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Large-Scale Faulting in the Auckland Region

J.A. Kenny, J.M. Lindsay, and T.M. Howe

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J.A. Kenny[1] J.M. Lindsay[2] T.M. Howe[2]

[1] Geomarine Research, Auckland
[2] School of Environment, University of Auckland

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INTRODUCTION

The Auckland region is generally considered to be one of New Zealand's most tectonically stable areas. On the GNS Science active faults database there is only one fault entered for the region (The Wairoa North Fault), and this is therefore the only significant crustal fault in the Auckland Region that feeds into the National Seismic Hazard Model (Stirling *et al*. 2002). Despite this, the area does experience seismicity; since 1983, the seismic network has recorded ca. 80 earthquakes above ca. M 2.5. These earthquakes have all been of high-frequency, tectonic type; no low-frequency, volcanic earthquakes have been recorded (Sherburn *et al*. 2007). Although it does not appear in the active faults database, the Hauraki Rift to the east and south of Auckland is still considered to be active (De Lange & Lowe 1990).

Several presumably older faults have been mapped in the Auckland Region, particularly to the South East in the Hunua Ranges, and in the west in the Waitakere Ranges (Edbrooke 2001). North Auckland is structurally complex, due to the southward nudging of the Northland allocthon into the area. Several faults in the Manukau lowlands and on the Awhitu Peninsula have also been inferred based on geophysical data and borehole information (eg. High 1977). In previous studies there was a distinct lack of mapped faults in the central Auckland area. This can partially be explained by the overprint of the deposits of the Auckland Volcanic Field (AVF) masking any obvious fault traces in underlying rocks. Recent events in Canterbury have highlighted the potential of unknown faults to cause significant damage and loss of life in built up areas in New Zealand. Although the seismic hazard in Auckland is low relative to the rest of the country, the presence of (albeit minor) seismicity, together with numerous faults of unknown age surrounding the central Auckland area, indicates there could be buried faults in Auckland.

The AVF is a potentially active basaltic volcanic field and is currently the focus of a major interdisciplinary research project called DEVORA (DEtermining Volcanic Risk in Auckland). One of the main aims of DEVORA is to investigate how and where volcanoes of the AVF have erupted, possible controls on magma ascent, and paleotopographic controls on lava flows. This information can then be used to infer how the field may behave in the future, including determining 1) the location of possible vents based on underlying structures, and 2) the style of eruption based on underlying geology. Much of this work relies on a good understanding of the structure of the crust beneath Auckland, and also the nature of the pre-volcanic topography.

Here we present a detailed study of the pre-volcanic topography of Auckland, using borehole and geophysical data, and combine this with structural information gleaned from current topography and exposed geology to identify previously unrecognised concealed faults in the Auckland region. The main aims of the study are to:

- Develop new fault maps for the Auckland Region that include concealed faults
- Gain a better understanding of the crustal structure beneath Auckland, in particular depths to key geological boundaries
- Investigate whether there is any relationship between the faults in Auckland and the location of past AVF vents.

REGIONAL SETTING

The Auckland region lies within the Australian Plate, 400 kilometres west of the present plate boundary with the Pacific Plate (Smith 1989) (Figure 1 inset). At that distance, Auckland has a relatively low level of seismicity (Sherburn *et al*. 2007), with the main geological hazard related to its recent history of small eruptions from the Auckland Volcanic Field (AVF) (Allen & Smith 1994, Bebbington & Cronin 2010).

The basement in the Auckland region consists of three late Paleozoic to early Mesozoic NNW-trending terranes (Figure 1). They are tectonostratigraphically juxtaposed in an accretionary prism regime associated with a westward-dipping subduction zone that was active in late Jurassic to mid Cretaceous times. The westernmost terrane is the structurally simple greywacke- and argillite-dominated Murihiku Terrane, deposited in a relatively inactive arc-trench gap / frontal arc basin environment (Spörli 1978, Isaac *et al*. 1994). The easternmost terrane is the structurally complex greywacke and argillite assemblage of the Waipapa (composite) Terrane, deposited in an active arc-trench environment (Spörli 1989). Separating the two is a terrane made up largely of variably serpentinised ultramafic ophiolitic rocks of the Dun Mountain-Maitai terrane, represented at depth as strong NNW-trending gravity and magnetic anomalies known collectively as the Junction Magnetic Anomaly (JMA) (Hatherton & Sibson 1970, Woollaston 1996, Eccles *et al*. 2005, Williams *et al*. 2006, Cassidy & Locke 2010) (Figure 2). It is thought to represent the forearc of a subduction zone (Sivell & McCulloch 2000), with Permian to early

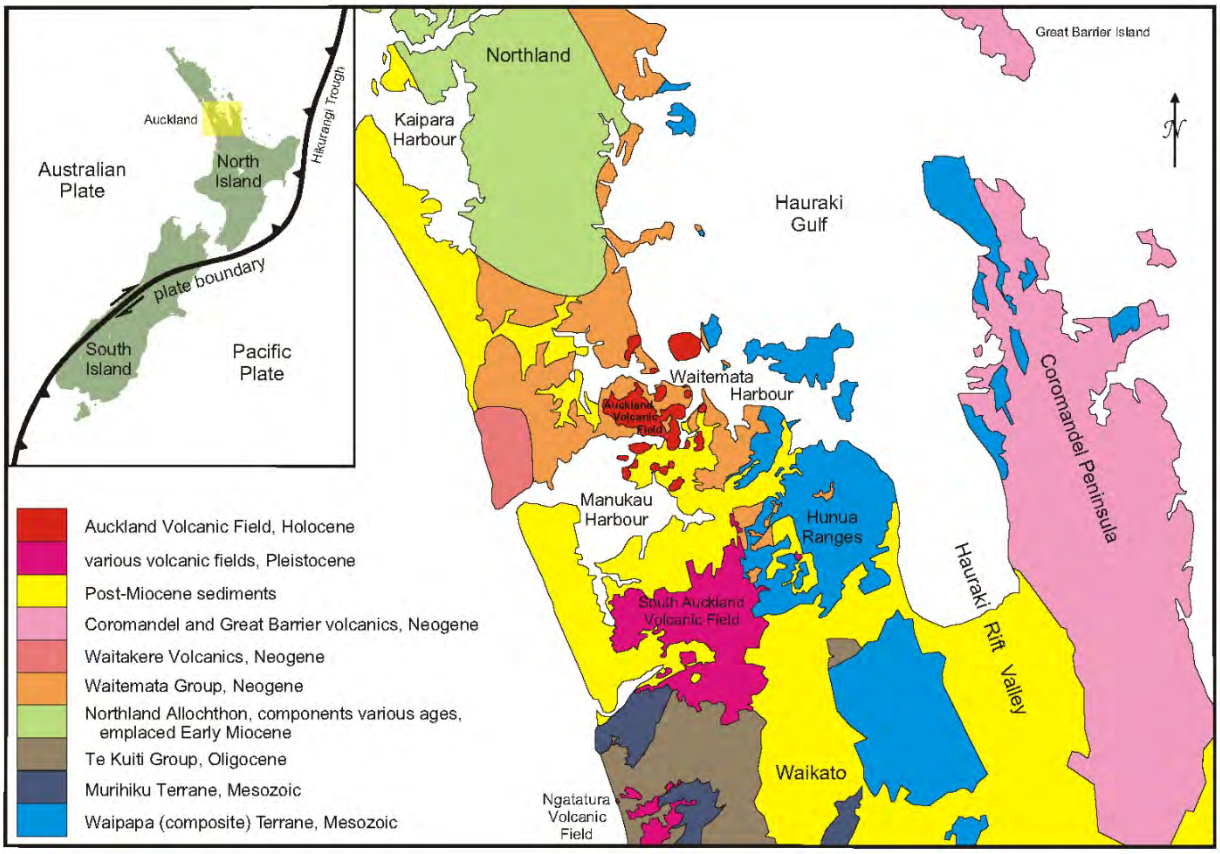


Figure 1: Simplified geology map for the Auckland region. Inset: Plate boundary through New Zealand.

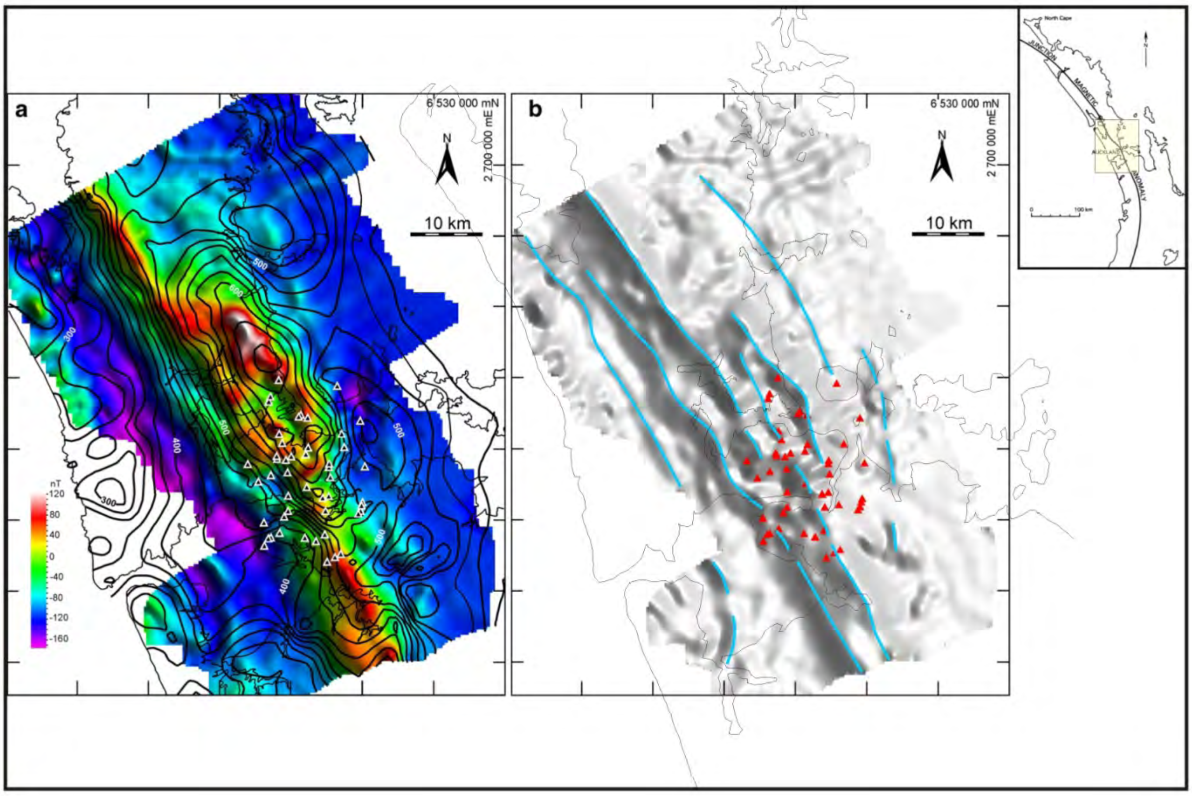


Figure 2: Two relief images modified after Cassidy & Locke (2010), showing regional gravity field superimposed (a) and interpreted magnetic lineaments (b) with Auckland coastline added. The inset shows the position of the Junction Magnetic Anomaly as it passes beneath the northern North Island (including the Auckland area) (after Schofield 1983).

Triassic Maitai terrane arc-derived sediments resting with both sedimentary and faulted contacts upon upper volcanic members of the Dun Mountain Ophiolite Belt (Frost & Coombs 1989). The anomaly occurs as a 6–8 km-wide band along the length of New Zealand (Figure 2 inset shows it passing through the northern North Island), but in the Auckland region it widens abruptly, forming a complex zone of sub-parallel lineaments up to 14 km wide, extending from the Auckland isthmus north as far as Orewa (Figure 2a) – about the same size as other such pods in the South Island (Williams 2003). This unusual widening is thought to represent a pod of NNW-trending serpentinised shears (Eccles *et al*. 2005, Cassidy & Locke 2010) (Figure 2b).

Greywacke basement rocks outcrop east of a line from Tiritiri Matangi Island in the north to Papakura in the south (Figure 1) (Localities mentioned in the text are shown in Figure 3). West of this line, but still in the east of the region, basement is known to be at depth from numerous boreholes. Still further west, basement is very deep and has yet to be encountered by drilling, but it is thought to be within 30 m of the base of a drilled borehole in the suburb of Mt Roskill that penetrated to a depth of 592 m (equating to 532 m below sea level) (Edbrooke *et al*. 1998). It probably shallows again further west, as indicated from boreholes in the Henderson Valley, where greywacke is 485 m below sea level, and a borehole at Grahams Beach, northern Awhitu Peninsula, where greywacke occurs at 340 m below sea level (Waterhouse 1989). Rocks associated with the Dun Mountain-Maitai terrane, and the faults inferred to separate it from terranes either side, are covered by more recent lithologies in the Auckland area and have as yet not been reached by boreholes.

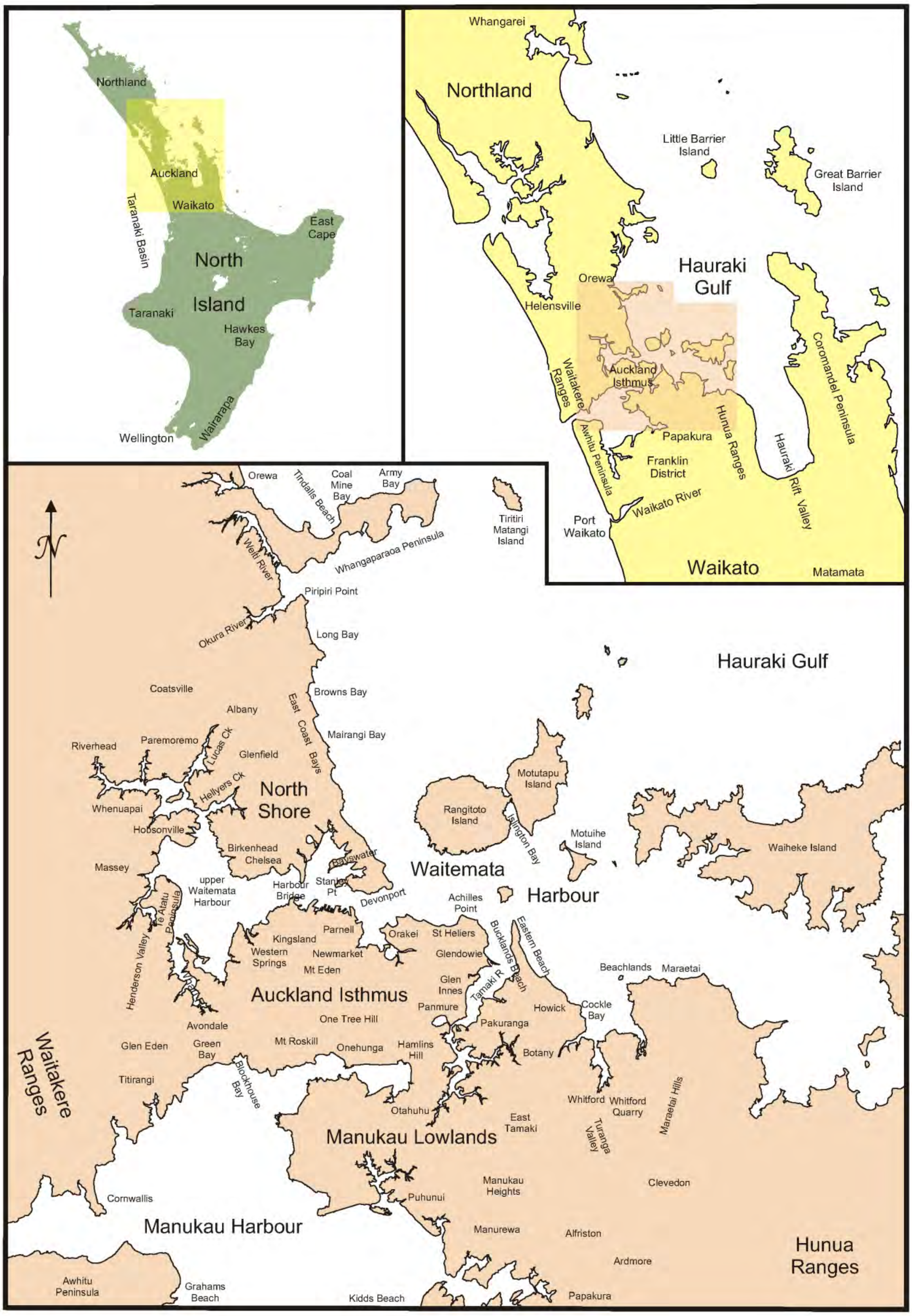


Figure 3: Map of the Auckland region showing localities mentioned in the text.

An extensional regime associated with the opening of the Tasman Sea was initiated about 80 Ma ago (late Cretaceous). In the Auckland area, this was manifested as block faulting of the basement, forming horsts and grabens bounded by NE/ENE and NW/NNW-trending faults (Raza *et al*. 1999). Te Kuiti Group sediments were deposited in the grabens, beginning in the Eocene with the Waikato Coal Measures (Kear & Schofield 1978) and followed with regional tectonic subsidence in the early to mid Oligocene by a transgressive sequence of estuarine, shallow marine and deeper marine sediments (calcareous mudstone, sandstones and limestones) (Kear & Schofield 1978, Edbrooke *et al*. 1994, Edbrooke *et al*. 1998).

Te Kuiti Group sediments do not outcrop in the Auckland area, but from numerous eastern boreholes from East Tamaki and Whitford southwards, sequences up to 30 m thick resembling Te Kuiti Group are known to exist at depth, resting on an irregular Mesozoic basement. An unusually deep borehole in Mt Roskill (DEVORA_0861) encountered 117 m of Te Kuiti Group, finishing in "fireclay" of the Waikato Coal Measures near the base of the Te Kuiti Group (Edbrooke *et al*. 1994). Davy (2008) also interpreted Te Kuiti Group as underlying Waitemata Group in some seismic reflection profiles within the Waitemata Harbour.

At the end of the Oligocene, plate boundary changes caused upheaval of the sedimentary basin northeast of New Zealand. In the early Miocene, huge nappes containing slices of the deep sea sedimentary pile and underlying ocean floor mafic and ultramafic rocks from this region were dislodged. They were emplaced hundreds of kilometres southwestwards as gravity slides on to northernmost New Zealand, forming the Northland Allochthon (Ballance & Spörli 1979, Hayward 1993).

During this time (c. 22 Ma ago) subsidence began in the Auckland region (Raza *et al*. 1999). Waitemata Group sediments, mainly flysch, began accumulating on an irregular basement topography, in a tectonically active environment within a rapidly subsiding basin. Most sedimentation occurred from about 22 to 19 Ma ago (Otaian) (Spörli & Browne 1982, Hayward *et al*. 1989, Spörli 1989, Isaac *et al*. 1994) (ages in millions of years are based on latest calibrations by Hollis *et al*. 2010).

The Waitemata Group sediments are now the most common rocks in the Auckland area (Figure 1). Near-horizontal undulating strata is dominant, with numerous local faults (Chappell 1963, High 1975, Kermode 1992). The oldest sediments are exposed in the east of the region, and include lenses of Papakura Limestone Formation (Hayward & Brook 1984). Sporadic, highly deformed intervals associated with volcanogenic Parnell Grit deposits, originating from active volcanoes to the west and northwest of the subsiding basin (Ballance 1974, Allen 2004, Shane *et al*. 2010) are found at many levels within an otherwise monotonous sedimentary pile. At other localities the Waitemata Group contains highly contorted zones up to 100 m thick, interpreted as being the result of intra-stratal disruption in a tectonically active subsiding basin (Gregory 1969, Spörli 1989, Hayward 1993, Isaac *et al*. 1994, Allen 2004, Spörli & Rowland 2007).

Much of the Waitemata Group sediment was derived from the Northland Allochthon, which was still advancing southwards. The toe of the allochthon reached as far south as Coatesville, 18 km northwest of Auckland (Isaac *et al*. 1994), by about the middle to late Otaian (c. 20 Ma ago). It infiltrated the accumulating Waitemata sediments in the northern part of the subsiding basin, incorporating and complexly disrupting some of the sediments into moving slices (Hayward 1982, 1993, Ballance & Spörli 1979), and carrying piggy-back other packets of largely undisrupted sediments (Spörli 1989).

Sedimentation continued within the subsiding Waitemata basin until at least 17 Ma ago. Sediments younger than 17 Ma, however, may have been subsequently eroded (Raza *et al*. 1999; Hayward & Smale 1992). Large-scale block faulting was initiated about 15 Ma ago, which possibly coincided with the extinction of Waitakere Arc volcanism to the west (Ballance 1974).

The Auckland area was uplifted, peneplained (Kermode 1992) and subjected to NW-SE then NE-SW extensional forces that created numerous outcrop-scale, steeply-dipping, cross-cutting normal faults (Spörli 1989).

After the infilling of the Waitemata basin, Plio-Pleistocene sediments were laid down in depressions formed by block faulting, infilling the valleys in the relatively uplifted Auckland isthmus area (Affleck *et al*. 2001) while overtopping the grabens in the lower-lying Manukau Lowlands area to the south (Berry 1986). One unit, the early Pliocene [Opoitian-Waipipian] shallow marine Kaawa Shellbed, which unconformably overlies Waitemata Group or Te Kuiti Group, is widespread in this southern region. It is an excellent aquifer and is an easily identifiable lithology in numerous boreholes drilled mostly for water (Berry 1986). It is disconformably overlain by late Pliocene (3–2 Ma ago) fluvial conglomerates of the Puketoka Formation (Hayward & Grenfell 2010) and late Pliocene to early Pleistocene coastal dune sand deposits of the Awhitu Group (Edbrooke 2001). Miocene to Pleistocene tectonism in the Auckland region is the subject of this report.

Around the shores of the Waitemata and Manukau Harbours, widespread pumiceous sands of the Tauranga Group unconformably overlie older lithologies. These brilliantly white sediments, derived from rhyolitic volcanism in the central North Island that commenced sometime after 2 Ma ago, were transported down an ancient course of the Waikato River (Briggs *et al*. 2005). Samples from coastal cliffs in Pakuranga have been dated at 1.2 Ma (Sandiford 2001).

The final stage in the geological history of Auckland is the Late Quaternary volcanism that now dominates the landscape. It appears to be the youngest phase of a northward-younging progression of episodes of basaltic volcanism, each lasting about 0.3–1 million years, from the Okete Basalts southwest of Hamilton (2.69–1.80 Ma ago), through the Ngatutura Basalts south of Port Waikato (1.83–1.54 Ma ago) and the South Auckland Volcanic Field from Papakura to Pukekohe to Mercer (1.59–0.51 Ma ago) (Briggs *et al*. 1990; Briggs *et al*. 1994) to the potentially active AVF, which has been active for about the last 250,000 years (Lindsay 2010).

PREVIOUSLY RECOGNISED REGIONAL FAULTS

Edbrooke (2001) summarised the geology of the Auckland region as part of the QMAP series. His compilation map shows recognised and inferred regional block faulting in the Hunua Ranges and Maraetai Hills in the east, in the Franklin District to the south, and in the Waitakere Ranges to the west (Figure 4). Many are thought to be remobilised older faults that extended into the Northland area, inherited from structures in the basement associated with the separation of New Zealand from Gondwana c. 80 Ma ago (Spörli 1982, Kamp 1986). Offshore to the west, in the northernmost Taranaki Basin, the QMAP also shows large-scale splay faults mapped using seismic evidence by Stagpoole (1997) trending approximately ENE. These faults have not been extrapolated eastwards onto land. A simplified map of previously recognised faults illustrates some of these western offshore splays (Figure 4).

Southern and eastern faults

Significant ENE-trending horsts and grabens in the southeast of the region are bounded by the Papakura, Brookby, Alfriston and Polo Lane normal faults between Whitford and Clevedon (Schofield 1979, Kermode 1986) (Figure 4). They parallel numerous faults mapped in the Hunua Ranges (Schofield 1979), the major Waikato Fault further south (Hochstein & Nunns 1976) that offsets Murihiku greywacke basement by 2.7 km at Port Waikato, and they appear to be analogous to the splay faults already mentioned off the west coast (Stagpoole 1997). Also paralleling this trend, but interestingly not shown on the QMAP, are faults forming a horst and graben pattern in both the basement and Waitemata Group sediments (Figure 4). These ENE-trending faults, with throws ranging from about 75 m to more than 220 m, include the Manukau Fault (Ballance 1968) that down-drops the Manukau Lowlands region with respect to the moderately elevated Auckland isthmus region. They also include concealed faults with smaller offsets (often less than 10 m) such as the Wiri, Karaka, Waiau and Glenbrook faults, which form horst and graben features across the Manukau Lowlands and are thought to have been active continuously into the latest Pliocene. They were located using geophysical and borehole data and delineate the Otahuhu Graben, Manurewa Horst, Seagrove Graben, Waiau Horst and Glenbrook Depression (High 1975, 1977, Berry 1986, Omerod 1989, Petch *et al*. 1991, Hull *et al*. 1995).

NNW-trending faults truncating these horsts and grabens have been determined using borehole data and geophysical measurements at Awhitu Peninsula and the Manukau Lowlands (High 1975, 1977, Barter 1976, Berry 1986, Omerod 1989) (Figure 4). Parallel faults with substantial normal offsets outcrop further east. The Drury Fault is a steep NNW-trending normal fault (Nixon 1977, Omerod 1989, Al-Salim 2000). South of Papakura it has a throw of 2.7 km down to the west, and forms an obvious escarpment in the present topography. Northwards it diminishes substantially, achieving a throw of 500 m west of Ardmore, then just 3 km further north at Alfriston there is no discernable throw. High (1975, 1977) speculated that it might curve to a more N–S strike to follow the Turanga Valley towards Whitford and the eastern Waitemata Harbour. Anderson (1977), however, was unable to detect it using geophysical methods and thought that the fault was probably truncated by an E–W trending feature, which would be directly west of an E–W-trending scarp later mapped by Schofield (1979) as the Brookby Fault (Figure 4). Nevertheless, Al-Salim (2000) may have detected ongoing movement on a northern extension of the Drury Fault north of the Papakura Fault, where a scarp appears to truncate a terrace of recent sediments.

Further east again, a major west-facing scarp is segmented into the Waikopua, Wairoa North and Wairoa South faults (Anderson 1977, Wise 1999) (Figure 4). In the middle section, south of the Clevedon Valley, Wise (1999) established that this NNW-trending steep normal fault was downthrown to the west by at least 120 m and was probably still active. Using gravity surveys,

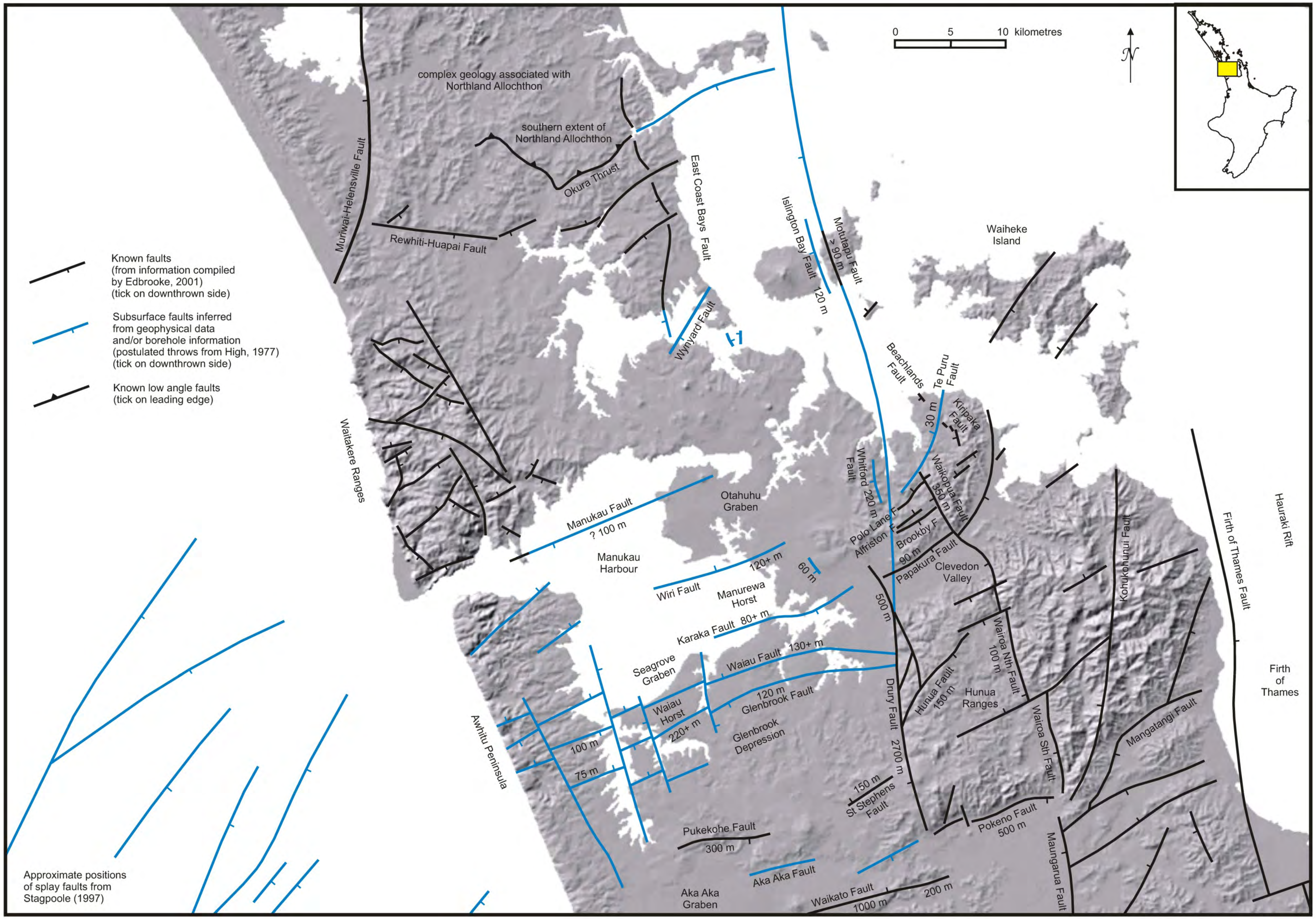


Figure 4: Faults previously recognised in the Auckland region (see text for many references).

Williams (2003) determined the vertical displacement was enormous, as much as 4.7 km, and that Wise's offset was likely to be just the more recent movement(s).

The northern segment, the Waikopua Fault trending NNW from Clevedon to the Whitford Quarry, was studied by Anderson (1977), as part of an attempt to link the Drury Fault with a fault mapped far to the north on Motutapu Island. She estimated that at the northern end, at the Whitford Quarry, the basal Waitemata Group contact with underlying Waipapa basement had 350 m of vertical displacement (west side downthrown) with a slight dextral slip component, then it suddenly died out northwards. She mapped it as offset to the east by a small NE-trending splinter fault, but this splinter seems to be insufficient to reduce the offset given the sudden reduction in throw northwards. A resolution to this situation is discussed later.

Using seismic profiling, Anderson (1977) mapped yet another NNW-trending fault in the area, the Whitford Fault; it offsets basement by about 220 m, but apparently does not affect the overlying Waitemata Group sediments. At this time she also discovered the NNE-trending Te Puru Fault southeast of Beachlands. Again it only offsets the basement, yet it part-parallels horst and graben-forming faults just further south that affect basement and overlying Waitemata Group sediments (Figure 4).

Other small faults occur in the Beachlands region including a series of short NNW-trending segments collectively named the Kiripaka Fault (Schofield 1979), which may be related to a small fault in the Beachlands cliffs that offsets Pleistocene tephra deposits (Firth 1930, Glading 1987, Tejaksuma 1998, Spörli & Stannaway 2007).

A feature with a similar trend, mapped as only a short fault and subsequently forgotten by all writers, was postulated by Firth (1930) at Manurewa. He recognised that a distinctive grit horizon in the Waitemata Group sediments outcropping at sea level at Weymouth, is uplifted to 60 m in the Puhinui Range (now called Manukau Heights) east of Manurewa township. He acknowledged that although this could be a result of monoclinal folding, faulting was more likely and drew a NNW-trending fault along the base of the hills, downthrown to the west. Scarcity of outcrops for verification was a problem then (1930) and more so now with urbanisation and mangrove swamps. He thought it may be a northern extension of the Drury Fault. This feature deserves more consideration in future work.

The Hauraki Rift, a major 250-km-long structural feature passing east of Auckland (Figure 1), and possibly still active (Hochstein & Nixon 1979, Hochstein *et al*. 1986, De Lange & Lowe 1990), follows these regionally significant NNW–SSE trends.

Hull *et al*. (1995) describe faults to the south and east of Auckland in detail, together with an assessment of possible Quaternary activity and earthquake risk.

Northern and western faults

To the west of Auckland, the Waitakere Ranges are also bounded by NNW-trending features – andesitic intrusions, dykes, craters and volcanic necks form a 2-km-wide belt along the eastern flank of the Waitakere Ranges, and a series of craters and volcanic necks line up along the coastline. Within the Waitakere block, however, faults form a grid pattern with NE and ESE orientations (Hayward 1975, 1983) (Figure 4).

