

STRUCTURAL ZONING OFFSHORE THE EAST COAST BASIN NORTH ISLAND, NEW ZEALAND

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Abstract

Offshore seismic reflection data from the East Coast Basin south of Hawke Bay are combined with onshore geological mapping to show five large-scale structural zones. Three are confined to the offshore region, one is entirely onshore and one occupies the coastal zone and is partially on- and partially offshore.

- 1) The onshore zone is dominated by thrusting and lies inland of the Coastal Strike-slip Zone.
- 2) The Coastal Strike-slip Zone is formed by a strike-slip dominated belt which may have taken up a large proportion of the movement of the Alpine Fault, perhaps as much as 500 km.
- 3) Immediately offshore below the Wairarapa Shelf is an eastwards or north-eastwards-verging thrust belt which terminates at a second strike-slip belt lying approximately 30 km to the southeast and running nearly parallel with the coastline. The Wairarapa Shelf thrust belt has remained stable since its formation in the Early Miocene.
- 4) The Shelf-edge Zone is underlain by a strike-slip belt lying approximately 30 km off the coast and striking approximately parallel with the coast.
- 5) Oceanwards of this strike-slip belt is a more enigmatic zone where seismic data are not good enough to resolve the structure. This zone grades into the deep water region where pure thrusting dominates as sediments are scraped off the subducting Pacific Plate.

The third structural zone, the offshore thrust belt, may, in places, have detached on the Waipawa Formation, a condensed marine black shale sequence and a potential source rock. This horizon also occurs at depth in the fourth structural zone, the coast parallel strike-slip belt. Below both of these structural zones, the Waipawa Formation is buried by more than 4 seconds of section. Seismic stacking velocities suggest that this equates to a burial depth of 5.2 km. Even a low geothermal gradient of 20° C/km could ensure that this source rock is hot enough to expel oil. The highly deformed and fractured thrust stack should not be a barrier to migration and it forms structures ideally placed as trapping mechanisms. Good structures are also formed in the offshore coast parallel strike-slip zone, although water depths are greater here (at approximately 250 m), above the shelf edge anticline.

Introduction

Exploration of the East Coast Basin (figure 1) for oil and gas started more than 120 years ago driven, in part, by the numerous examples of oil and gas seeps found onshore. Despite the continuing interest and activity of exploration companies, a commercial accumulation has yet to be discovered. The main reason for this has been a paucity of subsurface data. All of the elements for expulsion and trapping of hydrocarbons can be shown to be present in the East Coast Basin, but the geological evolution of the region is still poorly understood. Recent onshore mapping has shed new light on the increasing volume of subsurface data. Strike-slip faulting in the East Coast region has been generally accepted for many years, but recent suggestions of considerable dextral motion in excess of 500 km have led to this reinterpretation of existing data.

This paper outlines the geological history of the East Coast Basin with reference to potential source rocks and reservoirs. It then reviews the open-file seismic data before suggesting a possible tectonic history of the region and outlining some

consequences for petroleum exploration of the offshore Wairarapa region. Working hypotheses only are presented, and more definite conclusions will have to await a more complete analysis of the available data.

Geological Background

The geological map (figure 2) was compiled mainly from the series of 1:250 000 sheets published by the New Zealand Geological Survey (now the Institute of Geological & Nuclear Sciences Limited). These maps include Sheet QM 303 Raukumara (Moore and others, 1989), Sheet 8 Taupo (Grindley, 1960), Sheet 9 Gisborne (Kingma, 1964) Sheet 11 Dannevirke (Kingma, 1962) and Sheet 12 Wellington (Kingma, 1967). Further insights were provided by work published by Beu (1992) on the Pliocene limestones of the East Coast and by Mazengarb (1991; 1993), Moore (1980; 1988) and Crampton (1991) on Cretaceous and Paleogene sedimentary geology.

Basement

The Torlesse Supergroup, colloquially known as 'greywacke' although it consists of many rock types, was deposited along

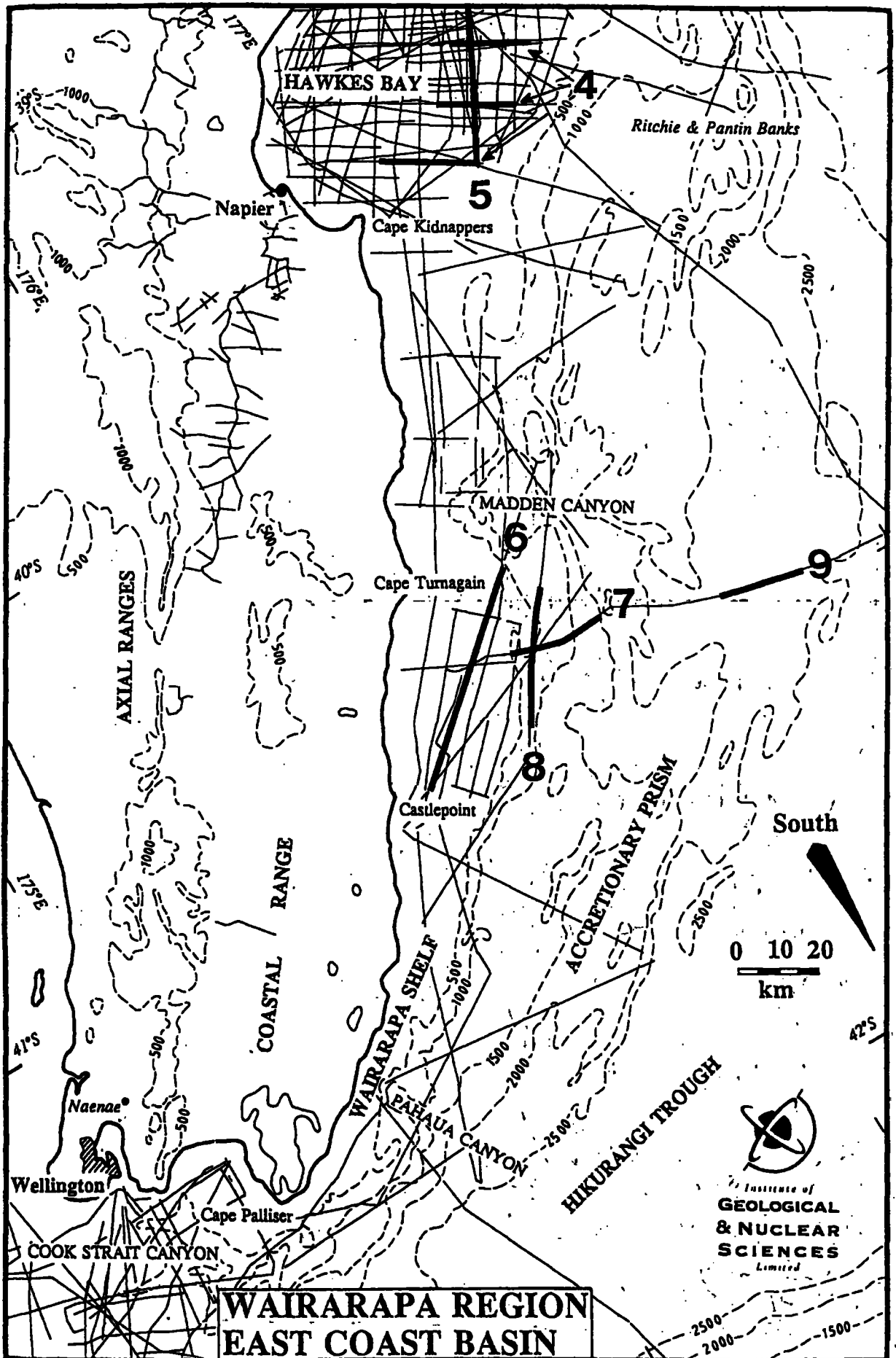


Fig. 1. Main geographical locations are named. Topography is shown by dashed contours every 500 m. Open-file seismic lines are shown both onshore and offshore. 4, 5, 6, 7, 8 & 9 are the locations of figures 4 to 9 inclusive.

