GEOLOGICAL STRUCTURE OF THE EAST COAST, NORTH ISLAND, NEW ZEALAND

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Abstract

The geological strata of the East Coast, North Island, have been folded and faulted due to oblique subduction of the Pacific plate beneath the Australian plate.

As part of the DSIR Cretaceous-Cenozoic Project (CCP), a series of east-west structural transects are being constructed to delineate changes in structural style from north to south and to determine features such as strain partitioning between strike, slip and compressional structures, and the tectonic history of the region. Each of these transects is being tied to offshore seismic.

The northern transect across the Raukumara Peninsula includes the East Coast Allochthon thrust over the autochthonous Motu Block. Miocene sediments deposited on both terranes have been thrust and normal faulted and folded.

The central transect in northern Hawke's Bay extends from the greywacke ranges across the Mohaka Fault and includes Miocene sediments that demonstrate tight fault-generated folding. Overlying Pliocene sediments show a decreasing south-east dip on approaching the coastline.

The southern transect in southern Hawke's Bay extends from the Ruahine Range to the coast. The transect crosses two transcurrent shear zones each flanked to the east by a fold and thrust belt, and near the coast by the extensional zone of the Maraetotara Plateau.

Additional transects in progress include northern Wairarapa, southern Wairarapa and Marlborough.

Understanding of the geological structure of the East Coast is important to the petroleum industry, leading to the identification of potential oil and gas traps in fold structures and migration pathways along thrust fault planes, as well as the relationship of reservoir units to structural development and the timing of burial relative to trap formation.

Introduction

Oil exploration in the East Coast, North Island, must come to terms with the complex structure of the area, which is located on the Hikurangi Subduction Margin. The numerous oil and gas seeps over the area, and identification of the likely source rocks demonstrate the petroleum potential. But does the complex structure of the region assist or hinder hydrocarbon accumulation ?

This paper discusses some of the methods and results of research aimed at understanding the geological structure of the East Coast, and assists in answering the above question.

Tectonic Setting

The East Coast region of the North Island lies on the Hikurangi Subduction margin. The Pacific Plate is subducting from the Hikurangi Trough beneath the Australian Plate (Figure 1), the relative plate motion being oblique transpressive. The rate of relative motion in the last 3 million years is 43.5 ±1.8 mm/yr with an azimuth of 263 ± 2.2° (DeMets *et al.* 1990) at the latitude 39° 50' South (Southern Hawkes Bay). This resolves into a convergent component of 35mm/yr and transcurrent component of 25mm/yr. Some of this relative motion has been transferred across the plate interface into the overlying Australian Plate, causing complex deformation visible at the surface. Deformation of the East Coast shows some degree of partitioning of the oblique-transpressive plate motion into convergent structures and transcurrent structures. Combinations of the two do, however, occur.

Major transcurrent faults occur at the margin of the axial ranges with the forearc basin. Examples are the Mohaka and Ruahine faults. Neogene dextral displacement of these transcurrent faults is estimated to be 150-200 kilometres, and late Quaternary movement rates are estimated to be 1-4mm/yr (Beanland and Berryman 1987, Raub 1985, Raub *et al.* 1987). Transcurrent faults also occur within the forearc basin. The Rangiora Fault, in central Hawke's Bay has an estimated late Quaternary movement rate of 4.5mm/yr (Cutten *et al.* 1988). Although surface Pliocene strata shows no appreciable displacement, pre-Pliocene fault displacement of Miocene strata beneath, is a real possibility. Convergent structures observed, are thrust faults and folds associated with these thrusts. Normal faults also occur but these appear to be largely secondary features, sometimes resulting from relaxation of thrust faults (Mazengarb 1984), or from surface extension in response to deeper seated uplift (Cashman *et al.* in press).

