranaki Basin, both in time and geography. North of Taranaki is the Northland Basin and to the northwest is the deepwater extension of Taranaki into the head of the New Caledonia Trough. Sedimentary systems have taken little heed of the arbitrary boundaries between these regions. Seismic data show that a considerable section is present below rocks previously thought of as economic basement. One well, Wakanui-1, drilled coal measures of Middle Jurassic age which extends the potentially productive succession by some 50 million years. Abundant source rocks, reservoir and seal are present in units ranging from 140 Ma to the present. Five distinct sedimentary systems are now recognised, each of which may contribute to petroleum systems:

1) The oldest, of Jurassic age, is seen in Wakanui-1 and at outcrop near Auckland. It was deposited into an inland or marginal seaway near the margin of Gondwana and contains known coaly units, which may be valid source rocks. The Astrolabe survey of 2001 showed possible correlatives in the Deepwater Taranaki Basin.

2) The second system, also indicated by the Astrolabe survey, is tentatively correlated with the Strzelecki Group of the Gippsland Basin. It is thought to be mainly terrestrial and may contain lacustrine and coaly source rocks.

3) The third system is the Taranaki Delta deposited in the head of the New Caledonia Basin. Its basal unit is correlated with the Taniwha Formation and it culminated with the Rakopi Formation.

4) The Late Cretaceous and Paleogene transgressive marine successions buried the Taranaki Delta and remaining basement highs in the region. During low stands, sediments by-passed the very broad shelf to be deposited into the head of the New Caledonia Basin. This system culminated in deposition of the widespread Oligocene limestone and contains transgressive, shore-face and turbidite sand units.

5) The Neogene was dominated by turbidite deposition and contains a range of features including slope and basin-floor channels and fans. Levees and overbank deposits and mass transport units are common.

Introduction

While onshore and shallow water basins, particularly Taranaki, continue to provide good scope for petroleum exploration, most discoveries since Maui have been relatively small and structures are almost never full to spill. The reasons for New Zealand's modest success start with the modern plate boundary between the Pacific and Australian plates. This boundary has been the main influence on development of the New Zealand region, not only is it responsible for the existence of the New Zealand land mass, but it also formed the trapping structures for most of New Zealand's known hydrocarbon accumulations. On the negative side, the plate boundary is also responsible for disrupting those trapping structures by tilting and fracturing them. Many structures that once held oil and gas are now dry. Even Maui, New Zealand's largest success so far has been estimated to have once contained several billion barrels of oil (Matthews, 2002), subsequently largely replaced by 4 billion cubic feet of gas. Uruski

(2000; 2001) suggested that structures further away from the plate boundary stand more chance of remaining intact. It was proposed that attention should be given to the deepwater parts of the New Zealand Exclusive Economic Zone (EEZ) resulting in acquisition of the 6,300 kilometres Astrolabe 2D speculative seismic survey in 2001 (Uruski et al, 2002).

New Zealand's petroleum basins were considered to have originated as rift basins formed as the Gondwana super continent broke apart and are generally dated from the Late Cretaceous. The northwest New Zealand basins are probably the best known although recently, Jurassic rocks have been revealed as potential members of petroleum systems (Milne and Quick, 1999; Uruski and Stagpoole, 2004; Uruski et al, 2004). In Taranaki, Late Cretaceous successions include terrestrial and marine rocks (King and Thrasher, 1996). However, the limited lateral extent of data coverage revealed only part of the Late Cretaceous sedimentary system. Fluvial units with intervening coaly swamps suggest widespread river systems with locally-derived flow directions. Until the Astrolabe survey was acquired from the Deepwater Taranaki Basin, there was little evidence of the Late Cretaceous marine environments into which the rivers flowed and discharged their sediment load. The Astrolabe data set (Uruski et al, 2002) shows that the main Taranaki Cretaceous coal measure unit, the Rakopi Formation, is the final unit deposited as the topset beds of a large delta which built out into the head of the New Caledonia Basin from about mid-Albian time to the Maastrichtian when the delta was buried by the transgressive marine North Cape Formation. The delta created an extensive terrace covering more than 20,000 km2 beyond today's shelf edge as well as much of the present-day shelf. This terrace strongly influenced all subsequent deposition, such that a small change of relative sealevel resulted in very large lateral shifts of facies belts.

Transgression continued through the latest Cretaceous and Paleogene until the modern plate boundary was initiated near the start of the Miocene. During the Neogene, clastic sediments were sourced from the rising New Zealand landmass and are represented in Deepwater Taranaki by a succession dominated by turbidite and mass flow deposits.

Past exploration successes commonly set trends for future exploration. By considering the sedimentary systems of northwest New Zealand and the controls imposed upon them by tectonics and paleogeography, the geographical distribution of facies similar to those that provide the known habitats of oil and gas may be predicted in deeper water.

In deeper water, away from the disruptive influences of the plate boundary, Cretaceous fluvial sandstones facies, similar to the Paleogene Kapuni Group reservoirs of the major Kapuni, Maui and Pohokura fields are present across a wide area. Likewise, shore face sands of Late Cretaceous and Paleogene ages are likely analogies of the Tui-Amokoura-Pateke field reservoirs (Matthews, 2000, 2002; Matthews and Lewis, 2001), developed as the transgressive system crossed the older delta causing facies belts to sweep back and forth in response to relative sealevel changes. Analogies of Paleogene and Miocene turbidite systems are present and are also widespread in very large individual fan bodies. In addition, channel facies, which have yet to be proven productive are present in many units in deep water and may be future drilling targets.

Physiography and basin disposition

The Taranaki shelf is broad and up to 150 kilometres across (Fig.1). To the north the shelf narrows to less than 50 kilometres and trends to the northwest along the Northland peninsula. The head of the New Caledonia Basin occupies the region between the Northland Peninsula and the Challenger Plateau and is truncated at its southeastern end by the Taranaki shelf. The main structures within the New Caledonia Basin also trend northwest-southeast parallel with the Northland peninsula and with the ancient Gondwana margin. The West Norfolk Ridge is mostly buried by sedimentary rocks in the area of interest although it is emergent further to the northwest. This ridge plunges to the southeast to impinge on the Taranaki shelf edge, effectively forming a boundary between the Deepwater Taranaki and Northland basins. A second, but discontinuous ridge, the Northland Ridge, bisects the Northland Basin splitting it into two main depocentres. The Northland Boundary Fault is a major back-thrust to