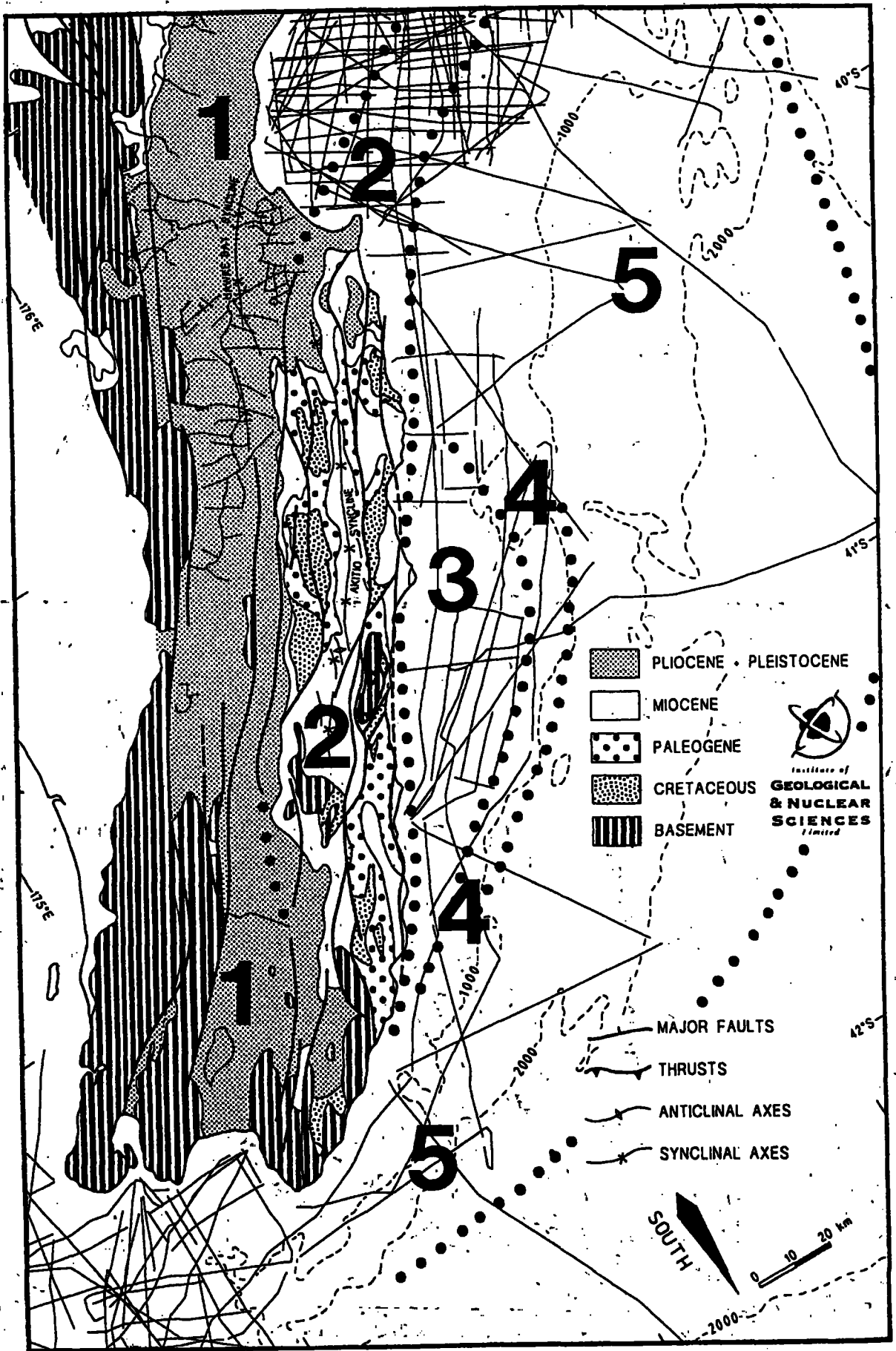


Fig. 2. Generalised geological map of the Wairarapa-Hawke Bay region. 1 to 5 are the five zones referred to in the text. 1 is the onshore zone, 2 is the Coastal Strike-slip Zone, 3 is the Wairarapa Shelf Thrust Block, 4 is the Shelf-edge Strike-slip Zone and 5 is the Accretionary Prism.

the New Zealand section of the Gondwana continental margin from Paleozoic times to the Early Cretaceous. It is thought to be a large submarine fan (Bradshaw and others, 1980) similar to that of the present day Bengal Fan, which extends some 2500 km southwards from Bangladesh and is approximately 700 km across. Much of the similarly vast and long-lived Torlesse fan was metamorphosed, but, in places grades into unmetamorphosed Early and Late Cretaceous sediments.

The Torlesse forms the axial ranges (figures 1, 2) from the western Raukumara Peninsula to Wellington as well as much of South Island. It crops out in the Aorangi Ranges and at several locations in northern Wairarapa and southern Hawke Bay where it has been mapped as thrust slices. Torlesse basement has also been penetrated by two wells in the region, Ongaonga-1 (Leslie, 1971a) and Takapau-1 (Leslie, 1971b). Basement in these wells occurs in the cores of compressional anticlines.

Cretaceous

The largest volume of Cretaceous sediments outcropping in the East Coast Basin is in the Raukumara Peninsula where it is downfaulted into Torlesse basement. A second major zone of Cretaceous sediments lies along the coastal blocks of the southern Hawke Bay and Wairarapa regions (figures 1 & 2) where it generally occurs in the cores of tight anticlines. The widespread occurrence of outcropping Cretaceous sediments suggests that they are probably equally well distributed in the subsurface. Outcrop geology (Mazengarb, 1991; 1993) suggests that much of the Raukumara Cretaceous was deposited across a continental margin. Facies include northwards-flowing slope channels and turbidite fans. In the southern Hawke Bay/Wairarapa region there is a suggestion of eastwards provenance for the Cretaceous sediments (Crampton, 1991). The East Coast Basin can be subdivided into three gross structural units. The first is from the Raukumara Peninsula to onshore Hawke Bay, the second is an offshore domain from offshore Hawke Bay to Cook Strait and the third is the broad, linear zone dividing the above two domains. This zone includes the highly tectonised coastal zone of the Wairarapa. It runs offshore to the south of Hawke Bay, crosses the mouth of Hawke Bay and continues obliquely across the Gisborne Shelf to form the shelf edge northeast of Gisborne.

Paleogene

Paleogene depositional patterns continued from those of the Cretaceous. Sea-floor spreading stopped in the Tasman Sea in the Late Paleocene (Weissel and others, 1977) and was followed by regional thermal subsidence of the East Coast passive margin. This led to deposition of deeper water mudstone facies with occasional incursions of fan sandstones. Faulting continued into the Paleogene, as it did in other parts of New Zealand (Kamp, 1986; Uruski and Wood, 1991; Wood and Herzer, 1993).

The onshore Paleocene sequence (Moore, 1988) consists mostly of the upper part of the Whangai Formation and the Waipawa Formation. Although the Whangai Formation is dominated by fine siltstones and mudstones, a significant proportion is sandstone with some metre-thick greensand beds. Possible reservoirs within the Whangai Formation include thick greensands and glauconitic sandstones and fractured chert and shale. Some outcrops are oil saturated (Laing, 1961; Francis, 1992). Log-derived fracture porosities

of 30% have been determined from well data in the Raukumara Peninsula (Ministry of Commerce, 1992).

Greensands are also common in parts of the overlying Waipawa Formation. The Eocene Wanstead Formation contains minor volumes of conglomerate, sandstones and greensands but is dominated by mudstones. Minor sands also occur in the overlying Oligocene Weber Formation. The mudstones which dominate the Paleogene include bentonites which would provide a good regional seal.

Miocene

The Miocene saw the onset of compressional activity caused by the initiation of the present subduction zone. Southwestwards-verging thrusts are common in the southern Raukumara Peninsula and gave rise to the concept of the East Coast Allochthon (Stoneley, 1968). Following emplacement of the allochthon, a complex and major strike-slip system developed between the Raukumara Peninsula and the offshore Wairarapa blocks, running from offshore East Cape to the Aorangi Range of southern Wairarapa, across Cook Strait and into the Alpine Fault system. Faulting became increasingly compressional with time and resulted in uplift of the Coastal Tectonic Zone between the Aorangi Ranges and Cape Kidnappers, the Lachlan Ridges and their northwards extension through Mahia Peninsula and a shelf-edge thrust-stack to the east of Raukumara Peninsula.

The Miocene is well-developed in the Hawke Bay region where it forms a relatively gentle, broad syncline. Along the present Coastal Ranges of southern Hawke Bay and the Wairarapa, narrow Miocene basins developed between rising anticlinal ridges; this pattern is also seen in the offshore Raukumara area. The offshore Hawke Bay/Wairarapa region saw basin development similar to that of Hawke Bay, with relatively broad synclinal basins between rising anticlinal ridges.

Plio/Pleistocene

The post-Miocene saw a continuation of trends started in the Miocene. Synformal basins tightened in most of the regions in response to the changing subduction vector and many more compressional features appeared. Basins inland of the Hawke Bay/Wairarapa Coastal Zone developed during this time, although they may have been initiated in the Late Miocene. Offshore from the Raukumara Peninsula, the Miocene synclinal basins were tightened and filled with Plio/Pleistocene sediments, leaving Miocene sediments exposed at the surface in a similar fashion to that observed for the Miocene in the Coastal Ranges of southern Hawke Bay and the Wairarapa. Subduction-related compression formed basins such as the Waihora Syncline in the Raukumara Peninsula and the Hawke Bay Syncline.

Depocentres in the offshore Hawke Bay region changed location rapidly several times after the end of the Miocene. Slope basins in the offshore region developed into smaller, more tightly folded features between rising slope thrust ridges, although the shelf offshore southern Hawke Bay and the Wairarapa seems to have stabilised during the Miocene. The Wairarapa Shelf acted as a discrete, almost rigid block through the Late Miocene and Pliocene.

Structure

Many styles of deformation are present within the East Coast Basin. Compressive faults and folds are common (Stoneley, 1968; Katz and Wood, 1980; Lewis, 1980; Pettinga, 1982),

strike-slip motion has been postulated in various zones of the East Coast Basin (Cole and Lewis, 1981; Cutten, 1988; Delteil, 1992) and normal faulting is seen both as a reaction to deeper seated folding and as a result of slope instability (Lewis, 1971; Pettinga, 1982). More recently, normal faults have been recognised as primary basin-forming structures of the Cretaceous rift episode (Laird, 1992). Much of the East Coast Basin is characterised by tight anticlinal folds with gentle synformal structures between (Ministry of Commerce, 1992). The intervening synformal areas are often more complex at depth (Leslie and Hollingsworth, 1972) where surface expressions of geology are relatively featureless, but stacked thrust sheets are apparent in the subsurface. Cashman and others (1991) describe present-day zones where coast-parallel faulting dominates while in others coast-perpendicular faults dominate. Emplacement of the allochthonous bodies in the Raukumara Peninsula (Stoneley 1968) and further afield in Northland (Brook and others, 1988) was from the northeast although whether as a compressional event or as uplift followed by gravity sliding, is still uncertain.