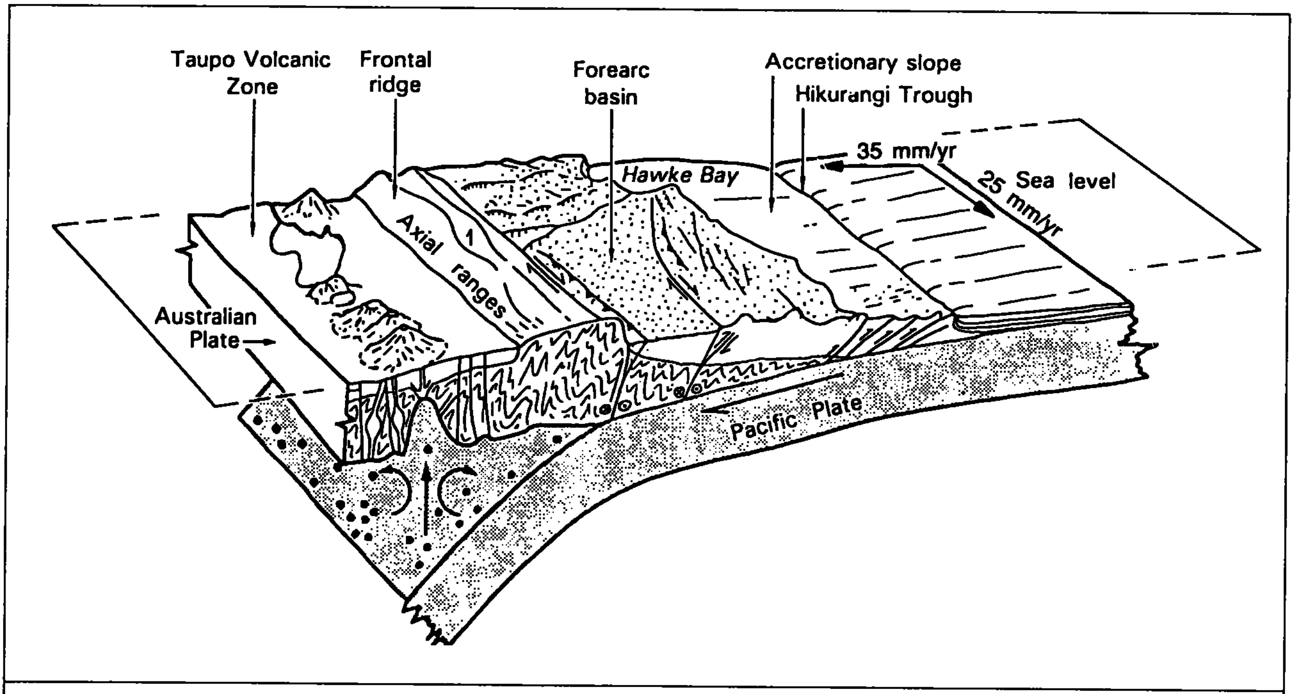

Figure 1: Diagrammatic cross-section (after Kamp 1982) across Hawke's Bay, East Coast, showing the context of the axial ranges and forearc basin with respect to the subducting Pacific Plate. Black dots beneath the Taupo Volcanic Zone represent earthquake epicentres.

Petroleum Potential

The potential of the East Coast Region is apparent from the observation of numerous oil and gas seeps. Carbonaceous Cretaceous and Paleogene source rocks are present and migration pathways are likely to be abundant as suggested by the tectonic environment and surface observations of faulting. Neogene stratigraphy suggests that permeable reservoir rocks and impermeable seal rocks are also present. With such a favourable environment, determination of the geological structure and identification of structural traps is of paramount importance in any exploration programme. It should be noted that in the Taranaki Basin all of the producing accumulations are found in structures formed in the Neogene. Neogene structures in the East Coast would appear to have as much potential for trapping hydrocarbons.

East Coast Structural Transects

Studies of the structure of East Coast include a series of structural transects to which the interpretation of thrust-related folding and the techniques of cross section balancing are being applied. These are part of a study of Cretaceous and Cenozoic basins in the East Coast region by DSIR Geology and Geophysics. These onshore transects will be coupled with offshore seismic lines. The transects (Figure 2) have been located as much as possible across areas of recent geological mapping and are also placed to give a coverage of areas from north to south along the East Coast with the aim of determining structural variation. In this paper the Raukumara and Mohaka transects are discussed in detail and brief comment is made on the Southern Hawkes Bay transect, which is still in preparation. The remainder of the transects shown on Figure 2 will be completed at a later date.

Cross-section balancing

The transects show thrust-related folding: fault-bend folds and fault-propagation folds (Figure 3). Interpretations involving such folds can be tested for feasibility by 'restoring'

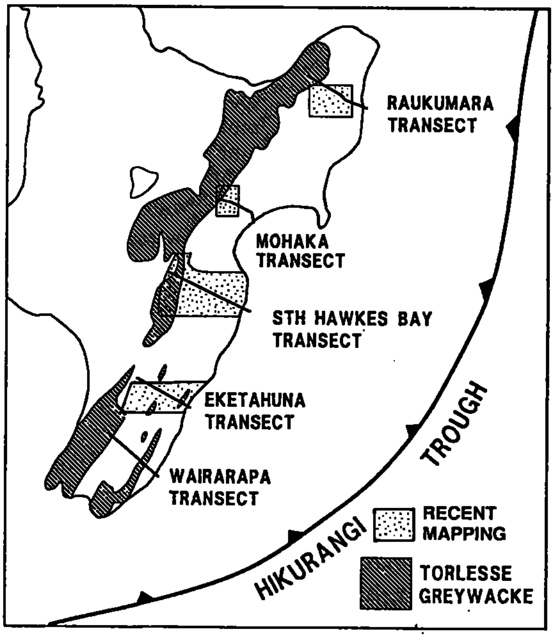

Figure 2: Location of structural transects across the East Coast. Areas of recent geological mapping (stipple) are: Y 16 Raukumara Transect (Mazengarb *et al.* in press), V19BD Mohaka Transect (Cutten in press), Sth Hawkes Bay (Cashman et al. in press), Eketahuna Transect (in prep.).