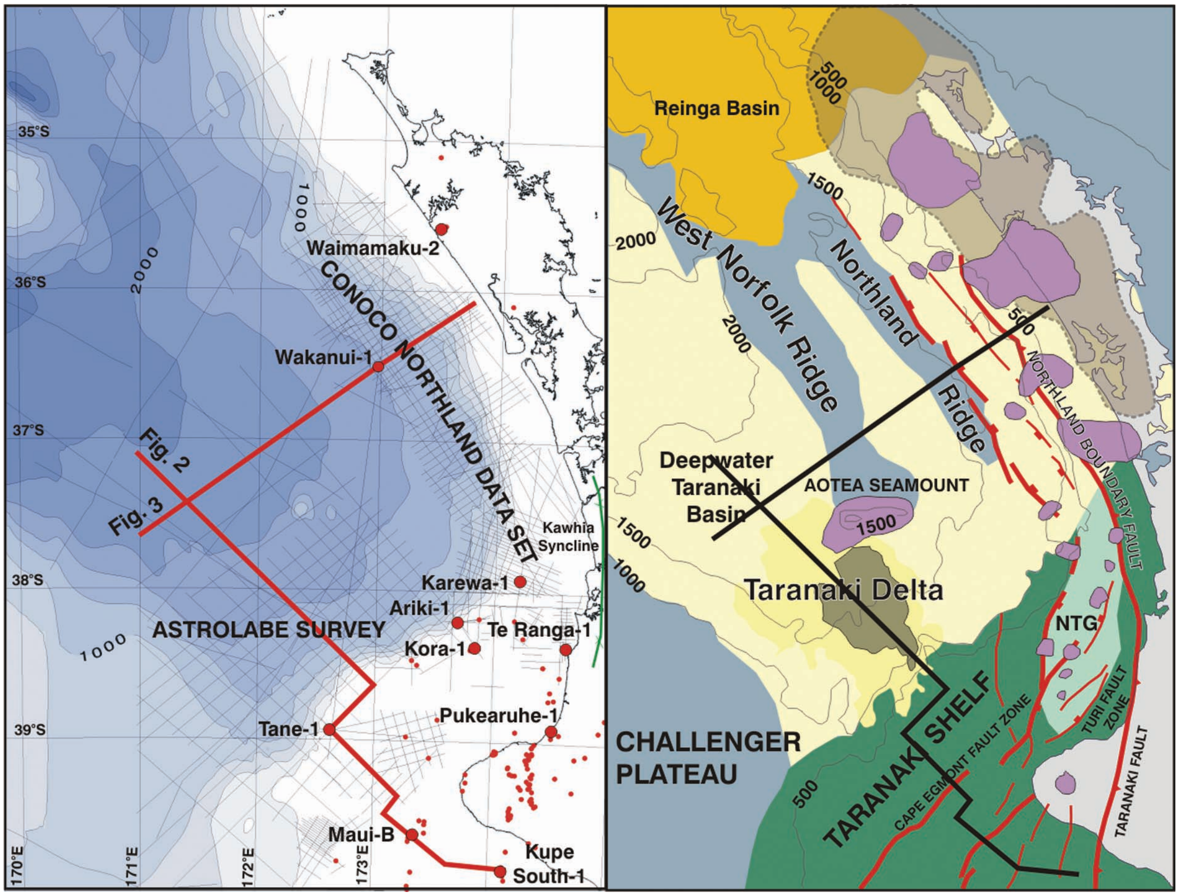

Fig 1: The left hand map shows bathymetry and locations of well and seismic data. Red dots are wells. Named wells are mentioned in the text. The red track lines are the locations of seismic lines shown in figures 2 and 3. The Taranaki Shelf is very well covered by seismic data, although little is shown for clarity of other features. The right hand map shows regions and features mentioned in the text. The orange polygon in the north is the Reinga Basin, the brown polygon covering the Northland Peninsula is the extent of the Northland Allochthon, main deepwater depocentres are shown in light yellow, the Taranaki Shelf is green and the North Taranaki Graben (NTG) in light green. Volcanic edifices are purple.

the Gondwana subduction system, while the Taranaki Fault is a similar feature reacting to the modern plate boundary. To the northwest of the Northland basins lies the little known Reinga Basin (Herzer et al, 1997; 1999).

Much of the exposed surface of the Northland Peninsula is formed by a series of thrust sheets called the Northland Allochthon (Isaac et al, 1994), which were emplaced from a northerly direction during the Early Miocene. The Allochthon, Northland Peninsula and North Taranaki are pierced and overlain by a series of large volcanic mounds ranging in size from the 30 kilometre Mount Egmont in Taranaki to more than 100 kilometres across (Fig. 1). These shield volcanoes and numerous smaller examples occupy much of the present-day shelf of Northland. In the centre of the New Caledonia Basin, Aotea Seamount is a Miocene volcanic centre extruded across the flank of West Norfolk Ridge to form a large present-day bathymetric high.

Basement

In northwest New Zealand basement consists of a series of Paleozoic and Mesozoic terranes, grouped into two provinces. The western group consists of pre-Permian rocks of the Gondwana margin, and the eastern group are mainly Permian and Mesozoic metasedimentary rocks. Between the two is the Median Tectonic Zone or Median Batholith, which includes a range of subduction-related plutonic, volcanic and sedimentary rocks of Mesozoic and older ages (Mortimer et al. 1999).

Several offshore Taranaki wells drilled to basement providing information on the nature and extent of the basement rock types (Mortimer et al. 1997). Basement rock types are subdivided into a series of north-south-trending belts correlating with the terranes of northern South Island. To the west are the dominantly quartzose Takaka and Buller terranes, while to the east lie the components of the Gondwana arc system dominated by the products of Andesitic volcanism. Between the two is the younger Median Batholith as typified by the Separation Point granite. The large area of granitoid rocks are excellent sources for quartzose sand.

The Murihiku terrane forms part of the Eastern Province and has long been considered to be part of the economic basement. This terrane outcrops onshore close to the coast of Northland in the Kawhia Syncline where it consists of a thick sequence of gently dipping, structurally simple, little metamorphosed, marine and non-marine rocks of Permian to Early Cretaceous age. Close to the North Island coastline, prominent seismic reflectors within Murihiku rocks show marked continuity, little deformation and gentle dips. Offshore, Wakanui-1 drilled Middle Jurassic coal measures assigned to the Murihiku Group. Both Jurassic coal measure units are characterised by relatively low vitrinite reflectance values suggesting that the Murihiku rocks may still have petroleum potential (West, 1999) and are not economic basement.

Sedimentary systems

Seismic sequence stratigraphy may be approached at several levels from outcrop to basin-wide and regional scales. Sequences are generically-related packages of sediments; those on a basin-wide scale are referred to as first-order sequences, while those at outcrop scale may be fourth-order or higher (eg. Mitchum et al 1977). Sequence boundaries are unconformities and disconformities, or otherwise times when relatively rapid change took place. On the seismic scale, first-order sequences are commonly referred to as mega-sequences denoting major differences in sedimentary style due to relative sealevel changes or changes in sediment supply. Most seismic sections may be easily subdivided into first-order sequences, for example, a unit of clinoforms may overlie a horizontal unit suggesting that the two units were deposited in different environments, the change being marked by the interface between the two. A sedimentary system is a first-order sequence or mega-sequence in its entirety affecting at least the whole sedimentary basin and possibly a wider region across an ocean margin zone as far as clastic sediments are transported. Only regional high-quality seismic coverage can image all or most of a sedimentary system. In northwest New Zealand, the Astrolabe survey of Deepwater Taranaki Basin and the exploration data acquired by Conoco (1996) and reprocessed by Spectrum in 2004, together with the mass of data from the Taranaki shelf, come close to providing the necessary coverage for imaging complete sedimentary systems of the region (Fig. 1). The distribution of sequences within each sedimentary system assists construction of paleogeographic maps and recognition of the distribution of the elements of petroleum systems.

Five sedimentary systems are recognised in Deepwater Taranaki (Figs. 2, 3) extending into the Taranaki shelf and Northland regions. Each system contributes some, or all of the elements of petroleum systems.