Moore (1988) classified the East Coast Basin in terms of the Cretaceous facies, structure, distribution of igneous rocks and presence of unconformities. North of Hawke Bay he recognises two major blocks:

- the Motu Block covering the western part of the Raukumara Peninsula
- the East Coast Allochthon covering the eastern part

South of Hawke Bay he subdivided the region into the Woodville, Aorangi, Pongaroa, Tora and Coastal blocks, and envisaged two main belts:

- the Western Sub-belt containing the Woodville, Aorangi, Pongaroa and Motu blocks
- the Eastern Sub-belt consisting of the Tora and Coastal blocks and the East Coast Allochthon

Delteil (1992) suggest that the Eastern Sub-belt south of Hawke Bay, has been translated along a major strike-slip fault, the Adams-Tinui Fault system, from a position approximately adjacent to the Raukumara Peninsula. Many of the oil and gas seeps south of Hawke Bay appear to be associated with this fault system, suggesting that reservoirs may be breached where such faults reach the surface.

Seismic data

Figures 1 and 2 show the locations of all of the open-file seismic data in the study area in relation to geographical and geological factors. Marine data include early multi-channel lines acquired by BP, Shell, Aquitaine and Todd (BPSAT) (Davies, 1968) and by Magellan (1970). Neither data set is of great value, although some BPSAT lines of similar vintage have proven amenable to reprocessing offshore from Gisborne (Greason, 1989). Both Australian Gulf (1973) and Mobil (1972) shot good quality data in the region during their reconnaissance surveys of New Zealand, but the most useful line was acquired as part of a joint USGS/DSIR programme in 1983 (Davey and others, 1986). New Zealand Conquest Limited (1990) acquired nearly 1200 km of high quality data in Hawke Bay, some of it along strike from the offshore Wairarapa region and much of it of value in determining structural domains of the region, particularly as it is now open-file. In addition, Amoco (1990) shot more than 1000 km of high quality seismic data in the inshore part of their exploration licence offshore Wairarapa, but much of this remains confidential until 1995 and is no lines from that survey are included on the maps.

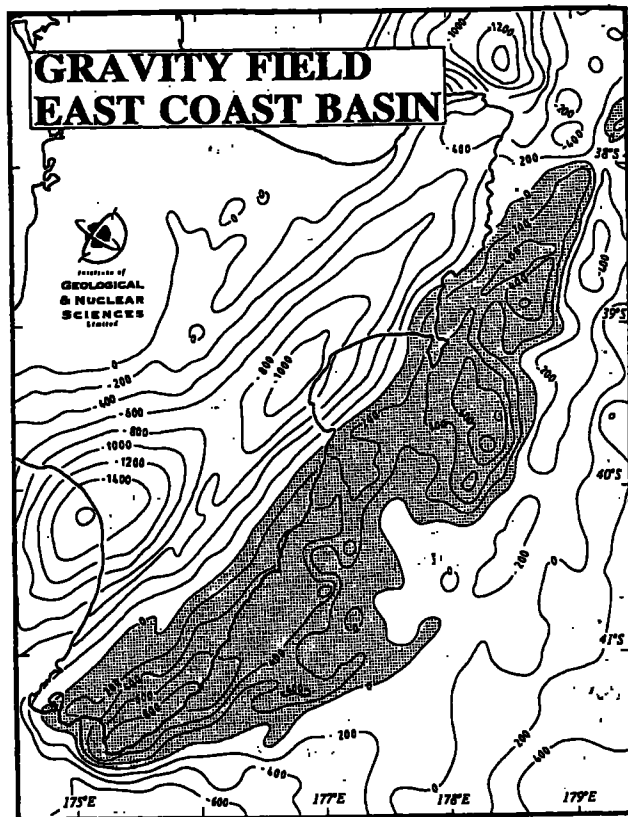


Fig. 3. Gravity map of North Island, New Zealand. Redrawn from Rose (1991). Anomalies over the marine areas are Free Air Anomalies and over land areas are Bouguer Anomalies. Contour interval is 200 micro Newtons/kilogramme. Note the shaded region, which is a high marking the approximate extent of the East Coast accretionary wedge.

Coastal Strike-slip Zone

The gravity anomaly map (figure 3) shows a major high overlying the coastal ranges of southern Hawke Bay and Wairarapa. This linear feature extends obliquely across the mouth of Hawke Bay and runs into the shelf edge to the east of Gisborne, suggesting that the highly folded strike-slip zone may follow the same trend. Figure 4 shows three of the CQX lines which cross the region previously referred to as Lachlan Ridge. Here it is shown to consist of two ridges, one a northeastwards continuation of the Cape Kidnappers high and the other a southwestwards extension of the Mahia Peninsula structure. Between the two ridges is a thick sedimentary sequence interpreted here as a large flower structure overprinted by a highly compressive tectonic style. Line CQX 16 (figure 5) is a regional strike line across Hawke's Bay which illustrates the basin's complex history. This line shows a "dolphin structure" bedding pattern. The flower structures seen on the dip lines and the undulating depositional sequences are both commonly associated with strike-slip zones (Lowell, 1985). The offset of the strike-slip fault zone, from the Cape Kidnappers/Lachlan Ridge, eastwards to the Mahia Peninsula high, appears to have resulted in an intervening pull-apart basin.

The strike-slip displacement established by Kingma (1962), Cutten (1988) and Delteil (1992) on several onshore fault traces together with seismic evidence of large flower structures and highly variable unit thicknesses in the vicinity, suggests that the coastal ranges and the Lachlan/Mahia Ridge comprise a continuous, broad strike-slip zone offshore across the mouth of Hawke Bay.

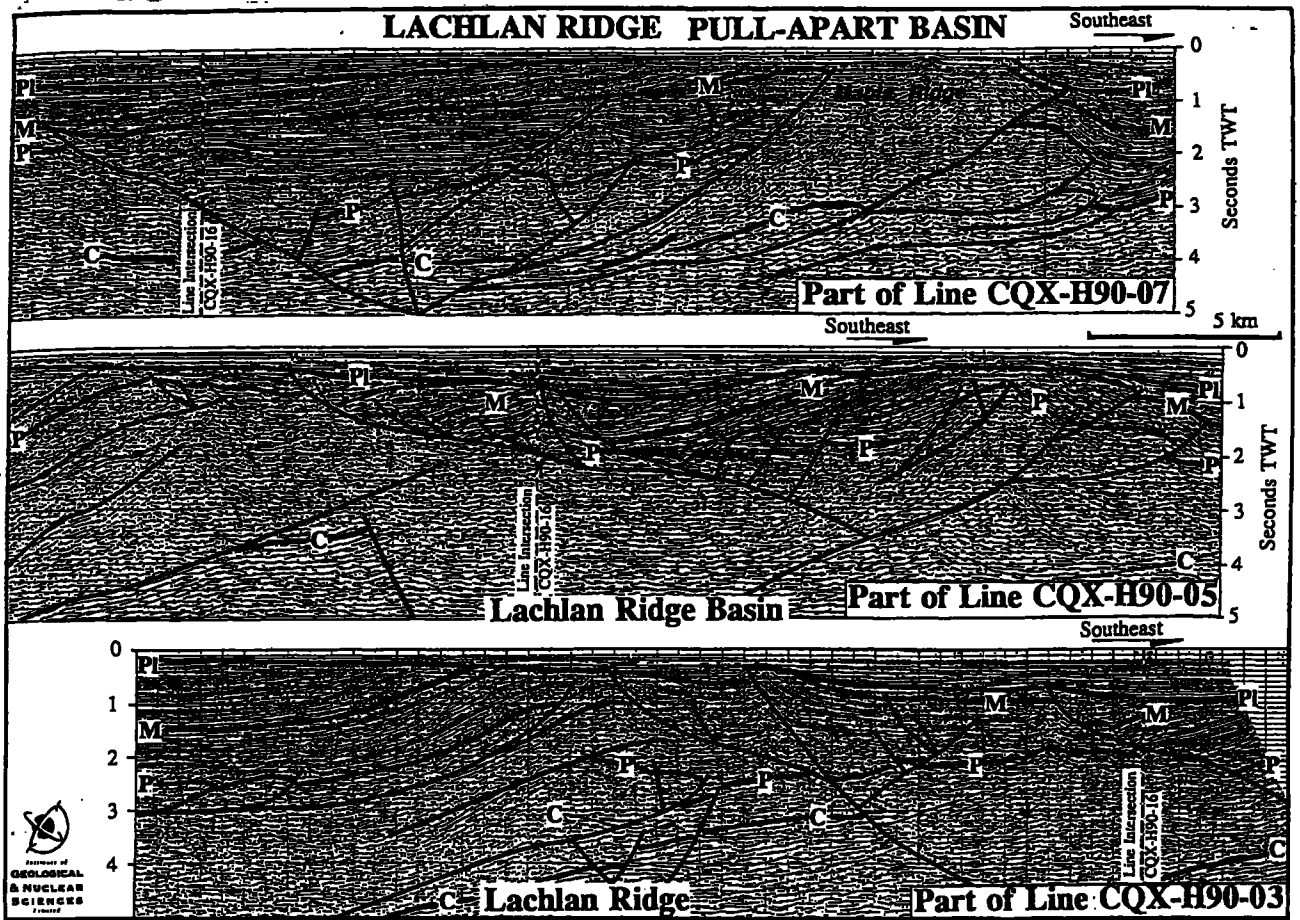


Fig. 4. Three dip lines across the mouth of Hawke Bay, the region where the Coastal Ranges strike-slip zone must extend offshore. Relationships of reflector packages strongly suggest formation of a pull-apart basin between the two structural highs which underlie Lachlan Ridge. 'C' is the top of the possible Cretaceous sequence, 'P' is the top of the Paleogene (=top Oligocene), 'M' is the top of the Miocene and 'Pl' is the top of the Pliocene. Pliocene and Miocene reflectors were tied in to the Hawke Bay 1 well which was located on line CQX H90 07. The top Paleogene is jump-correlated from the well. Location of these lines is shown on figure 1.