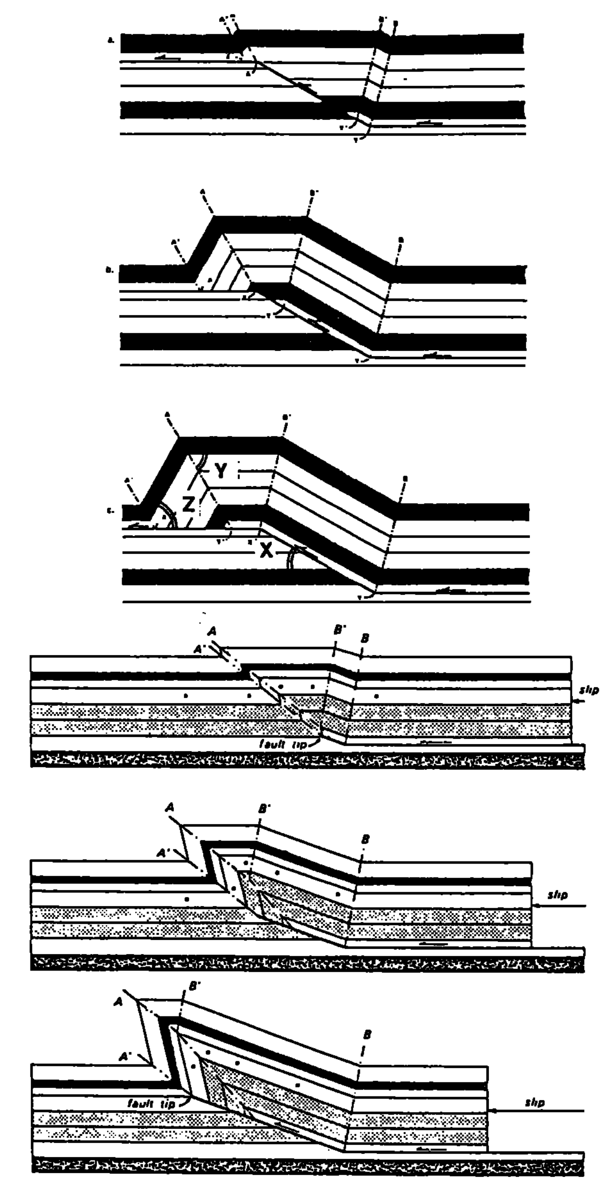

Figure 3: Schematic progressive development of (a) a fault-bend fold as a thrust sheet rides over a decollement-thrust-decollement configuration and (b) a fault-propagation fold as a thrust sheet rides over a decollement-thrust configuration (suppe 1983). X=dip of the thrust, Y= interlimb angle of the fold, Z=dip of the forelimb.

the section to its undeformed state. A section must be able to be restored without loss or gain in sediment 'volume' (simplified to 'bed length' in a two dimensional cross-section), for the section to be feasible. Some of the principles of the technique are here discussed before outlining their application to the East Coast transects.

A balanced cross-section needs to be oriented parallel to the direction of tectonic transport or shortening, that is, at right angles to the trend of fold structures, and to the trend of any thrusts. Any tectonic transport in or out of the cross-section (e.g., transcurrent faults, or where the trend of fold structures is oblique to the section line) complicates the balancing technique. Further complication arises where the sedimentary sequence contains beds which thin out. Suppe (1983) and Woodward *et al.* (1985) outline the methods of cross-section balancing and development of fault-bend folds and fault-propagation folds using kink-band geometries. The construction of these folds involves geometrical constraints relating the dip of the thrust fault to the interlimb angle of the fold, and to the dip of the forelimb. These constraints allow the subsurface configuration of ramps and flats to be determined from surface structural data. Jamison (1987) outlines further constraints relating the degree of thinning or thickening in the forelimb to the dip of the thrust and the interlimb angle of the fold.

Raukumara Transect

The northernmost transect is located across Raukumara Peninsula using data from recent 1:50,000 scale mapping by Mazengarb *et al.* (in press), as well as Moore *et al.* (1984), Moore *et al.* (1989), and earlier reports. A complication with this transect is that tectonic deformation is multiphase, and tectonic transport into the section has occurred with the emplacement of the East Coast Allochthon from the north-east. For this reason the transect has been divided into three blocks, each treated separately. These are: the Motu Block; East Coast Allochthon; and the East Neogene Block.

