

Geological structure of the forearc basin in central Hawke's Bay, eastern North Island

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Abstract

Central Hawke's Bay lies within an extensive forearc basin in eastern North Island that developed during the Late Miocene to Pleistocene. The onshore structural elements of Hawke's Bay can be classified into four structural domains, each reflecting differing styles and scales of deformation. These domains are from west to east, the axial range domain, the range front contractional domain, the central forearc basin domain, and the eastern contractional domain.

Some degree of the oblique-interaction of the Australia and Pacific plates on the subduction thrust is inferred to be partitioned across the four structural domains and to be expressed dominantly as oblique-(dextral) slip on faults bordering the axial ranges, and as shortening on reverse faults and folds in more eastern parts of the forearc. The axial range domain involves the eastern parts of the North Island axial ranges where there is marked oblique-slip displacement on major faults. Some dextral offset is accommodated in the range front contractional domain, although dip-slip displacement is more significant.

The central forearc basin domain is comparatively undeformed with only minor reverse faulting and (fault-force driven) folding. By comparison, the adjacent eastern contractional domain, which comprises an accretionary wedge, is characterised by imbricate reverse and thrust faulting and associated folding. A small degree of dextral-slip is also accommodated in this domain. The uppermost parts of the inboard margin of the accretionary wedge, particularly the part onshore, is currently undergoing gravitationally-driven collapse expressed as deep-seated landslides and normal faulting.

Many folds in the basin are fault-cored, several of which have been targeted in recent years by petroleum exploration companies (e.g. Hukarere-1, Whakatu-1 and Kereru-1).

Most deformation of the forearc basin fill in central Hawke's Bay is post early Nukumaruan (2.4 Ma) and much of this has occurred since the early Pleistocene (1.8 Ma). Dextral-slip on Mohaka and Ruahine Faults since the Early Pliocene is likely to be less than 10 km. Significant unconformities in the basin fill reflect early phases of development of oblique-slip faults in the axial ranges. New dextral oblique-slip faults are developing in the basin fill to the east of the main oblique-slip faults bordering the ranges.

Keywords: Hawke's Bay; structure; faulting; folding; North Island shear belt; strike-slip; Pliocene-Pleistocene

Introduction

Hawke's Bay province lies within the forearc region of the subduction zone within the obliquely convergent Australia-Pacific plate boundary (Fig. 1), known as the Hikurangi Margin. The purpose of this paper is to provide an overview of the geological structure onshore in central Hawke's Bay, which involves chiefly the principal forearc basin, but extends west into the main structural ridge and east into the accretionary wedge. We describe the character of deformation and place constraints in its timing and magnitude. This work builds on prior studies of Cashman *et al.* (1992), Erdman and Kelsey (1992), and Beanland *et al.* (1998). Although the focus here is on deformation of the rocks, our ongoing investigations have been more broadly focussed on analysis of the forearc basin in Hawke's Bay, particularly development of the stratigraphic architecture, sedimentology, paleogeography, and sequence stratigraphy (e.g. Bland *et al.* 2004).

Geological Setting and Structural Overview

Hawke's Bay Basin is generically a forearc basin bounded to the east by the inboard part of an uplifted and semi-emergent accretionary wedge, and on its

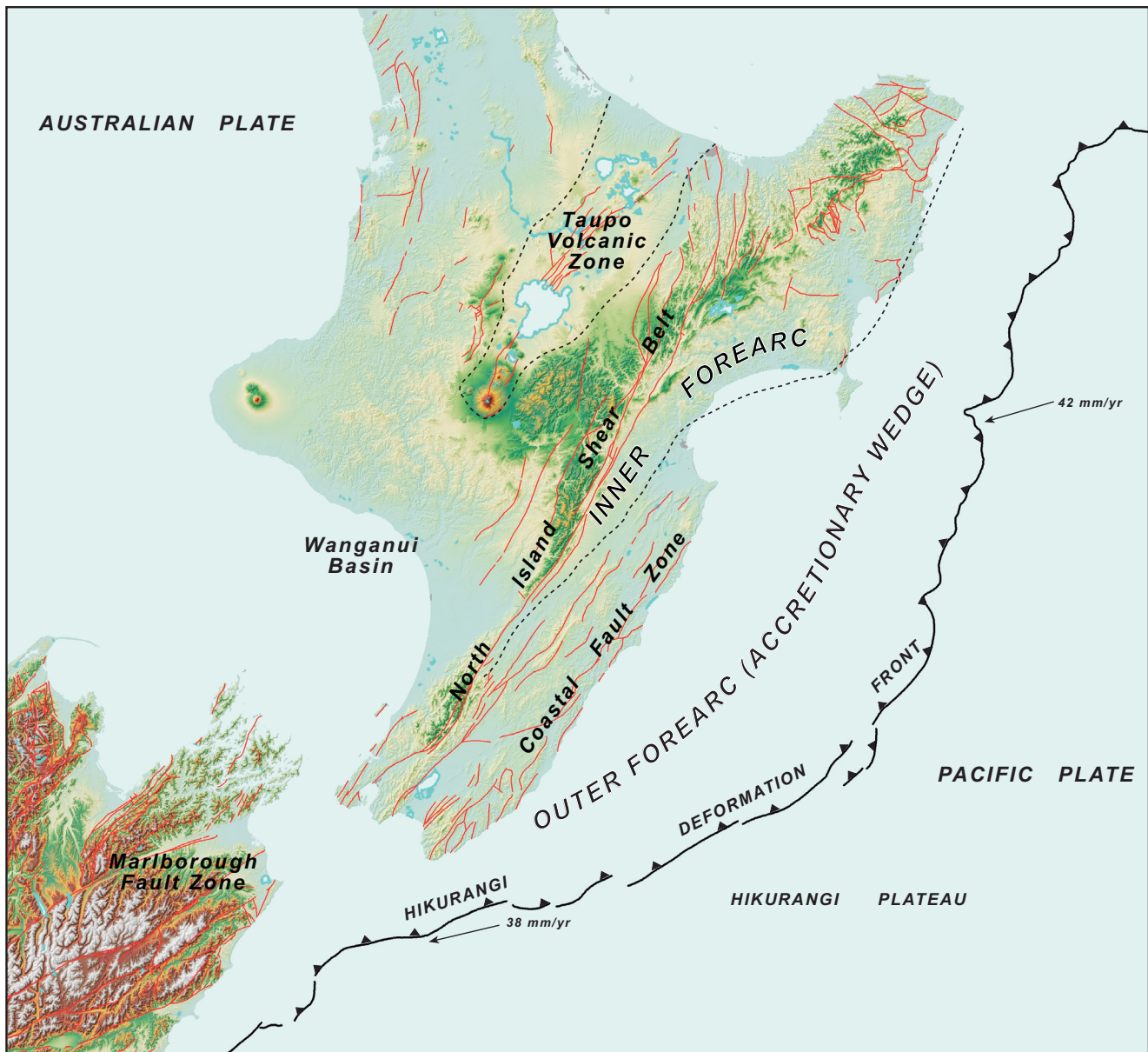


Fig. 1: Tectonic setting of eastern North Island, New Zealand. Adapted from Barnes et. al (2002)

western side by an elevated fault-bounded frontal ridge underlain by indurated Mesozoic basement. Hawke Bay is a major coastal indentation, reflecting the submarine northern continuation of the accretionary wedge, emergent in the hill country to the south as noted above. The frontal basement ridge to the west contains along its eastern side a zone of dextral-slip to oblique-slip faults collectively known as the North Island shear belt (Fig. 1). The present study area (Fig. 2) covers an area from the frontal ridge across the forearc basin succession to the inboard margin of the accretionary wedge. The forearc basin began to develop during the late Miocene and was at its greatest extent as a depocentre in the middle and late Pliocene. While much of the basin is now inverted and subaerially exposed, part remains submarine in

Hawke Bay, and active non-marine deposition is occurring in the Heretaunga Plains. Essentially, during the Pleistocene, accretionary processes have resulted in the eastern margins of the forearc basin becoming involved in the accretionary prism, albeit mildly, while the oblique- to dextral-slip faults bordering the axial ranges have extended in to the basin succession on the western side.