1 Jurassic syn-rift system

The Jurassic System sedimentary system is considered separately mainly because of its novelty as the Jurassic has long been considered part of the economic basement. The first high-quality seismic line acquired in the head of the New Caledonia Basin (TL-01; Uruski, 2000) suggested that either the Cretaceous succession was of very great thickness or that the clearly sedimentary succession below the top Cretaceous reflector includes an even older succession. It was suggested that, being remote from the effects of both the modern and the Gondwana plate boundaries, older sediments in the head of the New Caledonia Basin may have escaped the tectonism and metamorphism associated with those boundaries. This perception was strengthened by the Astrolabe seismic data which confirmed the presence of the delta and the thick underlying succession (Uruski et al, 2002; fig. 2).

Murihiku Supergroup rocks of Triassic and Jurassic ages crop out onshore and include coal measures of the Late Jurassic Huriwai beds, deposited in braid-plain and delta environments, which include thin coals of high-volatile bituminous rank (Ballance 1988; Suggate, 1990). The confirmation of Jurassic equivalents offshore came when the results of the Wakanui-1 well (Figs 1, 3) were released in 2003 (Milne and Quick, 1999; Dolan and Istadi, 2003; Uruski and Stagpoole, 2004). Wakanui-1 was drilled in 1999 by Conoco (now part of Conoco-Phillips) in partnership with Inpex Northland Limited and Todd Petroleum Mining Limited. This well was drilled in the Northland sector of northwest New Zealand in 1455 metres of water to a total depth (TD) of 3681 metres. The target was a Cretaceous coal measure succession interpreted as overlying the dip slope of a large rift block. However, it proved to be a marginally mature Middle Jurassic coal measure succession and no Cretaceous rocks at all were encountered. Wakanui-1 results therefore revealed a potential Jurassic petroleum system.

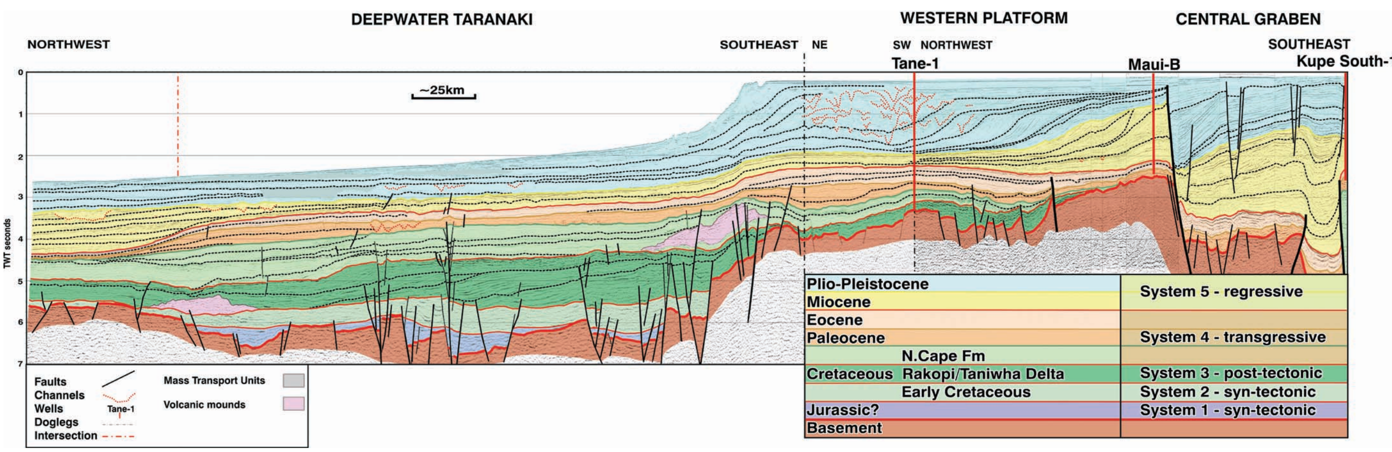

Fig 2: Composite of several seismic lines intended to show a comparison of nearshore and deepwater structure and stratigraphy through Taranaki Basin. If the effects of water velocity are removed, the top of the delta would be almost flat below the shelf edge. (Uruski et al, 2002). Location of this approximately 450 kms-long seismic composite is shown of Figure1 as are the location of the wells intersected.

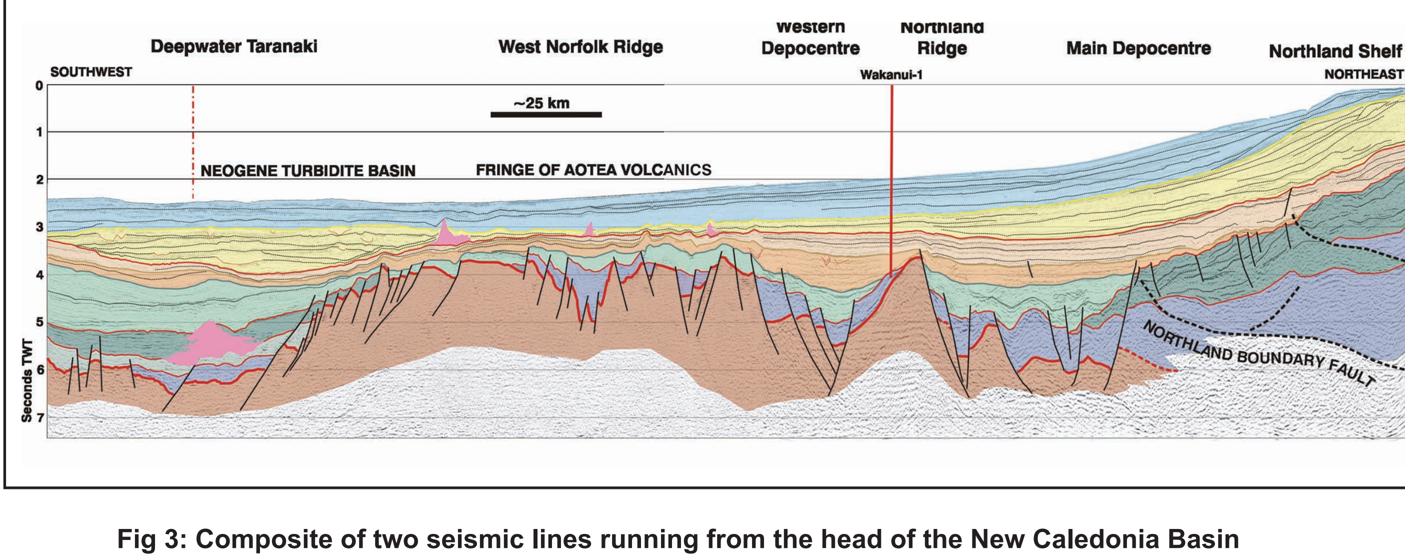

Fig 3: Composite of two seismic lines running from the head of the New Caledonia Basin to near-shore Northland. Seismic composite is approximately 307 km long; its location is shown on figure 1 as is the location of Wakanui-1. Colour scheme is as for figure 2.