Motu Block: Middle Cretaceous Waitahaia Formation, Matawai Group (mw - Figure 4) of indurated alternating carbonaceous sandstone and mudstone is deposited on early Cretaceous Urewera Group (u - Figure 4) of strongly indurated greywacke and argillite. Figure 4 shows what is considered to be the gross structure of the Motu Block and is based on rather limited surface geological data. Extensive folding at the surface shows folds with eastern limbs dipping steeply or overturned to the west and these folds are interpreted as fault-propagation folds resulting from east directed thrusting. Structure at depth is likely to be a complex series of imbricate thrust. This thrusting ceased by the (early late Cretaceous) as the folded rocks are unconformably overlain by Karekare Formation (mk - Figure 4), indurated mudstone and sandstone, which dips to the south-east. Another unconformity separates these rocks from Owhena Formation (siltstone and muddy sandstone) and Whangai Formation (poorly indurated siliceous mudstone) of the late Cretaceous Tinui Group. Thrusting of Urewera Group over Matawai Group on the western flank of the Motu Block is probably much younger than the thrusting within the Matawai Group.

East Coast Allochthon: The East Coast Allochthon comprises middle Cretaceous Ruatoria Group (r - Figure 4), indurated sandstones and mudstones (deposited at the same time as the Waitahaia Formation in the Motu Block), and overlain by the Tinui Group (tw - Figure 4), which includes Waipawa Black Shale. A thick melange unit is associated with the Waitahaia and Te Rata thrusts which were active at the time of allochthon emplacement in the Waitakian (lowermost Miocene). The allochthon has travelled from the north-east a distance of at least 40 km (Mazengarb pers. com.), possibly by a gravity mechanism on a gentle south-west dipping slide plane (Stoneley 1968), or by thrusting on a steeper north-east dipping thrust plane (Rait *et al.* in press). Subsequent uplift (post Miocene) of the eastern margin of the Motu Block has tilted the complete allochthonous sheet giving it a south-east dip. A thin sheet of Paleogene Mangatu Group has been thrust over the allochthonous sediments.

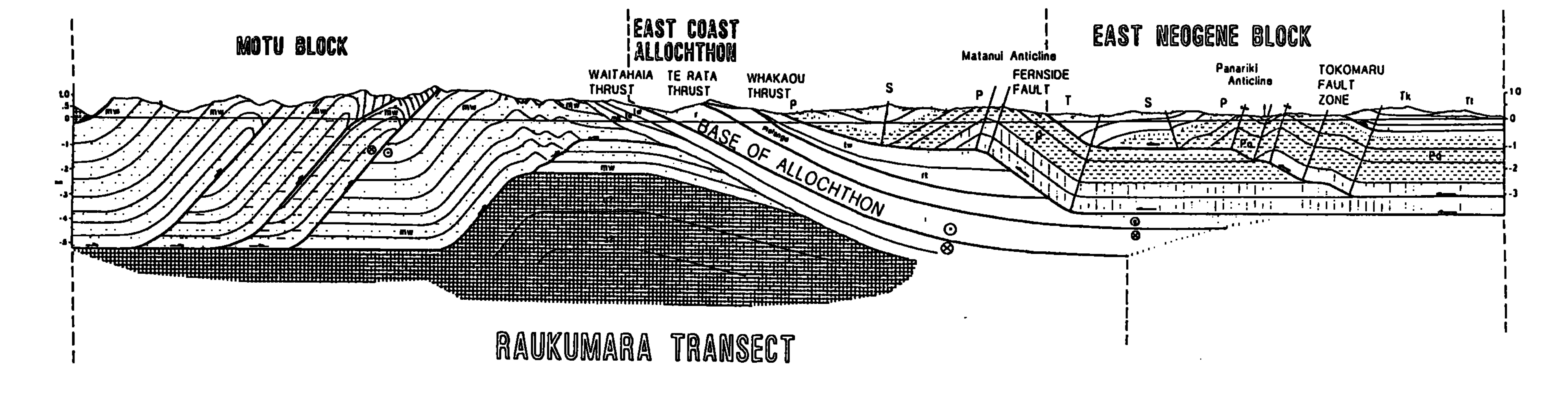

Figure 4: Raukumara Transect cross-section The Motu Block shows steep easterly directed thrusting (in mid Cretaceous). The East Coast Allochthon has thrust (in lower Miocene) into the section from the north-east and subsequently tilted south-east. The East Neogene Block shows westerly directed thrusting (post Miocene) and more recent normal faulting.