To the north of Auckland, most of the structures mapped by Schofield (1989) and others, including the Okura Thrust at Albany, and faults in the Riverhead, Paremoremo, Lucas Creek and Hellyers Creek areas (Figure 4), are now thought to be associated with the sliding southwards of the Northland Allochthon (eg. Hayward 1982, 1993, Ballance & Spörli 1979, Spörli 1989, Spörli & Rowland 2007, Kenny 2008b). One exception is the Rewhiti-Huapai Fault west of Riverhead. Clark (1948) inferred Pleistocene movement on this concealed E–W-trending feature, which coincides with the rather straight scarp on the northern side of the wide valley between Huapai and Waimauku. It is not shown, however, on subsequent regional geological maps (Schofield 1967, 1989).

Another exception is the East Coast Bays Fault, trending approximately NNW through the North Shore, which has an unusual history with respect to its mapped position, its sense of movement, and even its very existence. Schofield apparently spoke of a change in morphology of the landscape through the East Coast Bays suburbs (B. Hayward pers. comm. 2005). He noticed a vague NNW-trending demarcation in the landscape, with terracing on the hillsides near the coast, but no similar terracing further west. He assessed terracing to be an erosional feature on flat-lying Waitemata Group strata, and associated a lack of terracing with steeper, highly disrupted bedding he believed to be lower down in the Waitemata Group pile (G. Mansergh pers. comm. 2007). Most of this area is now covered in houses, making on-site verification impossible. Terraces are clearly detectable in 1950s and 1960s aerial photographs of the East Coast Bays before urban sprawl had spread there, and well-developed terraces are still visible in the hills behind Long Bay. Unfortunately, even these last vestiges are under threat from housing development.

A line separating areas of terraced topography in the east from unterraced land to the west, sometimes displaced to the east or west by cross-cutting faults, was mapped as a steeply dipping normal fault, downthrown to the east, juxtaposing older contorted strata in the west against younger flat-lying strata to the east. The “East Coast Bays Fault” was published some years later (Ballance & Schofield 1983, Schofield 1989). In the interim, Hayward (1982) suggested in that the offset was the opposite sense (downthrown to the west), arguing that the disrupted strata was associated with influxes of volcanogenic deposits or allochthonous material positioned higher up in the sequence. He proposed that the southern extrapolation of this fault could link with a northern extension of a fault, mapped by Cornwell & High (1975) under the Auckland Harbour Bridge (Figure 4) during investigations for an across-harbour tunnel. Hayward (1982) was the first researcher to attempt a connection between faults on the North Shore of Auckland and those in southern Auckland, suggesting they were extensions of the Drury Fault.

In the Hauraki Gulf, an unnamed N–S-trending fault between Whangaparaoa Peninsula and Tiritiri Matangi Island (Spörli & Rowland 2007) was earlier postulated by High (1977). He linked this major structure to the N–S-trending Motutapu Fault, surveyed by Milligan (1977), which cuts across Motutapu Island, down-dropping greywacke basement at least 90 m to the west. He considered that both faults could be a northern continuation of the Drury Fault. Gravity surveys by Milligan (1977) also detected the Islington Bay Fault, a major NNW-trending fault between Motutapu and Rangitoto islands, downthrown 120 m to the west (Figure 4). She suggested that this fault may pass to the east of Bucklands Beach peninsula and continue southwards to the Wairoa North Fault, but Anderson (1977) found no evidence in the Whitford area to support this.

MAPPING THE WAITEMATA GROUP ERODED SURFACE

If regional faults have been mapped to the north, south, east and west of Auckland, why are they so difficult to detect in Auckland itself? To understand the reason they may have been missed, it is necessary to investigate distinctive characteristics of Auckland's geology and to determine how best to utilise subtle changes.

IS THE APPARENT LACK OF MAJOR FAULTS IN THE AUCKLAND ISTHMUS AREA REAL?

With the complex tectonic history associated with extension- and compression-related faulting regimes surrounding the Auckland area, visible also in the contorted nature of some strata in Auckland, why is it that so few major faults have been recognised traversing Auckland isthmus itself? This anomaly seems not to have been noticed in the past. Many small- to medium-scale faults in the cliffs and shore platforms bordering the Waitemata and northern Manukau Harbours are involved in complex intra-stratal disruptions and thrusting, or they belong to later development of extensional regimes with steep NW-trending normal faults cutting steep NE-trending normal faults (eg. Chappell 1963, High 1975, Spörli & Browne 1982, Spörli 1989, Kermode 1992, Spörli & Rowland 2007). However, except for the imprecise East Coast Bays Fault, the fault mapped under Auckland Harbour Bridge (Cornwell & High 1975, Hayward 1982), and small structures discovered in Boomer seismic sections of the inner Waitemata Harbour (Davy 2008), Auckland maps are noticeably devoid of large-scale faults (Figure 4). Perhaps they have been missed because there are no convenient marker horizons within the Waitemata sediments that can be followed sufficiently far to establish fault offsets (Ballance 1974), or because much of Auckland is now covered by a thin veneer of ash, silt and lava.

Geophysical studies that might have revealed hidden faults are often restricted by Quaternary ash from the AVF. Two small studies used borehole and detailed gravity data to determine the pre-volcanic topography beneath the Mt Eden–Epsom area and under the southeastern flank of One Tree Hill (Affleck *et al*. 2001, Murray 2010), but no faults were discerned. Williams (2003) studied basement structures across the Auckland isthmus, using for her gravity modelling the basic assumption that there were no discernable vertical offsets in the basement-cover interface.

Shallow water "noise" in seismic profiles is also a problem, especially in profiles recorded from the Manukau Harbour and middle to upper reaches of the Waitemata Harbour (B. Davy, pers. comm. 2007). A few attempts have been made, but they have only revealed a mesoscopic fault under harbour sediments near Wynyard wharf and two others between Devonport and Orakei (Davy 2008).

Recently the problem of apparent lack of large-scale faults traversing Auckland has been researched and indirect evidence has been collated for block faulting (Kenny 2008a) and allochthon-related low-angle faulting (Kenny 2008b). This evidence will be discussed later.

LACK OF MARKER HORIZONS

On the outskirts of Auckland, different lithologies are sometimes juxtaposed against each other, making fault recognition easy (Figure 1). Within Auckland itself, the oldest and most widespread lithologies are monotonous, sub-horizontal, alternating turbiditic sandstones and mudstones of the Waitemata Group (Ballance 1964, 1974, Gregory 1969). Within this sequence there is a general lack of marker horizons – any obvious horizons cannot be traced for more than a few hundred metres (Chappell 1963, Morris 1983). Outcrop-scale faults are ubiquitous (High 1975, Spörli 1989, Kermode 1992), with offsets often determined by matching patterns of bed thicknesses on both sides of a fracture.

Other than the alternating sandstones and mudstones, the most well-known unit within the Waitemata Group is the Parnell Grit (Ballance 1976a, Allen 2004). This lithology is actually a series of volcanoclastic gravity flow deposits occurring at many intervals. Although this lithologically distinct unit would seem an ideal marker horizon to determine if any fault offset exists, the position of any individual flow unit in the sequence cannot be reliably traced from one outcrop to the next. At other localities, the sub-horizontal alternating sequences of the Waitemata Group are disrupted by highly contorted zones (eg. Spörli 1989, Spörli & Browne 1982, Spörli & Rowland 2007). As with the Parnell Grit units, these contorted zones cannot be traced with sufficient reliability between outcrops.

To make mapping more difficult, much of the Auckland isthmus and Manukau Lowlands are covered with Late Quaternary sediments, volcanic ash and lava flows, concealing any existing fault traces. As mentioned above, the volcanic material in particular also inhibits detailed geophysical analyses by obscuring any subtle anomalies that may occur in the Waitemata Group sediments beneath.

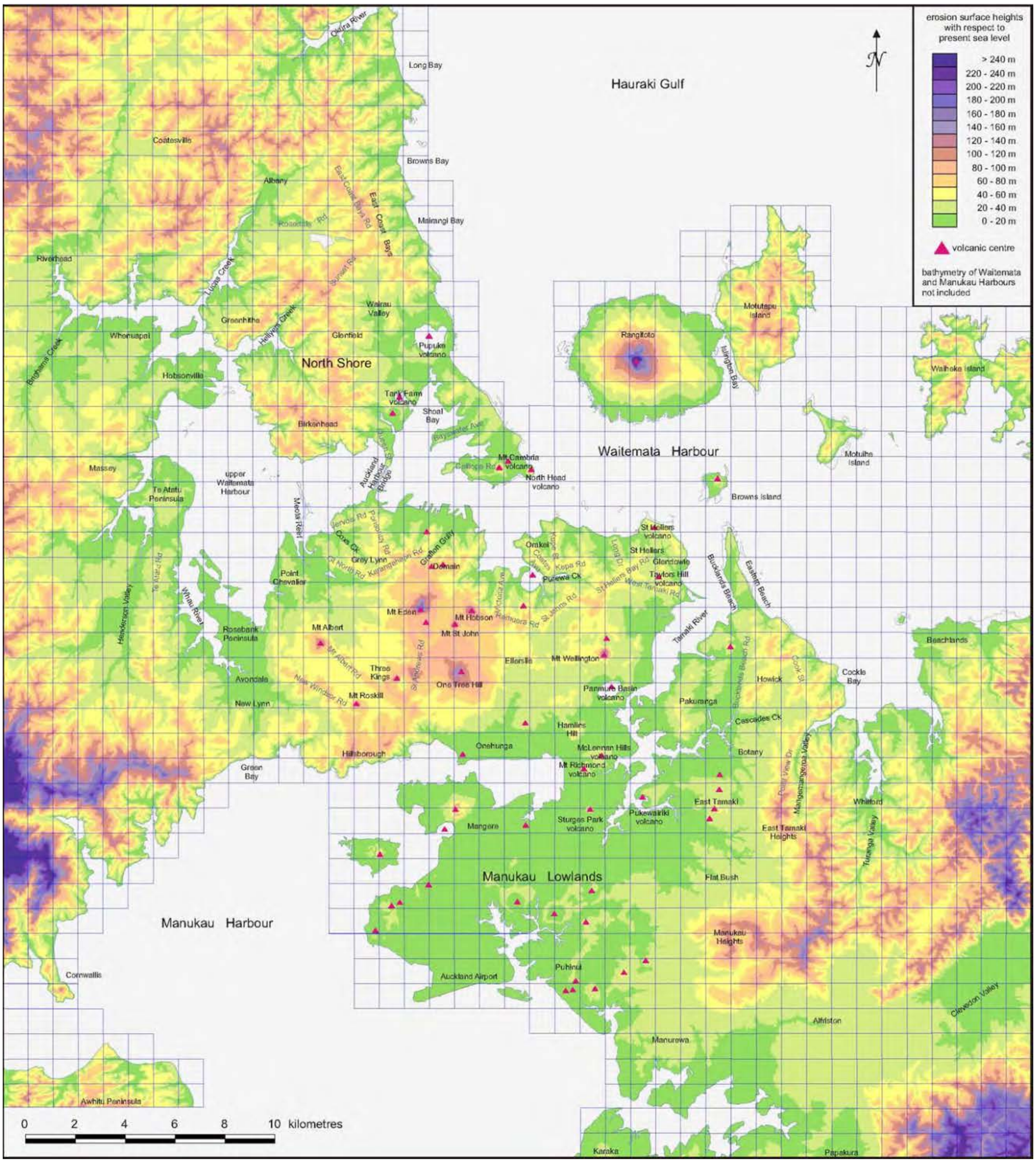
A UNIQUE MARKER HORIZON: THE LATE MIOCENE ERODED SURFACE

There is only one marker horizon that can be followed with any certainty, namely the late Miocene eroded surface of the Waitemata Group, which has been recognised as a region-wide peneplain (Kermode 1992, Kenny 2007). Across the northern Auckland isthmus, in western Auckland and on the North Shore this erosion surface equates to the present topographic surface. To the south, the erosion surface has been down-dropped and is covered by younger material. To the east, the erosion surface has been up-thrown and removed completely (eg. in the Hunua Ranges).

With a practised eye, it is possible to recognise remnants of this old peneplain surface still present as near-horizontal or slightly undulating broad ridges along which many of Auckland’s main arterial roads are constructed, for example Calliope Road (in the suburb of Devonport), Bayswater Ave (Bayswater), Queen Street (Northcote), Jervois/Ponsonby Roads (Ponsonby), Karangahape/Great North Roads (Grey Lynn), Mt Albert Road (Mt Roskill), New Windsor Road (Avondale), Te Atatu Road (Te Atatu), eastern Remuera Road/St Johns Road (Meadowbank), Victoria Avenue (Remuera), Coates Avenue/Kupe Street/eastern Kepa Road (Orakei) (Figure 6), much of St Heliers Bay Road/Long Drive (St Heliers), West Tamaki Road (Glendowie), and Cook Street (Howick) (Figures 3, 5 & 6).

However, this erosion surface no longer exists at a constant height above sea level, but rather is broken into blocks at subtly different heights. There is height uniformity within blocks, but a discordance between blocks (Figure 7). The Waitemata Group erosion surface exposed at Whenuapai, Te Atatu Peninsula, Avondale and Rosebank is less than 20 m above sea level. At Pt Chevalier, New Lynn and Beachlands ridge heights show the surface is at approximately 20 m above sea level. At Glendowie and Pakuranga it is at 40 m above sea level and at Grey Lynn, Parnell, Orakei and St Heliers it is at 50 m above sea level. The Hillsborough and Howick ridges reach 60 m above sea level. On the North Shore, Glenfield, Birkenhead and the East Coast Bays ridges are at approximately 80 m above sea level.

Figure 5: Elevation map of current Auckland topography. Green colours are lowest elevations; purple colours are highest elevations. Heights refer to metres above sea level.



To the east and southeast, tectonic uplift has exposed the oldest Waitemata Group lithologies (Hayward & Brook 1984) and subjected them to the most erosion. In these highly dissected areas, the peneplain is no longer visible, but ridge tops at subequal elevation at East Tamaki Heights average 120 m above sea level, while the hills north of Alfriston are at greater than 140 m above sea level. A high erosion surface over 350 m above sea level, gently tilted to the northwest, is preserved in the Waitakere Ranges (Hayward 1983, 2009).

The Manukau Lowlands have been down-dropped relative to other blocks and in this area boreholes encounter the unconformity between Waitemata Group sediments and overlying lithologies at or below sea level (High 1975, 1977, Berry 1986, Omerod 1989, Petch *et al*. 1991, Hull *et al*. 1995). Boreholes and geophysical analyses in the central Auckland isthmus area, now covered by volcanic ash and lava, indicate that the underlying Waitemata surface is very irregular, but averages 70 m above sea level (Affleck *et al*. 2001).

Could post-peneplanation faults cause this discordance of heights? Could block faults criss-cross Auckland, as seen in outcrop-scale NE- and NW-trending normal faults, as well as in regional fault trends already mapped in the Hunua Ranges, Waitakere area, North Auckland, Manukau Lowlands and northern Waikato? This was the working hypothesis used by Kenny (2007) to investigate the possibility that regional faults traversed Auckland, despite not being represented on published maps.

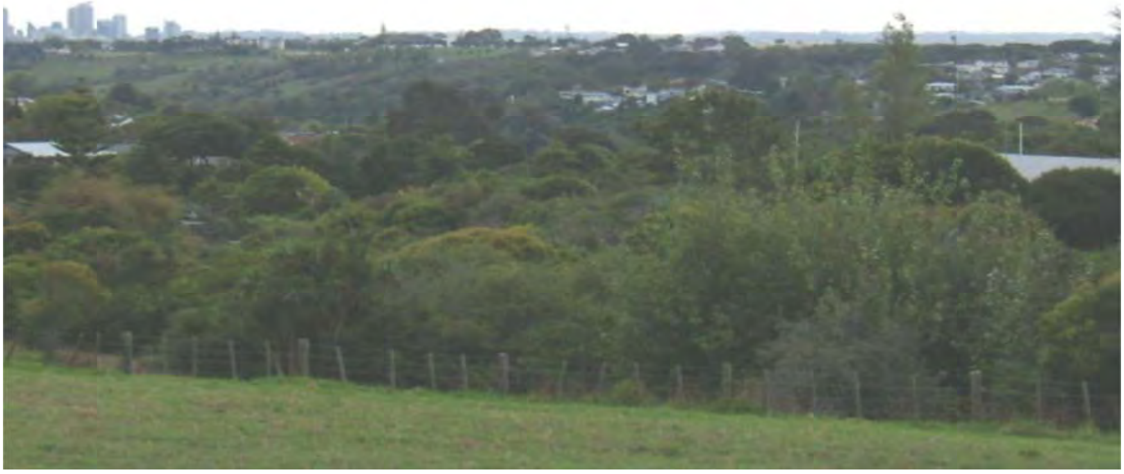


Figure 6: Peneplain surface forming a broad ridge along Kepa Road, Orakei (middle distance).

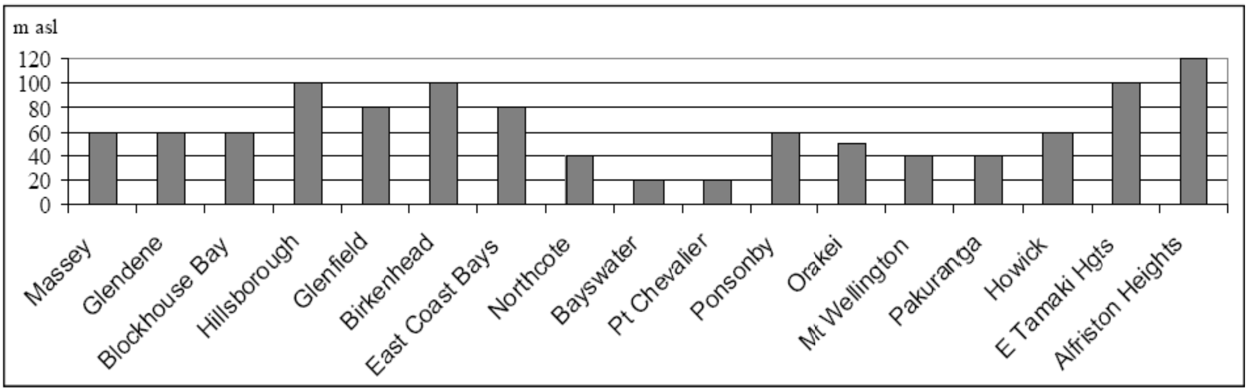


Figure 7: Average ridge heights on the eroded Waitemata Group surface, roughly NW to SE across Auckland (from Kenny 2007).

To confuse recognition of the regional late Miocene peneplain, coastal terraces attributable to oscillating sea levels in the Pleistocene also exist (Searle 1964, Ballance 1968). These terraces follow a predictable erosional pattern with respect to water courses and the coastline, and can still be seen in many parts of Auckland (eg. Long Bay hinterland, Shoal Bay, Te Atatu Peninsula, Rosebank Peninsula, either side of the Tamaki River and much of the Manukau Lowlands). Sea level changes do not, however, explain why there are elevation discrepancies between adjacent areas of uniform ridge height (Figure 7).

USE OF LINEAMENTS AS A MAPPING TOOL

We mapped topographic lineaments on aerial photographs in an attempt to delineate faults disrupting the Waitemata Group eroded surface in areas away from the coastlines where no outcrops exist. Streams, steep scarps or asymmetric valleys can sometimes be unusually straight (Davidson 1990, Tilsley 1993), or sections of them may be parallel to similar features nearby, showing up on aerial photographs as straight and/or parallel lineaments. Ridge notches may line up with these lineaments. These surface features may be reflecting subtle erosion upon subsurface structures and planes of weakness, producing long linear troughs.

Stereoscopic aerial photographs from the late 1950s to early 1960s were used for lineament mapping. These were the oldest available complete runs of aerial photographs spanning the whole of Auckland. They also predate many of the housing developments, roads and reclamations that have since obscured much valuable surface topographical information. In those days much of Auckland was still farmland on which subtle lineaments were clearly defined. Using stereoscopic photogrammetric techniques it became obvious that the density of visible geological lineaments is inversely related to density of housing and intensive farming, with its many fence lines, shelter belts and orchards obscuring any lineament. The most easily defined lineaments appear on sparsely populated rolling pasture with few artificial distractions. Lineaments were also recognised in areas where the Waitemata Group sediments are covered by only a veneer of more recent sediments and volcanic ash, where it was inferred that they are still effectively controlling the geomorphology.

Hundreds of lineaments have been mapped, but they are too numerous to depict on any map for this publication. Instead, a portion of one map is included. The example is from typical farmland and scrub in the area from Browns Bay to Mairangi Bay, extending westwards to where the Northern Motorway now exists (Figure 8). This area was chosen because it coincides with a small part of Auckland where Google Earth has collated historical aerial photographs from 1963 into a mosaic. It provides an ideal base map for the lineaments (Figure 9).

Lineaments in Figure 9 are typical of lineaments mapped over the whole of Auckland. They often represent erosion along bedding planes, visible in this figure especially along the coastline, in the northwest corner and in some valleys in the centre. Some lineaments that are sub-parallel to the general direction of East Coast Bays Road are parallel to the East Coast Bays Fault, shown in Figure 4, although mapped with some tentativeness in this vicinity and intentionally not depicted on the lineament map. Some lineaments have offset topography, and as such are mapped as faults, for example in the top left and bottom left corners of Figure 9.

Many lineaments cannot be equivocally attributed to bedding or with known faults. These are probably related to erosion of joint planes; such planes are more common on exposed Waitemata Group sediments than is actually acknowledged. Faults are common along the coastal cliffs and shore platforms, but they appear to be sutured shut and are not eroding any faster than the

Figure 8: **Historical Google Earth image from 1963 of the East Coast Bays area with modern roads (coloured) superimposed from the latest Google Earth image.**

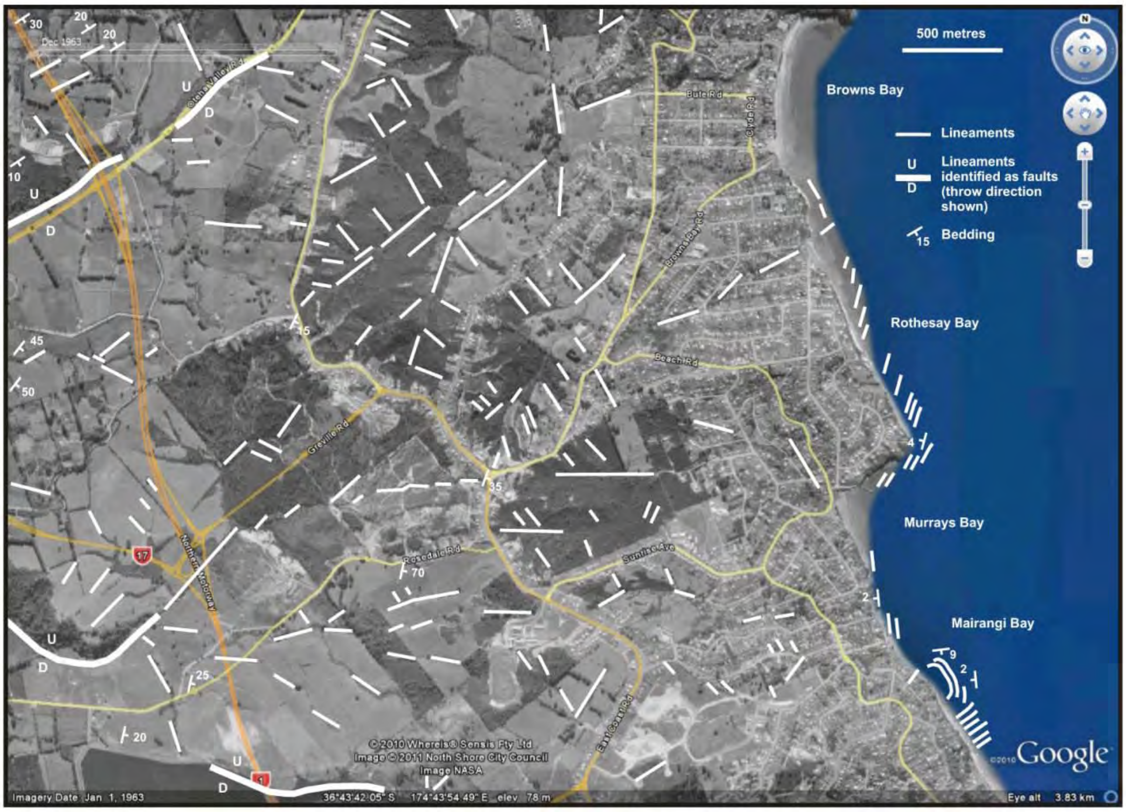


Figure 9: As in Figure 8, but with lineaments also superimposed on the historical Google Earth image. This is an example of how lineaments were mapped for the whole of Auckland, using 1960s stereoscopic aerial photographs. Bedding and lineaments identified as faults are also shown.

sediments they offset (Figures 10–12). In the same environments, however, joint planes are open and preferentially eroding (Figures 13 & 14). In undeformed outcrops, they often appear as two orthogonal sets of planes, at high angles to the near-horizontal strata, with NNW and ENE trends dominant (McManus 1981, Davidson 1990, Tilsley 1993).

These NNW and ENE trends are approximately parallel to the NNW-, NE- and ENE-trending faults mapped around the coastline (High 1975), to the outcrop scale NW- and NE-trending faults where NW trends truncate NE trends (Spörli 1989, Tilsley 1993), and to the NNW- and ENE-trending regional faults mapped around the outskirts of Auckland (Schofield 1979, Berry 1986, Omerod 1989, Petch *et al*. 1991, Kermode 1992, Hull *et al*. 1995, Edbrooke 2001).

Detailed mapping of lineaments on the Waitemata Group erosion surface shows that small-scale lineaments attributable to bedding or joint planes are truncated by larger lineaments. These larger lineaments also offset topography and are interpreted to be faults (Kenny 2007, 2008a). This is particularly obvious in east Auckland where the high, erosion-resistant, NE-trending ridges of Howick are truncated by a N–S lineament positioned approximately along Bucklands Beach Road, down-throwing eastern Pakuranga relative to Howick. They are also truncated by an E–W lineament along Cascades Creek similarly down-throwing the Golflands-Botany area relative to Howick. Both these lineaments show up clearly in the Howick area of the contour map of the present topography of Auckland (Figure 5).

Other topographical offsets along large lineaments are also visible in Figure 5, for example, along the Birkenhead coast separating Birkenhead from Hobsonville (NNW–SSE trend), Lucas Creek and Hellyers Creek in Greenhithe (NE–SW trends), along Brighams Creek west of Whenuapai (NNE–SSW), Henderson Valley (N–S), separating Massey Heights from Te Atatu Peninsula (NNE–SSW), western coast of Pt Chevalier (N–S), Hillsborough coastline (curved but averaging ENE–WSW), and the west-facing coast south of Beachlands (NNW–SSE). Kenny (2007, 2008a, 2008b) has interpreted most of these large lineaments as regional faults and others as arc-shaped faults associated with the Northland Allochthon (described later).

An obvious task would be to ground truth these lineaments to their outcrop expressions along the coastline. Invariably, however, the intersection of large lineaments with the coast coincides with areas of no outcrop, where splendid cliffs and shore platforms on either side inconveniently diminish to nothing except a beach, mudflats, or swamp exactly where the lineament should have been.

We are also aware that some major faults may not be represented by lineaments cutting across the topography. Often planes of weakness along fault zones have eroded to form valleys that have since filled with sediment, or, in Auckland's case, filled with lava from the many vents of the AVF. Also, in Auckland much of the central isthmus is covered with ash from those same vents, concealing the original Waitemata erosion surface and severely hampering any geophysical measurements of possible offsets of that surface.

One way to circumvent this problem is to use data from boreholes that penetrate superficial sediments and encounter the old erosion surface at depth.

Figure 10: A high-angle normal fault in Waitemata Group flysch in a cliff section at Achilles Point on the Waitemata Harbour coastline at St Heliers. Beds are offset here by 3 m, but there is no evidence of increased erosion along the fault plane. Photo courtesy of Bruce Hayward.

Figure 11: Fault zone in Waitemata Group flysch in a shore platform section between Blockhouse Bay and Green Bay on the Manukau Harbour coast. There is no evidence of increased erosion on this surface. Photo courtesy of Bruce Hayward.

Figure 12: Convoluted section within the Waitemata Group flysch at Coal Mine Bay, northern Whangaparaoa Peninsula. There is no evidence of increased erosion across this disrupted zone. Photo courtesy of Bruce Hayward.

Figure 13: Google Earth aerial view from 200 m elevation showing open joint planes at Piripiti Point, Okura, north of Long Bay. This view clearly shows that the shore platform has opened along 2 sets of joint planes and is vulnerable to erosion.

Figure 14: Google Earth aerial view from 100 m elevation showing open joint planes clearly visible in the shore platform at Chelsea sugar refinery, Birkenhead. As with the previous figure, the joint planes have opened and are vulnerable to erosion.

BOREHOLE DATA ANALYSIS

Kenny (2007) used data from a few hundred boreholes stored by the Auckland Regional Council, together with borehole information from Kermode & Searle (1966) and B. Hegan (pers. comm. 2007), to establish a crude contour map of the Waitemata Group erosion surface beneath Auckland (Kenny 2007). Preliminary results indicated that lineaments with topographical offsets could be inferred criss-crossing Auckland, some parallel to ENE-trending horst and graben structures and splay faults, but most extend along the NNW trends of the Hunua, Waikopua and Wairoa Faults (Kenny 2008a, 2008b).

Since then, data from thousands of boreholes has been collated as part of the DEVORA project and used to aid in the interpretation of the concealed Waitemata surface (Figure 15). Data has been held by the Auckland Regional Council, Watercare, private geotechnical firms, New Zealand Transport Agency and other organisations.

Created in 2008, the DEVORA borehole database was developed in order to further our understanding of the crustal structure beneath Auckland. Original goals included linking scientists with subsurface samples, determining the total volume of erupted deposits in the AVF, and finding possible locations for deep borehole seismometers. Since its inception, boreholes from across the city and from a variety of public and private sources have been added to the database, and today it includes >2000 boreholes. Although it began as a research tool for DEVORA scientists, the broad scale applications of the database became apparent as it grew, and in 2010, the database was made publicly available via PETLAB, GNS's national database (http://petlab.gns.cri.nz). For further information on the structure, logistics and current uses of the database, as well as how to view and download DEVORA data from PETLAB, please see Howe *et al*. (2011).

Unfortunately, borehole coverage is patchy, with holes often drilled in clumps for specific purposes such as building construction, road or rail foundations, or water bores. There are large gaps in the coverage, especially in the Manukau Lowlands, where the Waitemata Group is largely below sea level and covered by many metres of post-Miocene sediments. Some areas are so devoid of data that contours cannot even be guessed.

Identification of the upper surface of the Waitemata Group in boreholes is based on notes made by drillers or consultants during the drilling process. Actual core no longer exists. The Waitemata Group interface with overlying sediments is notoriously difficult to determine, because weathered early Miocene Waitemata lithologies appear very similar to Pliocene sediments. This problem was encountered by Hicks & Kibblewhite (1976) in their interpretation of boreholes drilled in the upper Waitemata Harbour to ground truth their seismic reflection profiling study. A similar situation occurred with Manukau Lowlands borehole interpretations (Berry 1986). Most of the borehole records rely on experienced drillers being able to "feel" the change as the drill bit passes through cover lithologies into Waitemata Group sediments.

It is also necessary to take into account that a borehole intersection with the erosion surface is only an indication of depth at that point. A borehole a few metres away may have a very different depth. Consequently the sub-volcanic topographic surface is very approximate and borehole data has only been used where there is some consistency to that data, or the depth makes sense with respect to present topography, seismic knowledge, or some other factor. Bear in mind the main purpose of this investigation is merely to gain an impression of major height differences in the erosion surface, so that offsets of the peneplain, visible across other parts of Auckland, can be followed under post-Waitemata material. It cannot, and does not, attempt to be more precise than estimating to the nearest 20 m contour interval.