In offshore Northland, Jurassic rocks (Fig. 3) were interpreted away from Wakanui-1 to extend offshore from Hokianga Harbour in the north to Kaipara Harbour in the south (Uruski et al, 2004). Their average thickness is approximately 2000 metres and they reach more than 3000 metres in grabens. They appear to extend across the Northland Boundary Fault and may lie as close as 5 kilometres offshore, where data coverage stops. Onshore from Port Waikato in the north to Awakino near the north Taranaki coast, the Kawhia Syncline contains more than 4,500 metres of Jurassic rocks (Kear, 1987). Most are marine shales, sandstones and conglomerates, although plant fossils are found in the Early and Middle Jurassic and coal measures in the Late Jurassic. Provenance of the conglomerate pebbles changes through time from andesitic volcanic to more acidic rocks. Some fine-grained beds are slumped suggesting active syn-depositional tectonics. Jurassic extension is suggested by fanning reflectors on the dip slope of the Wakanui fault block. This extension was probably driven by back-arc extension to the Gondwana margin. Jurassic extension set the scene for later basin development by initiating the topographic low now occupied and enhanced by thick sedimentary accumulations. Similar Jurassic extension is recorded elsewhere in the region, particularly along the eastern Australian margin.

At present, little is known of the relationships of the various facies recognised from outcrop, drill and seismic data and a full pattern of the Jurassic sedimentary system is not apparent. However, the Jurassic successions of Northwest New Zealand were probably deposited in two related basin systems. To the northeast, the Kawhia Syncline has been interpreted as a fore-arc basin, while the rifted units in the head of the New Caledonia Basin were deposited in what appears to be a back-arc environment.

2 Early Cretaceous syn-rift system

The Early Cretaceous sedimentary system appears to be the result of continued post-Jurassic extension and deposition Uruski et al (2002) subdivided the Cretaceous of Deepwater Taranaki into three megasequences; syn-rift, prograding and transgressive, which are only partly correlated with stratigraphic units closer inshore (Fig. 2). The age of the oldest sediments of the syn-rift megasequence is unknown, but is likely to be older than 105 Ma. It is thought to be mostly terrestrial with a possible marine incursion from the northwest towards its culmination. A hiatus between the syn-rift sediments and overlying prograding megasequence is marked by a single large volcanic mound near the northwest end of the Astrolabe data coverage and by downlapping reflectors of the prograding megasequence.

The driver for extension during this part of the Cretaceous may have been continuing back-arc extension inboard of the Gondwana margin. A time correlation with the Strzelecki Group of Gippsland was tentatively suggested by Uruski et al (2002) and Uruski et al (2003) although its composition is unknown. Seismic data suggests that much of this section was derived from immediately adjacent terranes. Thick talus overlies fault planes and fluvial and possibly lacustrine rocks fill grabens. Many of the adjacent terranes typically consist of quartzose metamorphic sediments (Roser et al, 1996) unlike Gippsland, where provenance of the Strzelecki Group is mainly volcaniclastic. Consequently, the Early Cretaceous succession of Deepwater Taranaki is likely to be similarly quartzose. A subtle seismic character change in the northwest combined with the paleogeographical location of the Early Cretaceous rift basins suggests the possibility of an early marine incursion into this low-lying rift zone (Uruski et al, 2002).

Early Cretaceous rocks were drilled in the Waimamaku-2 well of onshore Northland (Fig. 1) although their extent in the subsurface of Northland is unknown.

3 Late Cretaceous delta system

Most Late Cretaceous units around New Zealand are strongly dominated by fluvial successions suggesting that large rivers systems traversed the area, but known sites where these rivers entered the sea are few. Lacustrine deltas have been described from Western Southland (Lindqvist, 1990) and marine deltaic rocks from the Chatham Islands (Wood et al, 1989). Marine rocks of Cretaceous age are widespread in the East Coast Basin of North Island (Field et al, 1997), but the Cretaceous coastal region is neither exposed nor recognised on seismic data except, perhaps on two seismic lines in the far north (Uruski et al, 2006). The Astrolabe survey confirmed the presence of Cretaceous deltaic units in northwest New Zealand, first imaged by one seismic line; TL-01.

A large-scale prograding megasequence (Fig. 2) is interpreted as an extensive delta fed by the Late Cretaceous rivers systems of the region. Its basal unit is tentatively correlated with the Taniwha Formation of Albian age. This formation has been drilled by only two wells, Te Ranga-1 (Shell Todd Oil Services, 1986) and possibly Pukearuhe-1 (Forder and Bennett, 1986), both in northern Taranaki. The Taniwha Formation is therefore located on both sides of the Taranaki Fault. The unit can be mapped on seismic data as far west as the North Taranaki Graben, but currently available data does not allow differentiation of the deeper succession in the graben. It has been tentatively correlated with a unit which overlies the Northland Boundary Fault. In Northland, the Taniwha Formation and possibly other units of the prograding mega-sequence, downlaps onto an older succession, presumably the Jurassic sediments of the Murihiku Group.

The culminating unit of the delta is tied to the Rakopi Formation coal measures in Tane-1 (Shell, BP and Todd, 1976) and covers an area of approximately 20,000 km2. Five systems tracts are recognised including both high-stand and low-stand systems tracts. The final unit of this sedimentary system is a low-stand systems tract that onlaps the prograding Rakopi systems tract. Subsequent units are part of the transgressive system.

Rift faulting appears to have been active below the Taranaki Shelf, during deposition of the delta, but only small faults break the prograding units in deeper water. The relatively undeformed clinoforms of the delta cover a broad area which forms an extensive platform with low dips. The resulting palaeogeographic imprint persists to the present day.

4 Transgressive system

The transgressive system continued from the Maastrichtian to the end of the Oligocene, a period of approximately 50 million years. It is typified by deposition of fine-grained sediments, although most of New Zealand's petroleum has been found in Paleogene aged rocks.

Late Cretaceous

The transgressive megasequence progressively buried the delta, the Taranaki shelf and high-standing fault blocks such as at Wakanui. Although it is generally seismically bland, a complex pattern of reflector terminations can be discerned. The flat, extensive delta top was easily inundated and exposed as relative sealevel rose or fell and facies belts moved rapidly in response. Drilling results support this with for example, the post-Rakopi North Cape Formation sediments in Tane-1 (Shell, BP and Todd, 1976) where thin marine units were succeeded by coal measures of the Wainui Member and later marine sand of the Island Sandstone and succeeding fining-upwards marine clastic deposits.

The focus of rifting had changed by the time the North Cape Formation was deposited (King and Thrasher, 1996; Sutherland et al, 2001), not only was it mainly affecting the Taranaki shelf, but its north-south orientation was strongly oblique to the ancient Gondwana margin trends seen in both Deepwater Taranaki and Northland, where major structures trend northwest-southeast parallel with the ancient Godwana margin and the present Northland Peninsula. In Northland, extension may have continued through the latest Cretaceous although the presence of Cretaceous rocks in the offshore Northland Basin has yet to be proven. The seismic character of the inferred Cretaceous succession is that of a low amplitude package of continuous reflections which commonly onlap and bury basin centre highs (Uruski et al, 2004). Rafts of high-amplitude reflectivity are interpreted as coaly units similar to the Wainui Member within the North Cape Formation of Taranaki. The North Cape Formation equivalent onlaps along the Northland peninsula onto the paleoslope of the Northland Boundary Fault block and this region may be the site of development of paralic facies ranging from coal measures formed across coastal plains to shore face and offshore sands although facies belts are likely to be narrow. Large-scale progradation, such as in the Taranaki Delta, is not apparent.