The study area (Fig. 2) and the forearc basin in general display a strong NE-SW structural grain parallel to the modern plate boundary zone. The general strike of the beds making up the sedimentary fill of the basin is more easterly though than the oblique-slip fault system, meaning that progressively younger beds are truncated to the south by these faults.

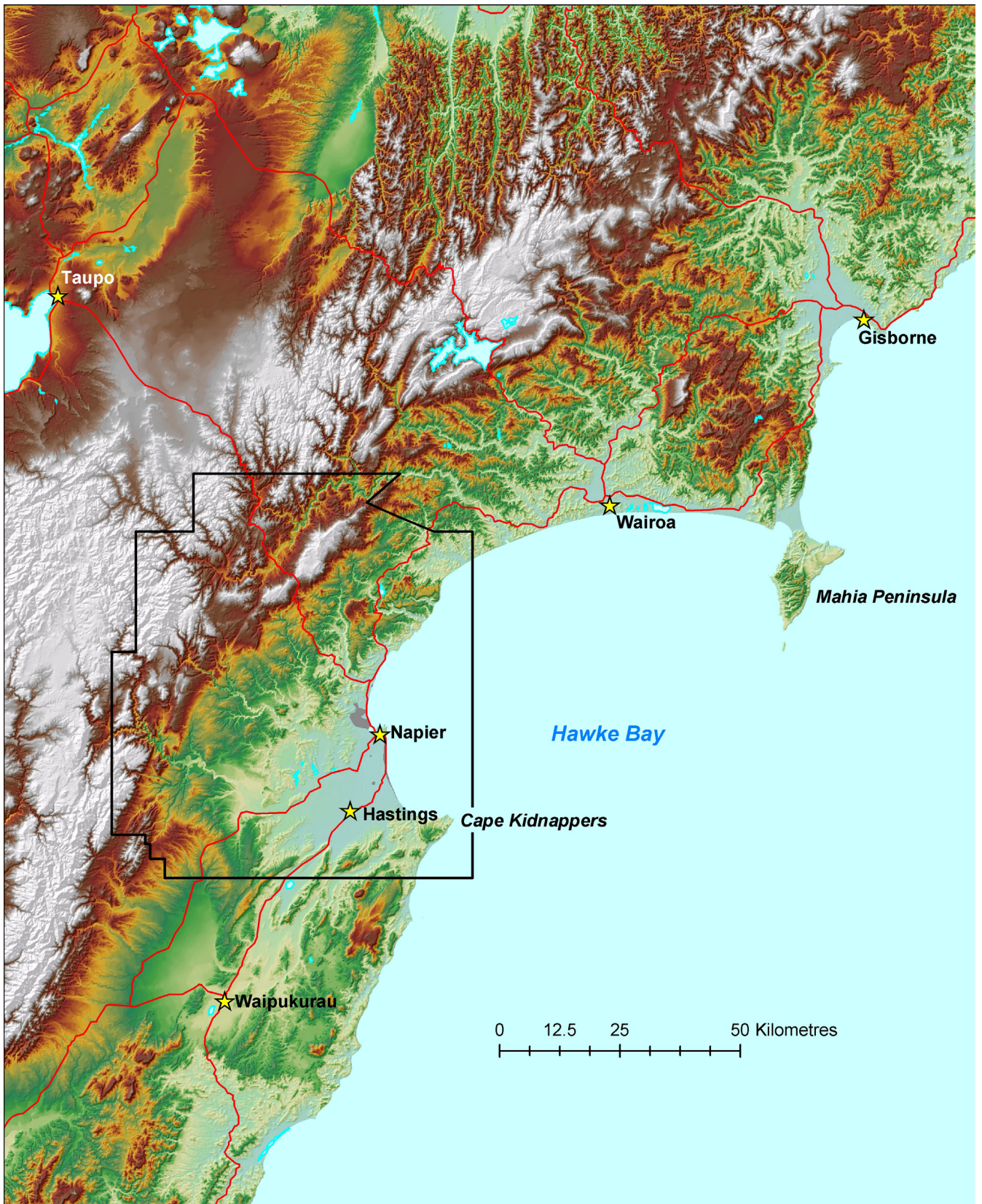


Fig. 2: DEM of eastern North Island also showing the extent of the study area (polygon).