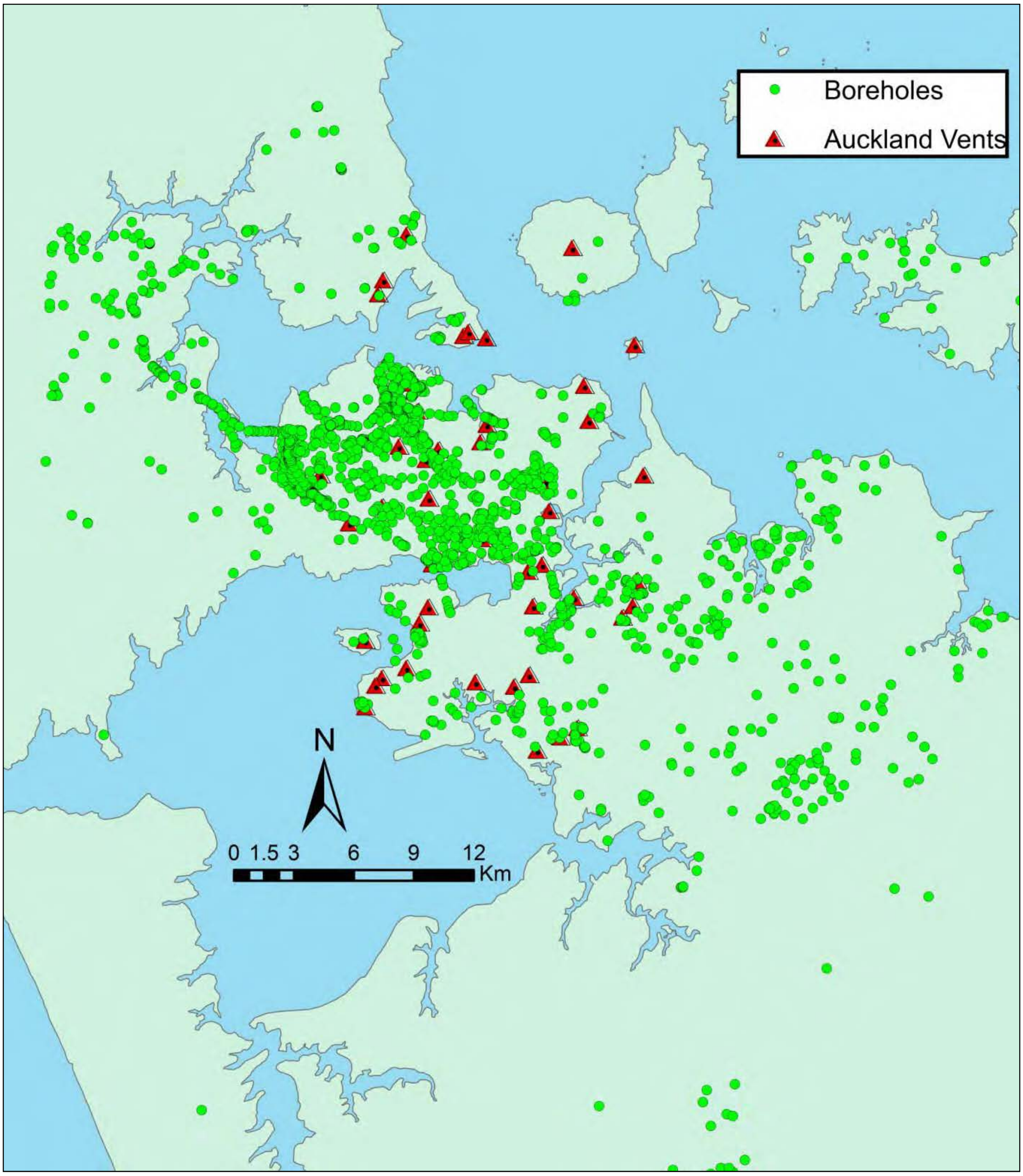


Figure 15: Location of boreholes used in this study.

WAITEMATA GROUP GEOMORPHOLOGY

In order to apply a morphological pattern to the inferred buried erosion surface that has been loosely and imprecisely established using borehole data, it is necessary to understand the geomorphology of the erosion surface where it is currently exposed. The exposed Waitemata Group erosion surface is moderately dissected, with steep-sided streams flowing into broad river valleys draining either into the Waitemata or Manukau Harbours. The dendritic drainage pattern is separated by broad, flat-topped ridges (associated with the erosion surface) with rounded spurs and headlands. Some of the drainage flows in the opposite direction to the nearest coastline, an aspect more related to the speed of coastline regression than to stream erosion (Figure 5). Examples include streams of the North Shore flowing southwest into the upper Waitemata Harbour, the location of the western Auckland isthmus catchment boundary within 1 km of Manukau Harbour, and streams draining Howick and Pakuranga first flowing south, then west to the Tamaki River, then north into the Waitemata Harbour.

A slope gradient map of the Auckland region (Figure 16a) and 4 slope gradient maps of more localised areas (Figures 16b–16e) have been computed using GIS techniques. In Figure 16a, deeply dissected slopes are clearly visible in the Waitakere Ranges and northern Awhitu Peninsula along the west coast, and in the Hunua Ranges on the east coast. The flat Manukau Lowlands in the centre of the map are depicted in yellow. Straight NNW-trending lines in the southeast quadrant, separating different colour concentrations, represent the Wairoa, Waikopua and Hunua Faults.

In the northern Auckland region (Figure 16b), many valleys have steep southeast-facing slopes and gentle northwest-facing gradients. The dissected areas are mostly eroded Waitemata Group slopes; the flat areas represent valley infill covering Waitemata Group sediments. In the Auckland isthmus (Figure 16c), much of this area is smoothed over by ash deposits, with little pinnacles representing volcanic cones clearly visible. Northward-directed spurs along the northern third of the isthmus and steep south-facing slopes along the Hillsborough coast are developed on Waitemata Group terrain.

In western Auckland (Figure 16d), the most obvious feature on the map is the steeply dissected western portion, corresponding to the Waitakere Ranges, separated by a NNW-trending lineament from low-lying terrain around the shores of the upper Waitemata Harbour. In the centre, in the vicinity of the suburbs of Massey and Swanson, valleys are similar to those seen in Figure 16b, with steep southeast-facing slopes and gentle northwestern slopes. Southeastern Auckland (Figure 16e) is dominated by three contrasting topographies. The most steeply dissected area is the fault-bounded Maraetai Hills greywacke block. The moderately dissected areas are eroding Waitemata Group sediments, and the yellow areas are the Manukau Lowlands, East Tamaki and the Clevedon Valley. The NNW-trending Waikopua Fault and curved NNE-trending Papakura Fault are clearly visible.

Using the exposed Waitemata Group erosion surface as a guide, it has been possible to estimate the most likely morphology for the erosion surface that is now covered by more recent material, especially by products of the AVF. Borehole data has provided an invaluable source of information regarding depth to the erosion surface, but only where it has been judged to be reliable.

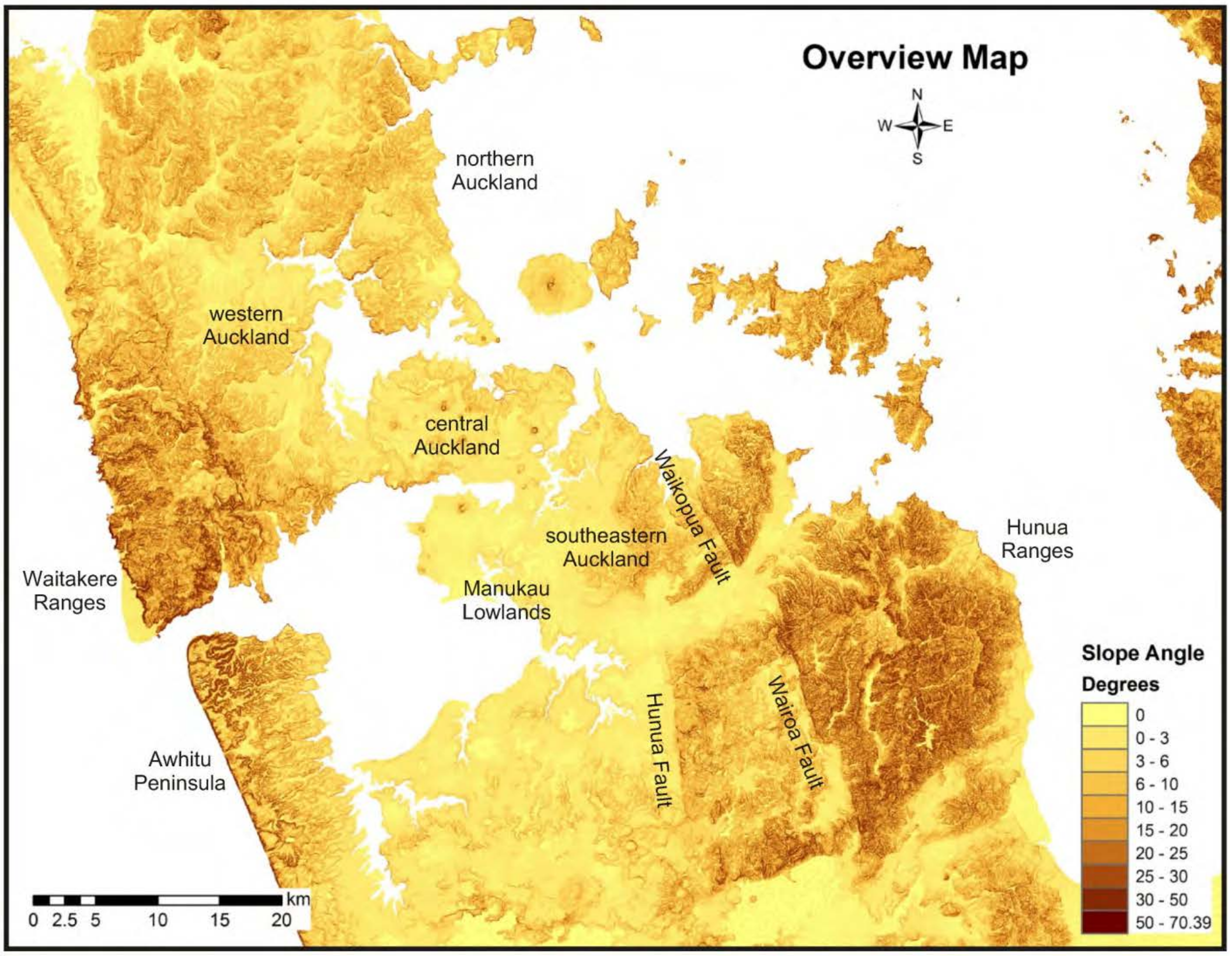


Figure 16a: Slope gradient map for the Auckland region, from flat planes or plateaux in yellow to steep hillsides in dark brown. No height elevations are implied.

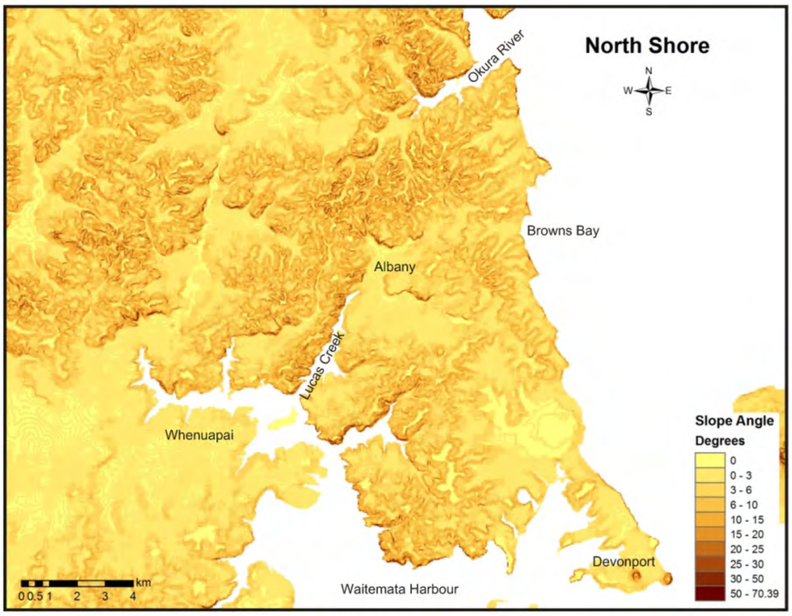


Figure 16b: Slope gradient map for northern Auckland.

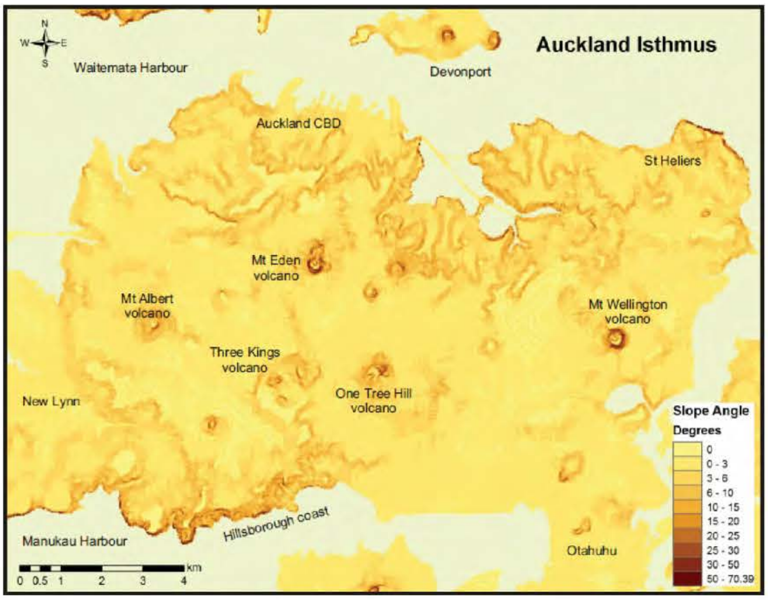


Figure 16c: Slope gradient map for central Auckland region.

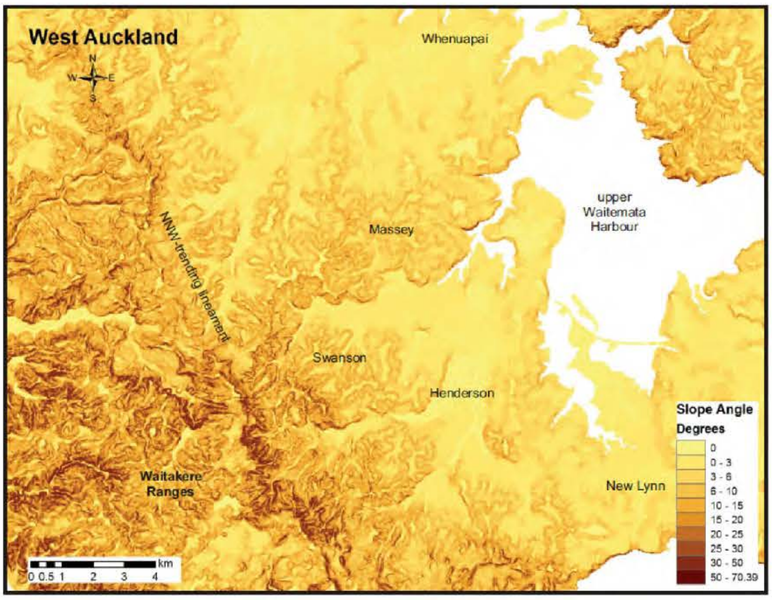


Figure 16d: Slope gradient map for western Auckland region.

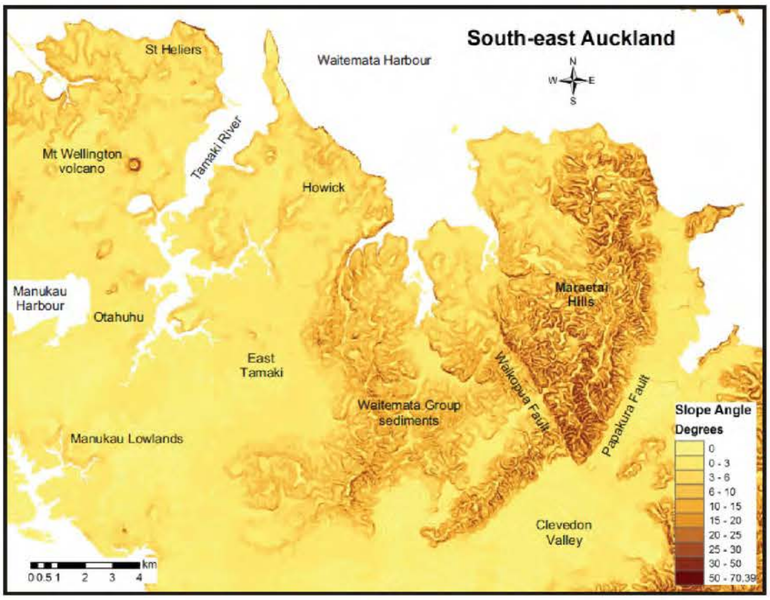


Figure 16e: Slope gradient map for southeastern Auckland region.

THE EFFECT OF THE OVERPRINTED AUCKLAND VOLCANIC FIELD

During the reconstruction of the erosion surface in the central isthmus and surrounding areas, the AVF was not taken into consideration, with the following exceptions:

1) As lava usually flows down topographic lows, the path of lava flows pinpoints pre-existing valleys in the Waitemata Group erosion surface. We assume these would not have over-topped catchment boundary ridges unless the valley had filled up first. Vast lakes of lava have formed across the central Auckland isthmus and around the Mt Wellington–Ellerslie area. Lava has poured down valleys and ponded, sometimes to considerable depths. The flat lava lake surfaces make estimating the original topography in these areas very difficult without borehole data. Lava flows escaping from these lakes would also flow down pre-existing valleys. Identifying the source vents can assist in contouring appropriate valley systems back to those vents.

2) Tuff conceals the erosion surface around the volcanoes. However, the more distal tuffs only amount to a relatively thin veneer that tends to mantle the pre-existing topography, retaining its basic shape, but at a slightly elevated height. So the ridges and valleys of the underlying landscape may be interpreted with increasing precision with distance from the vents.

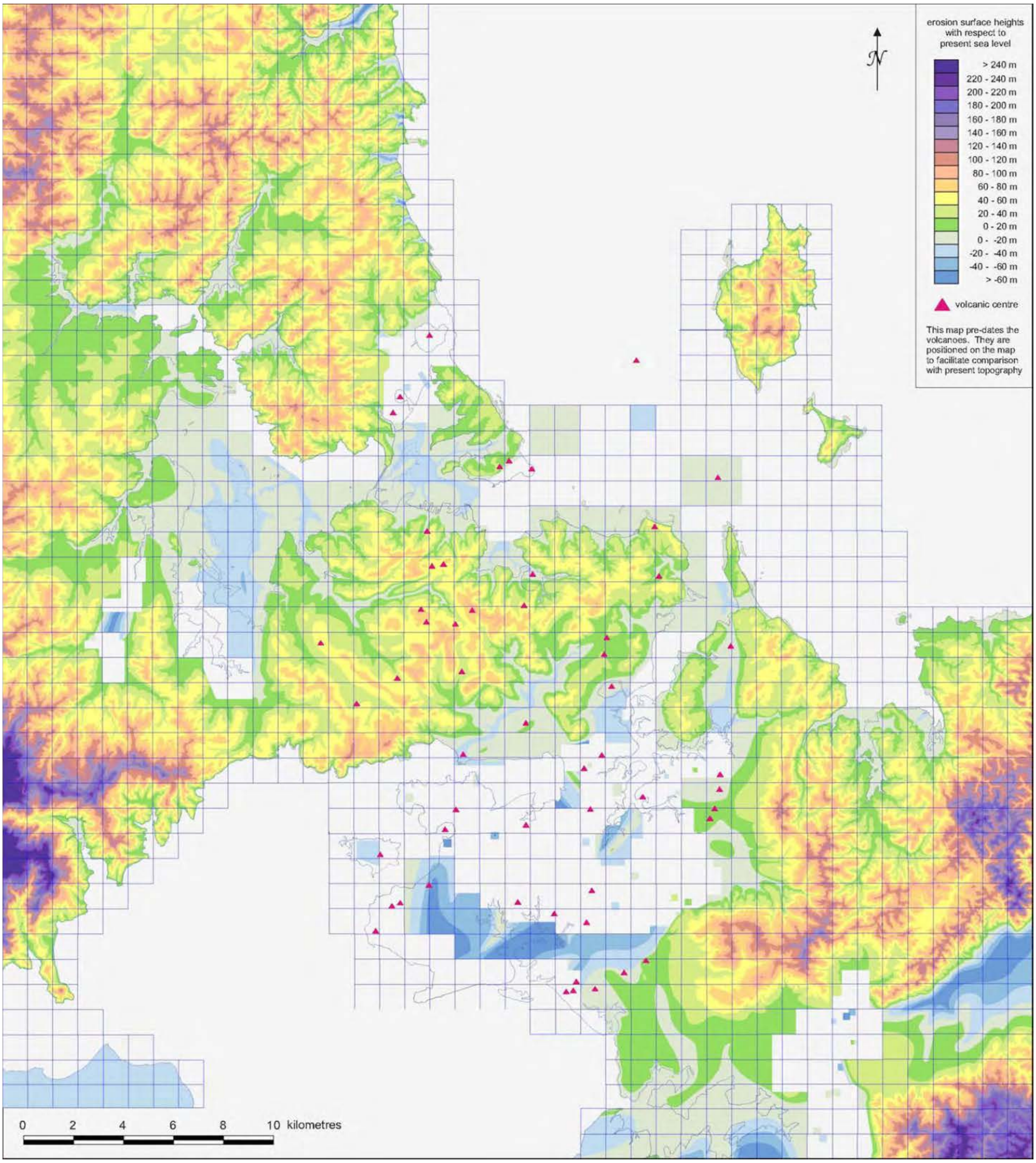
3) Inward-flowing depressions do not form naturally in the typical Waitemata Group dendritic drainage patterns. The only hollows in the erosion surface have been created by volcanic eruptions of the AVF blasting out explosion craters. Therefore any basin-like shapes determined from borehole data in the vicinity of volcanic vents probably represent explosion craters associated with those volcanoes, giving an artificially deep reading to the erosion surface. These boreholes have been disregarded and the erosion surface manipulated accordingly. Two geophysical studies (Affleck *et al*. 2001, Murray 2010) modelled the erosion surface of confined areas of the Auckland isthmus. Unfortunately, because the subtleties of typical drainage in this region were not considered, basin shapes appear in both models. They have also been disregarded here.

WAITEMATA GROUP "PALEO-SURFACE"

The description of the Waitemata Group erosion surface as a "paleo-surface" is not correct sensu stricto, although it is a surface eroded in former times. More precisely, it should be regarded as the top of the Waitemata Group as it exists at the present time, whether exposed or concealed.

Four new contoured topography maps were produced for this study – one map encompassing the whole area under investigation (Figure 17) at the same scale and colour scheme as the current topography map (Figure 5) and three detailed maps of specific areas, namely upper Waitemata Harbour, Auckland isthmus and Manukau Lowlands (Figure 18a–c). Volcano positions have been retained only to assist comparison with Figure 5. Although most of the coloured contours represent the upper surface of the Waitemata Group sediments, in the high eastern terrain, the Waitemata Group has been removed by erosion, exposing basement rocks, invariably greywacke, and this is what formed the depicted surface.

Figure 17: Topography of the eroded surface of the Waitemata Group as it is today, including that which is now concealed under younger sediments or volcanic material. Terrain in the highest eastern areas, where Waitemata Group sediments have eroded away, is greywacke. Patches of white represent areas of unknown depths.



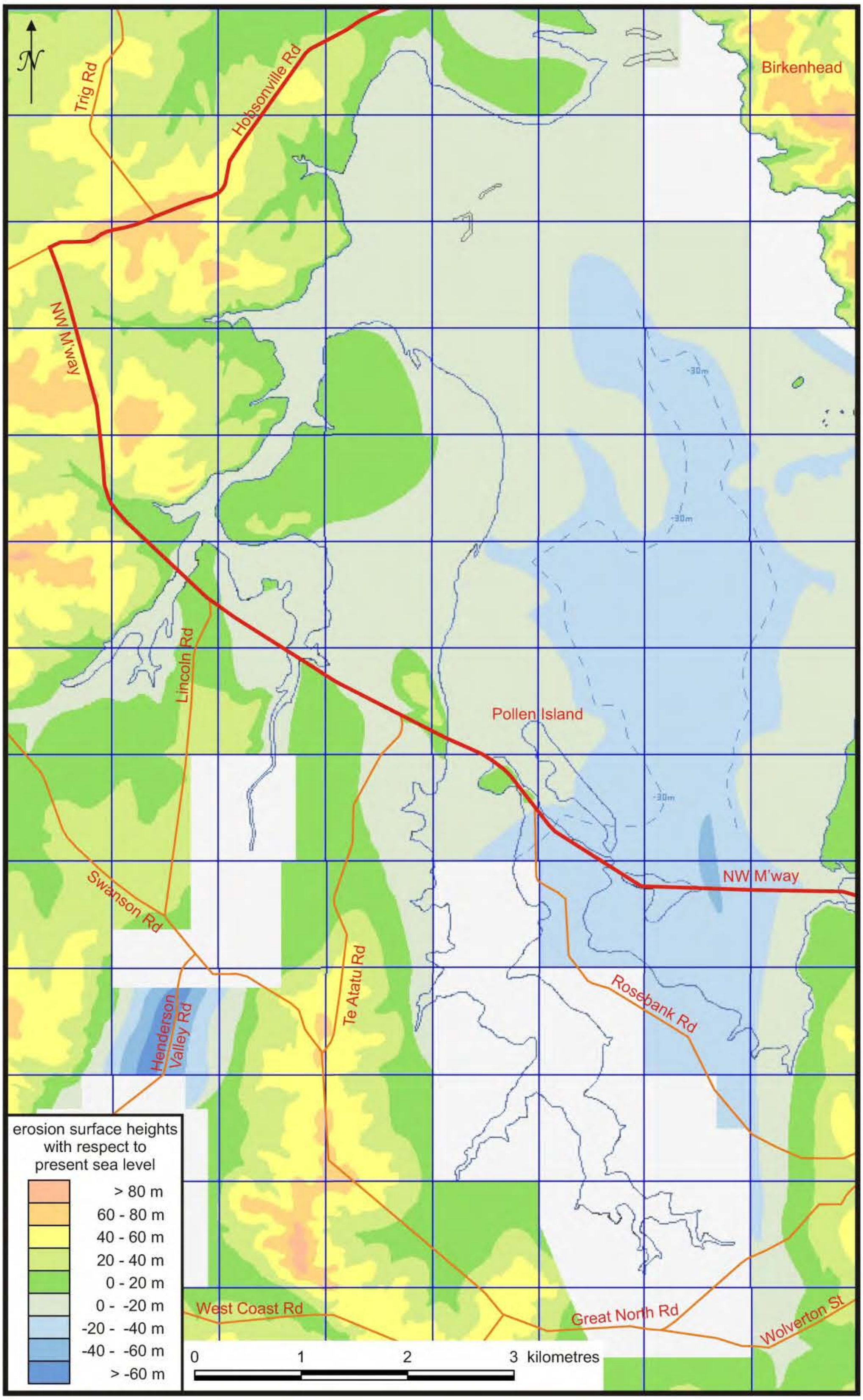


Figure 18a: A detailed map of the topography of the eroded surface of the Waitemata Group in the upper Waitemata Harbour area. Major roads have been added to provide orientation. Patches of white represent areas of unknown depths.

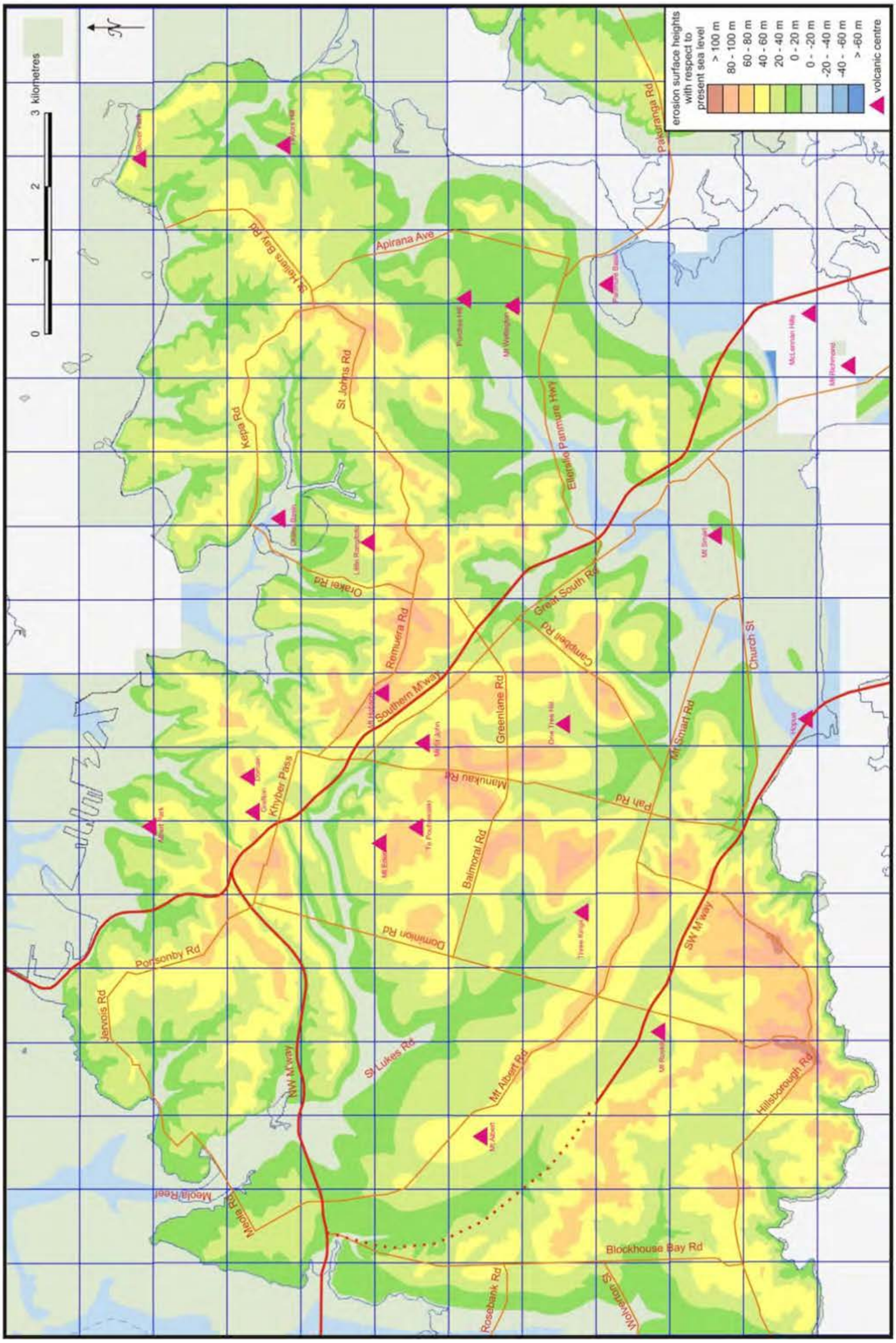


Figure 18b: A detailed map of the topography of the eroded surface of the Waitemata Group in the Auckland isthmus. Major roads have been added to provide orientation. Patches of white represent areas of unknown depths.

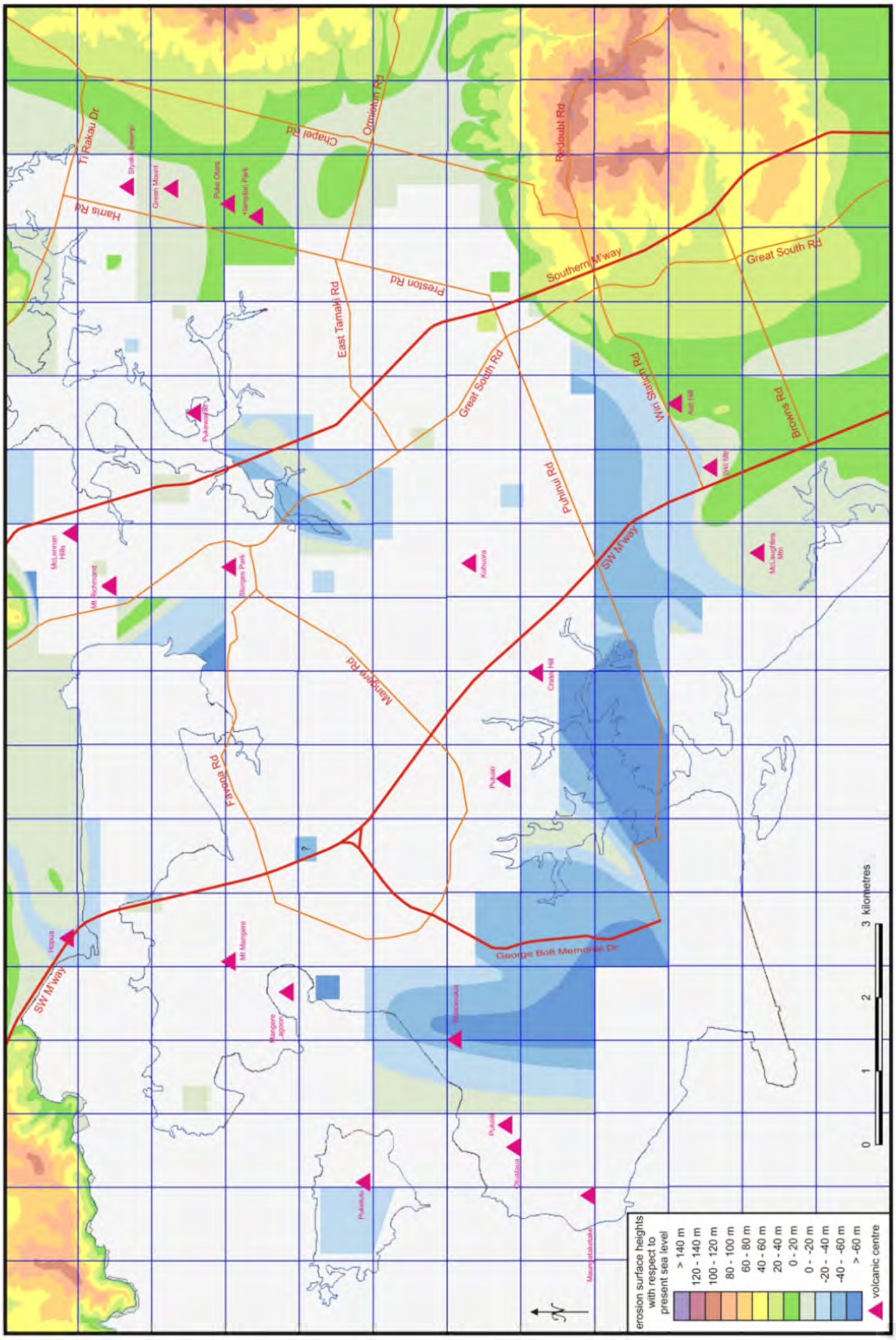


Figure 18c: A detailed map of the topography of the eroded surface of the Waitemata Group in the Manukau Lowlands. Major roads have been added to provide orientation. Patches of white represent areas of unknown depths.