Paleogene

The Paleocene part of the transgressive sedimentary system was a continuation of the Late Cretaceous transgressive megasequence, although possibly less complex. Below the outer Taranaki shelf, Paleocene rocks encountered are generally marine units of the Moa Group, with mudstones dominant. Terrestrial equivalents are common further inshore and include coal measures and fluvial sandstones of the Kapuni Group. Between the two regions, shore face and nearshore sands grade to offshore mudstones and clays. The marine and terrestrial subdivision persists through the Paleocene and Eocene and the terms Moa and Kapuni Groups apply to both periods (King and Thrasher, 1996).

In Deepwater Taranaki, the Paleocene is generally around 200 metres thick although it reaches about 600 metres in several depocentres. The Paleocene succession across the top of the Taranaki Delta is subdivided by a relatively high-amplitude reflector forming a broad, shallow clinoform reflector. The rather flat clinoform suggests that the Paleocene was deposited into a shallow marine region with water depths comparable with isopach thicknesses. The top of the Paleocene is occasionally draped over mounds which overlie channels suggesting differential compaction across channel systems. A relative drop in sealevel apparently occurred near the end of the Paleocene resulting in sediments transported across a broad shelf into deeper water in front of the ancient delta along these channels. The differential compaction further suggests that at least some of the sediments transported were of coarser clastic grains than the general fine grained deposits of the background sedimentation.

The present Northland Peninsula appears to have been emergent, or at least a high for much of the Cretaceous and Paleogene. Paleocene rocks onlap the paleoslope of the Northland Peninsula which remained a relatively high block through much of the Pleogene. Between Northland and the West Norfolk Ridge, Paleocene rocks continue filling small basins formed by Cretaceous and earlier rifting where they reach thicknesses of 1500 metres. In the North Taranaki Graben, Paleocene rocks reach similar thicknesses suggesting that the Graben originated as a Cretaceous structure.

A high-amplitude continuous reflection which ties to the Waipawa Formation black shale in Wakanui-1 commonly occurs near the top of the Paleocene succession in both the Deepwater Taranaki and Northland regions. The amplitude of this reflection increases across basin centres and decreases across highs suggesting that it may be either thicker across the basin centres or it may have attained a higher degree of maturity and may be expelling hydrocarbons in the deeper regions. Thermal modelling (Uruski et al, 2004) suggests that the Waipawa Formation lies within the oil window in the centres of some Northland sub-basins.

Eocene

The thickest Eocene succession in the Northland sector lies to the east of the Northland Ridge (Figs 1, 3) with more than 1700 metres across major grabens. The Eocene thins across the Ridge to less than 300 metres and thickens slightly to the west. In Deepwater Taranaki, Eocene rocks are thickest below the slope where they are up to 700 metres thick and along the flank of the Challenger Plateau where thicknesses exceed 500 metres, elsewhere, average thickness is around 200 metres.

Moa and Kapuni facies developed across similar regions as in the Paleocene. Fluvial sandstones and coal measures of the Kapuni Group have been of great economic interest being the habitat of most of the hydrocarbons discovered in New Zealand to date. Factors which differentiate the Eocene include relatively gentle tectonism and volcanism. Below the Taranaki shelf, the seawards and landwards migration of facies belts in response to oscillating sea levels had long been recognised (King and Thrasher, 1997; Matthews, 2002). Eocene volcanism and tectonics had also been noted in the deeper ocean and across the Challenger Plateau (DSDP, Carey et al, 1991). The Astrolabe data set showed the intermediate effects of gentle folding along the margin of the Challenger Plateau and minor volcanism along the flank of the Deepwater Taranaki Basin. In Northland the Eocene in the far offshore is more calcareous and Eocene limestone similar to the regionally significant Tikorangi Formation of the Oligocene was drilled in Wakanui-1 (Milne and Quick, 1999; Uruski and Stagpoole, 2004). Typical coal measure seismic signatures are not apparent, but the Eocene succession is subdivided by a relatively high-amplitude continuous reflection. Below, reflector packages appear to be approximately parallel, while above, progradation is observed. Onshore, south of Auckland, coal measures of Eocene and Early Oligocene age are still preserved.

Oligocene

The Oligocene is dominated by carbonate deposition and was the period of maximum flooding. Clastic supply was minimal as very little land existed. In onshore and nearshore Taranaki, the Early Oligocene is commonly represented by the Otaraoa Formation which includes locally-important sandstones such as the Matapo and Tariki sandstones. The Matapo Sandstone is the basal member of the Otaraoa Formation and is considered to be a transgressive unit overlying the productive Kapuni Group reservoirs. The Tariki Formation is a local submarine fan sandstone shed from an active fault into a deepening basin and is the reservoir for the Tariki and Ahuroa oil fields in onshore northern Taranaki.

The Tikorangi Formation in Taranaki and its equivalent on Northland, the Whangarei limestone are present throughout the region in various facies. In southern onshore Taranaki, this limestone was the reservoir for the Waihapa oil field, which produced from fracture porosity across the axis of the Waihapa anticline. The Tikorangi Formation and its equivalents provide a valuable seismic marker across much of the region, although similar calcareous facies are present both above and below the Oligocene limestone in the far offshore.

Subsidence due to differential compaction may have enhanced Oligocene water depths in the centres of basins, but in general the present shape of the Oligocene surface in the offshore regions, was effectively the geography at the end of the Oligocene (Uruski et al, 2002).

5 Neogene system

Initiation of the present plate boundary near the start of the Neogene resulted in a marked increase in tectonic rates, uplift of a growing landmass, renewed erosion and a copious supply of sediments. The Neogene sedimentary system is overwhelmingly dominated by marine deposits as the active nature of tectonism and resulting rapid erosion of the land is a poor environment for preservation of terrestrial sediments. However, several small occurrences of Neogene coal are documented, including Miocene coals in the Surville-1 well of southern offshore Taranaki (New Zealand Aquitaine Petroleum Limited, 1976), small outcrops of Miocene coal in Northland and lenses of lignite within Pleistocene sand dunes of the western Northland coast (Isaac et al, 1994). In the northwest New Zealand basins, the Neogene is characterised by a succession of prograding cycles and their deepwater equivalents deposited in reaction to the classic mix of sediment supply and relative sealevel changes and modified by local tectonics.

The first events associated with initiation of the modern plate boundary were concurrent obduction of the Northland Allochthon and the start of volcanism along the Northland Peninsula (Isaac et al, 1994). The addition of large volumes of rock available for erosion and re-deposition and the onset of active tectonics resulted in complex sedimentation in Northland. Tectonism also created accommodation space below the southeastern Taranaki shelf where shelf sediments were deposited nearly horizontally, further to the northwest, clinoforms developed and continue to the present seabed as the shelf developed and expanded. Across the Western Platform and in Deepwater Taranaki, the Early and Middle Miocene are thin and probably consist largely of carbonates, a continuation of the Tikorangi facies. However, the Late Miocene and Pliocene contain thick successions dominated by turbidite and mass flow units. In general, the mass flow units are more prevalent in Pliocene successions. Mass flow units are very large, typically consisting of chaotic seismic reflectors above a planar detachment. Headwalls are sometimes apparent as are toe thrusts. Dewatering of these large sediment masses commonly creates small-scale mud diapers.