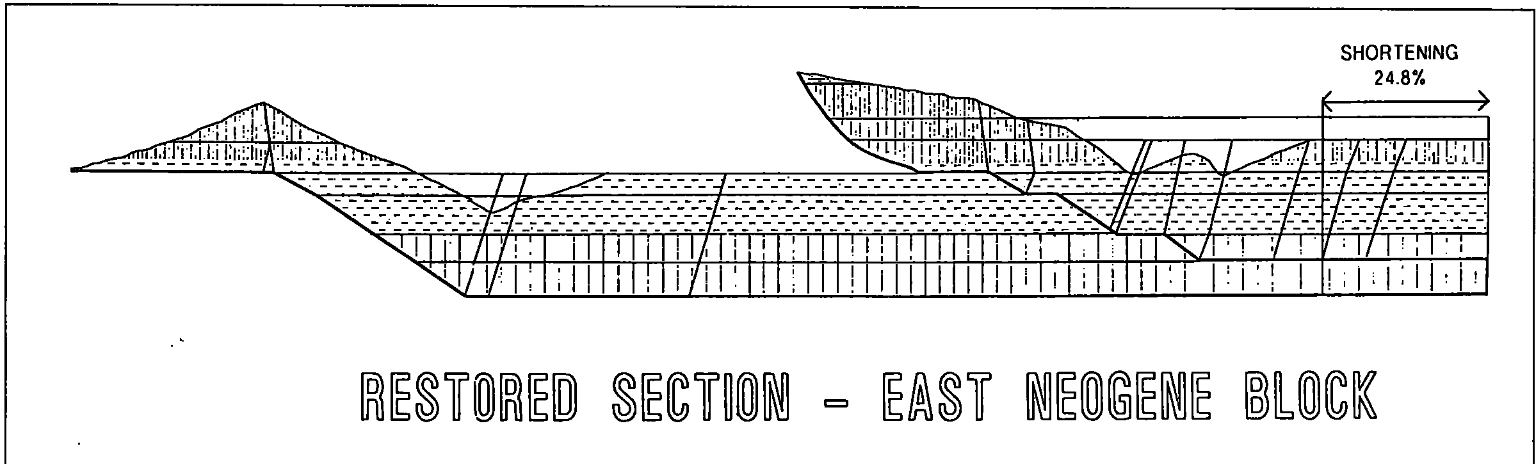

Figure 5: Cross-section of the Eastern Neogene Block with thrust movement restored. Area gained by folding equals the area lost by slip.

East Neogene Block: Sandstone, mudstone, limestone and conglomerate of the Tolaga Group (Miocene) were deposited unconformably of the eastern flank of the tilting East Coast Allochthon. Detailed surface stratigraphic and structural data and good age control allow a more confident interpretation of the subsurface for this end of the transect. Two major thrusts are identified, the Whakoau Thrust and the Fernside Fault; the latter is interpreted to have an undulating thrust ramp that has produced surface folding. The Fernside Fault shows normal movement possibly due to post-thrust relaxation (Mazengarb 1984). The Tokomaru Fault Zone also shows normal movement. The fold forelimbs associated with both of these normal faults shows the expected collapse of bedding (Williams and Vann 1987), dipping into the fault plane. A restored section of the Eastern Neogene Block is shown in Figure 5. Shortening of the East Neogene Block is c. 25%, compared with an estimated 45% for the Motu Block.

Mohaka Transect

The Mohaka transect is located across recent 1:50,000 scale mapping (Cutten in press). The structural trend swings from north-east in the Miocene sediments at the western end of the transect to more easterly in the Plio-Pleistocene sediments near the coast. For this reason the transect deviates from a straight line, so as to parallel the changing direction of tectonic transport.

Urewera Greywacke (Figure 6, u - Fig. 8) forms the axial ranges to the west, separated from folded Miocene sediments by the dextral reverse Mohaka Fault. Relatively undeformed Pliocene (east of the Mohaka River in Figure 8) lies unconformably on the Miocene sequence, dipping to the south-east and flattening out towards the coast. Detailed geological mapping of the folded Miocene shows a south plunging anticline (Pohokura Anticline) with a double hinge closure (note outcrop pattern of Waitere Sandstone in Figure 6) which is offset in a dextral sense by Te Kooti's Fault, a branch of the Mohaka Fault. The southern part of Pohokura Anticline has an overturned, west dipping, eastern limb and is identified as a fault-propagation fold. The northern part of the fold has uniform dips on both limbs and is identified as a fault-bend fold. Figure 7 shows the three dimensional structure of Pohokura Anticline, and how the fold developed. Figure 7a shows the decollement flats and thrust ramps which have caused folding. The background (northern) flat-ramp-flat configuration is responsible for the fault-bend fold. The foreground (southern) flat and ramp configuration is responsible for the fault-propagation fold. A tear fault must exist between the two thrust configurations. The two parts of the fold have also been offset by Te Kooti's Fault (Figure 7b), which dips steeply to the west in the background (north) but decreases in westerly dip to merge with the Pohokura Thrust ramp in the foreground (south). Dextral movement on Te Kooti's Fault and across the thrust ramp (Figure 7c) has superimposed the two parts of the fold. Figure 7d shows the present day configuration of Pohokura Anticline with a fault-propagation-fold in the hanging wall and fault-bend-fold in the footwall.