The map (Figure 17, supported by Figures 18a–c) shows contours of the Waitemata Group surface, with the superficial sediments stripped away. One of the most obvious changes from Figure 5 is that the area above present sea level is almost halved. If these conditions existed today, ie. no cover sediments, most of the Manukau Lowlands, including Otahuhu, East Tamaki and Botany, and a large area of the upper Waitemata Harbour, including Avondale, Te Atatu Peninsula and Hobsonville, would be underwater. Onehunga and Panmure would also be inundated, separated by Hamlins Hill "peninsula". There would be seaways along the Tamaki River and Clevedon Valley connecting the Waitemata and Manukau Harbours, making the large Howick–Manukau Heights–Maraetai Hills block into an island and disconnecting Auckland isthmus and Northland from the rest of New Zealand. Pakuranga, Bucklands Beach, Devonport and Bayswater would be islands as well, and there would be long incursions of seawater into Henderson, Newmarket, Ellerslie, Kingsland and Glen Innes, also reaching almost to Albany and Coatesville (Figure 17).

It is debatable, however, whether a seaway ever existed along the Tamaki River. The present catchment boundary between the Waitemata and Manukau Harbours is at Otahuhu, and is composed of volcanic material ejected from 4 volcanoes. Prior to their eruptions tens of thousands of years ago, the Tamaki River used to flow southwestwards and drain into the Manukau Harbour. The Tamaki River was dammed at Otahuhu by the volcanic detritus, and ponded. It eventually broke through the erosion-prone low ridge Waitemata-Manukau catchment boundary between Glendowie and the southern end of Bucklands Beach. It was then able to flow northwards, through that old catchment boundary, into the Waitemata Harbour. The reason for the catchment boundary's vulnerability to erosion will be discussed in the next section, under faults of the Auckland isthmus.

Similarly, a seaway through the Clevedon Valley may not have actually existed, with the depth to the Waitemata Group erosion surface being the result of down-faulting c. 2 Ma ago, rather than erosion. Rather than a seaway, the existence of a Clevedon River flowing west in this half graben, feeding Coromandel-derived pebbles to the Manukau Harbour, has been contemplated recently (Hayward & Grenfell 2010). Much of the erosion surface is well below sea level now, and would certainly form a seaway if the superficial sediments were removed.

The map in Figure 17 also looks strangely bare with Rangitoto and Browns Island volcanoes removed, but it highlights how exposed to erosion much of the Waitemata Harbour coastline would have been prior to eruptions of Rangitoto c. 600 years ago.

Having dismissed the likelihood of inward-flowing hollows in the drainage pattern, unless they represent explosion craters, a few large depressed areas are thought to have been formed by fault displacements. In times of lower sea level, as would have existed numerous times during the Ice Ages, the upper Waitemata Harbour would have been dammed by a low ridge where the Harbour Bridge is now, forming a lake. The horizon of white pumiceous clays at localities from Avondale to Hobsonville attests to this. A very deep depression has also been discovered from borehole data in the Henderson Valley (Figures 17 and 18a). Fault-controlled depressions are also postulated at Clevedon and Alfriston, where an inadequate number of boreholes suggest that the erosion surfaces are very deep, separated by a shallower ridge (Figure 17). There is also a possibility that the Lloyd Elsmore Graben in Pakuranga has no drainage outlet in the erosion surface; the present day outlet westwards through Pakuranga Creek has a shallower erosion surface than the down-faulted graben. There is unlikely to be a viable outlet northwards or southwards along the trend of the graben. Other fault-controlled hollows in the erosion surface could exist in the Manukau Lowlands, but with insufficient borehole coverage, it is impossible to complete the map in this region (Figures 17 and 18c).

The large pedestals of lava around Mt Eden and One Tree Hill conceal many subtleties in the old terrestrial landscape. Long, gently-inclined valleys protrude far into the Auckland isthmus. One sinuous valley, now only visible as far as Newton Gully, originates between Mt Hobson and Mt St John, converging with a straighter valley from Three Kings before reaching the Waitemata Harbour at Meola Reef (Figure 17 and top left corner of Figure 18b). Lava flows from Mt Roskill have filled a straight valley parallelling the Southwestern Motorway northwestwards from a saddle at Hillsborough Road. Lava flows from Mt Albert blocked the lower valley, creating a swamp in the upper valley and forcing the present stream to detour to the west (Figures 17 and 18b).

The Manukau Harbour encroached into Onehunga. From there, steep valleys drained the area now under One Tree Hill, Ellerslie Racecourse, Lake Waiatarua and Ellerslie-Panmure Highway (Figures 17 and 18b). Huge volumes of lava have virtually filled these valleys; those around One Tree Hill have been completely inundated, and lava has even over-topped saddles in the ridgeline to the east to reach the valley now occupied by the Southern Motorway (Figure 18b).

POSITIONING OF LARGE SCALE FAULTS IN THE AUCKLAND REGION

From this new insight into Auckland's hidden topography, large-scale faults have been postulated (Figure 19), using all the evidence available from borehole data, lineaments and long straight valley alignments, topographic and lithologic offsets, and geophysical parameters. None of the faults can actually be seen in the field. They have all been determined indirectly by some combination of speculated evidence (attributes), such as offset of the Waitemata Group erosion surface, presence of long straight valleys, strong lineaments and geophysical parameters (Table 1). Offsets of the Waitemata Group erosion surface are often hidden by eruptive products of the AVF or by thick layers of post-Miocene sediments. Therefore it has been necessary to judge offsets in the Auckland isthmus and Manukau Lowlands using discrepancies in depth to the erosion surface in neighbouring boreholes. With all these methods, positioning of each new fault is inherently imprecise.

Each attribute, when examined separately, gives only a vague indication that a fault may exist in that vicinity at depth. When all available attributes are combined, however, they add increasing certainty for the existence and placement of concealed faults. Attribute tables, listing 8 independent criteria for recognition, have been devised and give a confidence rating for each new fault. The confidence rating of high, moderate or low, defined as having 5–8, 3–4, and 1–2 attributes, respectively, has then been transferred to maps of the new faults. These will be described later.

A nodal analysis of intersections and cross-cutting relationships of new faults has not been attempted because the degree of accuracy needed for this type of analysis adds an element of certainty for new inferred fault placements that is not yet justifiable. Many new faults have been mapped as stopping short of a possible intersection with another fault for this very reason, even if cross-cutting relationships have been estimated. Each new inferred fault is described in the Appendix, and if an intersection with a neighbouring fault is known or probable, it is mentioned in the description.

For the purposes of positioning the proposed new faults on the map, any alignment of Quaternary volcanoes belonging to the AVF, or proximity of proposed faults to these volcanoes, has been deliberately disregarded, so as not to influence the mapping process. The relationship between postulated faults and volcanic vents is discussed later.

Using the newly proposed faults together with previously known and inferred faults, two faulting regimes have been recognised: 1) a series of cuspate, low-angle faults and 2) regional criss-crossing normal faults, the latter of which have disrupted the former (Kenny 2007, 2008a, 2008b).

LARGE SCALE BLOCK FAULTS TRANSVERSING THE AUCKLAND REGION

The most obvious faults displayed in Figure 19 are large-scale, near-vertical, cross-cutting regional faults, mostly aligned in NNW or ENE directions. Attributes for each fault and consequent confidence ratings are listed in Table 1 and shown as different strengths of colour in Figures 20a & b. The faults are described individually in the Appendix.

No faults fulfil all eight attribute categories (Tables 1, 2). Only four faults attain a confidence rating of seven. These faults are the Wiri Fault extension (east of the Wiri Fault, separating Manukau Heights from East Tamaki lowlands in the southern part of the study area), the Bucklands Beach Fault (offsetting the Howick block from the Pakuranga block in eastern Auckland, Figure 21), and the Oratia and Henderson Faults in western Auckland (down-dropping the Henderson Valley between them).

Inferred faults and disrupted zones offshore have been included (second to last entry in Table 1 and Figures 20a & b), although their existence and positioning are uncertain. Inadequate numbers of airgun seismic reflection lines and Boomer seismic sections have been carried out in the Waitemata Harbour and Hauraki Gulf and none have been achieved in the Manukau Harbour. Most of these seismic sections are difficult to decipher, with problems including few reflectors, disappearing reflectors or poor penetration into the strata (Davy 2008, Kenny, pers. obs. with B.Davy, GNS, 2011). Some sections are highly disrupted and riddled with faults (eg. Figure 22, sampled offshore from Beachlands); other sections have no obvious structures. The most reliable of these faults only reach a low confidence rating in their own right. Some of these are also attributed to on-land faults inferred in this study, adding one point to their individual confidence ratings.

One would assume that previously recognised faults coloured blue in Figures 20a & b should attain a high confidence rating, as they appear in multiple literature sources. However, with the exception of the blue-coloured splay faults offshore from the west coast, they have not been considered reliable enough to be added to the QMAP (Edbrooke 2001) because they appear only in the grey literature (reports, theses, newsletters) and therefore have not been peer-reviewed. As an experiment, we have assessed them according to our confidence scheme (Table 1) to establish how they compare with new faults inferred in this study. Surprisingly, as a generalised group they only attain a moderate confidence rating. This is because they tend to be buried by more recent material, so the existence of strong lineaments or long straight valleys is not known, and therefore cannot be included in the confidence rating process, losing 2 points. They also tend not to be continuations of known faults, having been mapped as independent entities, irrespective of positions and trends of known faults nearby. This reduces their potential confidence rating by another point, lowering it into the moderate confidence rating category. Interestingly though, this lower rating highlights the rigour of the ranking system, and means we can be quite confident in the existence of the new inferred faults ranked with a “high level of confidence” (Table 2).

Previously recognised faults, coloured black in Figures 20a & b, as well as those blue-coloured splay faults offshore from the west coast, have appeared in peer-reviewed literature and have been accepted as reliable in the QMAP mapping programme (Edbrooke 2001). These have therefore not been scrutinized in Table 1.

Figure 19: Large scale faults, both published and inferred in this study, superimposed on the topography of the eroded surface of the Waitemata Group (Figure 17). Areas of white represent unknown depths.

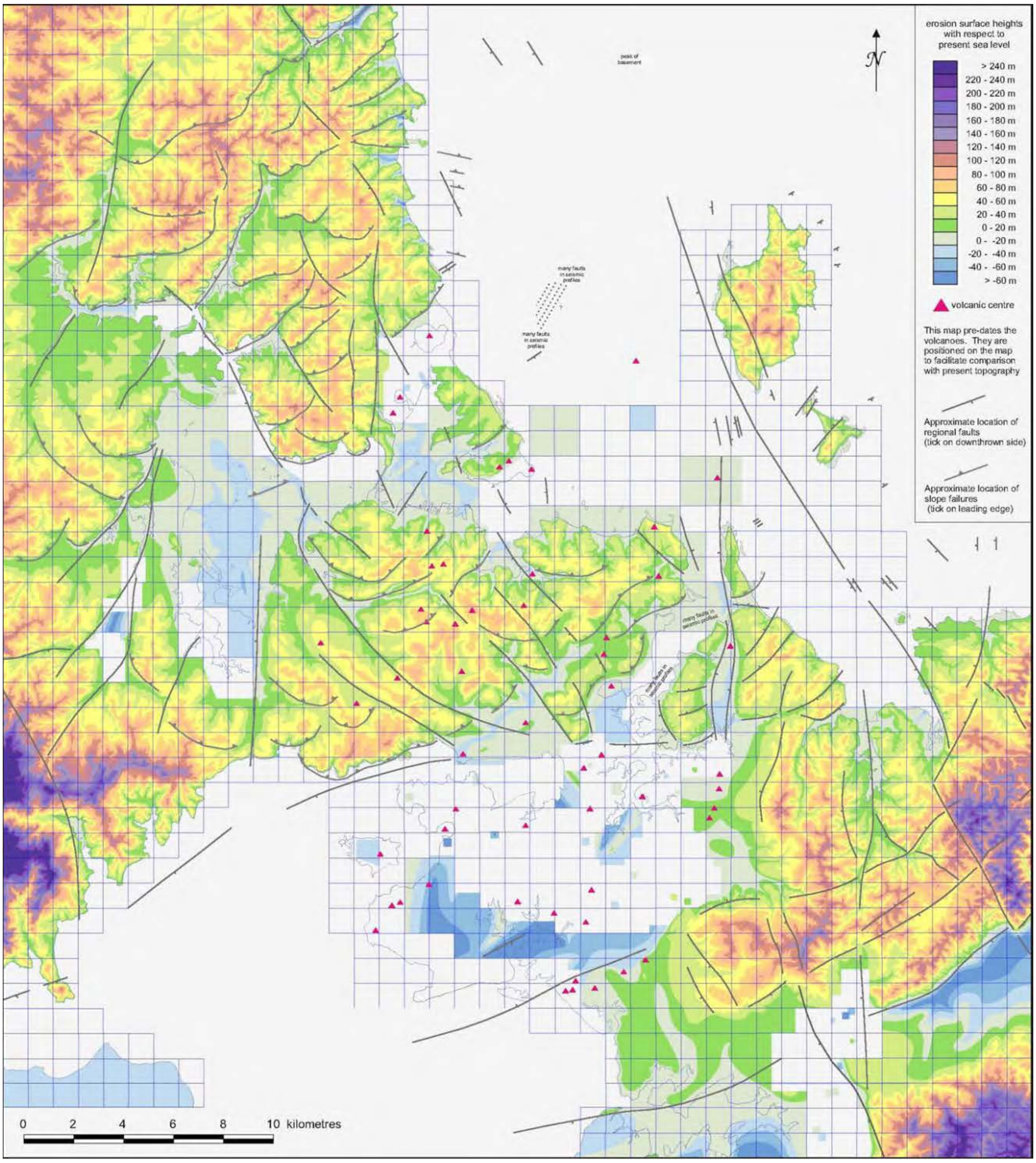


Table 1: Confidence ratings of new inferred regional faults. Each 'criterion for recognition' in the attribute list for each fault is given one point, leading to an individual confidence rating score. Scores of five or more are given a higher confidence rating, scores of three of four, a moderate confidence rating, and scores of one or two only a low confidence level.

Fault name	**Attribute List**								**Comments**	**CONFIDENCE RATING**
	Facing direction (downthrown)	**Criteria for recognition**								
		Borehole information	Topographic offset	Lithologic offset	Strong lineament(s)	Truncates other lineaments Long straight valley(s)	Continuation of known fault	Geophysical data		
SOUTHERN MANUKAU LOWLANDS, PAPAKURA, CLEVEDON										
Wiri Fault extension	north	1	1	1	1	1	1	1	Lithologic offset is buried	7
Weymouth Fault	west	1	1			1				3
Manurewa Fault	west		1		1					2
Fault linking Polo Lane Fault with Wiri Fault	north		1		1	1	1			4
Alfriston Fault extension	north				1	1	1			3
Western extension of Brookby Fault	south	1	1	1	1	1	1			6
NORTHERN MANUKAU LOWLANDS, MANGERE, PAPATOETOE										
Puhinui Fault	west		1		1					2
West Mill Road Fault	east		1		1				Continuation of other only inferred faults, so not included in criteria	2
East Mill Road Fault	west		1		1		1			3
Ihumatao Fault	south	1	1						Topographic offset is buried	2
Manukau Fault	south		1	1	1					3
Cornwallis Fault	south	1	1	1			1			4
FAR WEST, AWHITU PENINSULA										
Awhitu Fault	east		1				1			2
Faults on Awhitu Peninsula	various	1		1				1	Lithologic offset is buried. Continuation of other only inferred faults, so not included in criteria	3
FAR EAST, WHITFORD, BEACHLANDS										
North Waikopua Fault	west	1	1	1	1	1	1	1	? Continuation of Waikopua Fault	6
Drury Fault extension	west						1	1	Likely to be down-thrown to west	2
Turanga Fault	west	1	1	1	1	1 1				6
NEAR EAST, HOWICK, PAKURANGA, EAST TAMAKI										
Dannemora Fault	west	1	1	1		1			Continuation of other only inferred faults, so not included in criteria	4
Somerville Fault	south		1		1	1			Curved fault that deserves a higher confidence rating, but doesn’t fit some of the criteria of this table.	3

Table 1 continued

Fault name	Attribute list									Comments	CONFIDENCE RATING
		Criteria for recognition									
	Facing direction (downthrown)	Borehole information	Topographic offset	Lithologic offset	Strong lineament(s)	Truncates other lineaments	Long straight valley(s)	Continuation of known fault	Geophysical data		
Meadowlands Fault	south	1	1	1		1	1			Continuation of other only inferred faults, so not included in criteria	5
Panama Fault	south	1	1			1				Continuation of other only inferred faults, so not included in criteria	3
Pakuranga Fault	west		1			1			1		3
Stanniland Fault	east	1	1	1		1	1	1			6
Bucklands Beach Fault	west	1	1	1	1	1	1		1	Continuation of other only inferred faults, so not included in criteria	7
Howick Fault	west		1		1	1	1			Continuation of other only inferred fault, so not included in criteria	4
Mellons Bay Fault	west		1		1	1	1				4
MacLeans Fault	west		1	1	1	1				Offsets erosion-resistant lithology	4
Eastern Beach Fault	north		1	1		1				Offsets Parnell Grit	3
INNER HAURAKI GULF ISLANDS											
Islington Bay Fault	west	1	1	1					1		4
Whangaparaoa Passage Fault	west			1					1	Continuation of other only inferred fault, so not included in criteria	2
AUCKLAND ISTHMUS											
Glendowie Fault	south		1		1	1	1				4
Karaka Fault	east		1							Continuation of other only inferred fault, so not included in criteria	1
Hobson Bay Fault	west		1		1		1				3
Hamlins Fault	east		1			1				Continuation of other only inferred fault, so not included in criteria	2
Remuera Fault	east		1		1	1	1			Continuation of other only inferred fault, so not included in criteria	4
Penrose Fault	west	1	1		1	1	1			Continuation of other only inferred fault, so not included in criteria. Geophysical modelling across fault but presence of a fault not part of those computations, so missed	5
Newmarket Fault	?	1			1		1			Continuation of other only inferred fault, so not included in criteria	3

Table 1 continued

Fault name	**Attribute list**									**Comments**	**CONFIDENCE RATING**
	Facing direction (downthrown)	Criteria for recognition									
		Borehole information	Topographic offset	Lithologic offset	Strong lineament(s)	Truncates other lineaments	Long straight valley(s)	Continuation of known fault	Geophysical data		
Sandringham Fault	south	1	1		1		1				4
Stoddard Fault	south	1	1		1		1				4
Coxs Bay Fault	south		1		1	1	1				4
WEST AUCKLAND											
Avondale Fault	west	1	1	1	1	1	1				6
Kelston Fault	east		1		1	1	1				4
Oratia Fault	west	1	1	1	1	1	1	1			7
Henderson Fault	east	1	1	1	1	1	1	1			7
Swanson Fault	east	1	1	1	1	1		1			6
Opakunui Fault	south		1		1	1	1	1			5
East Scenic Drive Fault	east		1	1	1	1		1		Known fault, but now opposite facing direction, and extended at each end	5
West Coast vent alignment	?				1					Alignment of craters and volcanic necks	1
W & E Taupaki Faults	?				1		1			Strong lineaments but no topographic offsets	2
Brigham Creek Fault	east		1	1	1	1	1				5
Waiarohia Stream Fault	east	1	1		1		1				4
NORTH SHORE											
Alexandra Fault	east		1		1	1	1				4
Birkenhead Fault	west		1	1	1				1		4
Kaipatiki Fault	west		1		1	1	1				4
Glenfield Fault	east		1		1	1					3
Northcote Fault	east		1		1	1					3
Newly positioned sections of East Coast Bays Fault	west			1	1	1	1	1			5
Ngataringa Fault	east		1		1						2
NORTHEAST AUCKLAND											
Weiti Fault	west		1		1		1				3
Tindalls Fault	west		1			1	1				3
Shakespear Graben	E & W		1		1	1	1				4

Table 1 continued

Fault name	Attribute list									Comments	CONFIDENCE RATING
		Criteria for recognition									
	Facing direction (downthrown)	Borehole information	Topographic offset	Lithologic offset	Strong lineament(s)	Truncates other lineaments	Long straight valley(s)	Continuation of known fault	Geophysical data		
NORTHWEST AUCKLAND											
Rangitopuni Fault	east			1	1	1	1	1			5
Riverhead Forest Fault	?				1		1			Parallel to 3 other nearby faults that are downthrown to the east	2
Faults seen in offshore seismic profiles	various			1					1	Airgun and Boomer seismic sections in Waitemata Harbour and inner Hauraki Gulf	2
Previously recognised blue-coloured faults for confidence rating comparison as a group	various	1	1	1					1		4

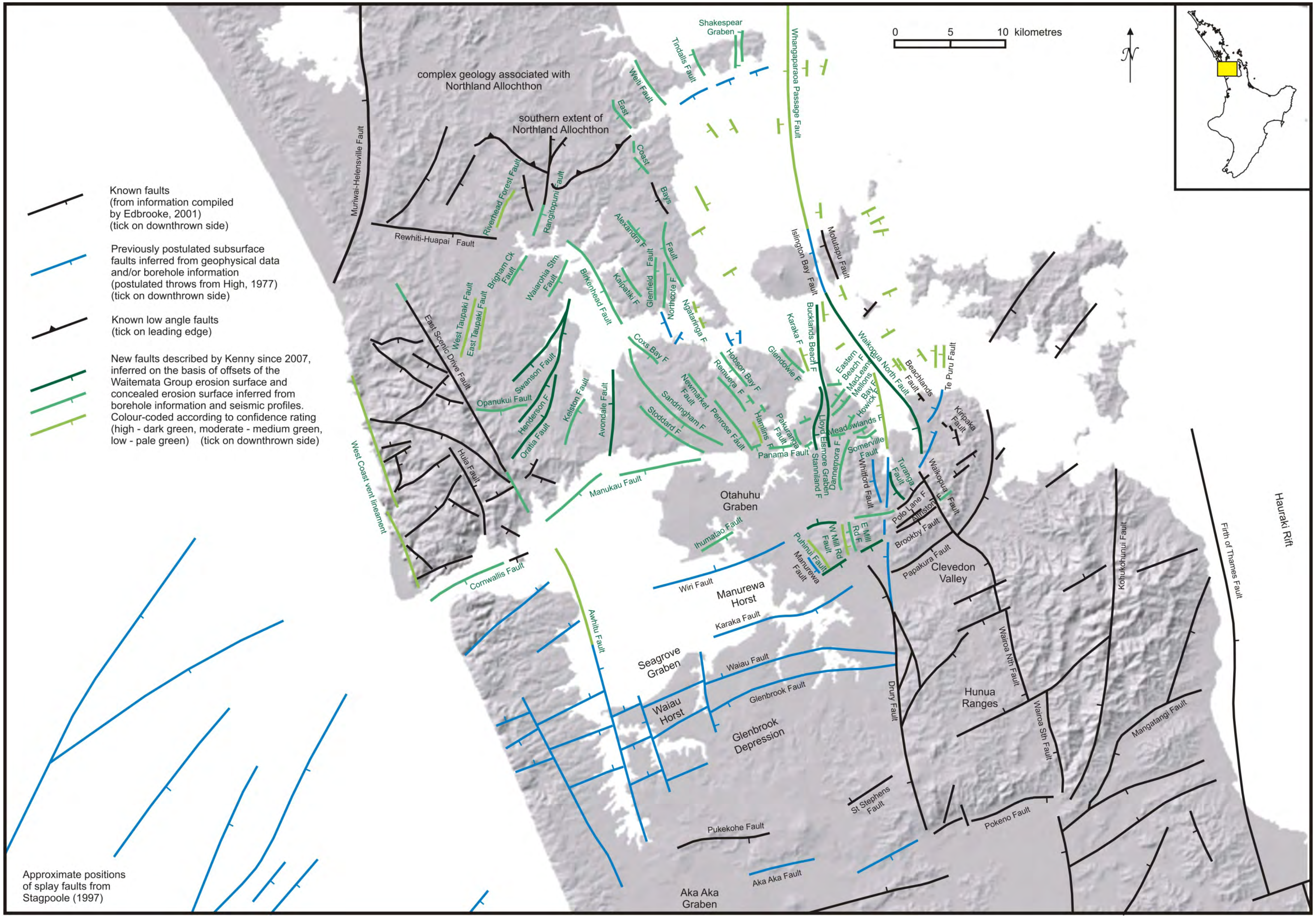


Figure 20a: Regional faults, both published and inferred in this study, superimposed on a greyscale map of Auckland. Confidence rating colours have been applied. Fault names have been added. The decrease in fault density in the region south of the Auckland isthmus is a function of limited borehole coverage rather than an absence of faults. See text for data sources.

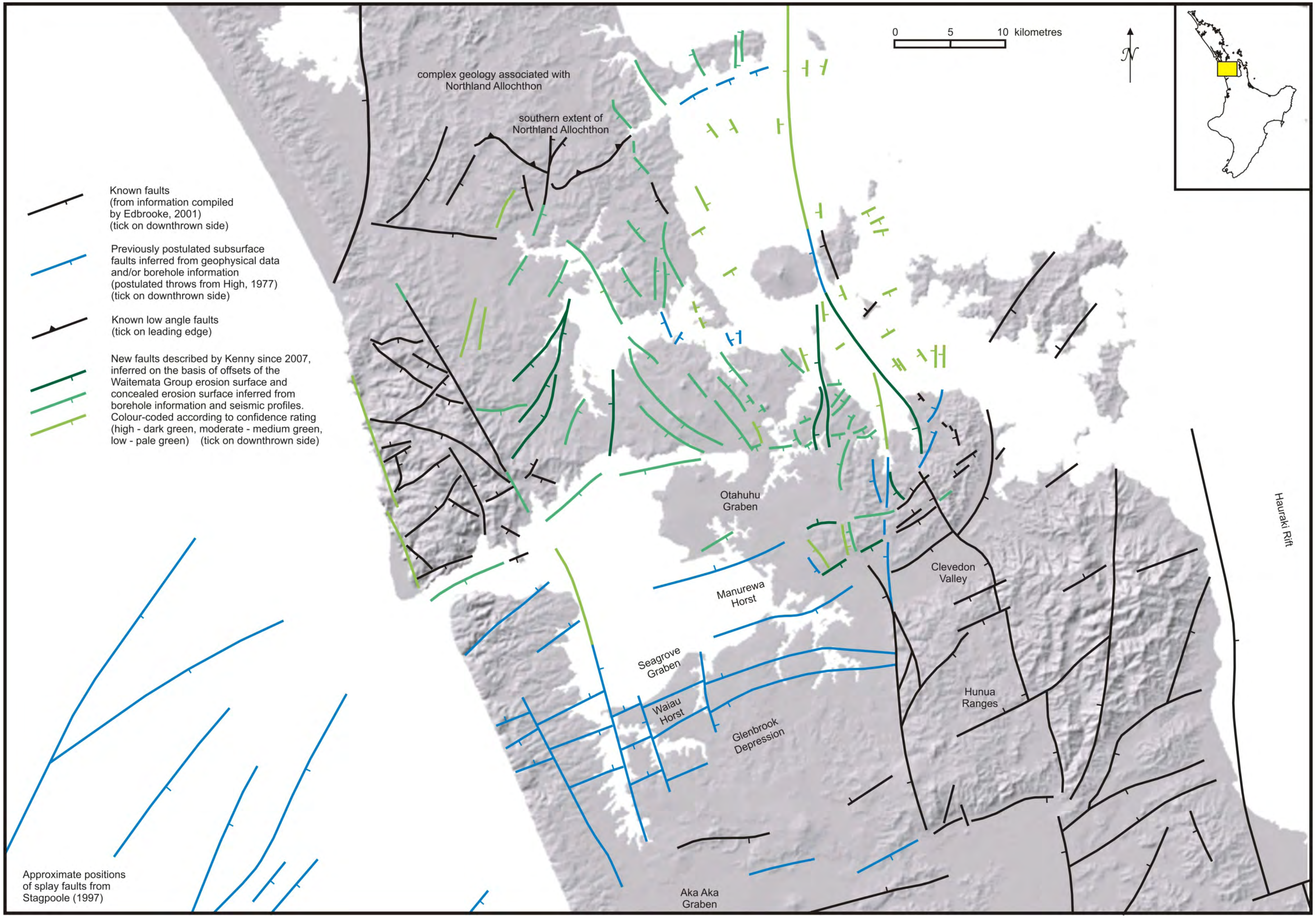


Figure 20b: The same map of regional faults as Figure 20a, but with fault names removed for clarity.

Figure 21: Approximate position of the new inferred Bucklands Beach Fault (white arrows), photographed towards the SSE from the lower slopes of Pigeon Mountain volcano. Pigeon Mountain and the houses in the foreground are situated on the downthrown Pakuranga block, west of the fault, while the slopes in the background of the photo (above the arrows) are located on the upthrown Howick block, east of the fault. The lime green building in the centre of the photo is on the fault.

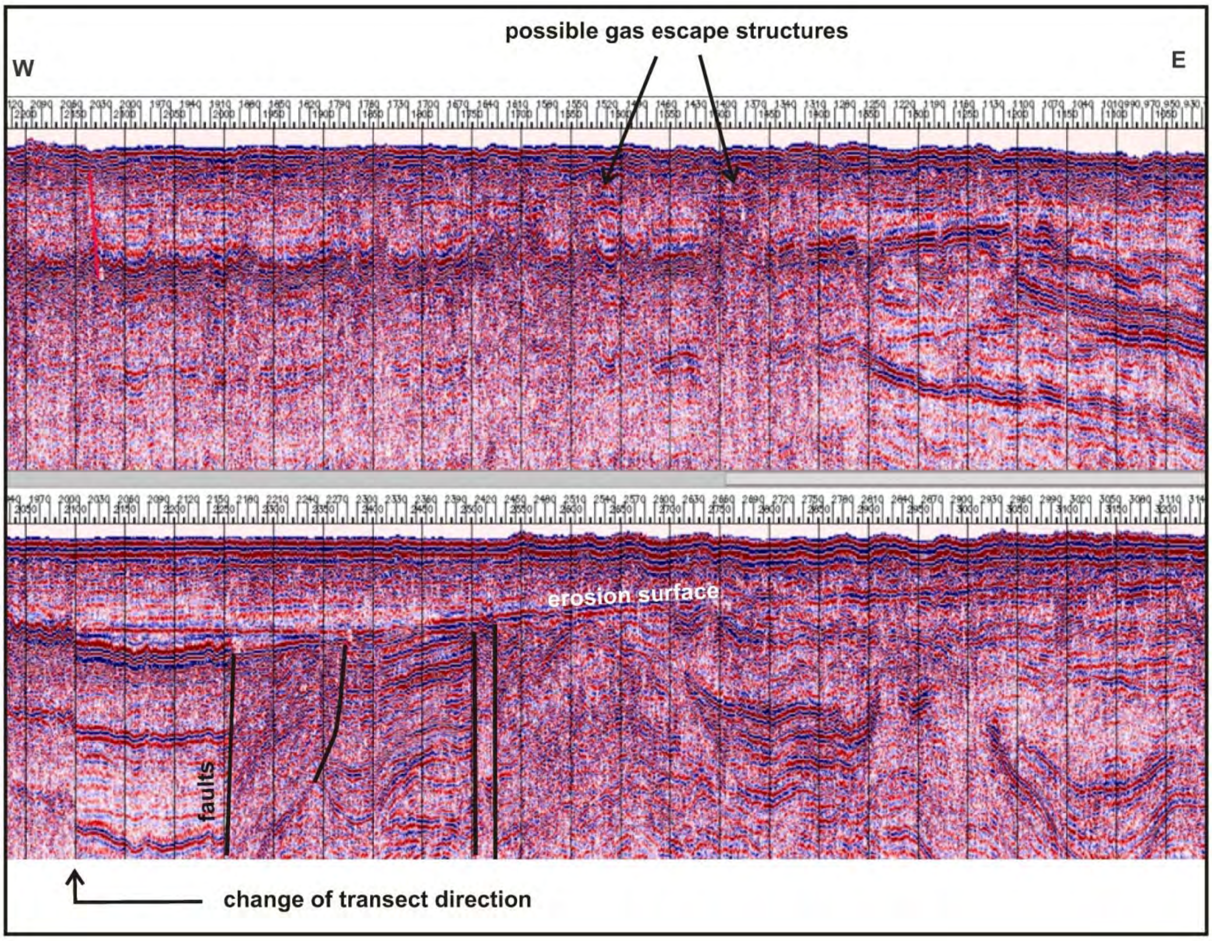


Figure 22: Fault disruption of strata north of Beachlands, as displayed in two parallel west to east Boomer seismic sections, each about 6km long. Some possible faults have been informally identified by B. Davy (2011) (red near-vertical lines), while other disruptions have been left untouched so that the features are not obscured. Seismic profiles are considerably vertically exaggerated.