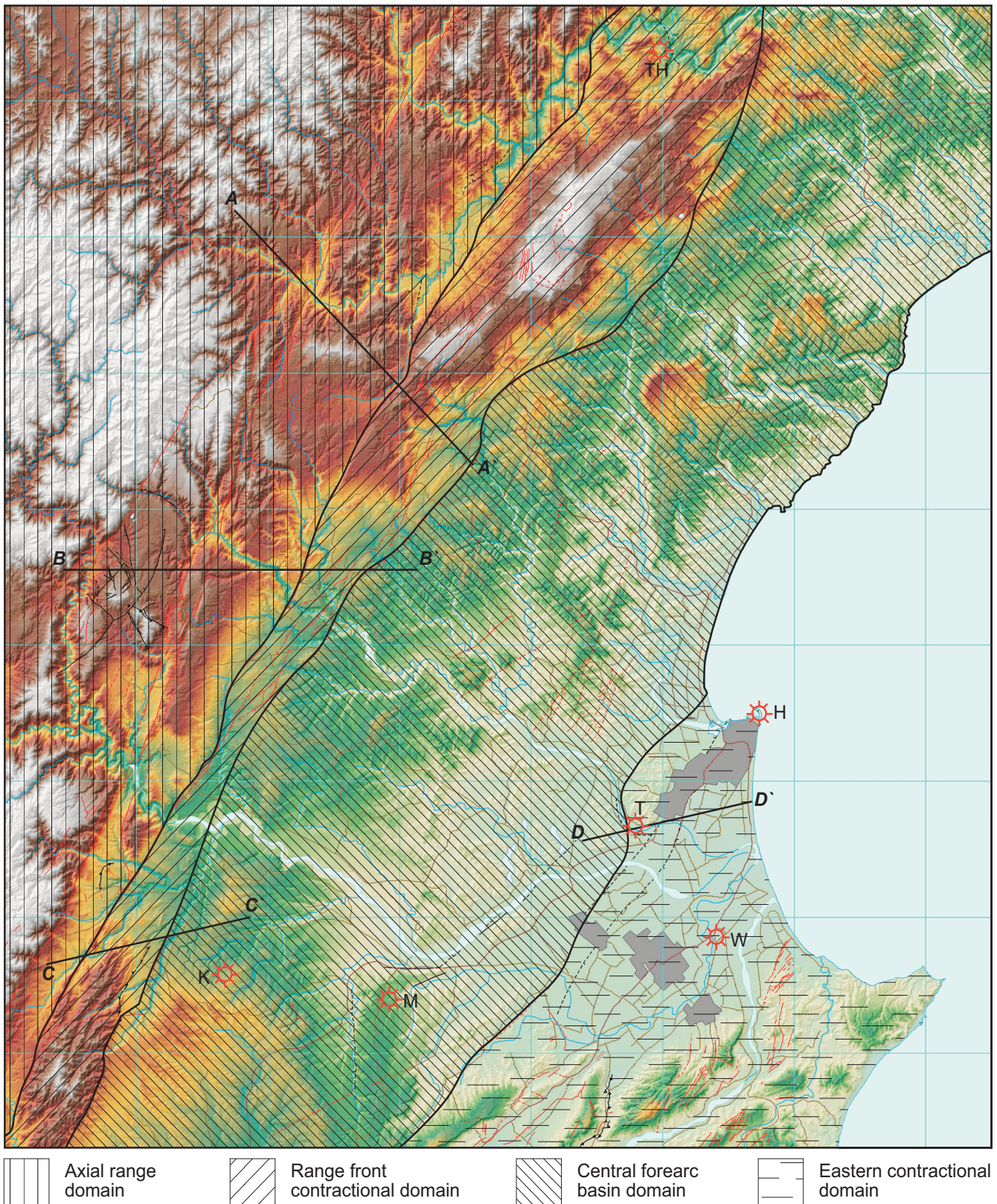


Fig. 3: Digital elevation and hillshade relief models showing the extent of four structural domains described in this report. Blue grid lines are the 10 km NZMS260 topogrid. The positions of hydrocarbon exploration wells in the study area are indicated by red symbols: TH=Te Hoe-1, K=Kereru-1, M=Mason Ridge-1, T=Taradale-1, H=Hukarere-1, W=Whakatu-1. The locations of geological cross-sections (Figs 5-8) are indicated.

Structural Domains

Central Hawke's Bay can usefully be subdivided into four structural domains following the approach of Cashman *et al.* (1992) and Beanland *et al.* (1998) (Fig. 3). Each domain displays a characteristic style of deformation that allows it to be differentiated from adjacent areas. The four domains (from west to east) are the axial range domain, range front contractional domain, central forearc basin domain, and eastern contractional domain.

Axial range domain

The axial range domain (Fig. 3) contains the Wellington, Ruahine, Mohaka and Whakatane Faults, which all display oblique-slip displacement, and related structures. These structures have prominent active traces that at a broad scale are almost linear and extend for up to 400-500 km in a NNE direction (Beanland *et al.* 1998). It appears likely that these major faults are older structures relating to late Mesozoic deformation and have been re-activated. The stratigraphy and sedimentology of late Neogene beds preserved on both sides of some of these fault zones suggest that while some oblique-slip displacement has occurred during the Late Miocene-Pliocene, the most significant phase of displacement post-dates 2 Ma. The Mohaka and Ruahine Faults are the most significant faults in terms of lateral continuity and amount of displacement (Fig. 4). They are both oblique-slip structures, each striking about 030°, and typically have well-developed fault traces (Fig. 9A-C). These two faults are dramatic because they mostly form the geological boundary at the surface between Torlesse basement underlying the axial ranges and adjacent Neogene sedimentary rocks of the forearc basin, but as shown in geological cross-sections basement occurs on both sides of these faults and underlies most of the forearc basin (Figs 5-7). Although characterised by oblique-slip faults, the axial range domain also contains common dip-slip (reverse-dominated) faults of varying scales. Some degree of oblique-slip does occur on the Mohaka and Ruahine Faults, as indicated by striae on their fault planes (Erdman and Kelsey 1992). However, the amount of vertical offset is less than the strike-slip component. The estimated ratio of horizontal to vertical offset on the Mohaka Fault in the Ohara Depression ranges between 1:1 to 8:1 (Erdman and Kelsey 1992). For the Ruahine Fault the ratio is estimated at 2.1:1. Between the Ruahine and Mohaka Faults folding and reverse fault displacement dominates modern deformation. Some significant thrust faults occur, such as the Miroroa Thrust where Torlesse basement has been emplaced over Late Neogene (c. 2.4 Ma) rocks

(Browne 1986). The Kaweka Fault, located west of the Ruahine Fault, is the main structure on which uplift of basement in the Kaweka Range has occurred (Figs 4-6). Both the Mohaka and Ruahine Faults continue outside the boundaries of the study area. Many of the significant faults along the axial ranges, such as the Kaweka and Glenross Faults (Fig. 4), are inferred to merge at depth with the more significant Ruahine and Mohaka Faults (Fig. 5, 6). Many faults in the adjacent range front contractional domain, such as the Patoka Fault (Fig. 9D), are also inferred to merge at depth with the Mohaka Fault (Figs 5-7), although they are mostly dip-slip in character.

Range Front Contractional Domain

Range front contractional domain structures mostly comprise reverse faults with associated monoclines (e.g. Wakarara Monocline, Fig. 7; 9F) and anticlines in a zone located west of the Mohaka Fault (Fig. 3). Some strike-slip faulting is evident in the domain. In the south of the study area (Kereru district) the domain is on average 5 km wide (Beanland *et al.* 1998), increasing to 13 km wide in the north of the study area (Maungaharuru Range area). This increase in width reflects the widening of the forearc basin north of the latitude of Napier and the Ohara Depression, and the lack of emergence above sea-level of the accretionary prism north of Cape Kidnappers. While range-front structures commonly form the boundary between uplifted Torlesse basement rocks and Neogene sedimentary rocks of the forearc basin in the study area (Fig. 7), they also extend into the basin fill succession (Fig. 5-6). Of note from geological cross sections (Figs 5-7) is the way in which Mesozoic basement rocks at or near the surface to the west of the domain are abruptly down-faulted to significant depths. This is also reflected in the dramatic increase in thickness of the Late Neogene basin fill from the axial range domain into the range front contractional and central forearc basin domains. The depths at which basement rocks underlie the central forearc basin domain (> 1.5 km; Fig. 7) indicates the large degree of vertical displacement accommodated on the faults in the range front contractional domain.

These latter faults (e.g. Rangiora, Rukumoana and Patoka Faults) presumably splinter off the Mohaka Fault at depth (Figs 5-7), splaying off at the surface at locations of left-stepping jogs in the Mohaka Fault trace (Halliday *et al.* 2003). Recent displacement on the Rangiora and Patoka Faults indicates dextral-slip displacement (Cutten *et al.* 1988; Halliday *et al.* 2003). The origin of the eastward development of