Wairarapa Shelf Thrust Stack

Line NZ 60 (figure 6) shows the general structure of the Wairarapa Shelf Thrust Stack with Miocene sediments draped over the crest of this thrust faulted anticline. Stratigraphy is inferred from analogy with onshore geology (Delteil, 1992) and from seismic character. Compressional tectonics is inferred to have started in the Early Miocene, as it appears to have onshore. The top Paleogene reflector marks the onset of structural growth, and subsequent burial is recorded by onlapping and draping sediments. There is some thinning over the crest of the Shelf Thrust Stack suggesting that gentle folding continued through the Neogene. The end of the Miocene is marked by a strong erosional unconformity on this line. Pliocene sequences onlapped the high from the east before themselves being uplifted and truncated.

The offshore Wairarapa Shelf is underlain by a gently folded belt formed by thrust faulting during an Early Miocene compressional phase. Since then, only minor movement has occurred on the controlling faults, although regional tilting has affected the shelf block from time to time, particularly since the end of the Miocene.

Shelf-Edge Strike-slip Zone

Line 203 (figure 7) was shot jointly by the USGS and DSIR in 1983. This deep penetration line is processed to 10 seconds and shows that the shelf edge is underlain by a

complex graben. Sediment deposition in this graben was controlled alternately by its bounding faults producing a characteristic alternating wedge infill pattern. Both sides of the graben have been subsequently inverted producing large structures which are in a good location to trap hydrocarbons from an underlying kitchen area containing Cretaceous or Paleogene source rocks (figure 7). This line is supplemented by NZ 61 (figure 8), shot by Gulf in 1973, an oblique strike line through the Shelf Edge structure. The large thickness variations of Neogene units along strike within this graben are clear. These two lines are together highly suggestive of deposition along a sinuous strike-slip fault where a unit adjacent to a restraining bend may be thin, while, along strike against a releasing bend, the same unit thickens. Figure 8 shows this relationship in extreme situations with a lower Miocene unit absent from the southwestern half of the diagram, but attaining a maximum thickness of nearly 2 seconds TWT in the right hand portion.

The two proposed strike-slip zones, the coastal and shelf edge zones are separated by the shelf thrust stack. The orientation of the shelf edge strike-slip zone is not well constrained as little good quality data exists along its strike.

Active accretionary prism

Seawards of the shelf break, pure thrusting becomes more important. This zone extends to the Hikurangi Trough, the

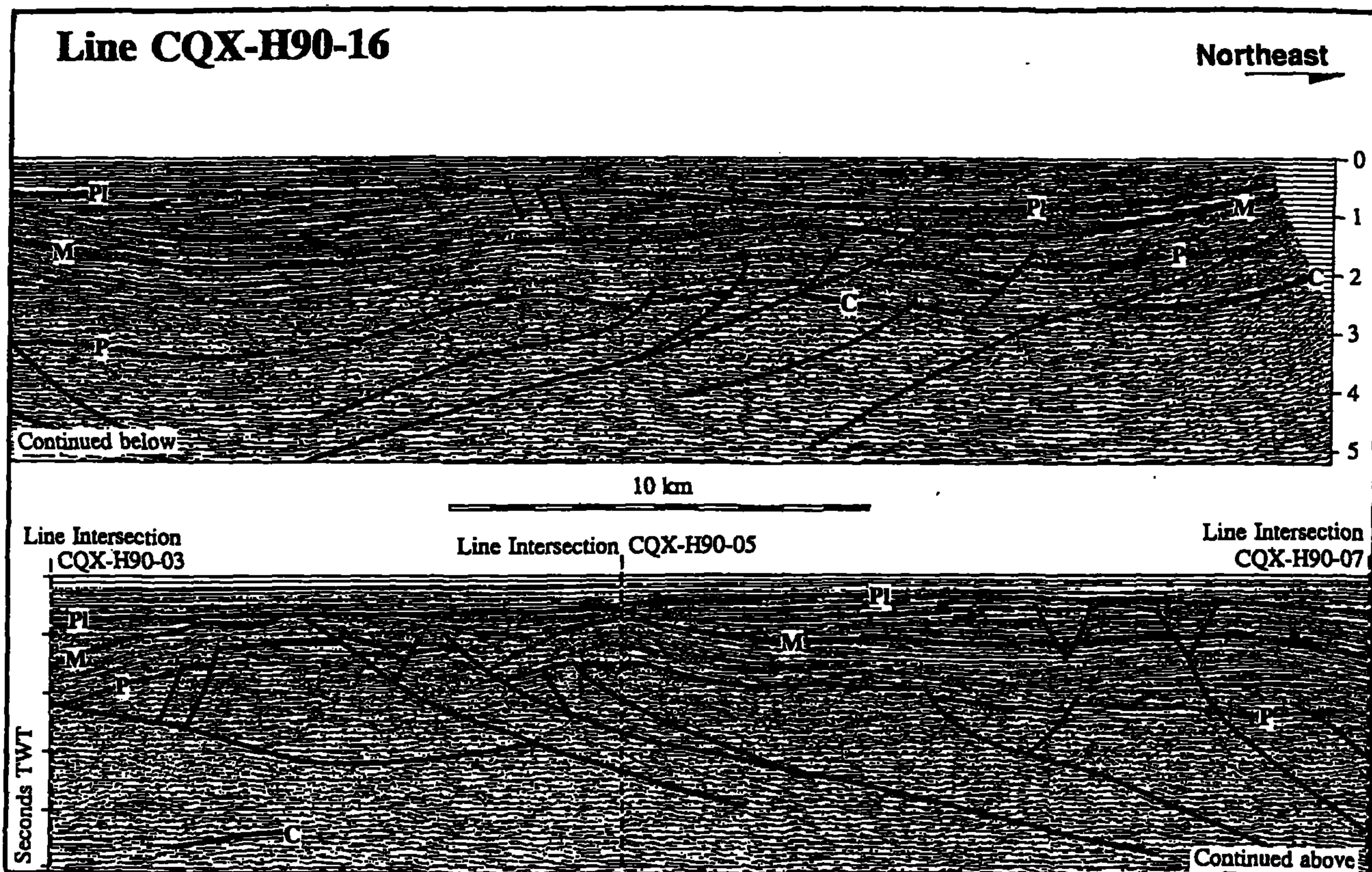


Fig. 5. Line CQX H90 16 is an oblique strike line through the Lachlan Ridge pull-apart basin. The opposing dips of the faults suggest a flower structure, and the undulating bedding plane reflectors strongly suggests deposition along a sinuous strike-slip fault. Major reflectors are marked as for figure 4 and the line is located on figure 1.

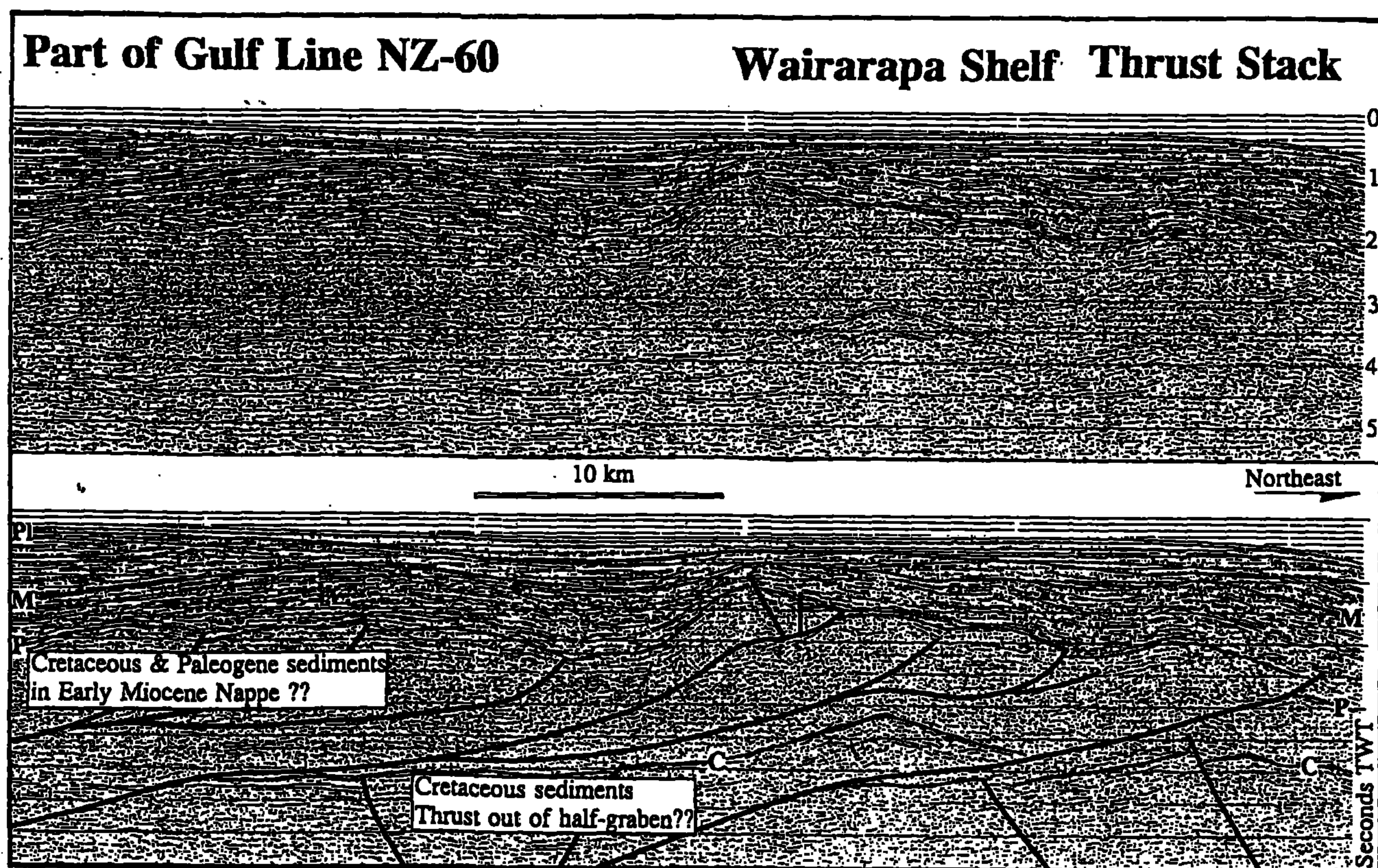


Fig. 6. Line NZ 60 is an oblique strike line through the Wairarapa Shelf. It shows possible rift blocks and suggests that some of the faults were reversed in the Early Miocene and Cretaceous sediments were thrust out of the rift structure. Post Paleogene sediments are unfaulted, suggesting that the shelf thrust zone locked in the Early Miocene and the Wairarapa Shelf was a relatively stable block from then.