ANALYSIS OF REGIONAL BLOCK FAULTING

Figures 19, 20a & 20b show distinctive fault trend patterns. Faults do not intersect on these maps. They are deliberately drawn imprecisely to reflect the inherent lack of accuracy of contour lines on the concealed Waitemata Group erosion surface. Despite a number of fault attributes and reasonable confidence ratings listed in Table 1, all inferred faults are still too inaccurately positioned to predict cross-cutting relationships. Only 23 percent of the inferred faults attain a high confidence rating (Table 2); more than half the faults reach a moderate confidence level.

The maps are dominated by NNW-trending faults, most of which are down-thrown to the west. They are inferred to be northern equivalents to the NNW-trending regional faults displaying NE-SW extension (Spörli & Rowland 2007), such as the Drury, Wairoa and Waikopua Faults in the southeast of the study area.

In the east, the Wairoa-Waikopua Fault system appears to step dextrally along the Te Puru Fault plane, then continue along the west coast of Beachlands as the North Waikopua Fault. The Drury Fault trace is difficult to follow in the Alfriston area. One splinter could continue north into the Turanga Valley and converge with the Waikopua North Fault northwest of Beachlands. The other splinter could link with the East Mill Road, Dannemora and Bucklands Beach Faults,

Table 2: New inferred faults listed in order of highest to lowest confidence rating. Faults are listed in alphabetical order within each confidence rating group.

High confidence level (rating 5 – 8)

Avondale Fault
Brigham Creek Fault
Bucklands Beach Fault
East Coast Bays Fault
- newly positioned fault sections
East Scenic Drive Fault
Henderson Fault
Meadowlands Fault
North Waikopua Fault
Opakunui Fault
Oratia Fault
Penrose Fault
Rangitopuni Fault
Stanniland Fault
Swanson Fault
Turanga Fault
Western extension of Brookby Fault
Wiri Fault extension

Moderate confidence level (rating 3 – 4)

Alexandra Fault
Alfriston Fault extension
Birkenhead Fault
Cornwallis Fault
Coxs Bay Fault
Dannemore Fault
East Mill Road Fault
Eastern Beach Fault
Faults on Awhitu Peninsula
Fault linking Polo Lane Fault with Wiri Fault
Glendowie Fault
Glenfield Fault
Hobson Bay Fault
Howick Fault
Islington Bay Fault
Kaipatiki Fault
Kelston Fault
Manukau Fault
MacLeans Fault
Mellons Bay Fault
Newmarket Fault
Northcote Fault
Pakuranga Fault
Panama Fault
Remuera Fault
Sandringham Fault
Shakespear Graben
Somerville Fault
Stoddard Fault
Tindalls Fault
Waiarohia Stream Fault
Weiti Fault
Previously recognised blue-coloured faults for confidence rating comparison as a group

Low confidence level (rating 1 – 2)

Awhitu Fault
Drury Fault extension
Hamlins Fault
Ihumatao Fault
Karaka Fault
Manurewa Fault
Ngataringa Fault
Puhinui Fault
Riverhead Forest Fault
West & East Taupaki Faults
West Coast vent alignment
West Mill Road Fault
Whangaparaoa Passage Fault
Faults seen in offshore seismic profiles

forming the eastern boundary of the notable Lloyd Elsmore Graben, before also merging with the Waikopua North Fault near Islington Bay. Combined, they all become the Islington Bay Fault, along the west coast of Motutapu Island, which is inferred to continue northwards to become the Whangaparaoa Passage Fault. This NNW-trending fault system, from Drury through to Whangaparaoa Passage, forms an important boundary through the Auckland region, where greywacke outcrops sporadically to its east but no greywacke is known to outcrop to its west. In addition, no volcanoes of the AVF occur east of this boundary.

In the west, the East Scenic Drive Fault is inferred to continue southwards as the Awhitu Fault, both down-throwing the erosion surface to the east. The region between these faults and the Drury to Whangaparaoa Fault system has formed a long NNW-trending graben, bisected by an east-west step at the Manukau Fault. In the graben, on the northern side of the step, a series of small NNW-trending faults, mostly down-thrown to the west, can be followed across Auckland isthmus to the North Shore area. Because of paucity of borehole data, these faults have not been traced southwards across the Manukau Lowlands, however, they may be represented by the Manurewa, Puhinui, West Mill Road and East Mill Road Faults slicing through Manukau Heights. It is conceivable that these are all additional splinters of the Drury Fault, with a dominance of westward facing directions.

In western Auckland, east of the East Scenic Drive Fault, a series of north–NNE-trending splay faults dominate, and collectively have formed a small graben creating the northwestern portion of the upper Waitemata Harbour depression. Together with other faults inferred in the foothills of the Waitakere Ranges, they are similar to faults mapped by Hayward (1983) west of the East Scenic Drive Fault. Some of these faults are compatible with splay faults mapped off the west coast by Stagpoole (1997).

The Manukau Fault is also inferred to be related to Stagpoole’s (1997) splay faults. Together with its inferred associated faults, the Cornwallis, Panama and Meadowlands Faults, it forms a major ENE-trending step between the Auckland isthmus, Howick-Pakuranga block and western Auckland (all at intermediate elevation) and the Manukau Lowlands where the erosion surface is below sea level. South of this step, other ENE-trending faults are part of a N–S extensional regime, forming the Manurewa and Waiau Horsts, the Seagrove Graben and the Glenbrook Depression. The Seagrove Graben continues on the eastern side of the Drury Fault as the Clevedon half graben. The submerged Manurewa Horst rises eastwards in a series of steps created by the Manurewa, Puhinui and East Mill Road Faults to become the Manukau Heights ridge. Further east the ridge curves round to the north as the Maraetai Hill block.

The NNW- and ENE-trending faults intersect with various cross-cutting relationships. In the south of the area, concealed NNW trends are thought to truncate concealed ENE trends (High 1975, 1977, Berry 1986, Omerod 1989, Petch *et al*. 1991, Hull *et al*. 1995). Further north, these same cross-cutting relationships could continue, but mapping is not accurate enough to be certain. In one interesting cross-cutting pattern, a cacophony of faults converging at “the asterisk”, between Glendowie and Bucklands Beach created a zone of weakness in the catchment boundary area (Figure 20a & b). The pattern becomes even more “asterisk-like” when cuspate faults, described next, are added to the mix. This weakness was exploited by erosion that facilitated the break-through of the Tamaki River northwards after its original southwesterly drainage was dammed by volcanism at Otahuhu.

CUSPATE FAULTS IN THE AUCKLAND REGION

In the north, west and centre of Auckland all inferred regional faults truncate or offset a series of curved asymmetrical ridges. Each ridge has a steep slope facing approximately south and a gentle gradient on the northern side, giving the appearance of back-tilted blocks. They have a different geomorphic signature to the regional block fault pattern and give the impression of fanning outwards for more than 30 km across Auckland from the Coatesville area, reaching to Glen Eden in the west and Glendowie in the east. Coatesville is regarded as the southern limit of the southward-sliding Northland Allochthon (Spörli 1989, Hayward 1993).

Kenny (2008a, 2008b) explored the possibility that each cuspate ridge and steep south-facing slope could represent the intact hanging wall of an arc-shaped sub-horizontal fault tracking along the base of each slope. Together they form imbricate packets of dislocated Waitemata Group sediments. Bedding is essentially intact within each packet, while highly disrupted zones visible at many outcrops are thought to represent the basal slide planes of these packets.

A short attribute table (Table 3), similar to the more comprehensive table drawn up for the proposed regional faults (Table 1), gives a confidence rating for each new cuspate fault. The confidence rating of moderate or low has then been transferred to a map of cuspate faults (Figure 23). There is no high confidence rating for any of these cuspate faults. Many more imbricate packets are likely to exist on smaller scales, represented by smaller asymmetric cuspate patterns across the landscape, but including all such ridges has not been attempted.

Table 3: Confidence ratings of new inferred cuspate faults. Criteria for recognition of each fault, and confidence rating scores, are the same as those used in Table 1.

Fault name	**Attribute list**									**Comments**	**CONFIDENCE RATING**
		Criteria for recognition									
	Facing direction (downthrown)	Borehole information	Topographic offset	Lithologic offset	Strong lineament(s)	Truncates other lineaments	Long straight valley(s)	Continuation of known fault	Geophysical data		
Albany Slide	All sliding in southward direction		1		1	1	1	1		Previously recognised as a thrust fault	5
Riverhead Slide			1	1	1	1				All associated with southward-directed slope failure	4
Hellyers Slide			1		1	1			1		4
other cuspate faults on land			1			1					2
other cuspate faults seen in seismic profiles in inner Hauraki Gulf				1					1		2

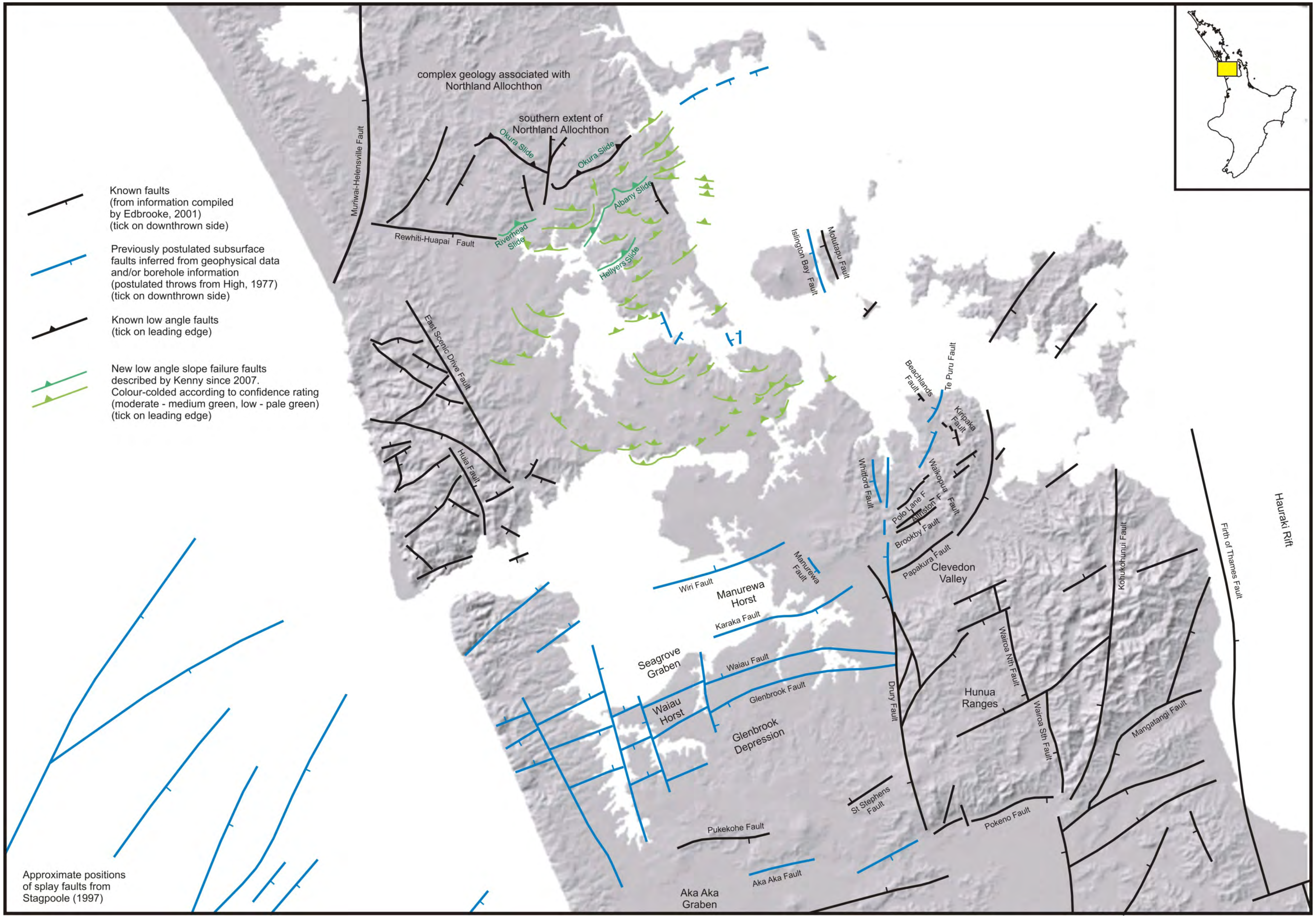


Figure 23: Cuspate faults inferred in this study, superimposed on a greyscale map of Auckland. Names have been added only where these faults have been specifically described in the text and in Table 3. Confidence rating colours have been applied. Previously plotted faults (Figure 4) are also shown.

ANALYSIS OF CUSPATE FAULTS

Catastrophic sub-seafloor slope failures of the mid Waitemata Group semi-lithified sedimentary pile occurred in the mid to late Otaian (Hayward 1993). Kenny *et al.* (2010) suggested that the failures were initiated on the slopes of the Waitemata sedimentary basin as the sedimentary pile was “nudged” by the toe of the southward-migrating Northland Allochthon in the early Miocene. Each inferred sub-horizontal fault is thought to have formed in this process. The imbricate packets are now even more jumbled in appearance because they have been dislocated by subsequent regional block faults.

Widespread asymmetric folds within the complexly deformed zones generally verge to the south (Spörli & Rowland 2007), but in the south of the region, folds also verge east (Spörli 1989, Spörli & Rowland 2007). Thrusting towards the south on E–W or SE–NW-trending fault planes has been frequently documented (for example Johnston 1999 at Albany; Davidson 1990 around the upper Waitemata Harbour; Geelen 1973, Spörli & Browne 1982, and Manning 1983 all covering parts of the northern Manukau Harbour coastline; Tejaksuma 1998 at Beachlands; and Berry 1986 around the southern Manukau Lowlands). Boomer seismic sections show possible gravity sliding off Browns Bay (Figure 24) (Kenny, pers. obs. with B.Davy, GNS, 2011). This is highly speculative; as discussed earlier in relation to regional block faulting, most of the offshore seismic profiles are very difficult to decipher.

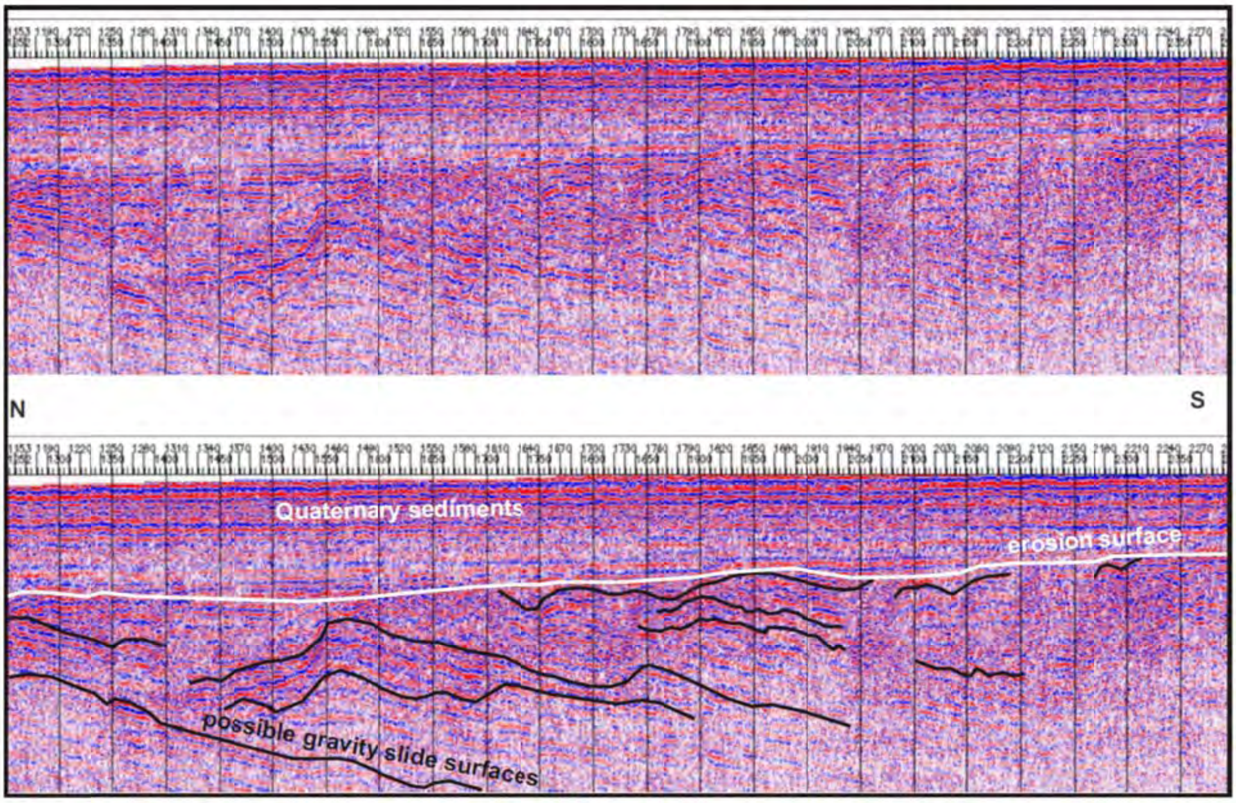


Figure 24: Black lines indicating possible gravity slide packets off Browns Bay, as displayed superimposed on a SSE to NNE Boomer seismic section about 10 km long from B. Davy (pers. comm.. 2011). The lower section is an interpretation of the upper section. Seismic profiles are considerably vertically exaggerated.

The furthest travelled cuspate packets are mapped as reaching Glen Eden in western Auckland, the northern coastline of the Manukau Harbour and the Glendowie area of the eastern Auckland isthmus (Figure 23). Kenny (2008a, 2008b) initially extended the inferred area covered by cuspate ridges as far as Howick in eastern Auckland. Evans (2008) suggested that Northland Allochthon-related thrust faults may extend as far as Papakura Fault and other E-W faults south of the Manukau Lowlands. It is considered in this report that the geometries of both these areas better fit the ENE-trending block faulting regime described earlier.

Incidentally, Allochthon-derived material was identified from boreholes drilled during construction of the Sky Tower in central Auckland (P. Black, pers. comm. 2007), but tangible evidence and all knowledge of this discovery has been lost. Ballance & Spörli (1979) speculated that the Allochthon may even have reached as far south as the Waikato Fault, based on information from the Karaka-1 well west of Papakura. However, results from this hole are considered to be totally unreliable, contaminated by the drilling mud (Isaac *et al*. 1994, Edbrooke 2001).

BLOCK FAULTING MODELS FOR THE AUCKLAND REGION

RELATIVE ELEVATIONS OF WAITEMATA GROUP FAULT BLOCKS

Both the regional block faults and the cuspate faults have thus far been described separately and have been linked to known features outside the study area (Figures 20a, 20b and 23).

These figures are now combined into Figure 25, with the new inferred faults still retaining their confidence rating colours. A block elevation map has been constructed from this figure (Figure 26). High ground or areas of extreme uplift clearly show up in red. Regions of intermediate elevation or moderate uplift are coloured orange, and relatively down-dropped blocks are depicted in yellow or white colours.

The map draws attention to the NNW-trending graben, bisecting the study area, which was discussed earlier in the analysis of regional block faulting. The ENE-trending step along the Manukau Fault and the ENE-trending horsts and grabens to the south are also clearly visible. Special mention should be made of the up-stepping of the Manurewa Horst and Seagrove Graben eastwards, becoming Manukau Heights and Clevedon Valley respectively. They then curve round to the north with Manukau Heights becoming the Maraetai Hills and the Clevedon Valley being lost in the strait between the mainland and Waiheke Island. The overall regional down-faulting to the west, discussed in the analysis of regional block faulting, is also evident in Figure 26.

On the western side of the map, the only very elevated area is the Waitakere block, where the equivalent of the Waitemata Group erosion surface is judged to be over 350 m above sea level (Hayward 1983, 2009). To its south, the Awhitu block is inferred also to be elevated, with respect to the graben to its east, based on evidence from Grahams Beach borehole (Waterhouse 1989). This block is also stepped down to the south, along the inferred Cornwallis Fault, a potential western extension of the Manukau Fault.

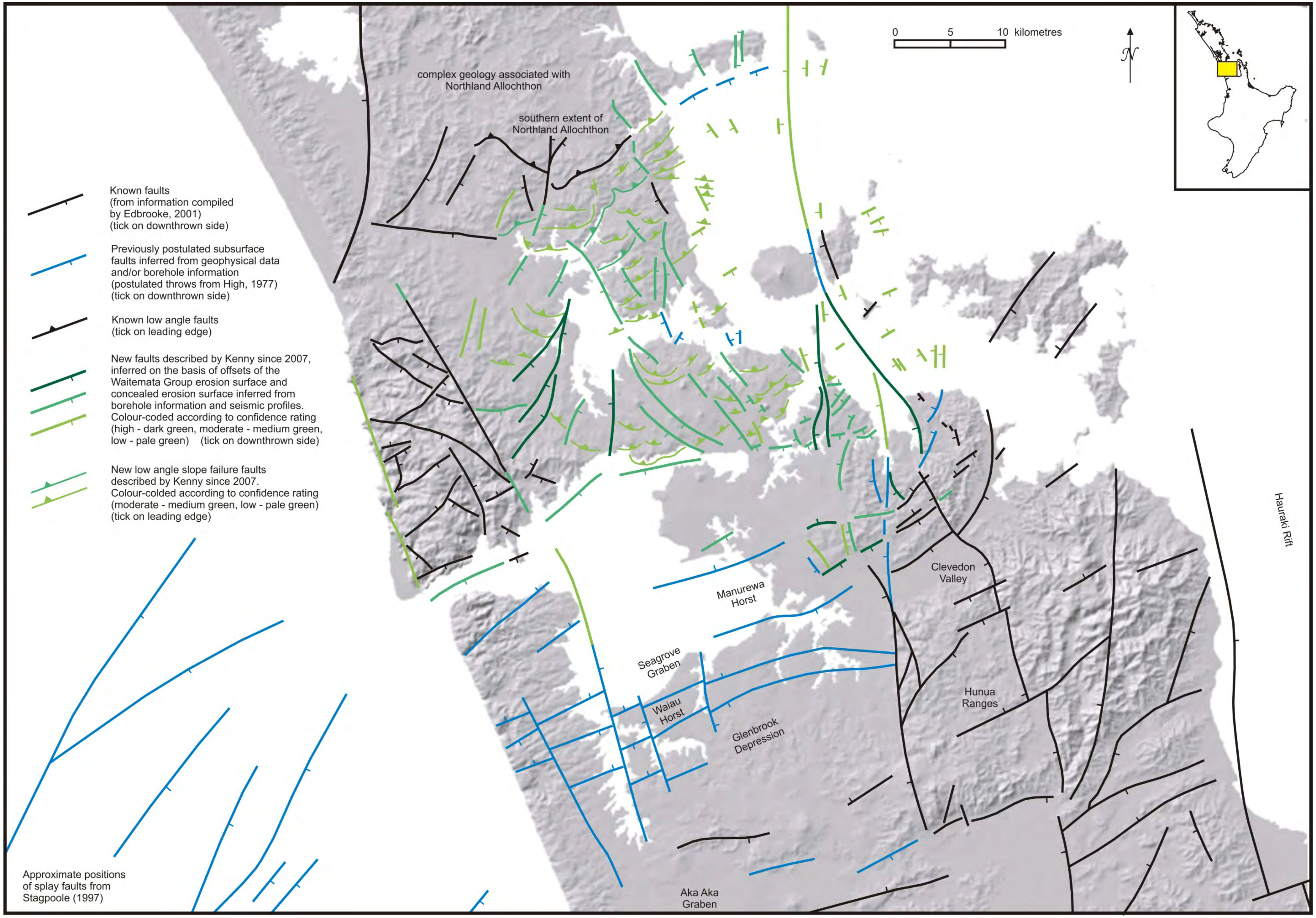


Figure 25: Composite map of all faults in the Auckland region, either recognised previously (Figure 4) or inferred in this report (Figures 20a, b and 23). The lack of faults south of the Auckland isthmus is artificial because of limited borehole coverage in this region.

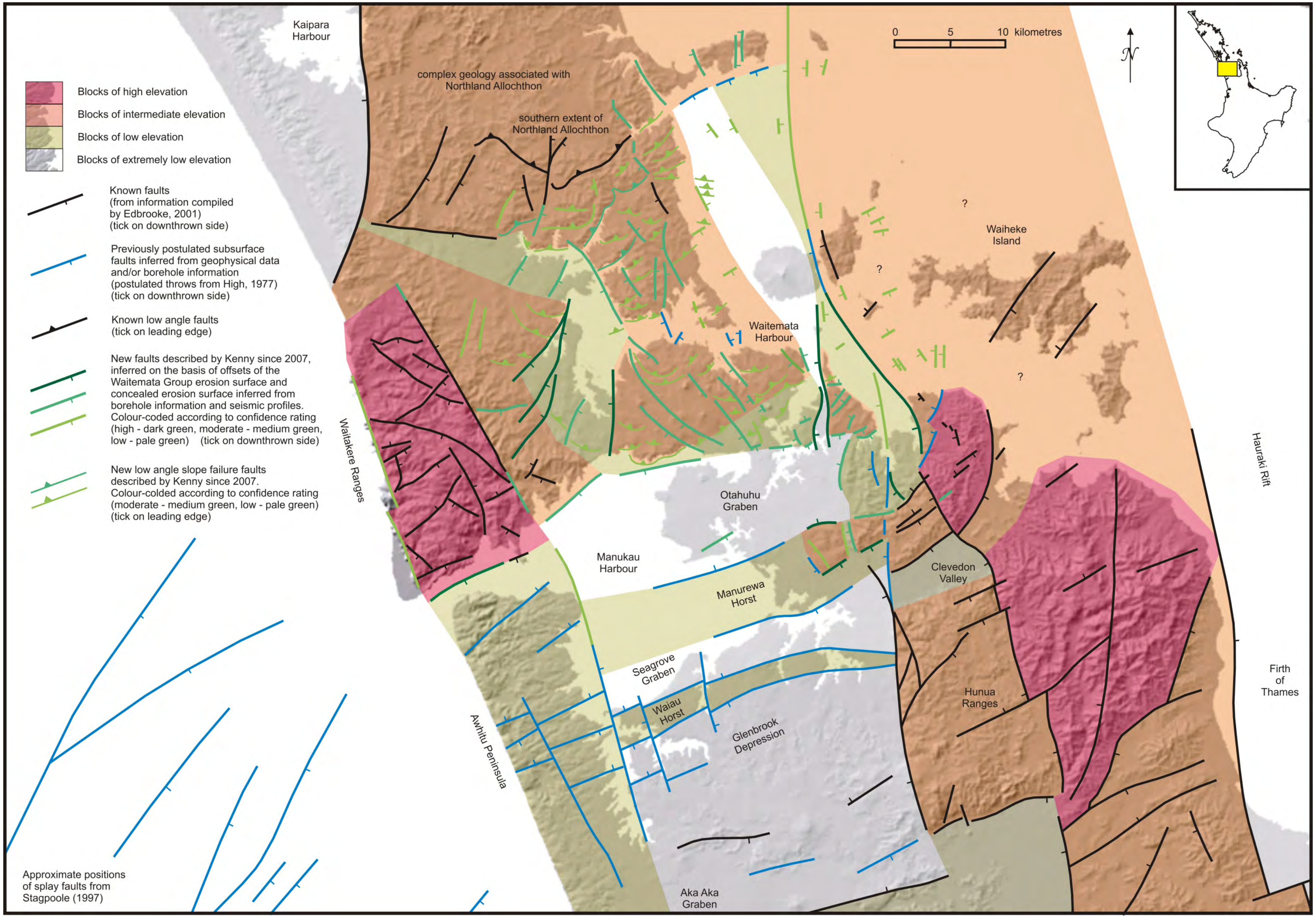


Figure 26: Block elevation map indicating relative heights of the Waitemata Group erosion surface, developed from Figure 25 and borehole data.

RELATIVE ELEVATIONS OF THE BASEMENT / WAITEMATA GROUP INTERFACE

As mentioned in the Introduction, structurally simple Murihiki Terrane greywacke and argillite is known to occur beneath Tertiary lithologies in the west of the Auckland area. Structurally complex greywacke and argillite belonging to the Waipapa (composite) terrane outcrops or underlies Tertiary lithologies in the east of the Auckland area (Figure 1). The two terranes are separated by a narrow band of rocks that displays a strong gravity and magnetic signature (the Junction Magnetic Anomaly), known from elsewhere in New Zealand to equate to serpentinised ultramafic rocks of the Dun Mountain-Maitai terrane. It has been shown as a 6–8 km-wide strip beneath the eastern shores of the Manukau Harbour, widening into a 14 km-wide pod shape from the Auckland isthmus to the Helensville/Orewa (Williams 2003, Eccles *et al*. 2005, Cassidy & Locke 2010) (Figure 2). It then thins again and deviates westwards, aligning with the eastern shores of the Kaipara Harbour. The associated NW-trending gravity anomaly has been used to model a discrete pod having a flat upper surface reaching to within 500 m of the ground surface, and a steep eastern boundary coinciding with a peak in the magnetic contours. The western and southern contacts have shallow gradients (Williams 2003). Up to ten slivers have been detected within the pod (Figure 2b), perhaps representing faulting sub-parallel to the JMA, strike slip duplex formation, or thrust repetition during accretion (Eccles 2003, Eccles *et al*. 2005, Cassidy & Locke 2010).

Greywacke is the dominant rock type in the Hunua Ranges, Maraetai Hills and Waiheke Island to the east of Auckland. Greywacke is encountered in successively deeper boreholes in a westward direction (Figure 27), but is deep under most of Auckland and yet to be penetrated. Seismic models illustrate basement at 0.5–1 km depth in this region (Williams *et al*. 2006; Davy 2008). Gravity surveys near Whitford show the greywacke-Waitemata Group interface dipping westwards (Anderson 1977) and a similar deepening was found north of Auckland (Daly 1988). Boreholes penetrate greywacke again in the west (being encountered at 450 m depth at Henderson and 350 m depth in northern Awhitu Peninsula), suggesting that basement is upthrown to the west – a reversal of the trend seen over the rest of the region (Figure 27).

The axis of maximum subsidence coincides with the extent of the cuspate faults formed by mid-Waitemata sedimentary pile catastrophic slope failures described earlier (Figures 23 & 26). Areas of deepest subsidence are bounded by steepest slopes, which would have been the most unstable and most likely to fail if nudged from the north by the toe of the Northland Allochthon.

Deep boreholes reaching greywacke basement usually pass through varying thicknesses of Waitemata Group sediments and sometimes overlying Pliocene or Quaternary sediments. Those boreholes within a few hundred metres of faults can be used to estimate possible fault remobilisation, where the elevation of the Waitemata Group peneplain within the borehole or at the surface can also be established. Many such boreholes in the East Tamaki–Whitford–Maraetai Hills area have yielded some interesting results and, together with a single borehole at Grahams Beach, northern Awhitu Peninsula, rudimentary cross-sections have been concocted (Figure 28).