The region above and northwest of the Cretaceous Taranaki delta formed a broad synform by the Late Miocene into which turbidite units were deposited. Turbidites of Late Miocene and Pliocene age onlap the Oligocene paleoslopes of the Challenger Plateau and the West Norfolk Ridge. The large resulting turbidite fans reach dimensions of some 30 kilometres across and a hundred or more metres long. In cross-section they commonly exhibit a central thick mounded channel system flanked by a thinning wedge to either side, often containing downlapping reflectors. As the central mound grows more quickly, it becomes isolated, causing channel switching with successive channel-fan systems filling available lows. Several channel systems can be traced back onto the Taranaki Shelf. Onlapping relationships against the paleoslopes commonly show high amplitude reflectivity, suggesting the presence of petroleum and possible compound stratigraphic traps.

Petroleum potential

The distribution of source, reservoir and seal rocks is controlled by location within sedimentary systems.

Source rocks and maturity

The presence and distribution of source rocks are commonly the first concerns for petroleum exploration and most of the sedimentary systems described above appear to contain potential source rocks. The Jurassic system is known to contain coal measures of Middle Jurassic age, as drilled by Wakanui-1, while Late Jurassic coals and examples of terrestrial plant fossils from Early and Middle Jurassic beds are known from onshore. Most of the Jurassic succession onshore consists of marine sediments and there may be potential for marine black shales or even a Kimmeridgian clay. Similarly, the Early Cretaceous system is likely to contain coaly and perhaps lacustrine source rocks.

In Deepwater Taranaki, the Late Cretaceous delta top is the most obvious of the Late Cretaceous source rocks. Tied to the inboard Rakopi Formation, this source rock covers an area of around 20,000 km2 in deep water and at least 10,000 km2 in shallow water. The presence of such extensive coaly deposits suggests a lush vegetation a percentage of which may be incorporated into the body of the delta. This is confirmed by the organic carbon content of the Taniwha Formation (SBPT, 1986) assumed to be the basal unit of the delta (Uruski et al, 2002). Seafloor fans deposited in front of the delta may also contain similar kerogen in quantities that would make them source rocks. Finally, the Late Cretaceous was a period when several world-wide anoxic events resulted in deposition of rich source rocks such that the Cretaceous sourced around 30% of all the known oil deposits in the world. The location of the delta in the head of the New Caledonia Basin suggests that it was deposited into a restricted seaway, an ideal location for rapid changes in water oxygen content.

Late Cretaceous source rocks in the inshore Taranaki Basin are well known and Late Cretaceous examples are similar to some of those in deep water. Oil from the Maui field has bee geochemically typed to the Rakopi Formation (Funnell et al., 2004), while the coals and carbonaceous shales of the Wainui Member of the North Cape Formation also have source potential. Thermal modelling (Uruski et al, 2002) shows that the Rakopi Formation in Deepwater Taranaki is marginally mature and that across much of the area of Northland (Uruski et al, 2004) Cretaceous units are mature and expelling oil today.

In offshore Northland, Late Cretaceous source rocks are yet to be proven but their presence appears to be likely. Similar arguments to those applied to the Taranaki Delta may be offered for the prograding succession carried by the Northland Boundary Fault. This unit is likely to include the Taniwha Formation which contains significant carbonaceous and coaly layers and it may include other analogous units. The inferred North Cape equivalent includes rafts of high –amplitude reflectivity which may represent coaly beds deposited during relative low-srtands.

In addition to the Kapuni Group coals in onshore and inshore Taranaki, the Paleogene has source potential in the organically rich and widespread Waipawa Formation black shale, which has average measured total organic carbon of around 5%. Oils from Kora-1 were geochemically typed, in part, to the Waipawa Formation, showing that this rich potential source rock is generating and expelling oil within the North Taranaki Graben. Wakanui-1 penetrated a 30 metres-thick interval of the Waipawa Formation, although no analyses have been performed to determine its source rock potential. Seismic ties suggest that the Waipawa Formation is widespread in the Northland Basin and modelling shows that it is likely to be mature within some deeper graben fill (Uruski et al, 2004). Although the Waipawa Formation is likely to be widespread in the Deepwater Taranaki Basin, it is unlikely to have been buried deeply enough to reach maturity.

Reservoir rocks

Oil and gas fields in onshore and nearshore Taranaki have been found in reservoir rocks from many facies with a wide age range, from the Paleogene Kapuni Group to the Early Pliocene. Productive facies include fluvial and shore face sandstones, fractured limestone and turbidite sands. The dominant reservoir facies are Eocene fluvial sandstones in gas and condensate fields such as Kapuni, Maui, McKee, Pohokura, Mangahewa, Stratford, Rimu and Kupe South. The Tui group of oil fields was discovered in Eocene shore face sands. Waihapa was once the most prolific of New Zealand's oil fields, where oil is contained in fractures in the Oligocene Tikorangi Formation limestone. The Kora oil accumulation is one of the strangest in New Zealand, being discovered in the volcaniclastic apron of a Miocene volcano on the western flank of the North Taranaki Graben. The habitat of the Maari oil field is the Middle Miocene Moki Formation turbidite, while the Ngatoro and Kaimiro oil fields are producing from Late Miocene Mount Messenger Formation turbidites. In northern offshore Taranaki, Karewa-1 discovered gas in Early Pliocene turbidite sandstones, while oil has been discovered in shelf sandstones of the Urenui Formation drilled by the Cheal wells in onshore Taranaki.

Following the discovery of Kapuni in 1959 and Maui in 1969, exploration effort was focussed on Kapuni Group reservoirs. Since then discoveries have been made in reservoirs of various facies and ages, many of them younger than the Kapuni and shallower. Wells have been successful where they have encountered reservoirs with good porosities lying along migration pathways from hydrocarbon kitchens in structures and stratigraphic traps that have not been breached catastrophically.

Cretaceous reservoirs have rarely been targeted in Taranaki and where they have been encountered, porosities are commonly low, generally as a result of diagenesis due to depth of burial. In Deepwater Taranaki, the Rakopi, models suggest that the Rakopi Formation is marginally mature and has not been buried to extreme depths. It is suggested that associated sandstones should maintain relatively high porosities. The Rakopi Formation is analogous to the Kapuni Group, being the fluvial component of the sedimentary system and is therefore an attractive exploration play. Other analogies can be drawn within this sedimentary system which probably contains both shore face and turbidite sands.

Cretaceous sediments are still not proven to be present in offshore Northland. However, Early Cretaceous rocks were drilled onshore in the Waimamaku -2 well and seismic data is tied to known occurrences of Cretaceous rocks in northern Taranaki. For example, North Cape Formation rocks were drilled by Ariki-1. Cretaceous rocks are most probably present and widespread in the offshore Northland region. Terrestrial and marine equivalents of the Rakopi Formation in Taranaki are likely and the presence of the North Cape Formation suggests that high-porosity Cretaceous transgressive sands, similar to the Island Sandstone of Taranaki, may also be present.