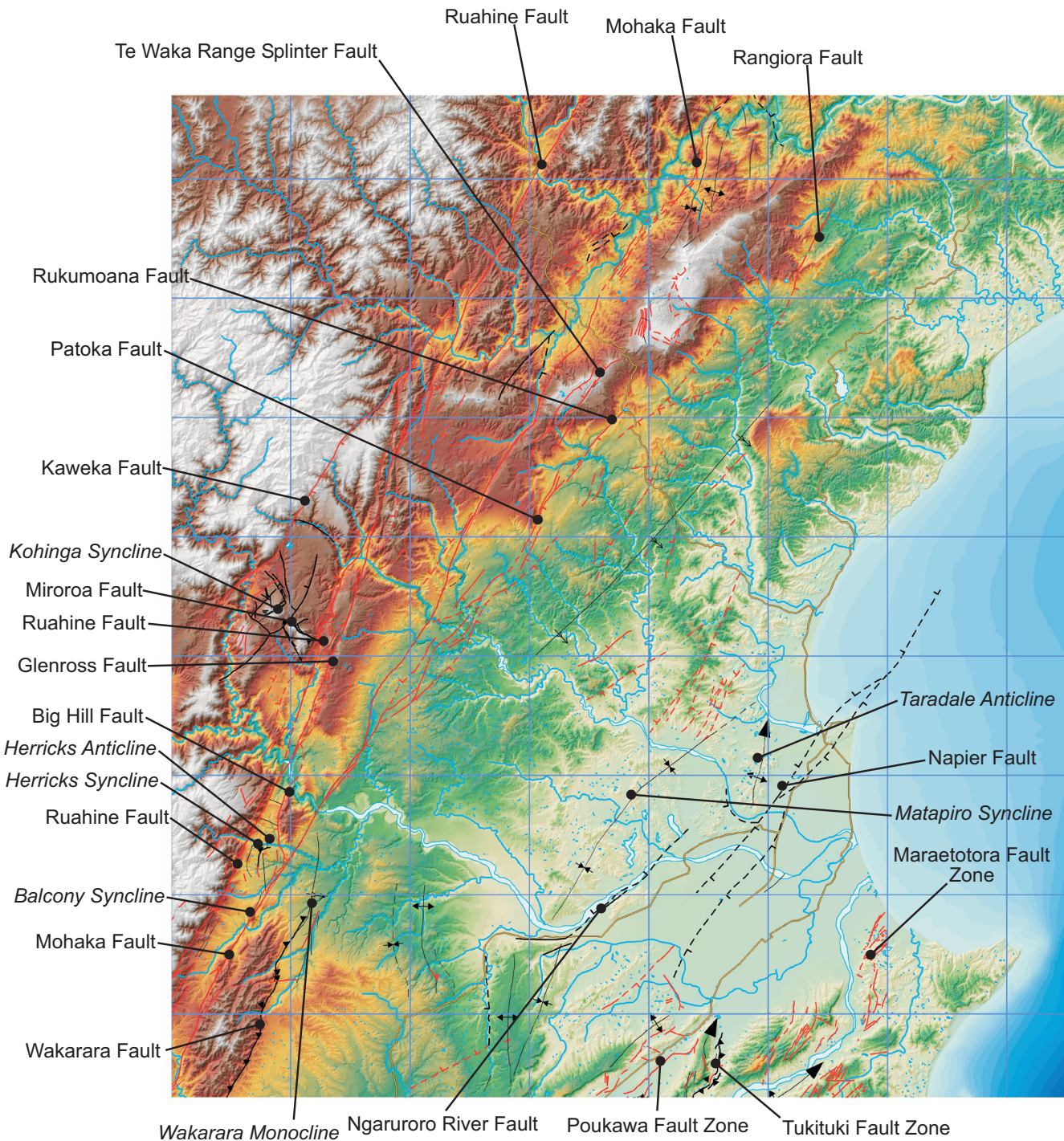


Fig. 4: Digital elevation and hillshade relief models showing the location of major faults and folds in the study area. Blue grid lines are the 10 km NZMS260 topogrid. Orange lines are main roads in the study area.

oblique-slip structures into the basin succession is not really known. It is probably related to dynamics at the shallow subduction interface between the plates, but could reflect wider tectonic forces such as the southward propagation of rifting in the Taupo Volcanic Zone and associated dextral rotation of the frontal ridge and East Cape area (Beanland and Haines 1998).

Central Forearc Basin Domain

The modern forearc basin is a 400-500 km long nar-

row (10-40 km) region containing a thick late Neogene succession bounded to the west by the range front contractional domain and to the east by the eastern contractional domain (Figs 1, 3). The sedimentary succession of the basin is relatively undeformed with mostly minor NNE-trending reverse faults and folds, and associated anticlines which broadly parallel the basin trend. Small-scale reverse and normal faults are common with vertical offsets typically less than 1 m, although displacements may be up to 20 m. West of

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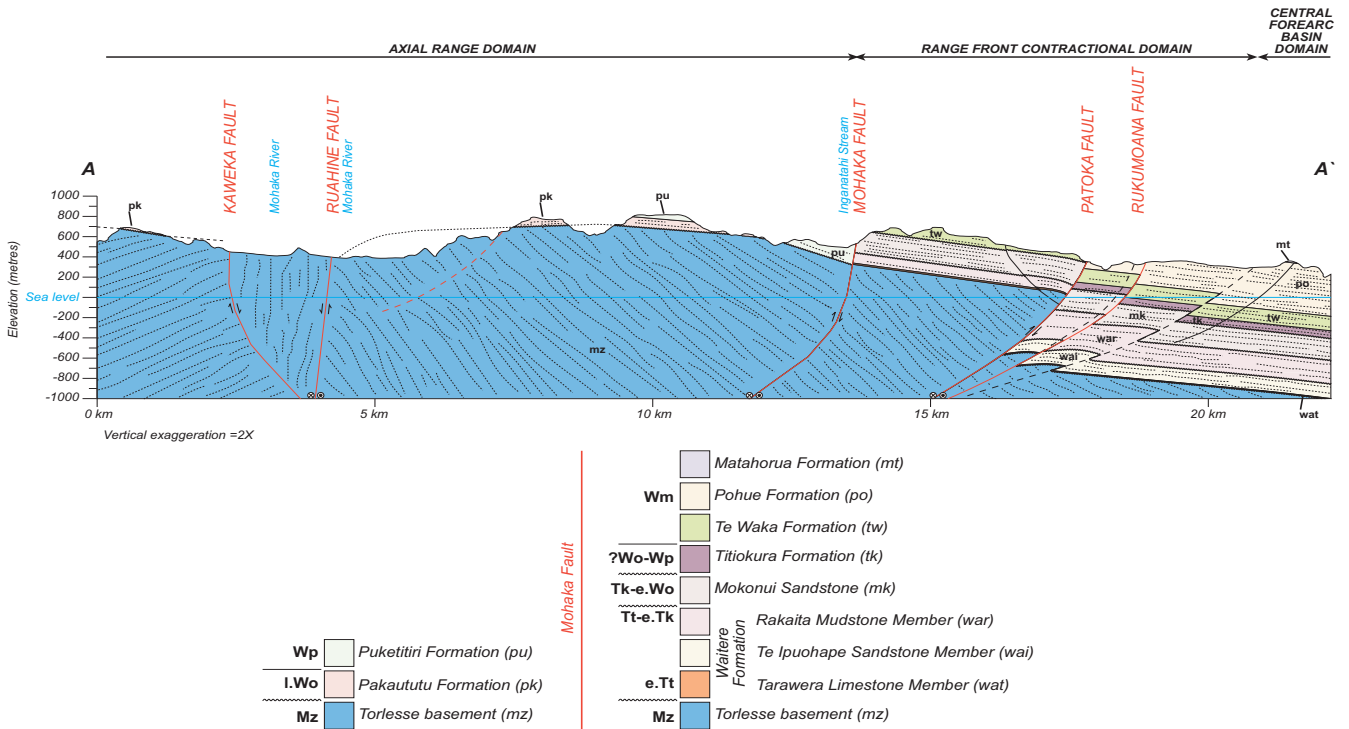


Fig. 5: Geological cross-section across the Axial Range and Range Front Domains in the Puketitiri area, western Hawke's Bay. MZ=Mesozoic, Tt=Early Tongaporutuan (Late Miocene), Tk=Kapitean (Late Miocene), Wo=Opoitian (early Pliocene), Wp=Waipipian (middle Pliocene), Wm=Mangapanian (late Pliocene).