A tentative model of a possible basement/Tertiary interface, depicting inferred block faulting in basement rocks under Auckland, has been attempted using borehole and published geophysical data (Figure 29). This is overlain by a subtle checker pattern covering the area of the widened JMA. The widened pod roughly coincides with the NNW-trending trough between a concealed greywacke high to the west and outcropping greywacke highs in the east. No boreholes have yet penetrated basement along this trough, but it is tempting to speculate that when drilled, they would encounter ultramafic lithologies, sometimes sheared and serpentinised, rather than greywacke. However, they could also encounter unsheared, unserpentinised arc-derived

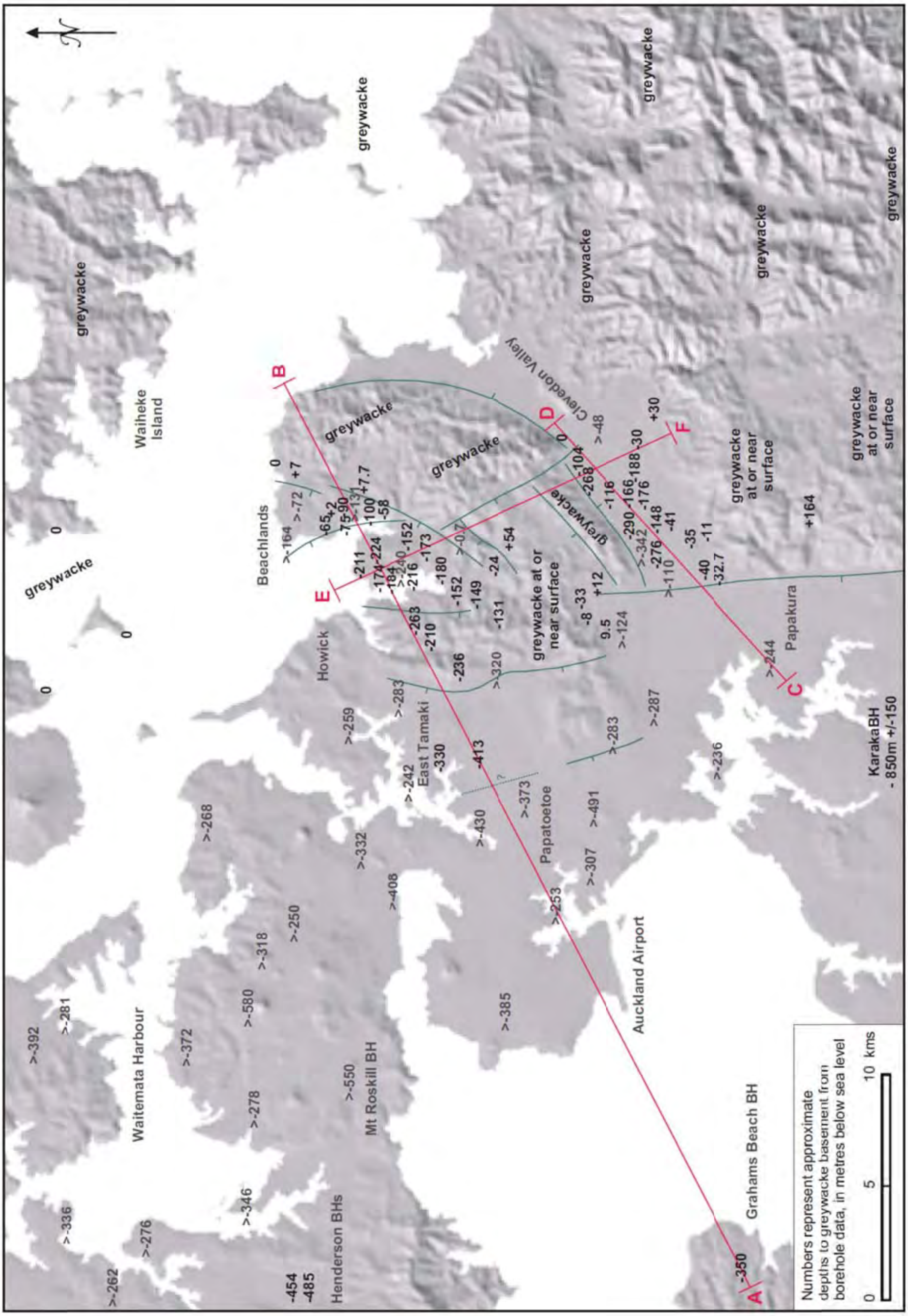


Figure 27: Locations of boreholes reaching greywacke (depth written in black numbers) or extending deep into thick Waitemata Group sediments without penetrating greywacke (grey numbers with a > 'deeper than' symbol). Cross-section lines A-B, C-D, E-F are shown in Figure 28.

sediments of the Maitai terrane. Elsewhere Maitai terrane is inextricably linked with strongly magnetic ultramafic lithologies of the Dun Mountain Ophiolite Belt along the line of the JMA (Frost & Coombs 1989). Hopefully the "relatively SiO_2 rich" Maitai terrane (relative to nearby Brook St Volcanic terrane in the Nelson area – Sivell & McCulloch 2000) would be distinguishable from Murihiku or Waipapa greywacke terranes in deep boreholes beneath Auckland.

Although rocks associated with the JMA do not outcrop in Auckland, two volcanoes positioned directly over the steep eastern boundary of the widened pod, St Heliers and Taylors Hill, have erupted xenoliths of unaltered ultramafic and sedimentary rocks similar to lithologies in the Dun Mountain-Maitai terrane (Searle 1959, Jones 2007). Searle (1959) thought they were schist. Jones (2007) noted a scarcity of greywacke xenoliths from the same vents. Ultramafic xenoliths have also been linked to other vents in the AVF – Pupuke (at Smales Quarry), Tank Farm (from sediments in Shoal Bay), North Head, Mt Cambria, all in the southern North Shore area (Rodgers 1966), in tuff from Pukewairiki and elsewhere in East Tamaki (Sibson 1968), and from Mangere Mountain and Puketutu (B. Spörli, pers. comm. 2011).

Numerous rootless, oblong-shaped, diapir-like serpentinite boudins, each less than 1 km long, are in sheared contact with sediments of the Northland Allochthon near Silverdale and in southern Northland (O'Brien & Rodgers 1973, Schofield 1983, Christie & Barker 2007). These bodies lie just to the east of the position of the JMA (Figure 29 inset), but those near Silverdale also coincide with the northern limit of a wider magnetic anomaly (Williams 2003, Eccles *et al*. 2005, Cassidy & Locke 2010). They most likely represent all that remains of a highly fragmented and eroded block of Tangihua ophiolite within the Northland Allochthon (Ballance & Spörli 1979, Spörli 1989). However, apart from the ultramafic xenoliths mentioned above, it is conceivable that they could also be the only tangible surface evidence that Dun Mountain-Maitai Terrane exists at depth beneath Auckland.

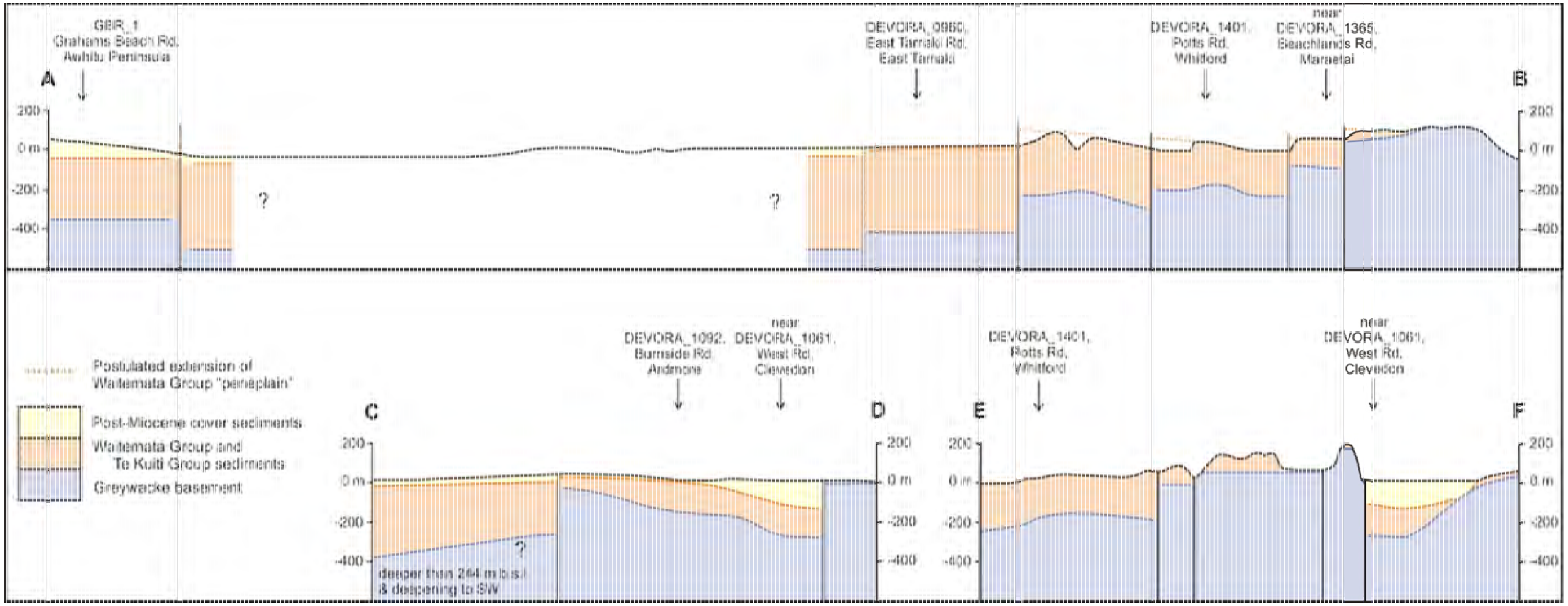
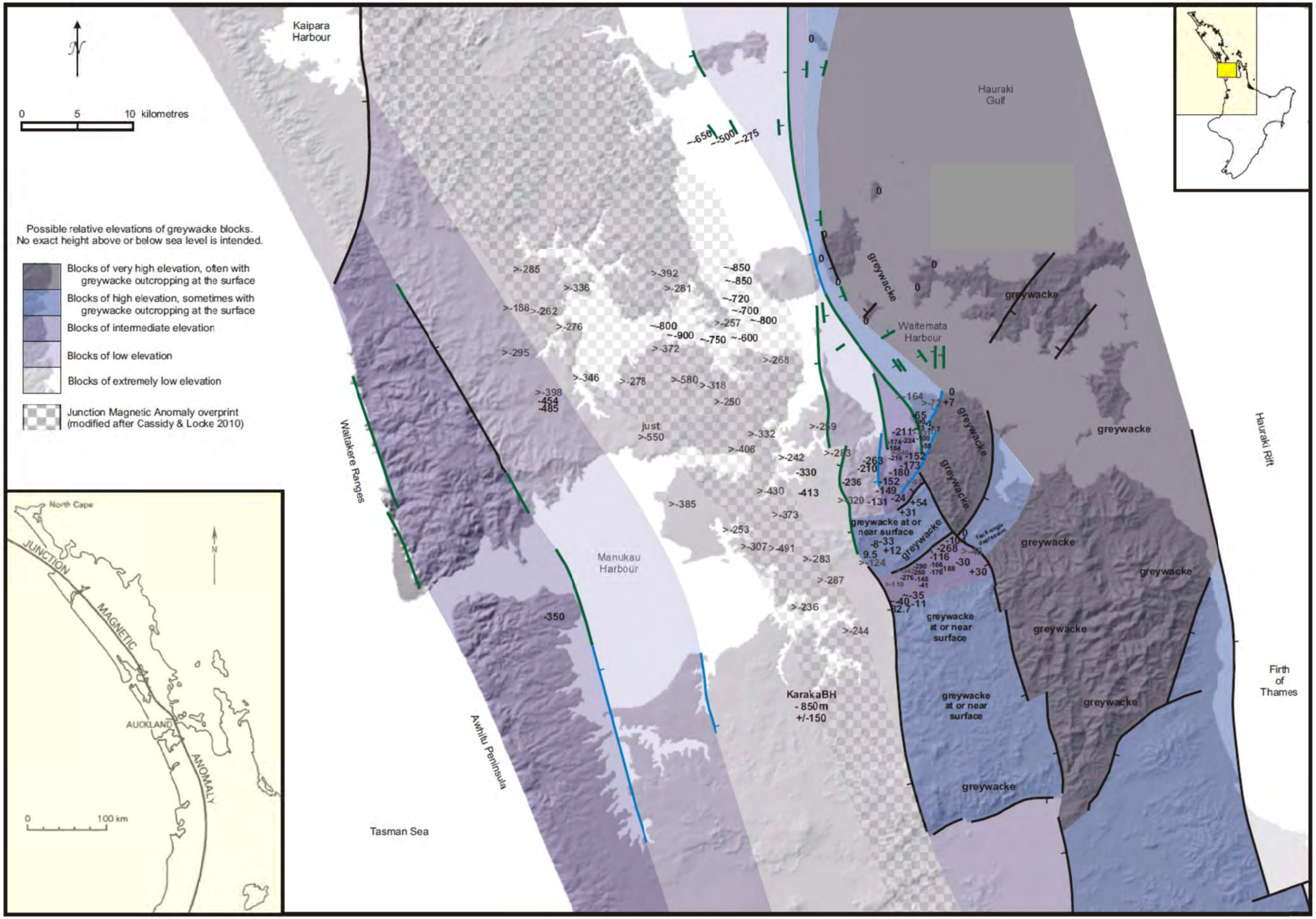


Figure 28: Simplified cross-sections based on Figure 27 show differential offsets of the greywacke erosion surface and the erosion surface developed on Waitemata Group sediments. Remobilisation is evident in cross-sections A-B and C-D (perpendicular to NNW-trending faults) from differences in offsets of these two surfaces on the NNW-trending faults. Remobilisation is not evident in cross-section E-F (perpendicular to the ENE-trending faults), where offsets on the two surfaces appear to be similar in magnitude. Locations of individual boreholes are indicated.

Figure 29: Speculative interpretation of relative elevation of basement blocks in the Auckland region, using faults described in the text and boreholes shown in Figure 27. No exact height above or below sea level is intended by these coloured zones. Blocks are inferred from outcropping greywacke from Murihiku or Waipapa (composite) terrances, from boreholes that reached greywacke (black numbers) and from boreholes that did not reach greywacke (grey numbers with a > 'deeper than' symbol). Numbers proceeded by a ~ symbol are approximate depths below sea level estimated from marine seismic profiles illustrated in Davy (2008). Position of the Junction Magnetic Anomaly has been superimposed as a subtle checker pattern (modified after Cassidy & Locke 2010).

Inset (bottom left), also included in Figure 2, shows the position of the Junction Magnetic Anomaly as it passes beneath the northern North Island (including the Auckland area) (after Schofield 1983).


N
0 5 10 kilometres
Kaipara Harbour
Hauraki Gulf
Waitemata Harbour
Manukau Harbour
Tasman Sea
Firth of Thames
Hauraki Rift
Waitakere Ranges
Awhitu Peninsula
KarakaBH - 850m +/-150
just >-550
greywacke
greywacke at or near surface
fault-angle depression
Possible relative elevations of greywacke blocks.
No exact height above or below sea level is intended.
Blocks of very high elevation, often with greywacke outcropping at the surface
Blocks of high elevation, sometimes with greywacke outcropping at the surface
Blocks of intermediate elevation
Blocks of low elevation
Blocks of extremely low elevation
Junction Magnetic Anomaly overprint (modified after Cassidy & Locke 2010)
North Cape
JUNCTION MAGNETIC ANOMALY
AUCKLAND
N
0 100 km

DISCUSSION

A new appreciation of the Waitemata Group erosion surface discussed above, together with known and inferred faults, information from boreholes and geophysical studies, has been used to map steps in the surface and thence to extrapolate faults traversing the Auckland region (Figure 19). New inferred faults have been assigned high, moderate or low confidence ratings based on attribute scores (Tables 1 & 2, Figure 25). Maps depicting relative block elevations, based on locations of known and inferred faults, have been devised for the Waitemata Group rocks and for the underlying basement (Figures 26 & 29 respectively). The most obvious feature of both maps is the NNW-trending graben bisecting the region, which appears to coincide with the JMA as it passed through Auckland. Uplift is more pronounced on the eastern side of the graben than on the west for both the Waitemata Group and basement rocks. The implications of our results are discussed below.

IMPLICATIONS OF BLOCK FAULTING FOR DRAINAGE

Uplift in the east of the area is accentuated by a gentle westward tilting of the Northland and Auckland regions. This tilting is not apparent in Figures 26 or 29 (relative elevations of blocks in the Waitemata Group and basement rocks respectively), but it is obvious in Northland, where all the major rivers flow westwards from their headwaters close to the east coast (Figure 30). A similar situation has been suggested further south, concerning the Clevedon Valley (Hayward *et al*. 2007, Hayward & Grenfell 2010). In this case, illustrated in the lower portion of Figure 30, an ancient ‘Clevedon River’ is required to provide a pathway for material to form the conglomerate at Kidds Beach on the southern shores of the Manukau Harbour. At Kidds Beach, clasts in the Pliocene-age Puketoka Formation (sensu stricto*) conglomerate (Berry 1986) can only have been supplied from the east – red chert pebbles from the vicinity of the northern Hunua block to Waiheke Island and creamy-white crystalline “vein” quartz pebbles typically found on the Coromandel Peninsula.[1]

A ‘Clevedon River’ is possibly located within the half-graben-formed corridor (Edbrooke *et al.* 1994) between the uplifted horst of the Maraetai Hills and Hunua Ranges, clearly visible in Figures 4, 17, 20 & 26. The river channels are depicted more precisely in Figure 31. This map also shows another west-flowing river further south. In this instance, the only known source for rhyolite and quartz pebbles making up some of the conglomerate clasts in the type locality for Puketoka Formation, near Maramarua, is southern Coromandel’s Whitianga Group (Hayward & Grenfell 2010).

Although smaller, the upper reaches of the ‘Manukau River’ catchment (Searle 1964) also extended to the eastern side of Auckland, with the catchment boundary between it and the ‘Waitemata River’ to the north originally being a ridge between Glendowie and southern Bucklands Beach. Blockages of the southwest-flowing Manukau River in the vicinity of Otahuhu by eruptions of some or all of the volcanoes in the area (Pukewairiki, Mt Richmond, McLennan

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[1] Note the Puketoka Formation in this report is restricted to the deposits described at the type locality at Puketoka hill near Maramarua by Kear & Schofield (1978) (Figure 31), as applied by Hayward *et al*. (2007) and Hayward & Grenfell (2010). It does not refer to the more generalised use of Puketoka Formation by subsequent workers, for example Kermode (1992), who included widespread alluvial, organic and volcanic deposits.

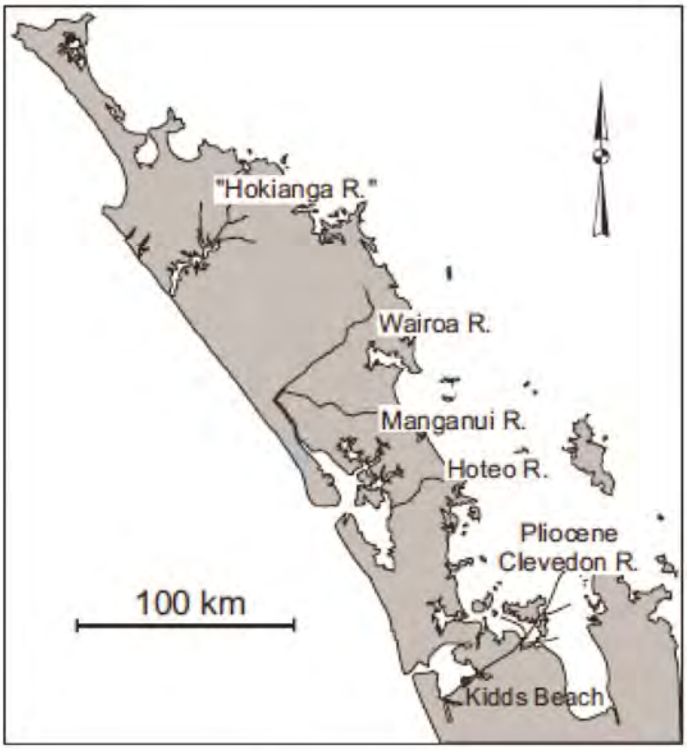

Figure 30: Present day Northland rivers flowing west due to regional tilting (from Hayward & Grenfell 2010, figure 5).

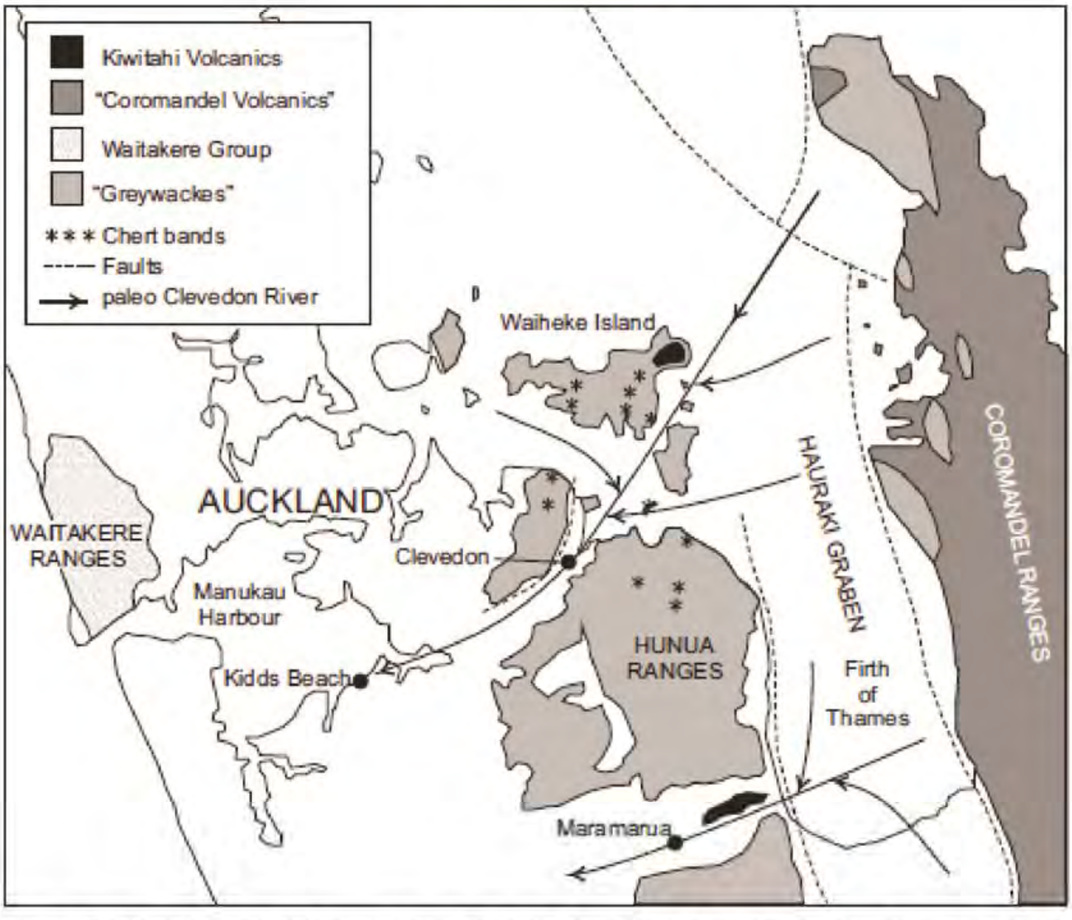

Figure 31: Simplified geological map of the Auckland region, showing location of the conglomerates at Puketoka (near Maramarua) and Kidds Beach and possible sources of their different pebble lithologies. The inferred northern Hunuas-Coromandel provenance and southern Coromandel provenance of the conglomerates points to the existence of west-flowing rivers through the Clevedon and Puketoka valleys prior to the major subsidence of the Hauraki Graben (modified after Hayward & Grenfell 2010, figure 4).

Hills, Robertson Hill and Panmure Basin) within the last 200,000 years dammed the whole East Tamaki catchment and formed a large lake before a lower section of the Glendowie ridge was breached by a breakout northwards at “the asterisk” to become the Tamaki River.

TIMING OF HAURAKI RIFT INCEPTION

Both the Kidds Beach and Puketoka ancient river systems required access westwards from Coromandel, which is now no longer possible since the inception of the Hauraki Rift (Battey 1949, Kear 2000, 2004, Hochstein & Nixon 1979, Hochstein *et al*. 1986) (Figures 1 & 31). Timing of rifting and graben formation has been contentious. Precursory uplift may have begun in the late Mesozoic (Skinner 1976) or from 10 Ma ago (early Late Miocene) (Hochstein & Ballance 1993), but authors tend to agree that major tectonic upheaval leading to substantial graben subsidence had commenced by the mid or late Pliocene (c. 3–2 Ma ago) (eg. Schofield 1967, Ballance 1976b, Skinner 1976). With recent analysis of pathways for Puketoka Formation conglomerate clasts, and a verified age from a species of beech extinct from New Zealand since 2–1.5 Ma ago (Cooper 2004, Hayward *et al*. 2007, Hayward & Grenfell 2010), deposition of Coromandel-derived Puketoka conglomerates could only have taken place from 3–2 Ma ago. Therefore most, if not all, the subsidence associated with the Hauraki Rift must have taken places since 3 Ma ago and may still be active (De Lange & Lowe 1990).

A 3-million-year, or less, time frame for Hauraki Rift subsidence has ramifications for fault displacement timing in the Auckland area. ‘Proto’ Hunua Ranges and Maraetai Hills must have been in existence as a continuous block prior to 3 Ma ago, uplifted along NNW-trending faults, preventing Coromandel-derived material from reaching the Manukau Lowlands. Rifting perpendicular to this high ground then formed ENE-trending valleys bounded by fractures such as the Manukau, Wiri, Karaka and Glenbrook Faults. The Clevedon–Papakura corridor and lowland around Maramarua also subsided, allowing rivers sourced in the Coromandel Peninsula to transport pebbles over 50 km westwards. Initiation of subsidence along the Hauraki Rift curtailed this flow soon afterwards and deposition of Puketoka Formation conglomerates was terminated. At the same time, which has now been compressed to c. 2 Ma ago, reactivation of Hauraki-parallel, NNW-trending faults in the Auckland region was also initiated, cutting the ENE-trending rifts.

As well as westward tilting and westward down-dropping of fault blocks in the Auckland region on the western flanks of the Hauraki Rift, to the east of the Rift much of the Coromandel Peninsula has an eastward tilt (Hayward & Grenfell 2010), suggesting that the Hauraki region may have been affected by arching of the crust (Hochstein & Ballance 1993) or by thermal up-doming (Hayward & Grenfell 2010) prior to its rifting and collapse.

REAPPRAISAL OF THE AUCKLAND REGION’S LATE CENOZOIC TECTONIC HISTORY

Timing of accretion of the basement terranes in the late Jurassic to mid Cretaceous, their subsequent uplift, erosion, subsidence and cover by Tertiary sediments is well established in the literature. The geological history of the Waitemata Group, surrounding lithologies in the Auckland region and emplacement of the Northland Allochthon are also well documented. Events since that time, from late Miocene to the present, are not so well understood, especially since a more complex late Cenozoic history of tectonic upheavals, block faulting, tilting, rifting and subsidence is suggested (eg. Figure 31).

A more detailed tectonic history of the late Cenozoic is now proposed. Sedimentation in the deep Waitemata basin was curtailed by regional uplift. Youngest existing sediments are early Miocene (mid Altonian, c. 17 Ma ago) (Raza *et al*. 1999; Hayward & Smale, 1992), implying uplift from bathyal depths to emergence above sea level was rapid and significant, commencing shortly after 17 Ma ago. Uplift was more pronounced towards the east, along a series of NNW-trending faults, upthrown to the east, some by hundreds of metres, forming the proto-Hunua Ranges/ Maraetai Hill block. However, there is no evidence to suggest the original Waitemata basin was ever shallower in the east, or that regional block faulting had been initiated prior to, or during, deposition of Waitemata Group sediments (Hayward & Brook 1984).

Tectonic quiescence lasted until 3Ma ago, during which time erosion formed a widespread low-lying plain (Hayward 1983, Kermode 1992) – the peneplain discussed earlier as the only marker horizon associated with the Waitemata Group from which any idea of fault offsets could be determined. After a significant sedimentary hiatus, the southern area was inundated by shallow seas, and early Pliocene shallow marine and coastal sediments were deposited. One of these, the Kaawa Shellbeds, now forms a useful aquifer throughout the Manukau Lowlands (Kermode 1992). It occurs in lenses up to 12 m thick (Kear 1957), and although it is dated as Opoitian-Waipipian in its type locality south of Port Waikato, it is slightly diachronous and is only Waipipian (3.5–3 Ma ago) at a well drilled in Otahuhu (Beu 1974).

ENE-trending faults, especially in the Manukau area, offset the Waitemata peneplain surface, occasionally by as much as tens of metres, forming a series of horsts and grabens. The largest, the Manukau Fault (including its east and west continuations – the Cornwallis, Panama and Meadowlands Faults), uplifted the region to its north, including the Auckland isthmus, Waitakere area, Howick/Pakuranga and the North Shore, to an intermediate level topographically, leaving the Manukau Lowlands near to sea level. If splay faults to the west of the northern North Island (Stagpoole 1997) are part of this regime, timing of ENE-trending fault activation may have implications for offshore tectonism as well.

It is debatable whether the Kaawa Formation was involved in this tectonism. The Kaawa Shellbed is known in the Manukau Lowlands from studies using seismic and gravity profiling, constrained by borehole data, and is depicted schematically as relatively thick deposits in the grabens and thin veneers draping the horsts (High 1975, 1977, Berry 1986, Omerod 1989, Petch *et al*. 1991, Kermode 1992). Until now it had been assumed to post-date faulting of the underlying Waitemata Group sediments. However, as lenses up to only 12 m thick, it is not thick enough to fill pre-existing grabens then spill out on to the intervening horsts as thin veneers. It is more likely to have been deposited prior to the ENE-trending rifting episode, then eroded to a thin veneer on the subsequent horsts. If this is true, and the shellbeds are 3.5–3 m.y. old in this region, ENE-trending faults were active after that time.

The disconformably overlying Puketoka Formation fluvial conglomerates were deposited in the late Pliocene (c. 3–2 Ma ago) from west-flowing rivers using the newly formed grabens as corridors through the Hunua-Maraetai high-standing block (Hayward & Grenfell 2010) (Figure 31). This evidence further constrains the timing of ENE-trending rifting. About 3 Ma ago graben formation was initiated, and once deep enough, rivers began to flow westwards, depositing Puketoka Formation conglomerate. A general westward flow of rivers suggests that westward tilting of the whole region (Hayward 1983, Hayward & Grenfell 2010) (Figure 30) had already begun.

In the latest Pliocene (c. 2 Ma ago) NNW-trending faults, with offsets up to tens of metres, were remobilised and the major Hauraki Rift to the east was initiated. Westward river flow from

Coromandel was halted by the deepening NNW-trending rift and by renewed uplift of the Hunua-Maraetai block (Figure 28), blocking corridors that had earlier enabled Puketoka Formation conglomerates to be deposited further west. By the Pleistocene, coastal and non-marine sediments were being deposited in faulted depressions. These sediments have not been offset, suggesting that regional tectonism had abated by c. 1.5 Ma ago and the pattern of fault-bounded blocks across the Auckland region as we know it today had already been established (Figure 26).

IMPLICATIONS FOR PRESENT DAY UPLIFT AND SEISMICITY IN AUCKLAND

Further evidence suggests that uplift may be still be occurring. Offsets of coastal terraces have been noted by Berryman (1984), tilting of Pleistocene terraces has been recorded from Beachlands (Tejaksuma 1998), Awhitu Peninsula (High 1975), eastern Hauraki Gulf (Spörli & Stannaway 2007), New Lynn (Turner & Bartrum 1929, Searle 1944) and upper Waitemata Harbour (Clark 1948), and warping of young tephra has been mapped on the Awhitu Peninsula (Barter 1976). To the northwest, there is an indication of very rapid Quaternary uplift, with a regional uplift of 150 m in the last million years being estimated by Claessens *et al*. (2009) in a study of coastal terrace deposits in the northern Waitakere area. Recall from earlier in this report that this is one of the highest uplifted blocks in the region, where the Waitemata Group erosion surface is now found at approximately 350 m above sea level (Hayward 1983, 2009).

To the east, several active faults have been plotted along the Hauraki Rift, including the Kerepehi Fault (Hochstein & Nixon 1979, Hochstein *et al*. 1986, De Lange & Lowe 1990, Hochstein & Ballance 1993). Cassidy *et al*. (1986) interpreted seismicity since 1960 as reflecting continued block faulting in the Hunua Ranges. Limited evidence of faulting is found at Beachlands, where a small low-angle thrust fault less than 340 000 BP offsets Pleistocene tephra (Firth 1930, Glading 1987, Tejaksuma 1998, Spörli & Stannaway 2007) and measurements across the Wairoa North Fault in the Hunua Ranges demonstrates it to be active (Wise 1999). Older basalts in the South Auckland field have been displaced at Bombay by faults active sometime between 0.6 and 1.3 Ma ago. Clearly there are not many examples of Quaternary uplift in the Auckland region, and some of those reported are now obscured by urban sprawl or erosion, but scarcity of exposed Quaternary structures should not be used to suggest that tectonic activity is trivial.

Most recent earthquakes have been located in the Hauraki Gulf (Sherburn *et al*. 2007). Minor tremors, infrequent in the Auckland region, have been documented by Urwin (2009). The largest earthquakes recorded recently were 3 tremors all on 21 February, 2007, in the Hauraki Gulf north of Auckland. They were focussed 30 km east of Orewa, at depths of 7–15 km and magnitudes of 4.5, 3.7 and 3.8 on the Richter Scale. Further south, the 5.5–5.9 magnitude Waikato Heads earthquake of 1891 caused minor damage in Auckland (Hull *et al*. 1995).

Potential present-day uplift and subsidence in the Auckland region has been modelled using C-band Envisat Synthetic Aperture Radar (Samsonov *et al*. 2010). It indicates that most of Auckland is stable and any large areas of ground movement, at millimetre scale only, can be linked to use of groundwater rather than to tectonism. Three main regions of subsidence (Henderson Valley, Westfield in northern Otahuhu, and a large area beneath Papakura and western Clevedon valley) coincide with wells used for groundwater extraction, where recharge cannot keep up with demand. Two regions of uplift (a corridor from Puhinui to East Tamaki and a small area at New Lynn) probably relate to increased groundwater recharge following abandonment of wells. Another region of uplift, at Titirangi, is not groundwater-related, but is more likely to be an artifact created by residual noise from the steep terrain.