The Mohaka Transect (Figure 8) shows Pohokura Anticline in cross-section with the two parts of the fold juxtaposed. Folding in the Miocene sediments is due to decollement and thrust faults extending east from the Mohaka Fault. The Miocene sequence further towards the coast, underlying the gently dipping Pliocene sediments, is probably similarly deformed, particularly as another dextral reverse fault (Rangiora Fault - Cutten *et al.* 1988) surfaces within the forearc basin. This active fault occurs in Pliocene strata which shows no significant offset, but could be a reactivation of an older (Miocene) fault as is the Mohaka Fault.

Southern Hawkes Bay Transect

The Southern Hawkes Bay transect (Figure 2) crosses an area recently mapped to determine strain distribution across the forearc basin (Cashman et al. in press). Construction of this transect is still in progress.

At the western end of the transect the range-bounding Mohaka and Ruahine faults separate the greywacke of the axial ranges from the Pliocene sequence to the east (Figure 9). At the eastern end a structural high exposes Miocene sediments. Just east of the Mohaka Fault is a thrust fault zone containing the Wakarara Thrust Fault and Wakarara Monocline. A relatively undeformed zone, the Ruataniwha Plain has only minor folding and is bounded to the east by the transcurrent Poukawa Fault zone. This zone is also flanked to the east by a thrust and fold zone. The structural high between here and the coast shows extensive normal faulting, and is considered a secondary feature resulting from deep seated uplift. Cashman *et al.* show that between 50-70% of

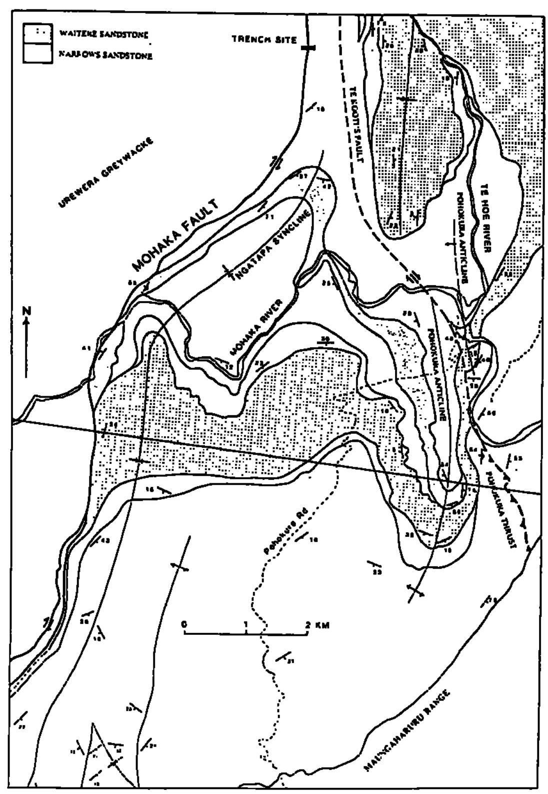

Figure 6: Geological map of folded Miocene flanking the greywacke axial ranges and Mohaka Fault, and unconformably overlain by Pliocene sediments dipping southeast. Pohokura Anticline plunges south and shows a double hinge closure offset in a dextral sense by Te Kooti's Fault.