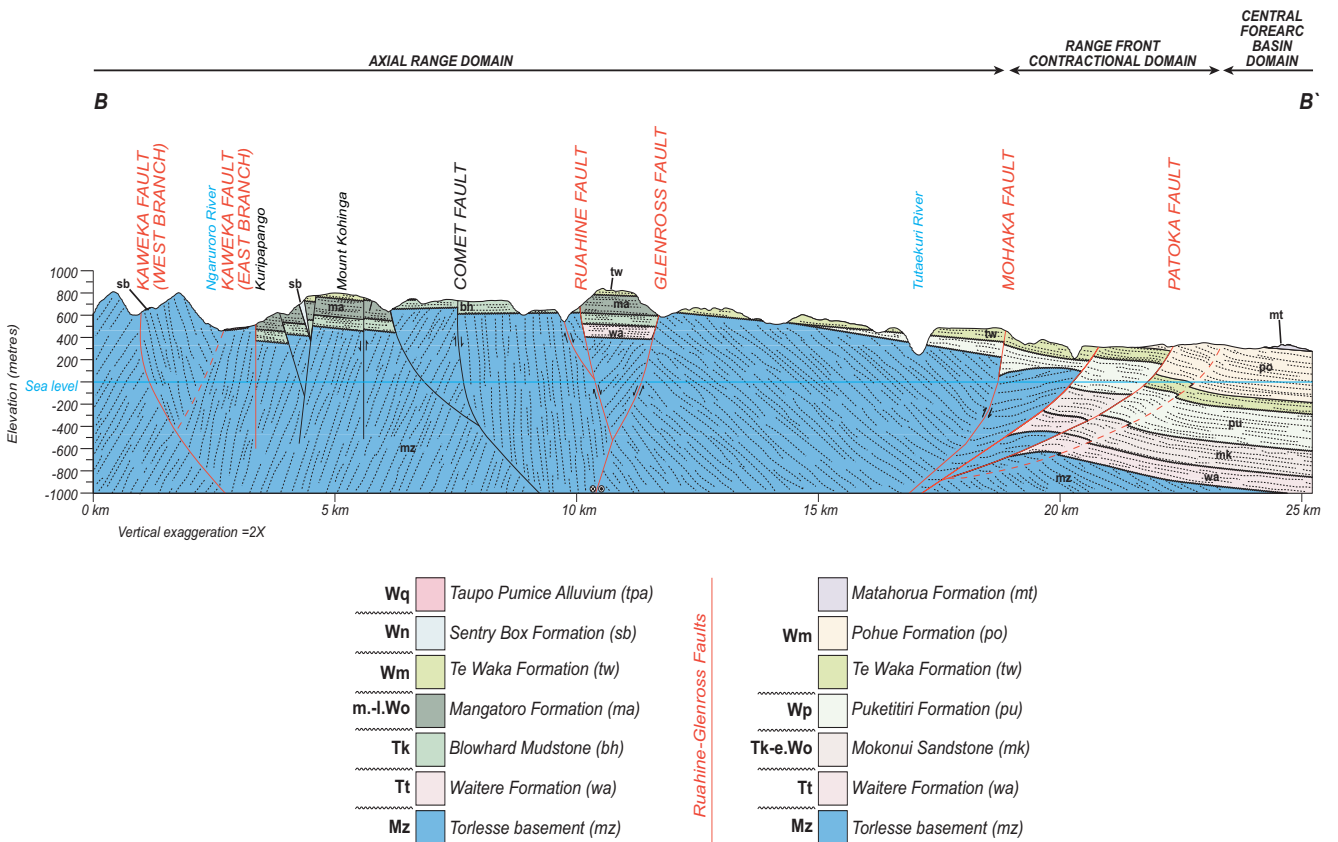


Fig. 6: Geological cross-section across the Axial Range and Range Front Domains in the Kuripapango area, western Hawke's Bay. MZ=Mesozoic, Tt=Early Tongaporutuan (Late Miocene), Tk=Kapitean (Late Miocene), Wo=Opoitian (early Pliocene), Wp=Waipipian (middle Pliocene), Wm=Mangapanian (late Pliocene), Wn=Nukumaruan (latest Pliocene-early Pleistocene), Wq=Haweran (Holocene).

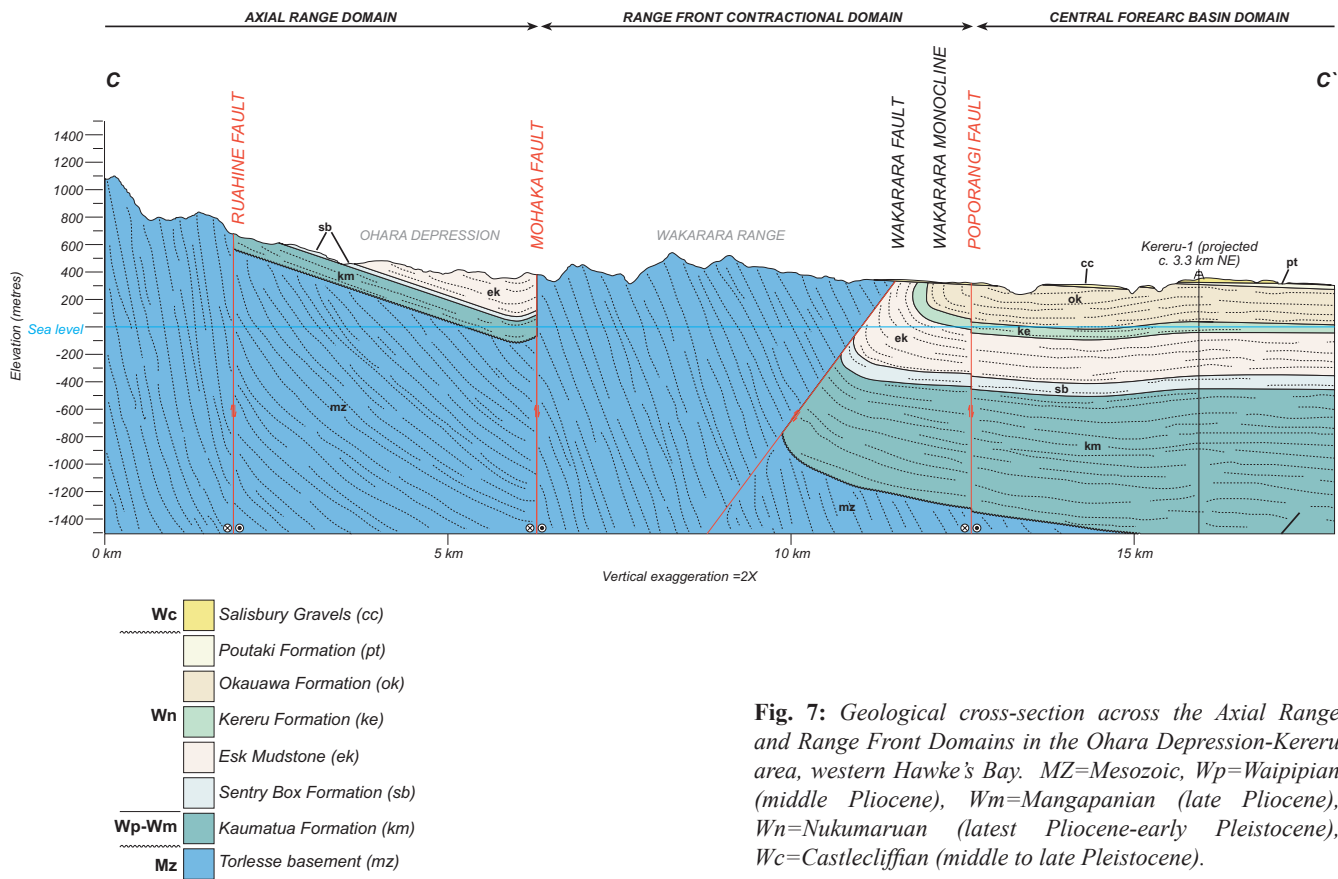


Fig. 7: Geological cross-section across the Axial Range and Range Front Domains in the Ohara Depression-Kereru area, western Hawke's Bay. MZ=Mesozoic, Wp=Waipipian (middle Pliocene), Wm=Mangapanian (late Pliocene), Wn=Nukumaruan (latest Pliocene-early Pleistocene), Wc=Castlecliffian (middle to late Pleistocene).