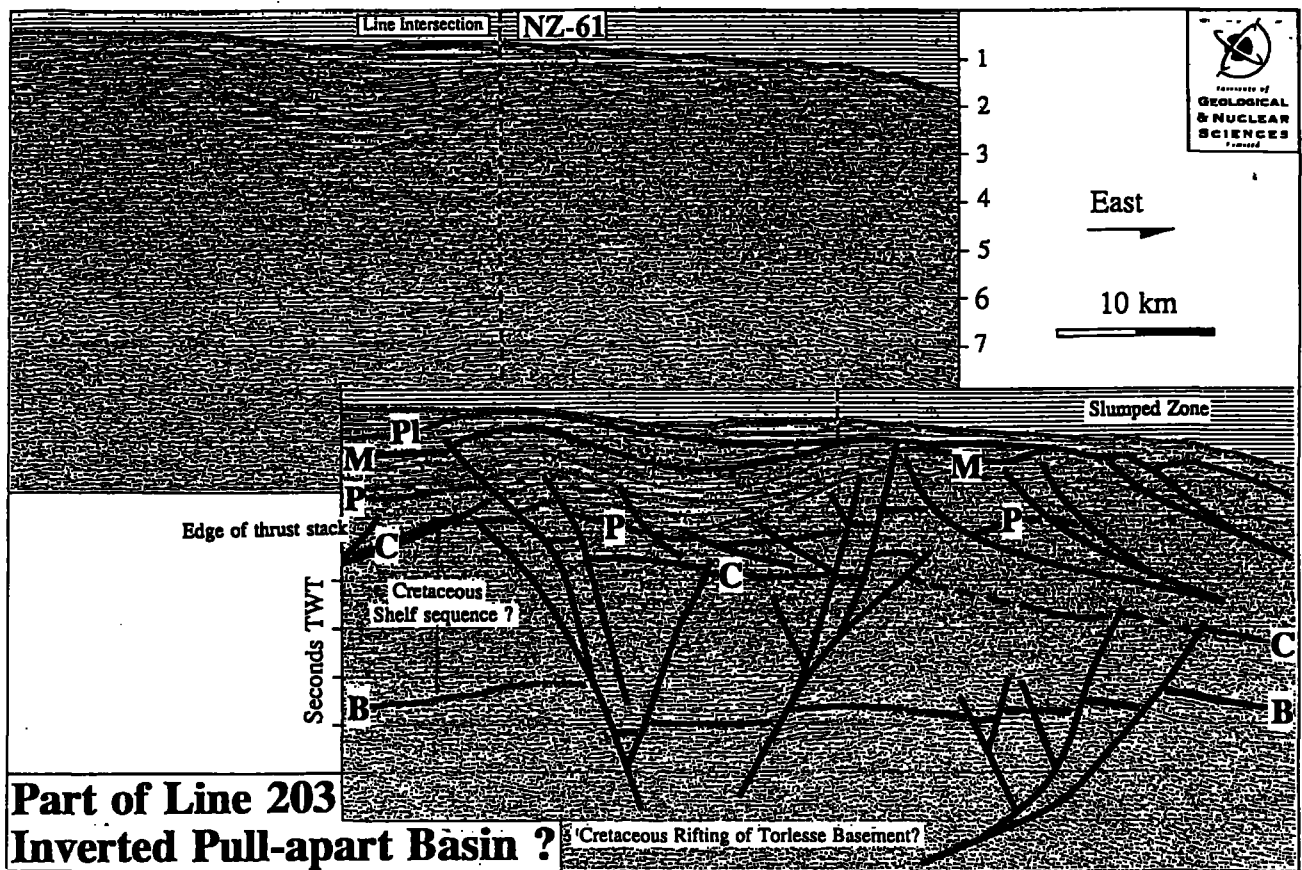


Fig. 7. This complex graben is located at the edge of the Wairarapa Shelf and forms the termination of the stable shelf thrust stack. Line 203 was shot by the USGS and DSIR in 1983. It is processed to 10 seconds and shows a complex sedimentary pattern within the graben. The alternating wedges suggest control by alternating faults. A slumped zone is interpreted in the eastern third of the diagram. 'B' may be the top of the rifted Torlesse basement, between 6 and 7 seconds TWT.

present location of the tectonic front. It is not seen in either bathymetry or seismic data north of Hawke Bay. It appears that accretion occurs only along this sector of the subduction zone and that a lack of sediment supply or other factors, such as the roughness of the subducting plate, do not allow accretion to the north of Hawke Bay. Although this zone of active accretion lies below deep water (1000 to 3000 m) structures are large and probably include a considerable volume of turbidite fan sediments which may prove to be good reservoirs. Line 203 (figure 9) is badly affected by strong sea-floor multiples but many features are visible. Figure 9 shows major thrusts traced to a common detachment surface. A bottom simulating reflector cuts through the anticlines attesting to the presence of hydrocarbons in the section.

Summary of tectonics from Paleogene to present day
Following cessation of subduction in the Cretaceous, the first tectonic episode to affect most of the East Coast Basin appears to have been rifting. Two periods of rifting affected much of the New Zealand micro continent (Laird, 1993 cf. Mazengarb, 1991; 1993). Seismic evidence for tensional faulting in the Cretaceous of the East Coast Basin is sparse but seismic evidence suggests that such faulting seems to have continued well into the Paleogene.

Oblique subduction began along the Hikurangi margin near the start of the Miocene. It caused southwestwards-verging thrusting which emplaced the East Coast allochthon onto Raukumara Peninsula at the same time that the Northland allochthon was emplaced in Northland. There is evidence

for southwestwards-verging thrusting in the Adams-Tinui region (Delteil, 1992) of northern Wairarapa/southern Hawke Bay and this may have had the same cause.

Soon after emplacement of the allochthon, dextral wrench faulting occurred as a result of the oblique direction of subduction. Strike-slip faulting probably focused along five main zones. One may have been along the foot of the present Adams-Tinui Tectonic Zone of Delteil (1992), past Hawke Bay, through the Lachlan Ridges across the mouth of Hawke Bay and continuing northeastwards past Mahia Peninsula (figure 2). Evidence for 350 km of dextral translation, though also inconclusive, is provided by the Adams-Tinui thrust sheet, which may have been part of the Raukumara allochthon. The present-day bend in the Lachlan Ridge fault zone would have been a releasing bend across the mouth of Hawke Bay for much of the Neogene and may explain Hawke Bay as a large pull-apart basin.

Eastwards-verging compressional faulting is also apparent from early Miocene (figure 6). The style of thrusting varies from place to place. Thrusting produced relatively broad structures on the Wairarapa Shelf (figure 6), while along the oceanward flank of Mahia Ridge (figure 4), and further north along the Raukumara Shelf edge, it resulted in more tightly folded, thrust stack structures.

Large-scale slumps have, from time to time, had a profound effect on structures in the region. Pettinga (1985) described one such large-scale feature between Cape Kidnappers and Poanui Point, extending onshore as a set of tensional faults