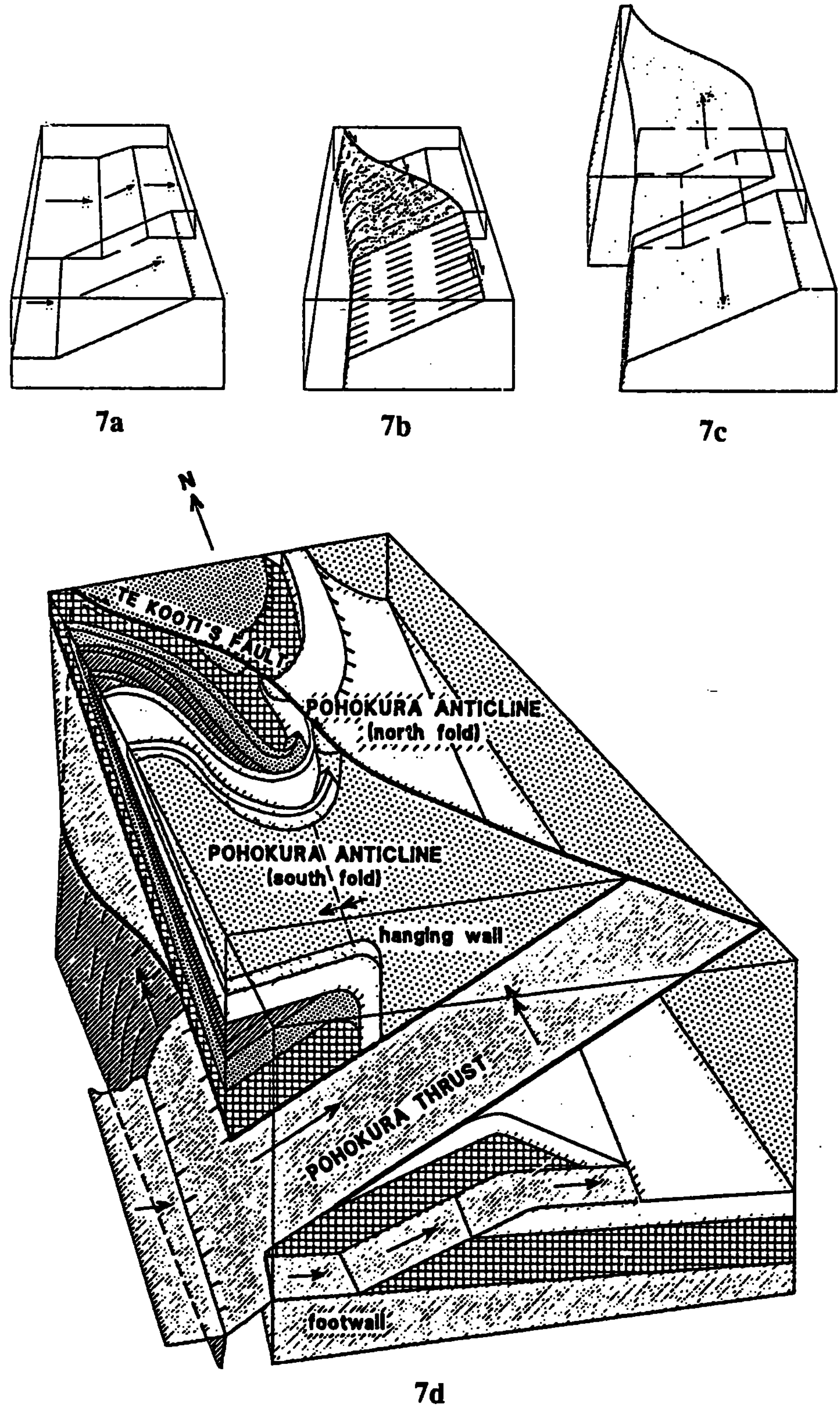

Figure 7: Schematic block diagram of Pohokura Anticline. (a) causative faults: a flat (decollement) - thrust-flat configuration in the north has produced a fault-bend fold, and a flat-thrust configuration in the south has produced a fault-propagation fold. (b) Te Kooti's Fault, dipping steeply west merges suth with Pohokura Thrust. (c) (d) Dextral movement on these faultplanes has juxtaposed the fault-propagation fold in the hanging wall with the fault-bend fold in the footwall.

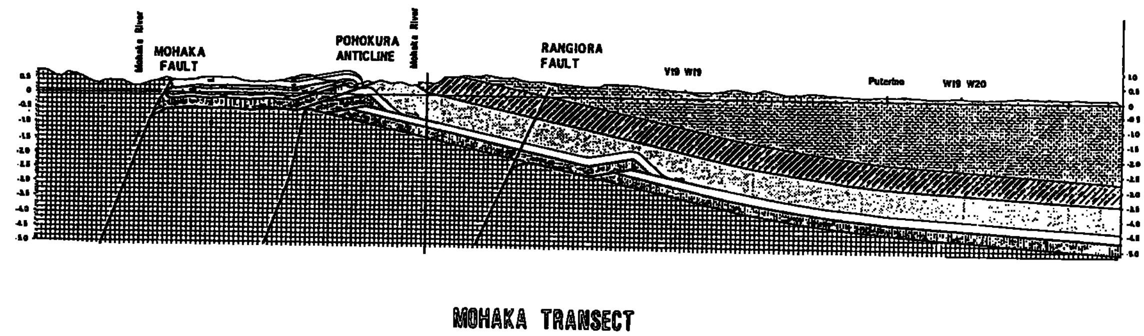

Figure 8: Mohaka Transect showing fault-related folding in the Miocene sequence flanking the greywacke axial ranges and Mohaka Fault, and unconformably overlain by the tilted Pliocene sequence. Subsurface folding associated with the Rangiora Fault is hypothetical.