Lateral equivalents of the Kapuni Group are mapped within the Deepwater Taranaki Basin. The broad shelf created by the Taranaki Delta resulted in large lateral shifts of facies belts in response to changes in relative sealevel, so the model for exploration in the Tui area (Matthews and Lewis, 2001) may be applied more broadly across the Taranaki Delta. In addition, the Paleogene channels crossing the shelf add two further possible exploration targets in the head of the New Caledonia Basin; channel sands and turbidites.

Similar considerations suggest that reservoir facies may be present in offshore Northland, but the area's more complex topography probably controlled distribution of sandstones. Wakanui-1 showed that the transgressive system overtopped the Wakanui horst during the Paleocene as the initial unit deposited on the Jurassic succession was of Paleocene transgressive conglomerate and sandstone. Shore face and turbidite sandstones are also likely away from the topographic highs. Several anomalous channel-like units are present in the Northland Paleogene succession. If these features prove to be channels, their sands may become a future drilling target. The presence of these large features also begs the questions of what it was they transported and where to. Large turbidite fan bodies may be discovered in regions not yet covered by seismic data.

Neogene reservoir facies in the offshore region are generally fan turbidites or large channels. In onshore Taranaki, shelf sands of the Urenui Formation have proved productive in the Cheal oil field and there is scope for similar shallow discoveries nearshore, particularly to the south of the Taranaki Peninsula. Turbidite fans have been mapped at several levels; The Moki Formation is of Middle Miocene age, the Mount Messenger fans seen in spectacular exposure in the north Taranaki cliffs are of Late Miocene age and Latest Miocene and Early Pliocene turbidites of the Mangaa Formation.

During the late Paleogene, the present-day outer Taranaki shelf and delta subsided to around 1000 metres below sealevel, therefore, when the modern plate boundary was initiated a new shelf began to build leaving the ancient shelf isolated a couple of hundred kilometres offshore. By the Late Miocene slope and basin floor turbidite fans of the Mount Messenger Formation were being deposited around the present North Taranaki coastline. The basin floor on which those fans were deposited formed the inboard part of a broad terrace and sediments began to by-pass the terrace probably near the end of the Miocene. Channel systems can be mapped from the Taranaki shelf edge and from the Northland region which carried sediments into the Deepwater Taranaki region where they were deposited as very large-scale turbidite fans during the Latest Miocene and Pliocene succession. Many of these turbidite units onlap the paleoslope and many stratigraphic traps may be present within this turbidite basin.

Seal

Regional seals are commonly related to maximum flooding events. Regional maximum flooding events mark the tops of the Rakopi Formation and the Oligocene. Although several examples of transgressive sands are well known in the region, subsequent sediments are commonly fine grained. For example, the Island Sandstone in Tane-1 is succeeded by a unit called the Tane Siltstone Member and by the Turi Formation, which is commonly marine shale and claystone. In Northland, Wakanui-1 also drilled thick Turi Formation claystones above the Paleocene transgressive sand. Apart from the onshore and coastal regions, where Kapuni Group sediments were being deposited, the background of deposition was provided by fine grained marine rocks for much of the Paleogene. By the Oligocene, most of the sediment source areas had been inundated and limestone deposition dominated at this second maximum flooding surface.

The initiation of the modern plate boundary resulted in renewed sediment supply. The background, particularly in the distal regions was calcareous, with fine-grained clastic input. Much of the Neogene succession is fine-grained and probably an efficient seal rock.

Conclusions

1) New survey data from Deepwater Taranaki and Northland greatly extends the scope of exploration of Northwest New Zealand

2) Inferences made from analyses of sedimentary systems strongly suggests the presence of source rocks, reservoirs and seals across much of the region

3) The presence of a large delta in Deepwater Taranaki shows that mechanisms for transporting large quantities of organic material into the head of the New Caledonia Basin were operating for much of the Late Cretaceous

4) The Late Cretaceous Rakopi Formation of Deepwater Taranaki is an analogy for the productive Kapuni Group of inboard Taranaki

5) Late Cretaceous reservoirs are likely to have maintained good porosity as they have not been buried as deeply as similar rocks below the present day shelf

6) Paleogene age shore face sands are likely to be present across wide areas of the Late Cretaceous Taranaki Delta, where they were deposited in response to relative sealevel changes

7) Large-scale Neogene turbidites may be excellent reservoir rocks as, they have yet to be deeply buried

8) Exploration to date has only scratched the surface of the petroleum potential of Northwest New Zealand or for New Zealand as a whole for that matter

Acknowledgements

Much of this work was completed under the terms of a New Zealand Government research contract. Sincere thanks are due to TGS-NOPEC for acquiring the Astrolabe survey data and to Peter Baillie who realised the potential of the area. Spectrum Energy & Information Technology Ltd. reprocessed some 9000 km of data acquired mostly by Conoco who also used their brand new deepwater drillship, Deepwater Explorer which extended New Zealand's petroleum basins by 50 million years with its first well. This paper also draws heavily on previous work done by the GNS Science Basin Modelling and Sedimentology teams.

References

Ballance, P.F. 1988: The Huriwai braid-plain delta of New Zealand: a Late Jurassic, coarse-grained, volcanic-fed depositional system in a Gondwana forearc basin. Pp. 430-444 *in* Nemec, W. and Steel, R.J. (eds) *Fan Deltas: Sedimentology and Tectonic Settings*. Blackie and Son.

Carey, C., Mortimer, N., Uruski, C. and Wood, R. (1991) Fire and brimstone on the western Challenger Plateau: further evidence from Mount Spong and Megabrick. *New Zealand professional fisherman 6 (6) pp. 5-9.*

Conoco Northland Ltd. 1996: CNL95 seismic survey, CNL95A and CNL95B lines PEP 38 602. *Open-file Petroleum Report 2207.* Ministry of Commerce, Wellington.

Dolan, P. and IstadiI, B., 2003 Deepwater play evaluation and post-drill analysis of the Waka Nui-1 well, Northland Basin, PEP 38602. In: *Crown Minerals open-file Petroleum report 2436,* Ministry of Commerce, Wellington.

DSDP (1973) Chapter 7, Site 207. In: *Inititial report of the Deep Sea Drilling Project,* Washington (U.S. Government Printing Office) volume 21, pp. 197-269.

Field, B.D.; Uruski, C.I. et al. 1998 Cretaceous and Cenozoic geology and petroleum systems of the East Coast region, New Zealand. *Institute of Geological & Nuclear Sciences monograph 19.*

Forder, S.P. and Bennett, D.J. 1986 Pukearuhe-1 well completion report, PPL 38 083. *New Zealand unpublished open-file petroleum report 1336*. Ministry of Economic Development, Wellington.

Funnell, R.H., Stagpoole, V., Nicol, A., MacCormack, N. and Reyes, A.G. 2004: Petroleum generation and implications for migration: a Maui Field charge study, Taranaki Basin.*in: Proceedings of the 2004 New Zealand Petroleum Conference, Auckland, 8-10th March.* Crown Minerals, Ministry of Economic Development, Wellington, New Zealand.

Herzer, R.H., Chaproniere, G.C.H., Edwards, A.R., Hollis, C.J., Pelletier, B., Raine, J.I., Scott, G.H., Stagpoole, V., Strong, C.P., Symonds, P., Wilson, G.J., Zhu, H. 1997: Seismic stratigraphy and structural history of the Reinga Basin and its margins, southern Norfolk Ridge system. *New Zealand Journal of Geology & Geophysics* 40: 425-451.