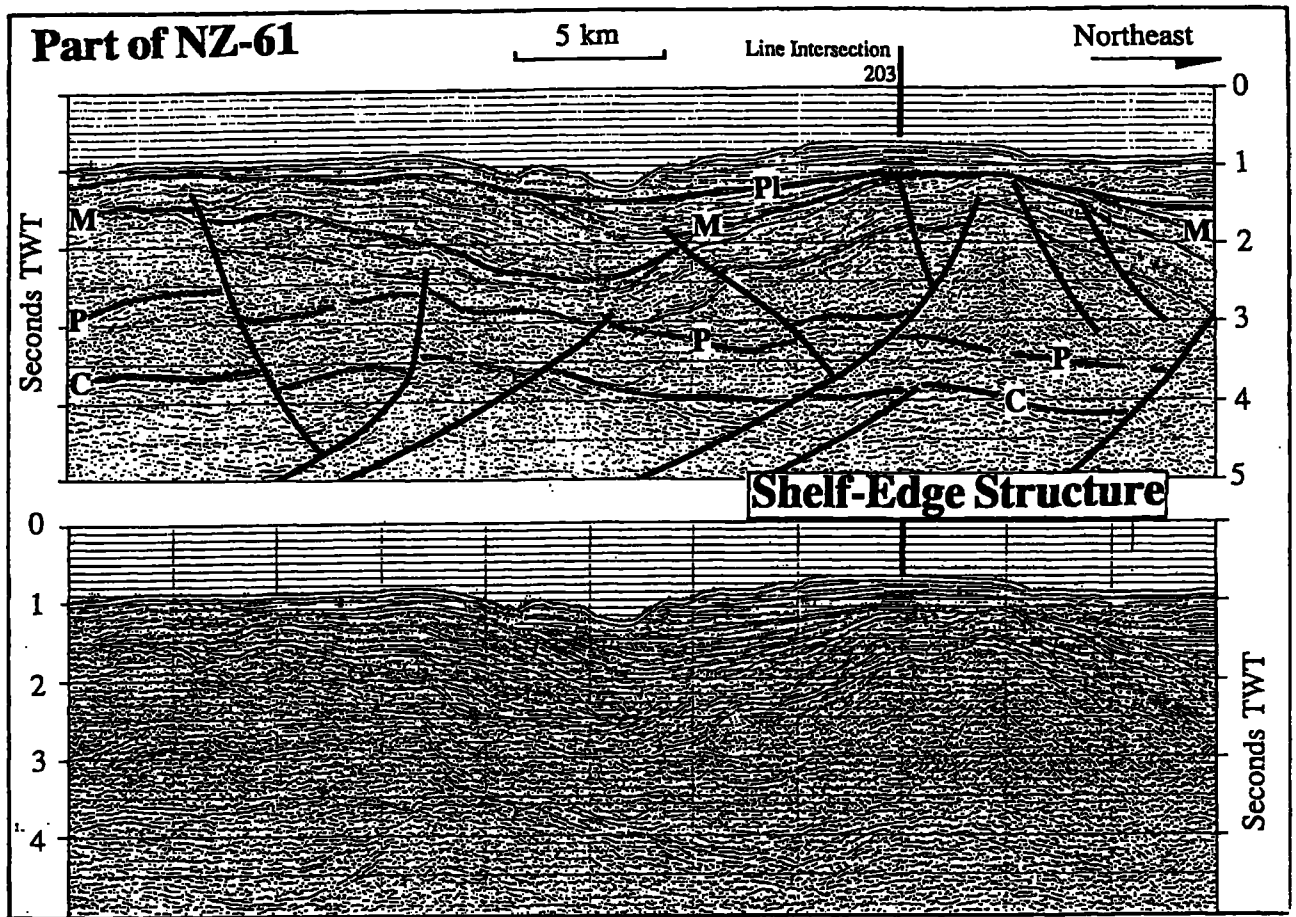


Fig. 8. NZ 61 crosses line 203 and is an oblique strike line through the shelf-edge structure. As for figure 5, the undulating bedding plane reflectors and the highly variable unit thicknesses suggest deposition along a sinuous strike-slip fault.

in an otherwise compressional regime. Low-angle listric faults, observed on offshore seismic sections, in the region date from the mid Miocene and support Pettinga's interpretation. In the southern Hawke Bay region another large slump is recorded on line 203, shot by the USGS in 1983 across the offshore Wairarapa region (figure 7). Such slumps can create trapping structures and provide migration pathways for petroleum.

Subduction-related accretionary thrust ridges continued to form to the present day (Lewis and Bennett, 1985). With an increasingly convergent direction of subduction, pure thrusting has played a more important part in the structural development of parts of the East Coast Basin.

End Cretaceous Reconstruction

The idea of strike-slip faulting in the East Coast Basin is not new. Kingma (1962) recognised the importance of strike-slip faulting to Miocene basin formation in the Dannevirke region, while Ridd (1967) described dextral transcurrent movement on the Pongaroa Fault, further south in the Wairarapa. Cutten (1988; 1993) described the Mohaka Fault and estimated a total 150 km of dextral strike-slip displacement since the Early Miocene. More recently, work by Delteil (1992) has elucidated geological relationships in the Pongaroa region and suggested that 350 km of dextral strike-slip motion could have occurred along the Adams-Tinui Fault in the Early Miocene. He further recognised two other major dextral strike-slip faults; the Pongaroa Waihoki Fault Zone, which started movement in the Burdigalian

(upper Early Miocene) but continued into the Pliocene, and the Akitio Fault Zone which dates from early Burdigalian times.

This strike-slip displacement must be considered if the paleogeography and structural evolution of the East Coast Basin is to be understood. Previous paleogeographic reconstructions have assumed that the East Coast region acted as a competent block and was rotated clockwise by up to 90° during the Neogene (Walley, 1992). The major problem with this reconstruction is that a large triangle of crustal material must be removed, without benefit of a known subduction zone and without major orogeny. A second problem is that the earlier models do not account for the change of shape of the East Coast Basin with time as strike-slip faulting stretched and narrowed the basin to its present configuration.

The model presented here (figures 10 & 11) obeys plate tectonic constraints as the Late Cretaceous locations of the major North Island and South Island blocks of Walcott (1978) were used as a starting point. The East Coast region east of the Mohaka Fault is split into 5 belts by the main strike-slip faults; the Wairarapa/Pongaroa, Adams-Tinui, Akitio and Shelf Edge systems. The blocks were moved sinistrally until the best fit was attained with minimal overlap (Uruski and Wood, 1993; figure 11). Broad facies belts (after Walley, 1992) are overlain and Cretaceous outcrops shown. This model suggests that this part of the subsiding passive margin formed a broad embayment in the generally linear trend of the margin and that sediments could have

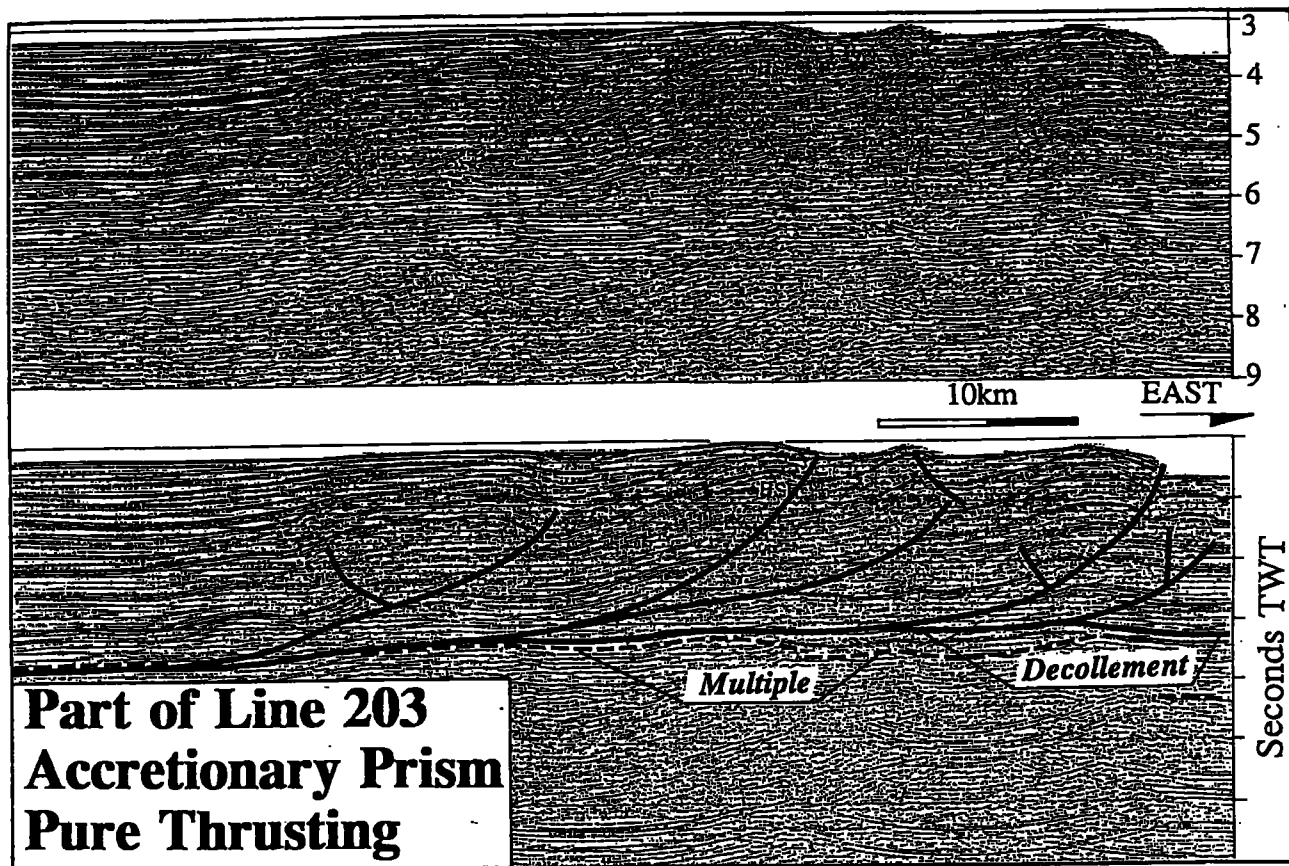


Fig. 9. Part of the oceanward extent of line 203 shot by the USGS and DSIR in 1983, illustrating the pure thrusting associated with the accretionary prism. The thrusts sole out on a decollement which is clearly separate from the sea-bed multiple at the eastern end of the diagram. A bottom simulating reflector is marked by open circles. Sediments involved in thrusting are probably mostly scraped off the subducting plate, although more recent deposition is apparent in the basins between the rising anticlines. Reflectors are not labelled on this line although sediments as old as Early Cretaceous or even Jurassic may be involved, perhaps the distal parts of the Torlesse fan.

come from a variety of directions. Different source directions have been suggested by workers from different areas (e.g. Mazengarb, 1991; Moore, 1988; Crampton, 1991).

The model accounts for the Neogene dextral strike-slip motion and obviates the need to remove a large crustal block. The model is a prototype as there are many as yet unknown factors. The first is the choice of locations for the major strike-slip faults. Surface traces are only accurate for the ages of the strata they displace. The flower structures illustrated by figure 4 show that surface traces may occur many kilometres away from the stem of the flower structure. As each branch is presumably a response of the sedimentary overburden to movement along a deeper crustal lineation, the locations of these deeper features should be mapped in the subsurface, but there is not enough available seismic reflection data to do so.

The second factor is the decision on how much translation there has been along the major strike-slip faults. Cutten, (1988; 1993) gives a figure of 150 km for the Mohaka Fault and Delteil (1992) suggests 350 km for the Adams-Tinui system (Delteil, 1992). A minimum total displacement of 500 km may have taken place along the North Island faults. In the South Island, the plate boundary is the Alpine Fault, a 650 km long feature on which at least 480 km, and possibly as much as 1000 km, of dextral strike-slip motion has occurred. Once again, a lack of data prohibits an accurate assessment of displacements.