AUCKLAND FAULTING IN A NEW ZEALAND-WIDE CONTEXT

The new faults postulated in this report can be used to re-examine the overall tectonic history of New Zealand.

Both the NNW- and ENE-trending fault sets traversing Auckland also occur beyond the Auckland region. Those already mentioned are the NNW-trending Hauraki Rift, which extends from east of Whangarei to beyond Matamata in the eastern Waikato (Figure 1), the ENE-trending fault-associated volcanic vents in the South Auckland Field and Ngatutura (discussed later), and ENE alignments of west-flowing rivers illustrated in Figure 30. Auckland trends have been drawn on a Google image of New Zealand and for curiosity other gross lineaments have been added (Figure 32). Lineaments known to equate to bedding have been removed, leaving lineaments that are probably surface expressions of faults.

On this rudimentary map, cross-cutting lineament patterns in the South Island, and even in the Wellington area, delineate the transpressional shear regime linked to dextral oblique-slip movement on the Alpine Fault (Norris & Cooper 2001, Furlong & Kamp 2009, Kearey *et al*. 2009). Conversely, NNE-trending lineaments in the southern North Island are parallel to large faults through the axial ranges and accretionary wedges of Hawkes Bay and Wairarapa – these are on land expressions of the current westward-dipping subduction zone along the Hikurangi Trough (Lewis *et al*. 1998) (Figure 1).

Lineaments at East Cape could be associated with lineaments in the upper North Island, if the 5 million year old wedged opening of the Bay of Plenty is pivoted back to its pre-5 Ma ago position (bear in mind that East Cape was positioned near northern Coromandel Peninsula before the Pliocene (Ballance 1999)). These cross-cutting lineaments, including those in the Auckland region, do not appear to be linked to either of the other two lineament sets described in the previous paragraph. NNW-trending lineaments, arcing around to the NNE in the Taranaki region, parallel the known JMA alignment (Figure 2 inset); they may have inherited their orientation from reactivation of faults in the underlying tectonically juxtaposed basement Murihiku, Dun Mountain-Maitai and Waipapa (composite) terranes (Figure 1).

The orthogonal patterns the NNW features make with the ENE-trending lineaments do not justify being linked to movement along the current plate boundary, as is the case with faults in the southern half of the North Island. Instead, perhaps the trends could be dip-slip faults (as now seen in Auckland), remobilised along pre-late Miocene strike-slip faults. In a Harold Wellman-type ‘Eureka Moment’, we could imagine that they are arranged in a similar pattern to the transpression patterns in the South Island, which are a manifestation of dextral oblique-slip along the Alpine Fault. If we are going to ponder this further, we need to find an Alpine Fault equivalent that was active prior to the late Miocene. The current plate boundary cannot be a contender because it did not exist in its present form at that time. A possibility could be the large linear feature off the northeastern coast of Northland – the Vening Meinesz Fracture Zone (Figure 33). It is oblique to the two fracture sets of the northern North Island, a necessary component of the transpression concept, and it has a complex Neogene history of being variously a sinistral transform fault and an often-reactivated transpressional zone with both sinistral and dextral movement at times (Ballance 1999).

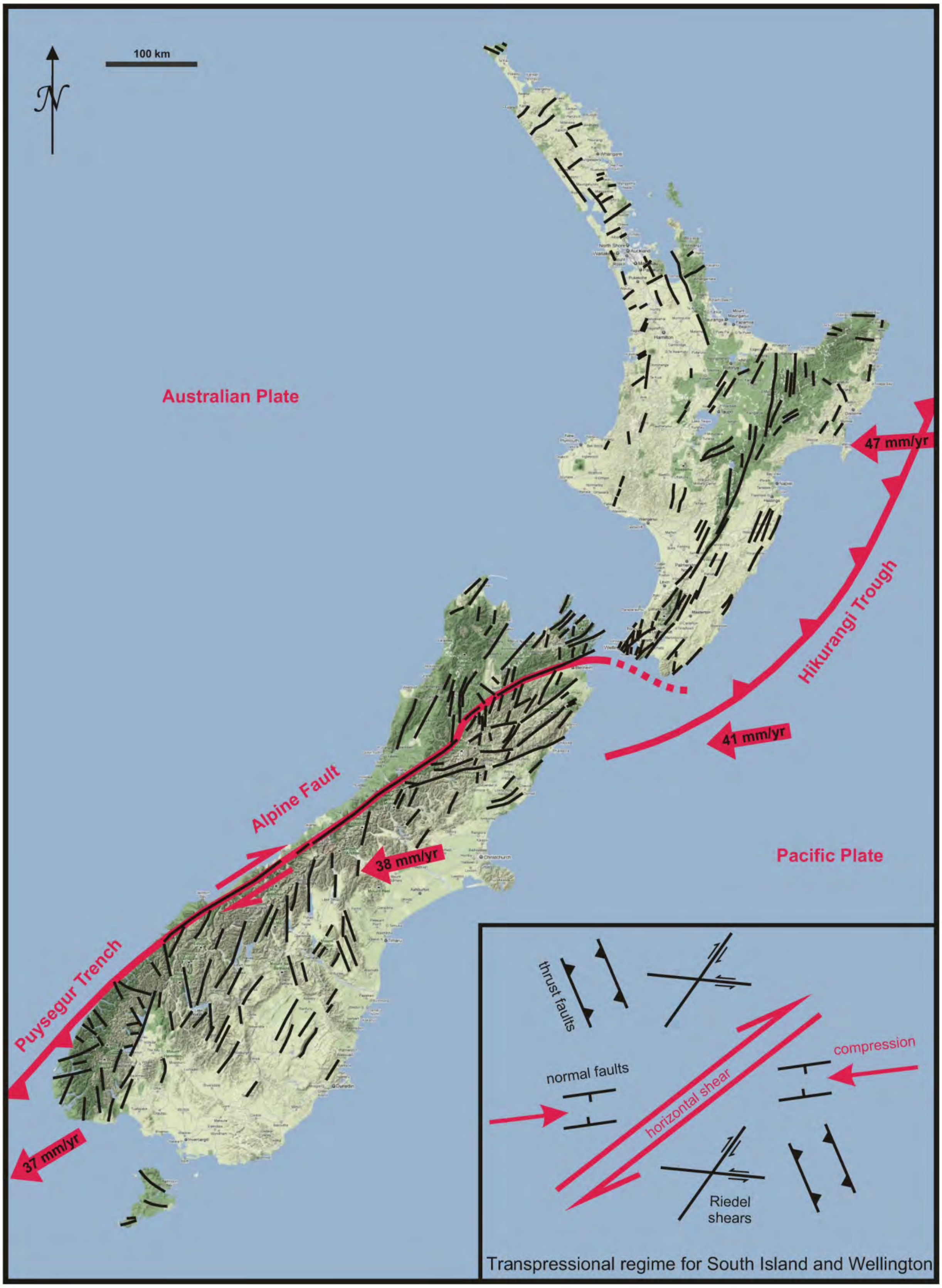

Figure 32: Lineaments throughout New Zealand, traced on to a Google Map terrain image. Those lineaments that are known to correspond to bedding have been removed. Plate boundary (in red) and arrows showing direction and rate of convergence are adapted from Herzer and Mascle (1996) and Edbrooke (2001).
Inset illustrates typical fractures associated with transpressional regimes, where elements of strike-slip and compression combine to form oblique-slip shear zones that include normal faults, reverse faults and Riedel shears at acute angles to the main fault. These variations are displayed by the South Island lineaments linked to the Alpine Fault (Norris and Cooper 2001, Furlong & Kamp 2009, Kearey *et al*. 2009).

If this notion is to be believed, consider that the NNW trends were initiated by dip-slip movement in a Mesozoic accretionary prism environment (juxtaposed basement terranes). Then the fracture planes could have been remobilised in the early Miocene, correlated with a major transpressional fault (Vening Meinesz Fracture Zone). Subsequently, since the late Miocene, the NNW fractures were again reactivated, this time as dip-slip block faults. This movement may still be continuing to the present day**.**

IMPLICATIONS FOR VOLCANISM

The results of this study have significant implications for our understanding of the behaviour of volcanism in Auckland. On a regional scale, our block faulting model for Auckland provides further support for the connection between the Junction Magnetic Anomaly and Auckland volcanism as suggested by Cassidy and Locke (2010), in that the eastern and western boundaries of this major crustal feature may in fact constrain the location of the outer boundaries of the volcanic field, and the terrane itself might provide a zone of weakness through which magma is able to ascend. This is consistent with the fact that there are no greywacke xenoliths in AVF juvenile material but several occurrences of ultramafic enclaves likely to be associated with the Dun Mountain-Maitai Terrane. Future work (e.g. the drilling of deep boreholes, and/or detailed geophysical studies) might help constrain the depth to and nature of this geological unit beneath Auckland, and thus provide insight into the geometry and speeds of magma movement through the crust.

The Waitemata Group paleosurface, although not exactly equivalent with pre-volcanic topography (in some cases AVF erupted onto sediments overlying Waitematas, e.g. Tauranga group), gives a very good indication of the topography of the area during past eruptions and thus may aid correlation of specific lava flows (now filling major fault-controlled valleys) with source volcanoes. For example, the proposal by Eade (2009) that the Meola Reef lava flow was sourced from Mt St John rather than Mt Eden or Three Kings is supported by paleotopogrphy data. Furthermore, an understanding of how lava flows behaved in the past can help us better define present day lava flow hazard in Auckland.

The identification of several new faults in the area covered by the AVF may mean that there is greater structural control on volcanism that was perhaps previously thought, and it is useful to compare the distribution of vents with fault locations.

Many attempts have been made to analyse patterns of vent alignments (eg. Magill *et al*. 2005, Allen & Smith 1994, Von Veh & Nemeth 2009, Bebbington & Cronin 2010, Hayward *et al*. 2011) but no dominant trends are really evident, a deficiency that is unusual compared with similar overseas volcanic fields (Cassidy & Locke 2010). Further south, in the South Auckland and Ngatutura fields, many vents align along major NE-trending faults (Figures 34a & b) (Briggs *et al*. 1990, 1994, Jukic 1995). A similar case could be put for the AVF (Figure 35a), however, it could be equally as convincing to align vents N–S, E–W, or NW–SE (Figure 35 b–d). Certainly vents appear to be positioned over the southern portion of the widened pod of sheared Dun Mountain-Maitai Terrane, thus exploiting the enhanced permeability of its shear zones for magma rising through the basement. This is a more simple explanation than that of requiring magma to form any conduits through surrounding solid greywacke masses.

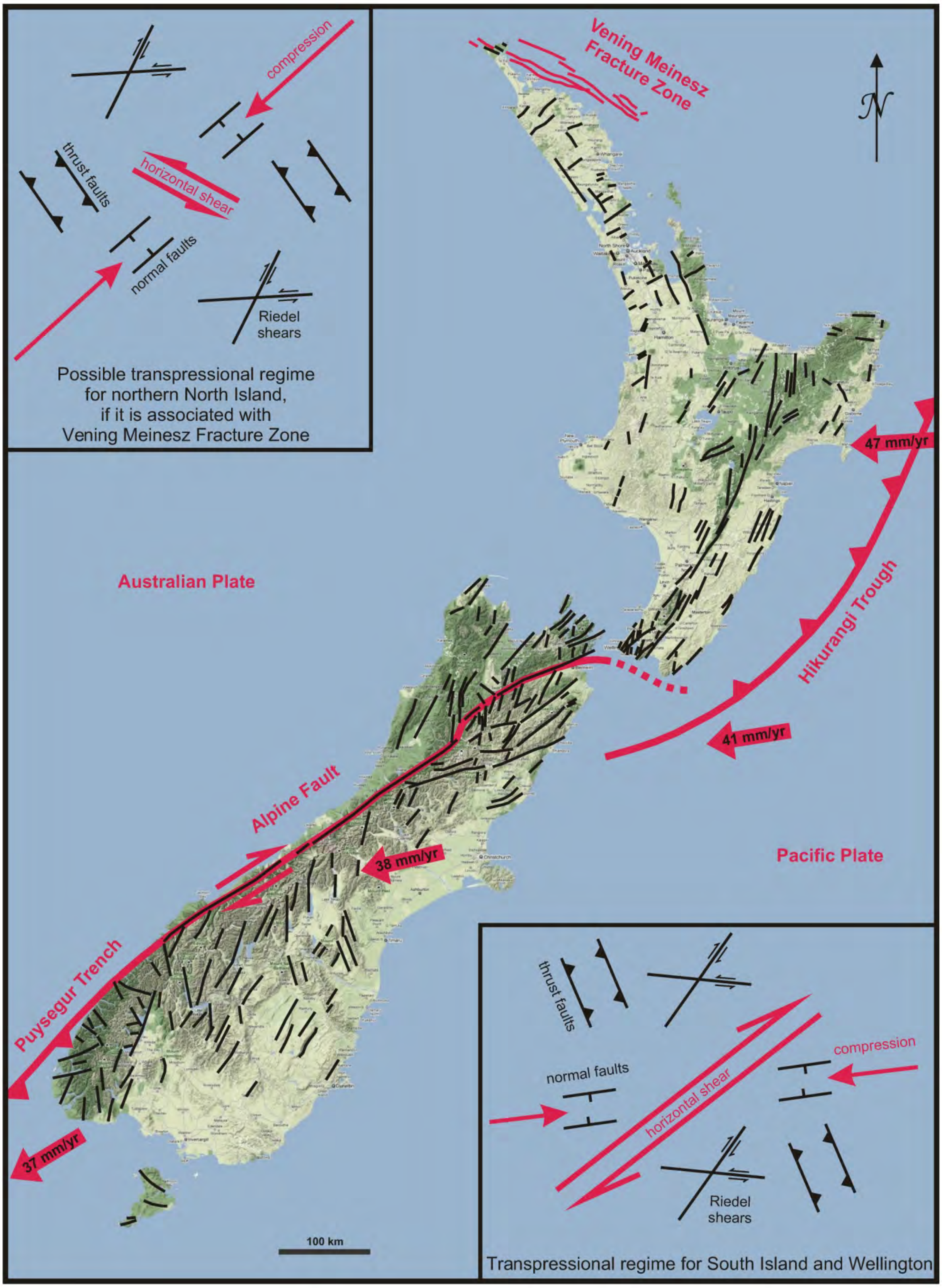

Figure 33: Same map as Figure 32, with Vening Meinesz Fracture Zone added off the northeast coast of Northland.
New inset (top left) illustrates a possible transpressional regime based on lineaments in teh northern half of the North Island, postulated to be linked to Vening Meinesz Fracture Zone.

Geochemical and geophysical analyses have established links between some AVF vents, both temporally and spatially (eg. Cassidy & Locke 2004, 2010). At present it can only be suggested that magma is using basement faults as conduits. These conduits could be related to reactivation of major NNW-trending crustal shearing associated with the JMA (Spörli & Eastwood 1997, Eccles 2003), or to remobilised extensional ENE-trending regional faults (Cassidy & Locke 2010), or to both.

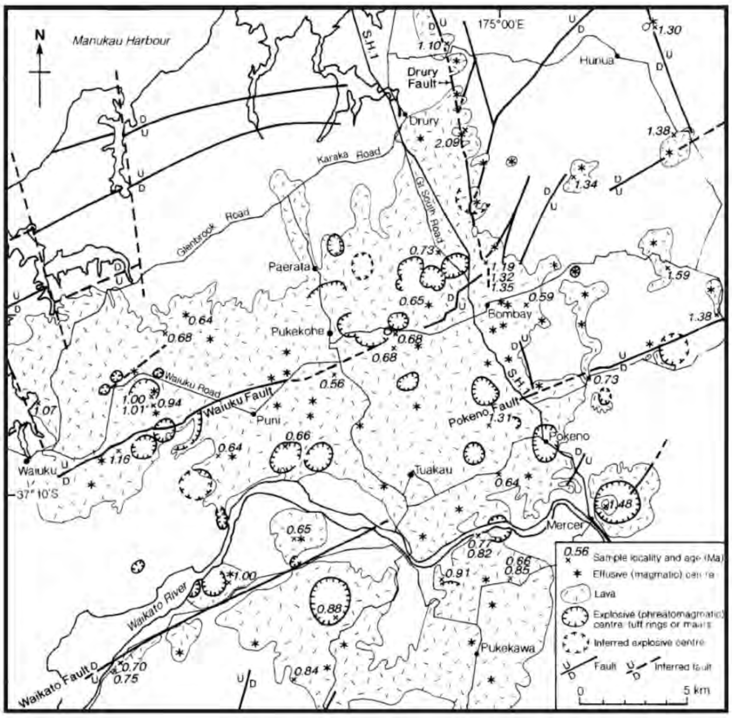

Figure 34a: Vent alignments in the South Auckland Field (from Briggs et al., 1994).

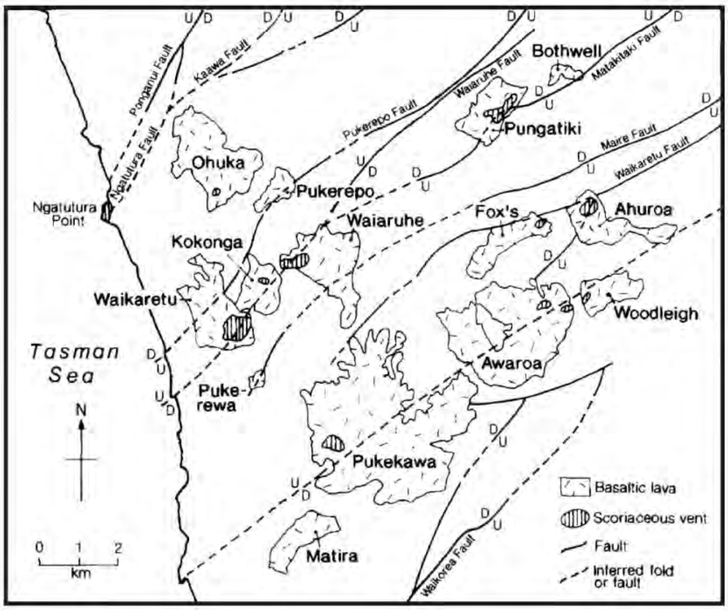

Figure 34b: Vent alignments in the Ngatutura Field (from Briggs et al., 1990).

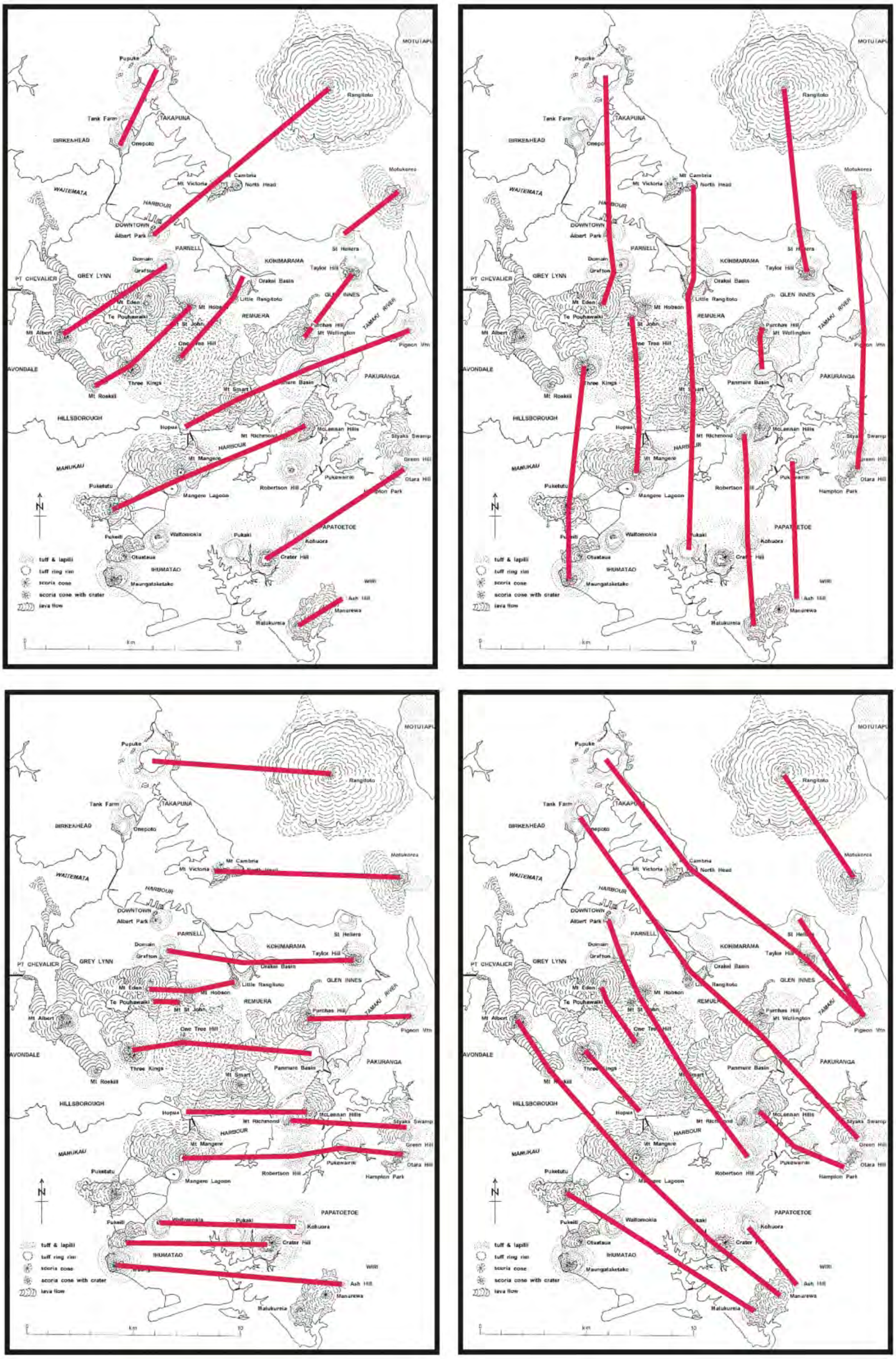

Figure 35: Experimental linkage of vents using specific trends superimposed on map of the Auckland Volcanic Field (modified after Kermode 1983).

Despite some faults probably being remobilised, vents do not seem to be aligned exactly with faults traced by topographical lineaments, although they are often close. As seen from shore platform and cliff exposures (Figures 10 & 11), faults offsetting Waitemata Group sediments tend to suture shut after movement has ceased. It is more likely that magma has reached the basement-cover rock interface then spread out along any plane of weakness it found within the overlying Waitemata Group rocks, possibly preferring joints, which tend to be more open (Figures 13 & 14).

The initial major Mesozoic shearing episode, together with numerous reactivations during the Cenozoic, could conceivably have provided a permeable environment along shear zones that eased the passage of magma through the crust. Magma could then rise from various sources in the upper mantle or asthenosphere to volcanic fields at Kaikohe and Whangarei in Northland, the AVF, the South Auckland Field, Ngatutura, and perhaps others further south.

The last section of the passage of magma to the surface would be through softer Tertiary material, in Auckland’s case, through the Waitemata Group. Magma would most easily ascend using open joint planes. The actual placement of any vent would be a function of 1) the position of a spot along the basement fault at the basement/cover interface, somewhere above a source in the mantle, to where the magma ascends, then 2) some vector from that spot in any number of ascending directions, which if grouped together, would fan outwards in an inverted cone shape. A vent position could be anywhere around the rim of the inverted cone. The narrowness of the cone would be dependent on the configurations of structures in the cover strata and the ascent speed of the magma. Suffice to say, the vent need not be directly above the point at which magma ascended through the basement.

Topographical variations (at most 100 m in the centre of Auckland isthmus), although conspicuous at ground level, are insignificant when considering that the Waitemata Group sediments are many hundreds of metres thick above the basement/cover interface through central Auckland (recall Figures 28 & 29). Therefore ridges and valleys in Auckland’s topography play no part in vent positioning.

It has often been said of the AVF that magma never erupts in the same place twice. Although latest research indicates that this adage may not be strictly true in all cases (eg. Needham *et al.* 2011, Hayward *et al.* 2011), this report finds that the statement is not far off the mark – magma reaches the basement/cover interface via basement shear zones then fans out once it reaches jointed Waitemata Group rocks. Subtle alignments along basement fault zones are retained, but vents are not positioned directly along reactivated fault traces that offset the covering Waitemata Group erosion surface, favouring joints or other planes of weakness instead.

It is likely that once magma has cooled and solidified within a conduit in the Waitemata Group rocks, it effectively blocks that route, necessitating other pathways to be utilised by subsequent magma batches.

CONCLUSIONS

- New faults have been inferred from a combination of attributes such as offsets of the Waitemata Group erosion surface, borehole and geophysical data, lineaments, and continuation of known faults. They have been assigned a high, moderate or low confidence rating, based on their total attribute score.

- As a result of estimating the topography of the concealed Waitemata Group erosion surface beneath Auckland, two significant faulting styles have been postulated:
  - A series of cuspate faults is thought to represent gravity slides within the Waitemata Group sedimentary pile, initiated as a result of nudging from the north by the toe of the Northland Allochthon.
  - Two sets of near-vertical normal faults, one dominantly trending NNW, the other trending approximately ENE.

- NNW-trending faults truncate ENE-trending faults, however, both sets have representative segments south of Auckland that may still be active – the NNW-trending Wairoa Fault in the Hunua Ranges is considered to have moved recently (Wise 1999) and an earthquake off Port Waikato in 1891 was probably centred on a western extension of the ENE-trending Port Waikato Fault (Hull *et al*. 1995).

- The present day erosion surface of the Waitemata Group exists at different elevations after being uplifted to varying heights by the block faulting.

- No correlation is evident between proposed faults and AVF vents, although magma rise may have been constrained eastwards and westwards by basement faults. Volcanic ash has concealed much of the erosion surface, but it is evident that lava flows have utilised long straight valley segments in that erosion surface. These valleys are mapped as lineaments representing eroded crush zones associated with faults separating the discordant blocks.

- The Northland and Auckland regions have been gently tilted to the west, possibly as a result of arching of the crust or thermal up-doming as a precursor event to formation of the Hauraki Rift.

- Rifting, as part of the block faulting, together with westward tilting, opened up corridors through which material from Coromandel could be channelled westwards. Subsequent uplift and rift formation closed these corridors.

- Some block faulting may be aligned along reactivated NNW-trending faults within the basement. Basement greywacke outcrops only in the east of the region. Further west, borehole and geophysical evidence indicates that the buried basement/cover interface deepens westwards along a series of NNW-trending faults. No boreholes have penetrated deep enough to encounter basement through the central Auckland region, but it rises again in the west to be less than 550 m deep under west Auckland and 350 m deep under northern Awhitu Peninsula.

From these findings, a number of speculations are mooted:

- The Junction Magnetic Anomaly widens in the Auckland region. Any boreholes drilled deep enough in this region may encounter serpentinised sheared material, not greywacke. This material likely provides much easier pathways than greywacke for magma to come to surface.

- It has been suggested in this study that there is no rational correlation of vent alignments in the AVF, however, most of the vents are actually within 100 m of the newly inferred faults (Figure 19). It has been suspected in the past by many researchers that magma has utilised basement faults. This would be logical, especially if it has penetrated through JMA-type sheared material rather than relatively intact greywacke. It is conceivable that when magma reaches the top of the sheared Dun Mountain-Maitai Terrane basement it encounters an obstruction of intact Waitemata Group sediments. It then exploits joints or other planes of weakness, fanning outwards to reach the surface near faults, but not necessarily exactly along them.

RECOMMENDATIONS

This work has exposed several other lines of possible research to better understand the seismicity and volcanism in Auckland, namely:

- Drilling to basement (JMA) within the AVF to confirm its presence and depth. The shortest distance to basement, where the JMA is modelled to be shallowest (Cassidy & Locke 2010) is thought to be Albany. Other useful sites would be Weymouth and the Auckland CBD.

- More seismic tomography; subsurface geology of the Waitemata and Manukau harbours is poorly understood. Airgun and Boomer seismic surveys of the Waitemata Harbour and western Hauraki Gulf follow widely spaced irregular courses. They are difficult to interpret and correlate. Large tracts show no structures at all, while other segments show so many disruptions that could be fault offsets, that any offset could be correlated with any other offset on a nearby transect. A detailed grid survey of this region is required. There are no useful seismic surveys of the Manukau Harbour. A detailed grid survey of this harbour is also required.

- Studies to investigate whether any faults are active. Deep borehole seismometers might detect small earthquakes occurring on faults.

- Updates and cross checks as new borehole data become available, especially in areas of currently sparse coverage, such as Manukau Lowlands, Manukau Harbour, Ardmore/Clevedon Valley, Tamaki River to East Tamaki, New Lynn, Henderson Valley, Takapuna and upper Waitemata Harbour.

- Ground-truth large proposed faults at the coast with ground-penetrating radar.

- Calculate volumes of lava flows and other volcanic deposits based on borehole information.

- Lava flow modelling based on past behaviour (but note that the Waitemata Group erosion surface does not equal the pre-volcanic topography in many areas).

- Statistical analysis of vent and fault locations to test the hypothesis outlined in this report.

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APPENDIX

New postulated faults, together with faults previously described by others within the study area, are described here. Since many of the major faults to the south of the region can be extrapolated northwards, faults in the southern part of the study area are described first. The remainder are described systematically from south to north, linking where possible with recognised faults around the northern, eastern and western margins of Auckland. Confidence ratings for the new inferred faults are given in square brackets (eg. [5]) after first mention. Known faults are not given confidence ratings.

Southern Manukau Lowlands, Papakura, Clevedon

The Papakura Fault (Papakura Valley Fault of Bartrum 1927, in Kermode 1992) strikes ENE and is downthrown about 450 m to the south, forming a north-dipping half graben along the Clevedon Valley. At the eastern end of the Clevedon Valley it curves round to the north. It may extend westwards to become the Karaka Fault.

Drury Fault – copied from Hull *et al*. (1995)

> *"Nixon (1977), using gravity, magnetic and seismic profiling, determined the Drury fault as a normal fault, trending NNW over a distance of 16 km and dipping between 65° and 90° to the west. Nixon determined a throw of 600 m on the basement rocks beneath the Clevedon depression, a throw which increased to 1.8 km* [south of Papakura]. *A subtle trace of the Drury fault can be followed on the 1:16,00 scale aerial photographs (Run nos 1927 / 11-12 & 1928 / 13-14) part way across the Clevedon depression through deposits mapped by Kermode (1992) as the upper-Pliocene Puketoka Formation. It is considered in this report however that the deposits are considerably younger than Pliocene.*
>
> *"Anderson (1977) found no evidence of an extension of the Drury fault north of the transecting Papakura Valley fault, although Yang (1989) recognised a basement structure that he called the Whitford fault, which he said could be a continuation of a basement Drury fault. His interpretation placed the Whitford fault some 4 km to the east on the north side of the Papakura Valley fault, but swinging back on strike with the Drury fault, some 3 km further north. To the south, the Drury fault is generally mapped as terminating at its junction with the Waikato and Pokeno faults, although Fellows (1987) suggested it may continue to the south as the Kimihia fault.*
>
> *"A number of basaltic eruptions have occurred along the Drury fault. Rafferty (1977) stated that all the basalts extruded along the fault have been displaced by subsequent movement along the fault except the Red Hill basalt. Rosenberg (1991) suggested that there has been up to 100 m of vertical movement of the Maketu Tuff ring on the Drury Fault since its eruption, but did not elaborate. Briggs et al. (1994) gives KAr ages for the basalts found along the fault as ranging between 0.59 and 1.35 million years with one date of 2.09 ± 0.37 million years. Nixon (1977) quoted Rafferty (pers. comm.) as saying that downfaulted basalt is, in places, buried by an average of 14 m of Quaternary material."*

High (1975) postulated a continuation of the Drury Fault northwards into the Turanga Valley through Whitford and northwards into the Hauraki Gulf. East of this major fracture Waipapa (composite) Terrane basement is often exposed. West of the fracture no basement outcrops. Ongoing movement may have been detected on a northern extension of the fault north of the Papakura Fault, where recent terraces are apparently truncated (Al-Salim 2000).

Northern Manukau Lowlands, Mangere, Papatoetoe

Wiri, Karaka, Waiau and Glenbrook Faults

From Hull *et al*. (1995) – "*High (1977) described the four faults as being continuously active up into mid-Nukumaruan times (1.0 to 2.2 million years), with the horsts representing stable blocks and the grabens subsiding between them. However, he says any post-Pliocene movement on the Karaka fault was confined to the western end beneath the Manukau Harbour, but presents no data to support this hypothesis. The north-trending offsetting faults are assumed to have been active at the same time or later than the east-trending faults.*"

Our study suggests that the Wiri Fault may continue eastwards along the base of the hills of Manukau Heights (Wiri Fault extension [confidence rating of 7], Table 1), uplifting those hills by more than 120 m as an eastward continuation of the Manukau Horst relative to East Tamaki lowlands. It may then cross the ridge into the Turanga Valley to become the Polo Lane Fault. The Karaka Fault, downthrown to the south by about 30 m, is also thought to continue eastwards. It lines up with the Papakura Fault along the northern side of the Clevedon Valley. The Waiau and Glenbrook Faults are truncated by the Drury Fault. These four faults were not included in the QMAP of Auckland (Edbrooke 2001) so they have been included in Table 1 as part of the last entry, achieving a moderate confidence rating of 4.