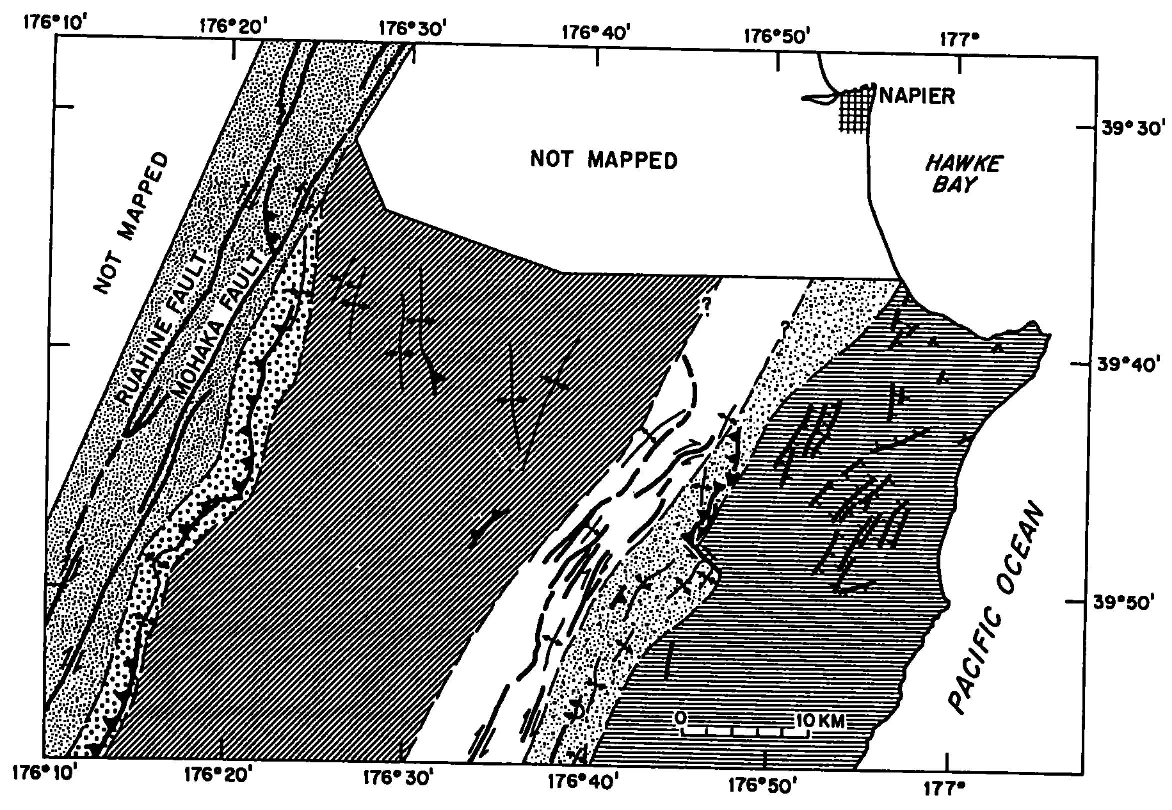

Figure 9: Map of strain domains in southern Hawke's Bay area (Cashman *et al.*, in press): transcurrent domain (stipple pattern) of Mohaka and Ruahine Faults: convergent domain (open stipple) of Wakarara Thrust and Wakarara Monocline; forearc basin domain (diagonal lines) of Ruataniwha Plains; transcurrent domain (no pattern) of Poukawa Fault Zone; convergent domain (stipple and pebble pattern) of Tukituki fold and thrust belt; extensional domain (horizontal lines) of Maraetotara Plateau/Cape Kidnappers.

the lateral component of relative plate motion has been taken up by the transcurrent faults (Mohaka Fault, Ruahine Fault and Poukawa Fault Zone). However only 3-6% of the convergent component of relative plate motion is apparent across the transect.

Conclusion

The three transects: Raukumara; Mohaka; and Southern Hawkes Bay, show the degree of variation of geological structure which occurs in the East Coast. Folding is largely a product of low angle thrusting driven by subduction tectonics. This has occurred largely during Hikurangi subduction from latest Oligocene/early Miocene to the present day. An earlier phase, probably related to Pheonix Plate subduction, is indicated by the structure of the Motu Block in the Raukumara Transect. Previous interpretations of East Coast structure have included: extensional tectonics (Katz 1974, Katz and Wood 1980); gravity emplacement of allochthonous terrain (Stoneley 1968); and diapirism (as an explanation for tight folding - Stoneley 1962). More recently the importance of thrust faulting, like that presented in these transects, has been recognised by Pettinga (1982), Rait *et al.* (in press) and others.

In an oil exploration context, in all three areas thrust-related folding is apparent in the Neogene strata of alternating permeable sandstone and limestone and impermeable mudstone. Tightly folded Miocene strata beneath less deformed Pliocene strata (as observed in the Mohaka transect) could be highly prospective. These structures are cored by thrust faults which could be migration pathways connected to oil-producing source rocks at depth. While many faults extend to the surface allowing escape of hydrocarbon, many likely do not, such as the thrust faults terminating within anticlinal structures as described.

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