Hastings and Napier the sedimentary succession dips gently to the southeast at about 20°-2° as part of the Hawke's Bay Monocline. The axis of the monoclinical folding is evident in the Tangoio Block north of Napier where beds in the northwest of the block dip around 10°SE, while beds in the southeast dip 2°SE. A central syncline completed by beds east of Hastings and Napier that dip up to 20°NW, lies in the lowlands (Heretaunga Plains) and is known as the Matapiro Syncline. The Matapiro Syncline extends from the north bank of the Ngaruroro River at Matapiro to approximately the Puketapu area and has folded late Nukumaruan rocks (less than 2.1 Ma) into a broad shallow (2°-4°) fold. The exploration well Kereru-1 targeted an anticlinal structure in the central forearc basin (Fig. 7).

Eastern Contractual Domain

The eastern contractual domain comprises the coastal hill country in the southeastern part of the study area from the Raukawa Range east to the Maraetotora Plateau (Fig. 3). It marks a zone of reverse faulting and related folding (Fig. 8). This domain includes the accretionary wedge on-land south of Cape Kidnappers. A similar style of deformation underlies Hawke Bay (Barnes *et al* 2002). Mild deformation of the forearc basin succession occurs in the Napier and Taradale areas (Fig. 8). Although slightly diffuse, the

western margin of the eastern contractual domain is marked by more dense faulting and folding that includes the Longlands, Poukawa (Kelsey *et al.* 1998), and Tukituki Faults (Fig. 4). It is inferred that some degree of strike-slip displacement is accommodated on structures in the western part of this domain, and structures in the eastern part accommodate principally contractional deformation (Cashman *et al.* 1992; Beanland 1995; Beanland *et al.* 1998).

Coastal parts of this domain (Maraetotora Plateau, Cape Kidnappers area) are cut by a network of recent normal faults 1-7 km long that have vertical displacements of up to many tens of metres (Kingma 1971; Cashman and Kelsey 1990; Cashman *et al.* 1992) (Fig. 4; 9E). Fault traces are discontinuous and the domain varies in width from several hundred metres to about 8 km (Begg *et al.* 1994). Normal faults bound both east- and west-dipping fault blocks (Fig. 9E). Fault-slip indicators show nearly pure dip-slip displacement (Cashman *et al.* 1992).

The relationship between the normal faults in this domain and the major reverse faults of the accretionary wedge at depth is unknown, as is the depth to which the faults extend (Begg *et al.* 1994). Both Pettinga (1982) and Cashman *et al.* (1992) suggested that normal faults in this domain are a surface response to

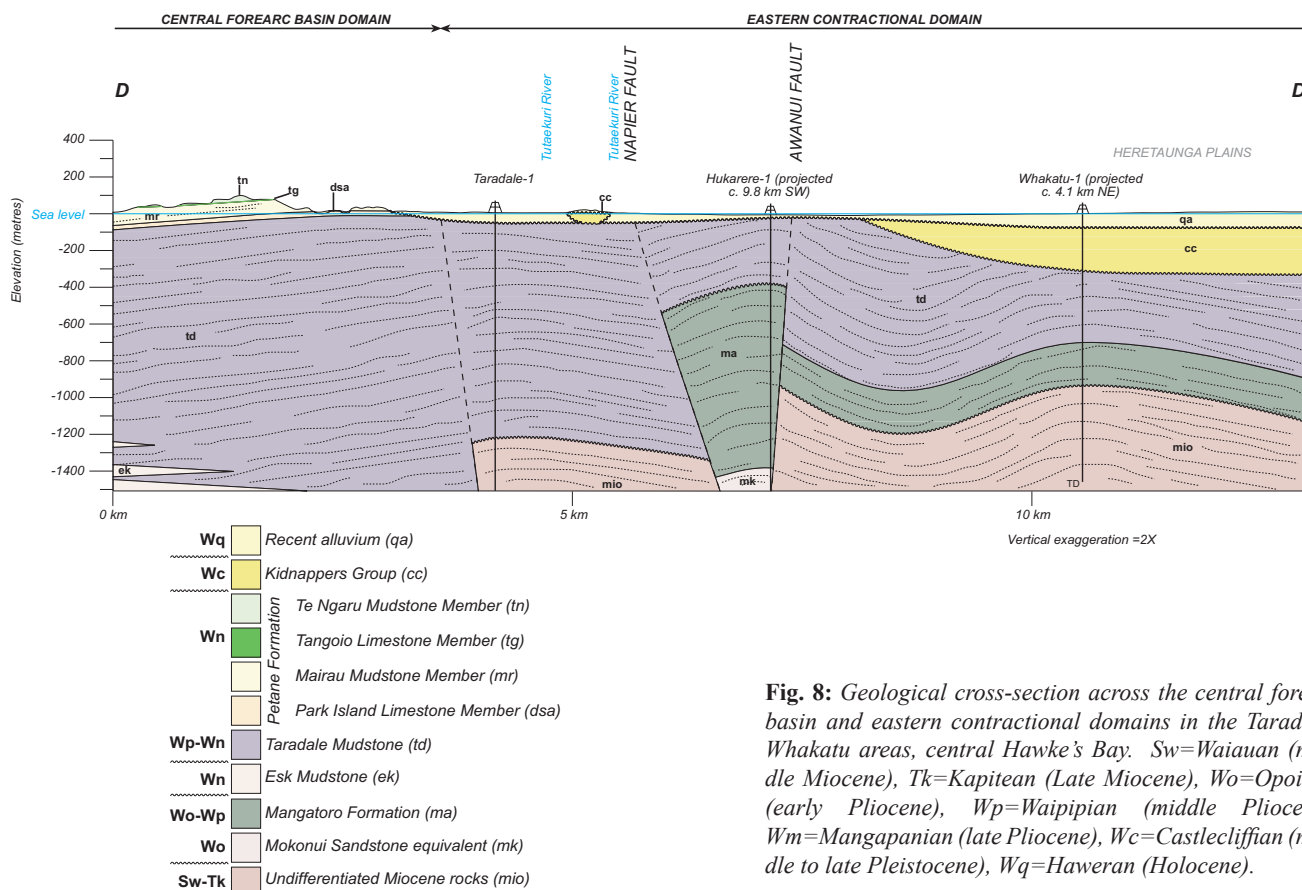


Fig. 8: Geological cross-section across the central forearc basin and eastern contractional domains in the Taradale-Whakatu areas, central Hawke’s Bay. Sw=Waiuan (middle Miocene), Tk=Kapitean (Late Miocene), Wo=Opoitian (early Pliocene), Wp=Waipipian (middle Pliocene), Wm=Mangapanian (late Pliocene), Wc=Castlecliffian (middle to late Pleistocene), Wq=Haweran (Holocene).

uplift and arching through contraction of the underlying accretionary wedge and are not representative of deformation at deeper levels. This was supported by Pettinga (2004) in a study of the character of large-scale gravitational collapse of the Maraetotora Plateau. In the Cape Kidnappers area late Pleistocene marginal-marine sediments have been uplifted to nearly 150 m above sea level, tilted to the northwest and cut by dominantly normal faults with displacements of up to 9 m (Fig. 9E). Cashman *et al.* (1992) suggested that normal faulting in the Cape Kidnappers area began during the late Pleistocene and continues to the present day. These extensional faults continue into Hawke Bay (Begg *et al.* 1994).

Several recent exploration wells (e.g. Whakatu-1, Hukarere-1) have targeted anticlinal structures in this domain. Hawke Bay-1 targeted an anticlinal structure in the offshore extension of this domain.

Timing and magnitude of deformation

A conclusion of this study is that most deformation of the forearc basin fill in central Hawke’s Bay is young, and probably of post latest Pliocene (middle-Nukumaruian, c. 2 Ma) age. Earlier phases of deformation can also be identified in the study area.