The third factor involves the amounts of contraction and expansion that has occurred. Many of the faults are curved so that when the intervening blocks are moved, overlaps or gaps are created. Overlaps suggest extension while gaps suggest compression and both are known to have occurred since the Cretaceous (figures 4,5,6,7 & 8).

Petroleum

Source rocks and maturity

The East Coast Basin contains marine source rocks, unlike most of New Zealand's basins where source rocks are generally terrestrial. Cretaceous units onshore, for example, the shallow marine Te Wera Formation (Mazengarb, 1991; 1993) and the shallow marine or bathyal fan Glenburn Formation (Moore, 1980, Pettinga, 1982) contain significant carbonaceous material, although TOC figures are not available. The Late Cretaceous Whangai Formation is a fine-grained, siliceous marine sequence which has some petroleum generation potential (Moore, 1988) as TOC values of 1.5% have been recorded and the unit's average thickness is around 400 m. The Waipawa Formation, of Paleocene age is a black or dark brown mudstone and is a much richer potential source rock with TOC values averaging 5.3%. This condensed marine sequence is found across most of the East Coast Basin and probably exists in the offshore region also. Samples yield hydrogen indices up to 550 mgHC/g of TOC suggesting that it is an oil-prone source rock. Although

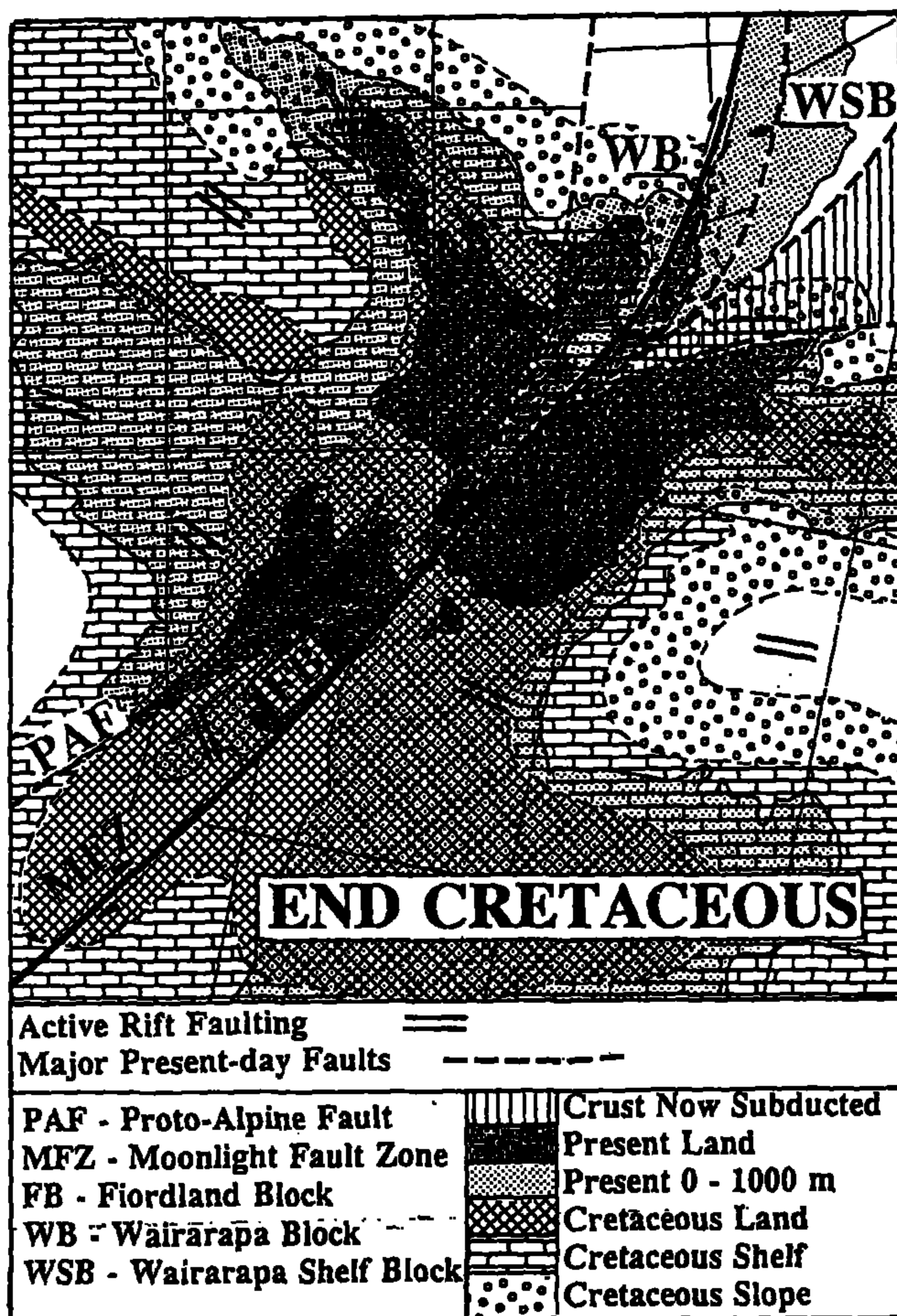


Fig. 10. Proposed End Cretaceous reconstruction showing major present day and end Cretaceous topographical zones.

vitrite reflectance figures suggest that the Waipawa Formation is immature at outcrop, oil drips from it in places. The post Paleogene succession thickens offshore (figures 5,6,7 & 8) and it is likely that the Waipawa Formation is mature in many areas. The Eocene Wanstead Formation is mostly bathyal mudstones, but contains carbonaceous beds which may have source rock potential (Lillie, 1953).

Reported geothermal gradients ranging from 23.1°/km (Geosearch, 1991) to 27°/km (Johnson, 1982) suggest that a burial depth of approximately 4 km should be sufficient to generate oil from these source rocks. The deep crustal seismic line 203, shot by the USGS and DSIR in 1983, parts of which are shown as figures 7 & 9, shows that more than 10 km of sediments are present below the Wairarapa Shelf (Davey and others, 1986) and that the postulated top Cretaceous reflector is buried by more than 4 seconds TWT of sediments below the Wairarapa Shelf and the Shelf Edge Strike-Slip Zone. Seismic stacking velocities suggest that those travel times equate to a minimum burial depth of 4 km.

Reservoir Formations

Cretaceous sandstone units from the Raukumara Peninsula are thoroughly described in Mazengarb (1991; 1993), from the Wairarapa by Moore (1988) and Crampton (1991) and from Marlborough by Laird (1992). Some potential Paleogene reservoirs are described in Moore (1988) and others in Johnson (1980) and Ministry of Commerce (1992). Sandstones are common in the Neogene and limestones may provide good reservoirs at a number of stratigraphic levels within the Cenozoic.

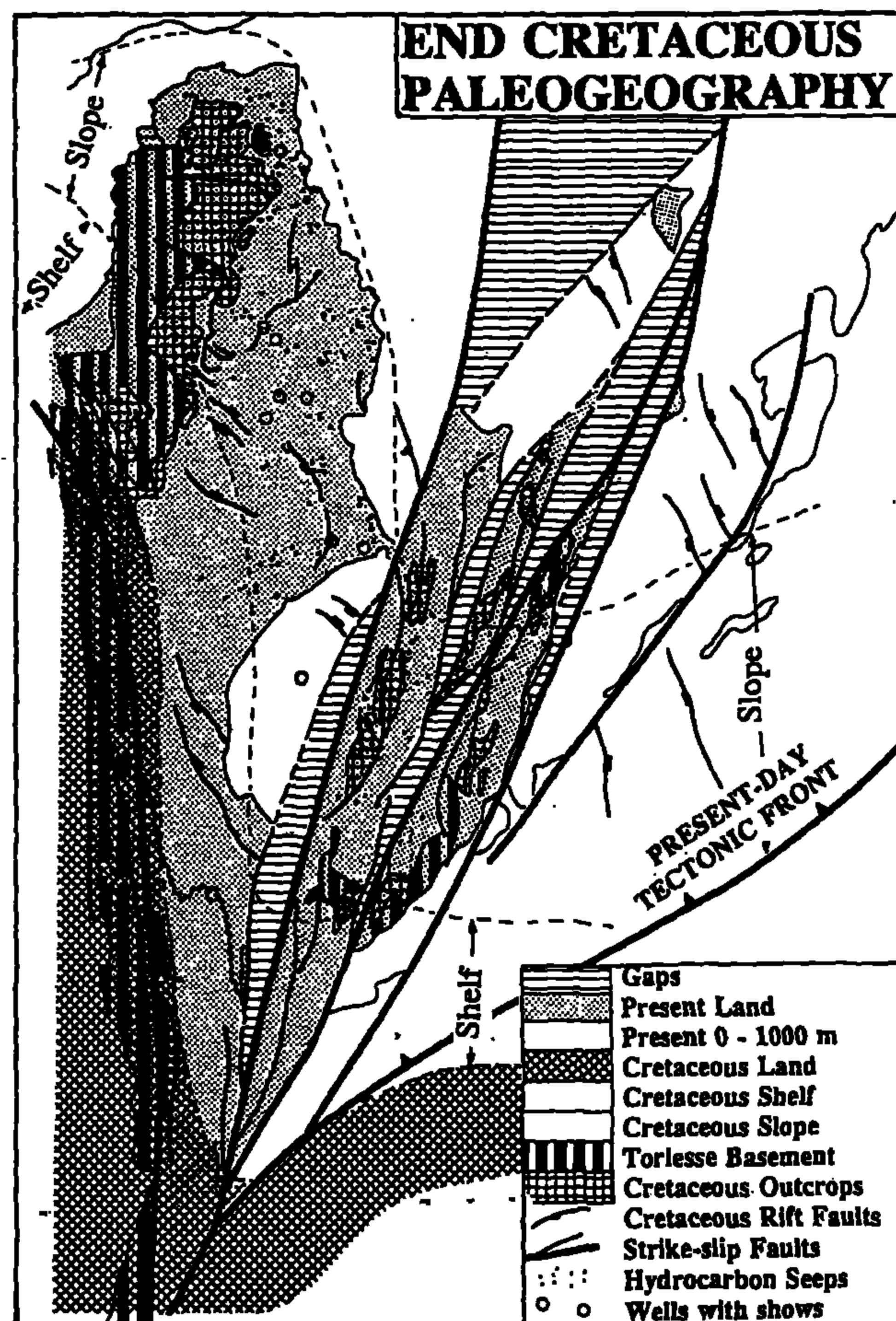


Fig. 11. Proposed paleogeography at the end of the Cretaceous.