Herzer, R.H., Sykes, R., Killops, S.D., Funnell, R.H., Burggraf, D.R., Townend, J., Raine, J.I., Wilson, G.J. 1999: Cretaceous carbonaceous rocks from the Norfolk Ridge system, Southwest Pacific: implications for regional petroleum potential. *New Zealand Journal of Geology & Geophysics* 42: 57-73.

Kear, D., 1978 Jurassic Stratigraphy pp 228-240 in: *Suggate, R.P., Stevens, G.R.and Te Punga, M.T. (eds.) The geology of New Zealand*. Government Printer, Wellington. 2 vols, 820 p.

King, P.R.; Thrasher, G.P. 1996 Cretaceous-Cenozoic geology and petroleum systems of the Taranaki Basin, New Zealand. *Institute of Geological & Nuclear Sciences monograph 13.*

Lindqvist, J. K., 1990 Puysegur Group: a mid-Cretaceous lacustrine fan-delta complex, Balleny Basin, southwest Fiordland. *Geological Society of New Zealand miscellaneous publication* 50A: 83.

Matthews, E. (2000) Offshore Taranaki Exploration In *2000 New Zealand Petroleum Conference Proceedings.* Ministry of Economic Development, Wellington.

Matthews, E. (2002) Implications of Neogene structural development on hydrocarbon prospectivity of the Tui-Maui area, offshore Taranaki, New Zealand In *2002 New Zealand Petroleum Conference Proceedings.* Ministry of Economic Development, Wellington.

Matthews, E.and Lewis, C. 2001: Geophysical definition of the Kapuni coastal facies of the western Taranaki Basin, New Zealand In: Hill, K.C., Bernecker, T. (eds) *Eastern Australasian Basins Symposium*, A refocussed energy perspective for the future, *Petroleum Exploration Society of Australia Special Publication*. 141-150.

Mitchum, R.M.,Jr., Vail, P.R. and Thompson, S. III 1977 The depositional sequence as a basic unit for stratigraphic analysis pp. 53-62. In: Seismic stratigraphy – applications to hydrocarbons exploration, Payton, C.E. (ed). *Memoir 26 American Association of Petroleum Geologists.*

Milne, A. and Quick, R., 1999 -Wakanui-1 well completion report PEP 38602. *New Zealand open-file Petroleum report 2436*, Ministry of Commerce, Wellington.

Mortimer, N., Tulloch, A.J. and Ireland, T.R., 1997 - Basement geology of Taranaki and Wanganui Basins, New Zealand. *New Zealand Journal of Geology and Geophysics.* 40 .223-236.

Mortimer, N.; Tulloch, A.J.; Spark, R.N.; Walker, N.W.; Ladley, E.; Allibone, A.; Kimbrough, D.L. 1999: Overview of the Median Batholith, New Zealand: a new interpretation of the geology of the Median Tectonic Zone and adjacent rocks. *Journal of African Earth Sciences 29*: 257-268.

New Zealand Aquitaine Petroleum Limited 1976 Well completion report, Surville-1 *New Zealand open-file Petroleum Report 677,* Ministry of Commerce, Wellington.

Roser, B.P., Cooper, R.A. and Tullock A.J. 1996 Reconnaissance sandstone geochemistry, provenance and tectonic setting of the Lower Paleozoic terranes of the West Coast and Nelson, New Zealand. *New Zealand journal of geology and geophysics* 39 pp 1-16.

Shell, BP and Todd Exploration Services (SBPT) (1976) Well resume, Tane-1 (offshore), PPL 38007. *New Zealand open-file Petroleum Report 698*, Ministry of Commerce, Wellington.

Shell BP and Todd Oil Services 1986 Well resume Te Ranga-1. *New Zealand unpublished open-file petroleum report 1197.* Ministry of Economic Development, Wellington.

Suggate, R.P. 1990: Coal rank in Permian-Lower Cretaceous rocks of New Zealand. *New Zealand Journal of Geology and Geophysics.* 33 pp.163-172.

Sutherland, R.; King, P. Wood, R. 2001: Tectonic evolution of Cretaceous rift basins in southeastern Australia and New Zealand: implications for exploration risk assessment. *PESA Eastern Australasia Basins Symposium*: 3-13.

Uruski, C.I. 2000 Petroleum potential of New Zealand's deepwater basins. *Proceedings of the 2000 New Zealand Petroleum conference, Christchurch.* Crown Minerals, Ministry of Economic Development, Wellington.

Uruski, C.I. and Baillie, P. 2001 Petroleum potential of New Zealand's deepwater basins. *PESA Eastern Australasia Basins Symposium*: 151-158

Uruski, C.I., Stagpoole, V., Isaac, M.J., King, P.R. and Maslen, G. 2002 Seismic interpretation report, Astrolabe Survey, Taranaki Basin. *New Zealand. Crown Minerals open-file Petroleum Report 3072,* Ministry of Commerce, Wellington.

Uruski, C. I., Stagpoole, V., Isaac, M. J., King, P. R. and Maslen, G., 2002, Seismic Interpretation Report – Astrolabe Survey, Taranaki Basin, New Zealand. Institute of Geological & Nuclear Sciences confidential client report 2002/70. *New Zealand. Crown Minerals open-file Petroleum Report 3055,* Ministry of Commerce, Wellington.

Uruski, C.I., Baillie, P. and Stagpoole, V., 2003 - Development of the Taranaki Basin and comparisons with the Gippsland Basin: Implications for deepwater Exploration. *APPEA Journal.*43 185-196.

Uruski, C.I., Stagpoole, V. 2004 Wakanui-1, independent well summary. *New Zealand. Crown Minerals open-file Petroleum Report 3053,* Ministry of Commerce, Wellington.

Uruski, C.I., Field, B.D.,. Funnell, R., Hollis, C., Nicol, A and Maslen, G. 2006 (in press) Developments in the central and northeastern East Coast Basin, North Island, New Zealand. *APPEA Journal*.46.

Wood, R.A., Andrews, P.B., Herzer, R.H., Cook, R.A., Hornibrook, N. de B., Hoskins, R.H., Beu, A.G., Maxwell, P.A., Keyes, I.M., Raine, J.I., Mildenhall, D.C., Wilson, G.J., Smale, D., Soong, R. and Watters, W.A. 1989 Cretaceous and Cenozoic geology of the Chatham Rise region, South Island, New Zealand. *New Zealand Geological Survey Basin Studies 3,* NZGS, Lower Hutt.

West, C. 1999 – Hydrocarbon characterisation study, Wakanui-1. Geotech, Geotechnical Services PTY Ltd, report in: *New Zealand open-file Petroleum report 2436*, Ministry of Commerce, Wellington.

Author

Chris Uruski is a petroleum geoscientist at the Institute of Geological and Nuclear Sciences in New Zealand where he has worked since 1987. His main area of expertise is seismic interpretation and he is a co-author of two major GNS regional basin studies publications; the Western Southland and the East Coast monographs. He holds a B.Sc. in geology from the University College of Wales, Aberystwyth and has worked at Aberystwyth and Durham Universities and for ECL in various parts of the world before arriving in New Zealand. He was the lead author of major reports on the deepwater Taranaki and Northland basins prepared for the current licencing rounds. 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.