Uplift and erosion occurred in several fault blocks in the axial range and range front domains in the Late Miocene and Early Pliocene (Late Kapitean to middle Opoitian, 5.3-4 Ma). Uplift and erosion during the early-middle Pliocene (Waipipian, 3.5-3 Ma) occurred in the axial range and eastern contractional domains. More widespread uplift of the proto-axial ranges occurred during the late Pliocene (latest Mangapanian to earliest Nukumaruian, 2.8-2.36 Ma) inferred from an influx of thick non-marine braidplains. Rapid basin-wide subsidence seems to have occurred during the late Pliocene (lower Nukumaruian, c. 2.3 Ma).

The most recent phase of deformation in the study area appears to have commenced at about 2.0-1.8 Ma, and continued up to the present. This more regional deformation coincides with the timing of initiation of rifting in the Taupo Volcanic Zone (Beanland and Haines 1998). Offset of the Late Neogene basin fill in central Hawke’s Bay on the Ruahine and Mohaka Faults has also mostly occurred since 2 Ma.

The presence of lower Nukumaruian (Late Pliocene, c. 2.4 Ma) marine Sentry Box Formation on the flanks of the Ruahine and Kaweka Ranges (Fig. 6) demonstrates that the basement under these ranges was mostly submarine at this time. Deformation

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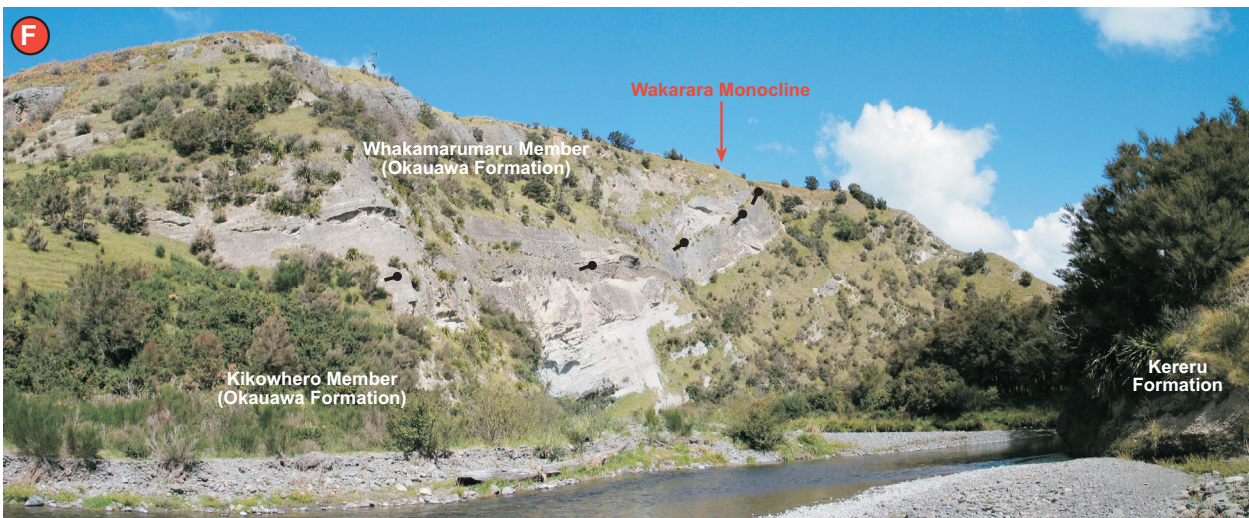
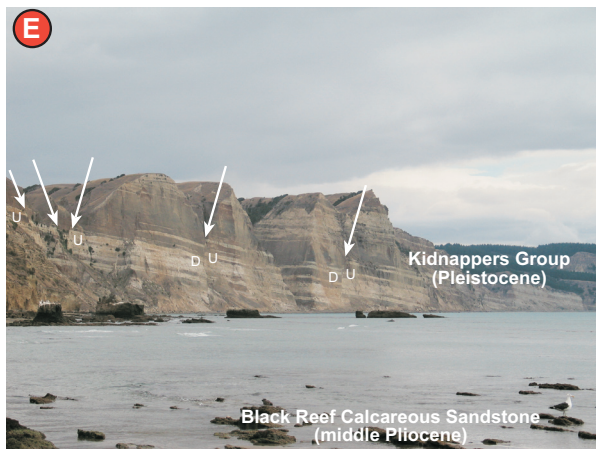
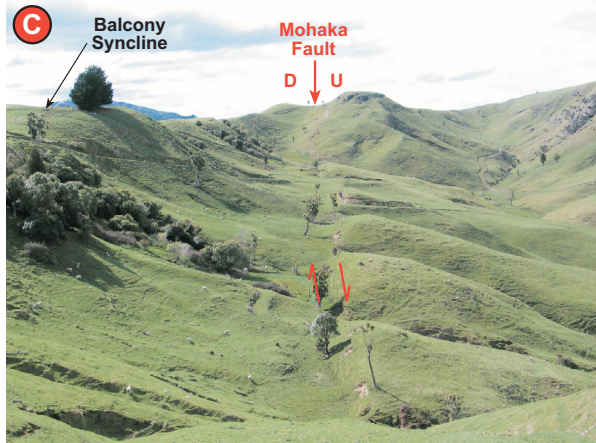
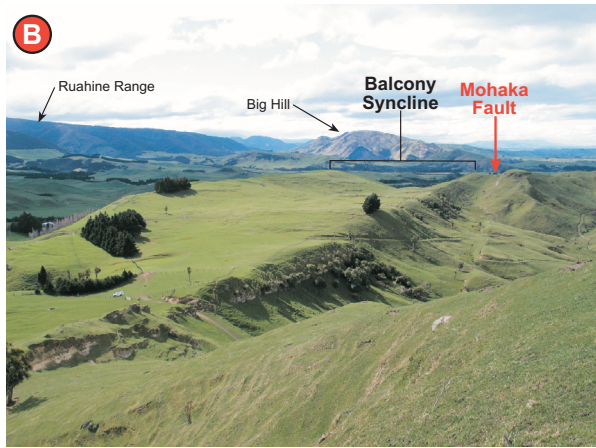
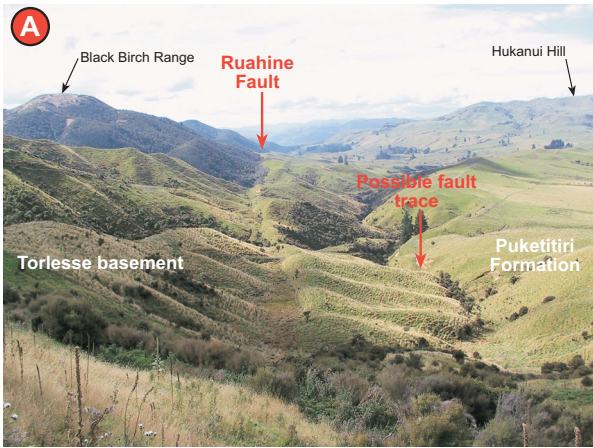


Fig. 9: (facing page) Field photographs of faults and folds in the Axial Range and Range Front Domains.

A) Trace of the Ruahine Fault looking northeast from Baldy Quarry, Whittle Road, Kaweka Forest Park.