The reconstruction proposed above (figures 10, 11) suggests that the Wairarapa was much closer or adjacent to the Raukumara Peninsula at the end of the Cretaceous so equivalents of Raukumara units may occur in the offshore Wairarapa region. In the Early Cretaceous (Albian), a range of marine sandstone facies are recorded in the Raukumara Peninsula and many good potential reservoirs are preserved. These include transgressive sands of the Koranga and Wairata formations, near shore, high energy sand bars of the Te Wera Formation, shelf sandstones of the Waimana Formation, sandstones in the slope deposits of the Karekare Formation, slope channel sands of the Taitai and Mangaohewa formations and deep water turbidite fans of the Tapuwaeroa and Waitahaia formations (Mazengarb, 1991; 1993).

The few porosity and permeability figures available indicate several fair to good quality reservoirs in the Early Cretaceous of the Raukumara Peninsula. They include the Koranga Formation with mean porosities of 9.57% and permeability of 0.65 millidarcies, the Te Wera Formation with mean porosity and permeability of 8.45% and 0.69 millidarcies (Liming, 1984), the Tapuwaeroa Formation with a mean porosity of 22% and permeabilities from 3 to 128 millidarcies (Pick, 1962) and the Tahora Formation with porosity measured at 22% and permeabilities of 112 millidarcies (BP Exploration NZ Ltd in: Isaac and others, 1991).

Cretaceous sediments of the Wairarapa include many units which may be good reservoir rocks (Moore, 1988; Crampton, 1991). Although it is dominated by mudstone, the Springhill Formation of western Wairarapa which contains thick

conglomerates, sandstones and turbidites. The Tangaruhe Formation fines upwards from coarse clastics to mudstone and the Glenburn Formation is dominated by coarse clastics, containing a 12 metre-thick conglomerate bed and many metre-bedded, well-sorted clean sandstones such as the Te Mai sandstone. Similarly, most groups in Marlborough (Laird, 1992) contain significant coarse clastics and sandstones, many with good reservoir properties.

Five groups are recognised in the Cretaceous of the Marlborough region (Laird, 1992) containing a large volume of sandstones and conglomerates. The Early Cretaceous (Albian) groups were deposited in rift basins which preceded and accompanied the break-up of this part of Gondwana. The basal Coverham Group is dominated by marine clastics and is represented by an overall fining-upwards sequence of as much as 2000 m of sediments. Only its topmost section is mud-dominated. The succeeding Wallow Formation consists of a series of fining-upwards cycles with coal measures at the base and including alkaline basalt lavas. Above the lavas, a return to fluvial conditions is locally observed. The Hapuku Formation is a shallow marine condensed sequence; the Burnt Creek Formation has a basal conglomerate and fines upwards until it is mudstone-dominated at the top. The final group, the Seymour, consists of glauconitic sandstones and fine sands in a predominantly muddy sequence.

The East Coast Basin developed through the Cretaceous as a transition from an active to a passive margin. In Marlborough (Laird, 1992) and along the East Coast of North Island, (Moore and Speden, 1979) deposition of Cretaceous sediments was controlled by active tensional faulting. Seismic data from the offshore part of the East Coast Basin (figures 6 & 7) suggest that this rifting episode (or episodes) was (were) extensive.

Highly fractured localities of the Whangai Formation (Moore, 1988) are another potential reservoir facies. Similar facies are important reservoirs in the Monterey Formation of California (Snyder and others, 1983).

Paleogene At the end of the Cretaceous (figures 10 & 11) the East Coast Basin formed a large, oceanwards-facing embayment (Weissel and others, 1977; Crook & Belbin, 1978) with clastic fans being deposited across the continental slopes (Mazengarb, 1971; 1973). As in most parts of New Zealand, tensional faulting ceased in the Paleogene following separation from Antarctica and the cessation of spreading in the Tasman Sea (Nathan and others, 1986; Field and others, 1989; Wood and others, 1989; Uruski and Wood, 1991; Thrasher, 1989, 1992).

During the Paleogene, the East Coast Basin continued to subside, receiving less coarse-grained clastic sediments and a higher percentage of mudstone. The Paleocene sequence (Moore, 1988) consists of the Whangai and Waipawa formations. Although the Whangai Formation consists mainly of fine siltstones and mudstones, a significant proportion is sandstone with some metre-thick greensand beds. Possible reservoirs within the Whangai Formation include thick greensands and glauconitic sandstones, which are locally saturated with oil at outcrop, and fractured chert and shale. Log-derived fracture porosities of 30% have been determined from wells in the Raukumara Peninsula (Ministry of Commerce, 1992).

Similarly, greensands are common in parts of the overlying Waipawa Formation and many of these are saturated with oil

at outcrop (McLernon, 1972). The Eocene Wanstead Formation contains minor volumes of conglomerate, sandstones and greensands (Lillie, 1953; Johnston, 1980), but from outcrop studies it is not considered to have significant reservoir potential. However, lateral equivalents may be better developed offshore and in the subsurface onshore. The overlying Oligocene Weber Formation is considered to have better reservoir potential, and porosity values averaging 10% have been obtained from outcrops. Equivalent sandstones in the Gisborne-2 well yielded oil and gas shows (Duff, 1990).

Neogene Most Miocene sandstones are turbidites and generally fine-grained. Many are very well-sorted (e.g. the Whakataki Formation, Johnston, 1980) and do not show graded bedding. Neef (1992) described the sedimentology of five Miocene turbidite units — the Whakataki, Greenhollows, Tanawa, Pakowhai and Waihoki formations — and suggested that the Greenhollows Formation, deposited from high density turbidites, may be the best Miocene exploration target. Gas shows in Miocene sandstones of the Mangaone-1 (Brown, 1961) and Gisborne-2 (Strong, 1930) wells suggest that Miocene sandstones have some reservoir potential. A thick sandstone unit in the Ruakituri-1 well yielded average porosities and permeabilities of 12% and 9 millidarcies respectively (Shell-BP-Todd 1962). Some outcropping Miocene sandstones in the Dannevirke area are reported to be thoroughly oil-soaked (Laing, 1961; Francis, 1992).

The main reservoir target in the Pliocene sequence is the Te Aute limestone and its equivalents and these have been thoroughly described by Beu (1992). These shallow water, well-sorted coquina limestones are widely distributed in the East Coast Basin. They often fringe structural highs which may or may not have been emergent, and the limestones therefore do not form a continuous sheet. This limestone facies was the major target of Hawke Bay-1, the only offshore well drilled in the East Coast Basin, but was extremely attenuated at that location. If the well had been sited on a structural flank the limestone probably would have been found to be better developed. Porosities of 10 to 35% have been measured and permeability reaches 2 millidarcies in the Te Aute Group limestones. Porosity of this limestone facies generally decreases with age.

Seeps and shows

Known petroleum seeps and wells with shows are noted on figure 11 and they are nearly all confined to the slope in the model. Their paleogeographical location may be significant as this may have been the zone where the Paleocene Waipawa Black Shale was deposited. Other explanations are equally possible; e.g. further work might show that the seeps are associated with faults which rupture reservoirs and allow hydrocarbons to escape to the surface. The origin of the seeps is an important topic for future research.

Conclusions

- 1) The East Coast Basin appears to be split into approximately five major blocks by large-scale strike-slip faults; the block northwest of the Coastal Belt, including the Raukumara Peninsula and western Hawke Bay, the Coastal Strike-slip Belt, The Wairarapa Shelf Thrust Belt, the Shelf-edge Strike-slip Zone and the Accretionary Prism.

- 2) The dominant style of tectonics is compressional although there are some major exceptions.
- 3) Two pull-apart basins are recognised adjacent to strike-slip faults; one between Lachlan and Mahia ridges in the mouth of Hawke Bay and the second below the Wairarapa Shelf Edge.
- 4) The Coastal Strike-slip Belt crosses the mouth of Hawke Bay where it forms a releasing bend. It may have caused the Hawke Bay depression and present extensional faulting in the Gisborne region.
- 5) The proposed end Cretaceous paleogeography is of a subsiding passive continental margin which forms a deep embayment in the future East Coast Basin region.
- 6) Petroleum generation is becoming better documented. Source rocks appear to be present in quantity and at a great enough depth to be expelling hydrocarbons. There are a large number of potential reservoir formations in the basin, good regional seals and abundant structures. The East Coast Basin is an attractive frontier basin.

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Acknowledgements

This work was completed under the terms of the Government, FRST-funded, East Coast Cretaceous and Cenozoic project. Thanks are due to many colleagues at the Institute of Geological and Nuclear Sciences and elsewhere for critical discussion and stimulation. In particular, I'd like to thank Brad Field, who reviewed the geological aspects and was not too outraged, Malcolm Laird who didn't disagree too strongly with the reconstruction and Sara, who rendered the paper into English.

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