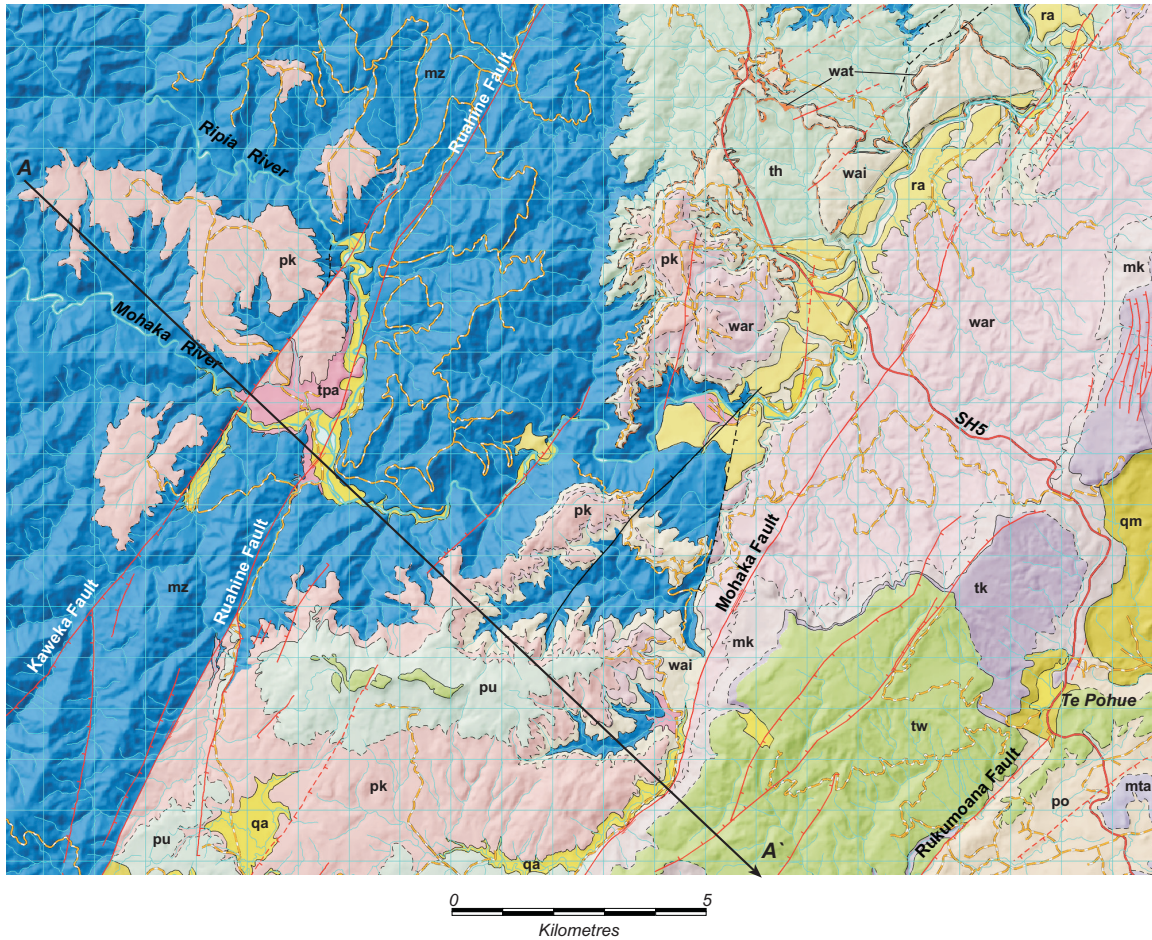
B) View of the Balcony Syncline from Mount Mary, Ohara Depression. This fold has developed adjacent to, and on the downthrown-side of, the Mohaka Fault (arrowed). It is cored by middle-Nukumaruan (Late Pliocene) Kereru Formation and Esk Mudstone. Formation of the fold clearly post dates deposition of these formations, providing some control on the timing of displacement on the Mohaka Fault.

C) Mohaka Fault trace from Mount Mary, Ohara Depression, looking northeast. Modern upthrow is to the east (right) of the fault trace.

D) Patoka Fault trace looking southwest near Patoka village. Note water-filled sag pond on the downthrown (eastern) side of the fault.

E) View of the Kidnappers section looking east from near Black Reef toward Rabbit Gully. Several small-scale normal faults, typical of the coastal extensional domain, are arrowed.

F) Hinge of the Wakarara Monocline exposed in the Ohara Stream immediately upstream of the Big Hill Stream confluence. This fold has developed in response to displacement of the subsurface Wakarara Fault, a large-scale reverse fault that bounds the Wakarara Range to the southwest of this section.



Legend

Recent alluvium (qa)	Recent alluvium (qa)
Wq Holocene fluvial terraces (ra)	Wq Holocene fluvial terraces (ra)
Taupo Pumice Alluvium (tpa)	Mass movement deposits (qm)
Wm Te Waka Formation (tw)	Deep Stream Member (Matahorua Fmn) (mta)
Wp Puketitiri Formation (pu)	Wm Pohue Formation (po)
I.Wo Pakaututu Formation (pk)	Te Waka Formation (tw)
e.Tk Rakaita Siltstone Member (war)	Wp Titiokura Formation (tk)
Te Ipuohape Sandstone Member (wai)	I.Wo Mokonui Sandstone (mk)
Tt Tarawera Limestone Member (wat)	e.Wo Rakaita Siltstone Member (war)
Te Haroto Formation (th)	Tt Te Ipuohape Sandstone Member (wai)
Mz Torlesse basement (mz)	Tt Tarawera Limestone Member (wat)
	Te Haroto Formation (th)

Fig 10: Geological map of the Pakaututu and Puketitiri areas. Note the offset on the Early Pliocene (Opoitian, Wo) Pakaututu Formation, providing some control on total displacement on this part of the North Island shear belt. The location of cross-section A-A' (Fig. 5) is indicated on this map. Mz=Meozoic, Tk=Kapitean (Late Miocene), Wo-Opoitian (early Pliocene), Wp=Waipipian (middle Pliocene), Wm=Mangapanian (late Pliocene), Wq=Haweran (Holocene).

of Late Pliocene sedimentary units adjacent to the Ruahine and Mohaka faults, particularly those in the Ohara Depression, indicates possible commencement of strike-slip displacement at approximately 2.0-1.8 Ma (Fig. 7). The presence of middle Nukumaruan Kereru Formation (c. 2.1 Ma) around the flanks of the Wakarara Range shows that this now highly-elevated (up to 1000 m) block of basement was still mostly submarine until after 2 Ma. The Kereru Formation forms the core of the Balcony Syncline on the western flank of the Wakarara Range. The Balcony Syncline is effectively a drag structure formed from the easterly uplift of the adjacent Mohaka Fault (Fig. 9B), and its formation helps to constrain the timing of the start of dip-slip displacement on the North Island shear belt to after 2 Ma. In the Ngaruroro River where it crosses the Mohaka Fault, lower Nukumaruan (c. 2.2 Ma) Esk Mudstone is in fault contact with Torlesse basement, clearly demonstrating vertical offset on this fault after deposition of the Esk Mudstone.

Throughout the study area rocks of upper Nukumaruan age (c.1.8 Ma and younger) display common soft-sediment deformation structures, including water-escape structures. Such features are relatively uncommon throughout most of the sedimentary succession in the basin. It is inferred that the appearance of these deformation structures supports the onset of the current phase of accelerated deformation from about 2 Ma.

Total horizontal offset on the Ruahine and Mohaka Faults since the Early Pliocene (late Opoitian), estimated from offset of sedimentary rocks either side of the faults (e.g. Fig. 10), is likely to be less than 10 km. Most of this has probably been accommodated since the late early Pliocene (upper Nukumaruan). The nature of the modern traces of the Mohaka and Ruahine Faults are consistent with limited through-going displacement on them. Traces are discontinuous, display frequent reversals in their sense of displacement and have common bends. It is inferred that not enough displacement has occurred to both "straighten out" the fault traces and to join the various fault segments together into a single through-going mature fault. Total strike-slip displacement on the Ruahine Fault in central Hawke's Bay appears to be greater than on that on the Mohaka Fault, and it is also probable that the Ruahine Fault began accommodating strike-slip displacement before the Mohaka Fault (about 2-1.8 Ma). Beanland *et al.* (1998) concluded that total strike-slip displacement on the Mohaka Fault since 3 Ma is likely to be less than 2 km.

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