The Manurewa Fault [2] was described by Firth (1930), but has not been included in maps since then. At that time, a distinctive grit horizon was visible both on the Weymouth coast and in the hills of Manukau Heights. He mapped the offset as a NNW-trending fault, postulating that it might be associated with the Drury Fault further south. The Manurewa Fault has been reinstated here because it corresponds with a subtle lineament visible through suburbia on Google Earth (Kenny 2009). Together with the Puhinui Fault about 1.5 km to the east, it uplifts the Manurewa Horst by at least 60 m to form Manukau Heights.

The Puhinui Fault [2] is a new NNW-trending fault inferred from evidence of topographic offset – this fault, together with the Manurewa Fault, have uplifted the Manurewa Horst by more than 60 m to form Manukau Heights.

The West Mill Road Fault [2] and East Mill Road Fault [3] are new N–S-trending faults inferred from evidence of topographic offset as together they form a small graben, down-dropped about 20 m, along the Manukau Heights ridge. They are rather insignificant in themselves, but further north similar faults form the Lloyd Elsmore Graben, which continues northwards between the Karaka and Bucklands Beach Faults. The East Mill Road Fault is in line with the northern end of the Drury Fault, and could be part of a major fracture including the Drury, East Mill Road, Bucklands Beach and Islington Bay Faults. No volcanoes belonging to the AVF exist east of this line.

The Ihumatao Fault [2] is a new ENE-trending fault, the approximate position of which has been estimated from buried topographic offset using borehole data. It is downthrown to the south by more than 60 m and is subparallel to the Wiri, Karaka, Waiau and Glenbrook Faults, suggesting it could be part of the horst and graben structures described above.

Since Auckland isthmus is elevated with respect to the Manukau Lowlands to the south, it seems logical to reinstate the Manukau Fault [3] of Ballance (1968) in spite of no apparent evidence from drilling or geophysical measurements, according to Kermode (1992). Its exact position is uncertain, but it may occur just off the Hillsborough coastline where Searle (1959) reported that a borehole encountered ‘shattered’ Waitemata Group sediments in a sudden drop off only 250 m offshore. It is along this ENE-WSE zone that considerable offset of the Waitemata Group erosion surface occurs; to the north, across the Auckland isthmus, the erosion surface is tens of metres above sea level; to the south, across the Manukau Lowlands and Manukau Harbour, it is tens of metres below sea level. Its offset is accentuated by the erosion-resistant Titirangi ridge and because the Waitemata Group erosion surface forms a high-standing ridge at Hillsborough, representing the leading edge of a complexly disrupted gravity slide package within the Waitemata Group sediments (described later).

The Manukau Fault is drawn as two separate sections, but this is only because of postulated offset by any possible southern extension of the Avondale Fault. It may be associated with the Cornwallis Fault to the west, but would be offset by a southern extension of the East Scenic Drive Fault and/or the new N–S-trending Awhitu Fault. It may also extend eastwards, to become the Panama Fault then the Meadowlands Fault, both of which are new inferred faults.

The Cornwallis Fault [4] is a new fault inferred from lithologic offset across a major fault mapped by Jones and Martin (1965) at Cornwallis Peninsula. With different lithologies either side of the fault, they describe displacement as impossible to measure, but estimate it to be in excess of 60 m, downthrown to the south. Hayward (pers. comm. 2011) suggests a much larger displacement, even up to 300 m. For this report, the Cornwallis Fault has been extended westwards through the Manukau Harbour entrance to downthrown Awhitu Peninsula (where the Waitemata Group erosion surface is below sea level) with respect to the Waitakere Ranges (which, together with the Auckland isthmus, is at least at intermediate height above sea level). It could also extend eastwards, to be offset with respect to the Manukau Fault by the East Scenic Drive Fault and/or the Awhitu Fault.

Far West, Awhitu Peninsula

The Awhitu Fault [2] is a new N–S-trending fault mapped as an inferred extension to a fault separating Awhitu Peninsula from the rest of the Manukau Lowlands that is itself inferred from seismic and borehole data. The latter was mapped in conjunction with defining the Wiri, Karaka, Waiau and Glenbrook Faults (described above). None was included in the QMAP of Auckland (Edbrooke 2001). The Awhitu Fault is thought to be upthrown to the west, which would bring Waitemata Group and basement lithologies closer to the surface. They are actually encountered in a borehole just to the west of the proposed fault, at Grahams Beach, but depth to these lithologies east of the fault is unknown. Trends from further east would suggest they are deeper. With the fault’s N–S alignment and eastern facing direction, it is possible that the Awhitu Fault is a southern extension of the East Scenic Drive Fault that separates the Waitakere Ranges from western Auckland (described later).

Awhitu Peninsula faults [3] – copied from Hull *et al*. (1995)

> *“Three unnamed faults have been recognised by Barter (1976) in the Awhitu Peninsula. Each is seen to displace Pehiakura Ash (0.74 ± 0.07 million years). The northern fault shows downthrow to the north of 10 m, and the middle fault a total of 25 m across the two branches. The southern fault is downthrown 24 m to the south. Barter suggested that the middle and southern faults may represent extensions of the Waiau and Glenbrook faults mapped by High (1977), thus adding support to High’s view that these inferred faults were active in Pleistocene time. Hollis (1986) replotted the positions of the faults*

> *recognised by Barter on the Awhitu Peninsula by moving the middle fault 2.5 km north, and mapping the southern fault at the position of Barter's middle fault.*"

These faults are truncated by a NNW-trending fault splitting Awhitu Peninsula in two. There are also two NE-trending faults at the northern end of Awhitu Peninsula. None of these faults was included on the QMAP (Edbrooke 2001), so they have been added as one package of faults in Tables 1 and 2.

Far East, Whitford, Beachlands

The Te Puru Fault was described by Anderson (1977) using geophysical parameters; it has no surface expression. It has now been better constrained for this report using data from boreholes that have penetrated the greywacke basement. There is still some uncertainty – it is more sinuous than Anderson's original version, or it may be offset by NNW-trending faults associated with the nearby Kiripaka or Beachlands Faults. Borehole analysis indicates that the greywacke basement / Waitemata Group interface has an average offset on the Te Puru Fault exceeding 100 m, yet the Waitemata Group erosion surface has been offset by only about 60 m. This establishes downthrow to the northwest on the fault prior to erosion of the peneplain, followed by remobilisation after peneplanation. Substantial faults zones have been detected in parallel Boomer seismic sections 3.5 km north of the Maraetai coastline, directly north of where the fault is mapped on land (Kenny, pers. obs. with B.Davy, GNS, 2011).

Located at the far eastern side of the map, the Waikopua Fault (the Clevedon-Waikopua Fault of Firth 1930) is the most conspicuous fault in the study area, juxtaposing uplifted erosion-resistant greywacke hills to the east against downthrown erosion-prone Waitemata Group lithologies to the west. According to Hull *et al*. (1995) –

> "*The Waikopua fault trends at 330˚ and dips to the west. Anderson (1977) determined a post-Miocene throw of basement rocks of 250 m. It extends over 6 km from the Papakura-Clevedon corridor towards the west branch of Waikopua Creek bringing Waitemata Group rocks in contact with Waipapa Group basement over most of its length. Recent drilling for Manukau City Council reveals that the fault continues at its northern end for a short distance through Waitemata Group rocks but with a diminished throw before it disappears beneath sediments mapped as Pliocene-Pleistocene.*"

The northern extent of the fault was confirmed during mapping and drilling associated with development of the Whitford Quarry. A post-Miocene offset of 350 m, downthrown to the west, was determined in this region before it rapidly dies out or is truncated less than a kilometre further north (Figures 19, 20a, 20b). A splinter fault, trending northeast and downthrown to the northwest, was also mapped in the quarry area (G. Mansergh, pers. comm. 2007). This splinter could be the southwestern limit of the Te Puru Fault, conveniently accommodating slip from the northern end of the Waikopua Fault, and providing an explanation for the sudden termination of the Waikopua Fault north of Whitford Quarry. Movement could then be transferred, via the splinter, northeastwards to the new inferred North Waikopua Fault further northeast (see below).

The Polo Lane, Alfriston and Brookby Faults were postulated by Yang (1989) to explain configurations of greywacke and Waitemata Group lithologies in the hills southeast of Whitford. They have parallel trends to the Papakura Fault (Figures 19, 20a, 20b). The Brookby Fault has a southward facing direction, similar to the Papakura Fault. The Polo Lane and Alfriston Faults have an opposite facing direction.

New inferred faults in this region may be continuations of these faults. A westward extension of the Polo Lane Fault, with a strong E–W lineament through the hills east of Manukau Heights, clearly offsets Manukau Heights by about 120 m against the low plains of the Flat Bush area (Figures 19, 20a, 20b). It is then directly in line with the Wiri Fault, forming the northern boundary of the Manurewa Horst. A small extension of the Alfriston Fault is now inferred on east side of Waikopua Fault. The Brookby Fault may continue westwards, forming part of the southern boundary of the Manurewa Horst, uplifting it by potentially over 100 m. Its association with the Karaka Fault to the south is not known.

Like the Te Puru Fault, the Whitford Fault has no surface expression. It was first mapped by Firth (1930) but not named. Anderson (1977) delineated "a major new fault, here called the Whitford Fault" using gravity surveys. It is strangely positioned, being half way up the western side of the asymmetric Turanga Valley. It could be better positioned along the axis of the valley, where High (1975) mapped a possible northern extension of the Drury Fault. Or it could be correctly placed half way up the valley side, with remobilisation being taken up along a new fault offsetting topography along the valley axis, represented on the map by High's Drury Fault extension or the new inferred Turanga Fault (described later).

Whichever the case, boreholes that penetrated basement in this region indicate that there has been displacement of the greywacke basement / Waitemata Group interface down to the west by about 100 m and offset of the Waitemata Group erosion surface by approximately 50 m. This establishes remobilisation of faulting in this area, similar to that demonstrated for the Te Puru Fault. There is downthrow to the west on perhaps more than one fault prior to erosion of the peneplain, followed by remobilisation after peneplanation.

The North Waikopua Fault [6] is deliberately named as such here because it is inferred to be the northern extension of the Waikopua Fault, but stepped northeastwards from that fault along a splinter fault (see Waikopua Fault above) (Figures 19, 20a, 20b). It was only suspected to exist as a subtle step in topography along the western Beachlands coastline, where the Waitemata Group erosion surface is offset by less than 50 m. With basement-penetrating borehole data becoming available recently, a clear offset in the greywacke basement / Waitemata Group interface by an average of 150 m down to the west, corroborates the suspected existence of a fault. Thus remobilisation along this fault can also be established, similar to the Te Puru and Whitford Faults.

Disrupted faults zones have been detected in parallel Boomer seismic sections north of Beachlands, directly in line with the North Waikopua Fault (Kenny, pers. obs. with B.Davy, GNS, 2011).

Beachlands Fault – copied from Hull *et al*. (1995)

> *"This fault has been described by Glading (1987) and Firth (1928)* [see Firth 1930] *as striking at 320˚, putting it on strike with the Kiripaka fault. Prebble (1991) mapped the Beachlands and Kiripaka fault as a continuous feature. The fault is seen as displacing the Waitemata Group and also the overlying Quaternary beds.*
>
> *"The Beachlands fault offsets an erosion surface cut into the Waitemata rocks dated at 105,000 YBP (High 1975) and two discrete ash beds in the overlying Quaternary terrace. Glading (1987) stated that the upper ash bed pre-dated the 50,000 year ash recognised elsewhere in Auckland, but could not assign a precise age to the offset ash."*

Disrupted faults zones have been detected in parallel Boomer seismic sections north of Beachlands, directly in line with the Beachlands Fault (Kenny, pers. obs. with B.Davy, GNS, 2011). An interpretation is attempted here (Figure 22).

Kiripaka Fault – copied from Hull *et al*. (1995)

> *"The Kiripaka fault comprises five segments striking between 280˚ and 340˚ and downthrown to the SW offsetting basement by up to 40 m. To the NW, Waipapa Group is faulted against itself, but to the SE Waitemata Group rocks are faulted against the Waipapa Group.*
>
> *"Firth (1928)* [see Firth 1930] *noted the presence of both faceted spurs and hanging valleys along the scarp of the Kiripaka fault. The scarp itself displays a youthful morphology which is interpreted as signifying that the Kiripaka fault has probably moved more recently than any other fault within the Hunua – Maraetai hills."*

A new N–S-trending extension to the Drury Fault [2] is inferred north of Whitford, between Beachlands and Cockle Bay, to link with the North Waikopua Fault. It was postulated previously by High (1975) to run through the Turanga Valley to Whitford, but this segment is now more constrained from borehole data which shows offset of basement and Waitemata Group erosion surface. However, the boreholes are not adequately positioned to distinguish between downthrow to the west taken up by the Whitford Fault or the Drury Fault extension individually.

Seismic profiles are full of faults between Howick and Beachlands where this fault is thought to exist (Kenny, pers. obs. with B.Davy, GNS, 2011). This is approximately the same area as the inferred location of the North Waikopua Fault – the two faults could converge here.

The Turanga Fault [6] is a new, small but significant, NW-trending fault in the eastern Turanga Valley, inferred from evidence of topographic offset and offset of Waitemata Group and basement lithologies, down to the west by more than 60 m.

Near East, Howick, Pakuranga, East Tamaki

The Dannemora Fault [4] is a new N–S-trending fault involving a considerable topographic offset, where the Point View Drive ridge is inferred to be uplifted more than 100 m alongside the East Tamaki lowlands to the west. Recent evidence from boreholes that have penetrated basement indicates that Waipapa (composite) Terrane basement is downthrown nearly 200 m to the west, while the Waitemata Group erosion surface is offset about 100 m – another example of fault reactivation (refer back to the Te Puru, North Waikopua and Whitford Fault descriptions). The exact nature of the Dannemora Fault is unclear. It could be curved, following the base of the hills, and therefore logically be associated with the Howick Fault to the north. It is more likely, however, given the amount of offset involved, to be straighter and linked to the prominent N–S-trending Bucklands Beach Fault and associated Lloyd Elsmore Graben (see below) and the West Mill Road–Drury Fault system to the south (see above).

The Somerville Fault [3] is a new inferred short curved (but mostly ENE-trending) fault with considerable topographic offset (over 60 m). It forms a boundary between the parallel NE-trending ridges topography of the Howick block and the more deeply weathered terrain of the uplifted hills between East Tamaki and Whitford. It also has a similar configuration to the southward-directed slope failures associated with the Northland Allochthon, discussed later, but this fault is much southeast than any other faults attributed to this group. Because of its curved nature, it loses points in the confidence rating of the Attribute Table (Table 1) because strong lineaments and straight valleys do not apply. It deserves a higher rating than the 3 it is given. It could be a splinter fault from the Meadowlands Fault.

Just to the north, the Meadowlands Fault [5] is a new ENE-trending inferred fault uplifting the suburb of Howick by about 60 m relative to the lowlands to the south. There also appears to be slight northward-tilting of the Howick block along this fault, which has caused the central valley within the suburb to be poorly drained (G. Mansergh, pers. comm. 2007). The throw diminishes eastwards, but it is unclear whether it dies out or continues northeastwards down the axis of the Cockle Bay valley. Westwards it could be linked with the Panama–Manukau–Cornwallis Fault group, which upthrows the Auckland isthmus to an intermediate level relative to the Manukau Lowlands, where the Waitemata Group is below sea level and hidden by more recent sediments.

The Panama Road Fault [3] is a new E–W-trending fault inferred from several en echelon topographic offsets, the western and eastern sections of which uplift Hamlins Hills and Pakuranga blocks respectively, north of the Manukau Lowlands. The middle section is not well defined at present because of a lack of boreholes across the upper Tamaki River. The en echelon pattern is thought to be a result of subsequent offsets by NNW-trending faults. This fault is one of four major inferred faults, namely the Cornwallis, Manukau, Panama and Meadowlands Faults, uplifting the region to the north from the Manukau Lowlands (Figure 19). One borehole, south of Hamlins Hill, shows the Waitemata Group erosion surface to be extremely deep – more than 60 m below sea level, giving an overall throw of over 100 m.

The Pakuranga Fault [3] is a new NNW-trending inferred fault that uplifts the southern hills of Pakuranga by more than 50 m with respect to the Tamaki River valley. Its southern continuation beyond the Panama Fault, and its association with the Panama Fault, is unknown without better borehole coverage in this area. It could also conceivably be linked to the disjointed Hobson Fault. There are many faults in seismic profiles in the Tamaki River north of this fault, directly in line with it (Kenny, pers. obs. with B.Davy, GNS, 2011).

The Stanniland Fault [6] is a new N–S-trending slightly curved inferred fault forming the western side of the Lloyd Elsmore Graben. Topography is downthrown significantly in the graben, with a borehole within Lloyd Elsmore Park revealing that the Waitemata Group erosion surface is deeper than 20 m below sea level. Recent sediments infilling the graben abut against Waitemata Group lithologies west of the Stanniland Fault. The fault may continue northwards to become the Karaka Fault and southwards to become the West Mill Road Fault, but there is no strong evidence for either continuation.

The Bucklands Beach Fault [7] is a new N–S-trending inferred fault forming the eastern side of the Lloyd Elsmore Graben. There is an obvious topographic offset, down-dropping the eastern Pakuranga area with respect to the Howick block (Figure 21). Considering the borehole in Lloyd Elsmore Park reveals a 20 m below sea level depth of the Waitemata Group erosion surface (as described for the Stanniland Fault), and the average height of the Howick block is 60 m above sea level (refer back to Figure 7), a throw of 80 m is estimated for the Bucklands Beach Fault. This major fracture could link up with other significant faults in the region, namely the Islington Bay Fault to the north and the East Mill Road Fault / Drury Fault system to the south. Associated with this, the Lloyd Elsmore Graben is a dominant N–S-trending feature, even within the present topography of Auckland, where it is covered by more recent sediments. It forms the northern borders of the Tamaki River and may continue as far south as the small graben in the Manukau Heights ridge between the East and West Mill Road Faults.

Seven volcanoes line up along this corridor, from Hampton Park, Otara Hill, Green Mount and Styaks Swamp volcanoes in East Tamaki, to Pigeon Mountain in Pakuranga, and Browns Island and Rangitoto in the Waitemata Harbour. There are no volcanoes associated with the AVF east of the corridor and its eastern border faults comprising the Islington Bay, Bucklands Beach, East Mill Road, Drury Faults.

The Howick Fault [4] is a new NNE-trending inferred fault with a small topographic offset of 20–30 m down to the west, that forms a strong lineament down the axis of the dominant asymmetric valley in the Howick block. This valley, mentioned in relation to the Meadowlands Fault, has unusual drainage, as if it has been back-tilted by uplift on the Meadowlands Fault that forms its southern boundary. The Howick Fault is a possible continuation of the Dannemora Fault, offset by the Meadowlands Fault.

The Mellons Bay Fault [4] is a new NE-trending inferred fault with small topographic offset of 20 m down to the northwest, but the associated strong NE-trending lineament can also be picked up at the southern end of the Pakuranga hills, across the other side of the Lloyd Elsmore Graben. The lineament may actually equate to strata – it is parallel to the strong NE-trending ridges that dominate the uplifted Howick block – but it is also parallel to the MacLeans Fault which has strong topographical expression.

The uplifted Howick block is truncated in the northwest by the MacLeans Fault [4],a new NE-trending inferred fault that also offsets erosion-resistant Parnell Grit. Similar to the Mellons Bay Fault, also with a throw of 20–25 m, it continues across the other side of the Lloyd Elsmore Graben, down-throwing the ridge line along the central Pakuranga Hills by 15–20 m.

The Eastern Beach Fault [3] is a new E–W-trending inferred fault forming the southern border of the low-lying corridor between Eastern Beach and Bucklands Beach. It also topographically down-drops the whole of the Bucklands Beach Peninsula by up to 50 m with respect to the Howick block. It forms a lithological boundary as well, with a Parnell Grit horizon outcropping on the shore platform south of the proposed fault position at the southern end of Bucklands Beach. The contact with other lithologies of the Waitemata Group is obscured by sand.

Inner Hauraki Gulf Islands

The Motutapu Fault of Mayer (1968, in Kermode 1992) trends NNW, about 1 km inland from, and parallel to, the western coast of Motutapu Island. It is downthrown to the west, offsetting greywacke-dominant terrain to the east from terrain dominated by Waitemata Group lithologies to the west. A fault with small offset, which shows up on an airgun seismic reflection line north of the island (Kenny, pers. obs. with B. Davy, GNS, 2011), is thought to be a northern extension of this fault.

Milligan (1977) suggested from geophysical studies that a major displacement of Mesozoic rocks occurs beneath Islington Bay, between Rangitoto and Motutapu islands. An inferred N–S-trending fault is named here as the Islington Bay Fault [4] to explain a sudden drop in topography along the western side of Motutapu Island. The Waitemata Group erosion surface west of the Motutapu Fault is approximately 60 m above sea level, while a borehole has encountered the erosion surface at more than 25 m depth beneath Rangitoto Island, making an inferred offset of at least 85 m. A fault downthrown to the west by about 100 m is visible on an airgun seismic reflection line directly north of northeastern Rangitoto (Kenny, pers. obs. with B.Davy, GNS, 2011).

The NE-trending Motuihe Fault of Schofield (1958, in Kermode 1992) on Motuihe Island is downthrown to the northwest, juxtaposing greywacke against basal Waitemata Group lithologies.

The Whangaparaoa Passage Fault [2] is a new N–S-trending fault postulated to exist in the seaway between Whangaparaoa Peninsula and Tiritiri Matangi Island. Greywacke outcrops east of the fault on Tiritiri Matangi Island but not to the west on Whangaparaoa Peninsula. This truncation of greywacke is also observed on the inferred southward continuation of this fault along the Islington Bay, North Waikopua and Drury Fault system. The exact position of the fault has been determined from an airgun seismic reflection line in the Whangaparaoa Passage, where both basement and cover lithologies have been significantly downthrown to the west, although reflectors are difficult to follow and the amount of offset is unclear (Kenny, pers. obs. with B.Davy, GNS, 2011).

Auckland isthmus

The Glendowie Fault [4] is a new NNW-trending inferred fault along a low-lying corridor from St Heliers Beach to Glendowie. It is upthrown to the northeast, uplifting the Achilles Point area by about 20 m and forming the western headland of the Tamaki River. It may be responsible for the truncation of cliffed Waitemata Group strata at the eastern end of St Heliers Beach.

The Karaka Fault [1] is located north of this same uplifted block above. There is very little evidence for this fault, other than that it truncates reefs east of Achilles Point. It is envisaged to form the western boundary of a northern equivalent of the Lloyd Elsmore Graben described earlier.

The Glendowie and Karaka Faults, together with the Bucklands Beach, Stanniland and Eastern Beach Faults described earlier, all converge in a confined area within the Tamaki River, forming a large asterisk-like pattern (Figures 19, 20a, 20b). Many fractures are also visible in Boomer seismic sections in this part of the Tamaki River (Kenny, pers. obs. with B.Davy, GNS, 2011). These intersecting faults have produced a zone of weakness within a former ridgeline, from Glendowie to the hills south of Bucklands Beach, which used to separate the Waitemata and Manukau river catchments. The northward breakout of the Tamaki River, less than 200,000 years ago, probably exploited this zone of weakness (discussed later).

The Hobson Bay Fault [3] is a new disjointed series of short NW-trending fault sections extrapolated from western down-dropping of topography by approximately 20 m, strong lineaments in small valleys in Remuera and borehole data where the fault is concealed by AVF-derived ash and lava in the Mt Wellington area. It is not specifically identified in seismic profiles of the Waitemata Harbour to the north (Davy 2008), but it could conceivably be linked to the Pakuranga Fault further south.

The Hamlins Fault [2] is a new NW-trending fault inferred from more than 40 m topographic offset. Together with the Penrose Fault, it forms a prominent southward-protruding peninsula jutting out from the “paleo” Auckland isthmus. It is thought to extend northwestwards to become the Remuera Fault.

The Remuera Fault [4] is a new NW-trending fault based on topographic offset and strong lineaments. Its southern portion, with 50 m offset, forms the eastern side of a prominent ridge jutting into Ellerslie from the catchment boundary. Its northern portion is delineated by a series of lineaments and subtle topographic offsets of about 20 m. It probably extends southeastwards to become the Hamlins Fault.

A major fault inferred to run parallel to, and just to the west of, the Southern Motorway has been named the Penrose Fault [5] (Figures 18b, 20a). Its greatest topographic offset of more than 60 m is at its southern end where, together with the Hamlins Fault, it forms a prominent southward-protruding peninsula. The northern portion is buried by ash and lava from the AVF but it is constrained by borehole data. Here it has no apparent topographic offset of ridgelines to the northeast or southwest of it, but a deep valley has eroded along it which has subsequently become a key channel for lava flows.

Firstly, easterly-directed lava flows from One Tree Hill volcano reached the northern part of the valley and from there were redirected southwards into valleys in the Onehunga area and towards Hamlins Hill. Mt Smart then erupted through some of these flows and added to lava thicknesses near Hamlins Hill. Lastly, lava flows from Mt Wellington, on the other side of the fault, flowed into a long SSW-trending valley hugging the side of Hamlins Hill, created by lava flow fronts from the west and Waitemata Group rocks to the east, upthrown by the southern portion of the Penrose Fault. In other words, the Penrose Fault has channelled lava flows from 3 volcanoes toward the Manukau Harbour. This fault crosses Murray's (2010) contour polygon modelled using geophysical parameters. The model shows the steep slopes of the valley system beneath the lava, but the presence of a fault was not one of the computation criteria used to form the model, so it was missed.

The Penrose Fault may be related to the Newmarket Fault (which also has no topographic offset) further north via a saddle in the Waitemata Group erosion surface.

The Newmarket Fault [3] is a new NW-trending inferred fault just west of the Southern Motorway. It has no obvious facing direction and just like the northern section of the Penrose Fault, to which it may be related, it has formed a significant valley buried by ash and lava, with no obvious topographic offset of ridges either side. It has become a key channel used by lava flows from Mt St John and possibly Mt Hobson volcanoes. Most significantly, Mt St John lava flowed down this valley in the first stage of its long journey towards Newmarket, and thence under Mt Eden (which had not yet erupted), finally terminating as Meola Reef (Eade 2009), the longest lava flow in the AVF.

The Sandringham Fault [4] is a new inferred fault defined by topographic offset of about 20 m and borehole data. It trends northwest over most of its length but curves northwards at its northern end, towards the Waitemata Harbour, providing a channel for lava flows from Mt Albert, Three Kings, Mt St John and Mt Eden volcanoes. The southern two-thirds of the fault is buried by ash and lava. Caves formed in Three Kings lava flows are directed northwestwards along this valley. Ash from Three Kings phreatomagmatic eruptions covers a high ridge of Waitemata Group strata on its eastern side, on the upthrown side of the fault, producing a tuff ring that looks far more impressive than it perhaps should. The Sandringham Fault is parallel to the Stoddard Fault and may join with the Birkenhead Fault to the north.

The Stoddard Fault [4] is a new NW-trending fault, parallel to the Sandringham Fault, and inferred from strong lineaments and slight topographic offset of up to 20 m. It follows a valley directly towards Mt Albert along which lava from Mt Roskill volcano was channelled until it was diverted to the west by lava flows from Mt Albert. The fault also aligns with a notch in the Hillsborough ridge, now occupied by the Southwestern Motorway. During construction of this portion of the motorway, disrupted Waitemata Group strata were exposed, but it is now mostly hidden by retaining walls (Kenny, pers. obs. c. 2006).

The Coxs Bay Fault [4] is a new, short, NW-trending fault inferred from a strong lineament towards Karangahape Road and a topographic offset that upthrows the Jervois Road area 40 m to the east. It also aligns with a subtle turn in Meola Reef lava flow, where the lava is thought to have followed a bend in what was then a distal portion of Coxs Creek (now inundated by seawater) that would have joined with the ancient Waitemata River valley. Together with the Sandringham Fault, this fault may link northwards to the Birkenhead Fault.

West Auckland

A series of large-scale block faults west of Auckland isthmus has formed a depression in the upper reaches of the Waitemata Harbour (Figure 19). A seismic and borehole study of this area (Hicks & Kibblewhite 1976) shows that the Waitemata Group erosion surface is more than 30 m below sea level at the T-intersection of the harbour east of Te Atatu Peninsula. That depth is deeper than the outlet of the harbour beneath the Auckland Harbour Bridge. A rim of Taupo-derived pumiceous clays around the upper harbour from Avondale to Riverhead (Kermode 1992) indicates that a lake once existed here, in the down-dropped depression surrounded by these faults.

The southeastern boundary of this depression is provided by the Avondale Fault [6], a new N–S-trending inferred fault that forms a 40 m offset of topography along the Point Chevalier western coastline, southwards into Avondale where the throw has increased to 80 m. It reaches the Manukau Harbour at Green Bay with an obvious lineation but no obvious topographic offset.

The Kelston Fault [4] is a small NNE-trending inferred fault within the southern part of the depression. It forms a strong lineament through a small notch in the ridge through Glen Eden, where it apparently offsets an older curved fault (one of a number of cuspate faults described later) up to the west by less than 20 m. It then follows a lineament northwards to the Whau River.

The Oratia Fault [7] is the southernmost of three new NE-trending inferred splay faults that curve northwards and converge, however this fault has the opposite facing direction. In the Henderson Valley borehole evidence shows it to downthrow the Waitemata Group erosion surface substantially to the west, making a deep valley with the Henderson Fault. Its throw of 20–40 m decreases northwards and is lost as it encounters the Henderson Fault. At its southern limit its topographic offset cannot be followed into the foothills of the Waitakere Ranges, but it may be a continuation of faults mapped within the Ranges by Hayward (1983).

The middle splay fault is the new Henderson Fault [7], inferred to trend NE through the Henderson Valley. It substantially downthrows the Waitemata Group erosion surface to the east before curving northwards to form part of the western boundary of the upper harbour depression. Here it loses much of its apparent offset and converges with the Swanson Fault. The deep valley between the Henderson and Oratia Fault is an enigma. From borehole evidence, the erosion surface beneath younger sediments is more than 40 m below present sea level on the western side of the valley and therefore, using probable valley side gradients, it is likely to be more than 60 m below sea level in the axis of the valley. This feature, in this location, is not understood. It gives the Henderson Fault a throw in this sector of potentially more than 100 m.

The northernmost of this group of faults is the new NE-trending Swanson Fault [6], inferred from topographic offset. Within the Henderson Valley it downthrows the Waitemata Group erosion surface by maybe 120 m to the southeast, before curving to the north, converging with the Henderson Fault and forming part of the western border of the down-faulted region around the upper harbour. As with the Henderson Fault, its continuation southeastwards is lost in the foothills of the Waitakere Ranges, but also may be a continuation of faults mapped within the Ranges by Hayward (1983).

The Opakunui Fault [5] is a new E–W-trending inferred fault forming a strong lineament and topographic offset about 60 m down to the south along the true left branch of the Henderson Valley. Its trend is unusual compared with others described above, but similar trends occur within the Waitakere Ranges to the west (Hayward 1983).

The East Scenic Drive Fault [5] was mapped by Hayward (1975) as a 12-km-long N–S-trending lineament made up of andesitic intrusions and dykes along the eastern margin of the Waitakere Ranges. It coincided with a fault that was thought to downthrow the western Early Miocene Waitakere Group volcanoclastic lithologies against slightly older Waitemata Group sediments to the east. This was despite the western side of the fault being topographically higher than the east, due to a resistant cap rock. With reappraisal of respective ages and spatial configuration, Hayward (2009) has reversed the facing direction, so its throw is now down to the east. In the current study, this fault has been extended at both its northern and southern ends and could continue southwards to link with the Awhitu Fault. The two faults would then form an important western boundary to the greater Auckland–Manukau Lowland block against the relatively higher Waitakere–Awhitu block.

On Auckland's west coast a new fault has been postulated along a line of vents – the West Coast vent lineament [1]. This NNW-trending feature, divided into two sections, is marked by the alignment of craters and volcanic necks (Hayward 1975, 1983). It has not been formerly identified as a fault by Hayward and only scores a confidence rating of 1 (Table 1).

The West Taupaki and East Taupaki Faults [2] also do not score well in the confidence rating. They are NNE-trending lineaments that cut other lineaments probably related to strata. Offsets are not obvious.

The Brigham Creek Fault [5] is a new NNE-trending inferred fault based on lineaments and slight topographic offset of less than 20 m. Kermode's (1992) map also indicates that Waitemata Group strata outcrop higher up the western slopes of Brigham Creek valley. It may contribute to the northwestern boundary of the fault-bounded depression occupying the upper harbour area.

The new inferred Waiarohia Stream Fault [4], parallel to the Brigham Creek Fault, follows an asymmetric valley between Whenuapai and Hobsonville. According to borehole information, it is down-faulted only about 10 m and is contained within the upper harbour fault-bounded depression.

North Shore

The Alexandra Fault [4] is a new NNW-trending inferred fault forming a strong lineament along Alexandra Stream north of Glenfield, with slight down-dropping of topography less than 20 m to the east. It cannot be followed north of Rosedale Road, but it can be traced southwards across Sunset Road ridge into the upper Wairau Valley, where it may link up with the Glenfield Fault.

The Birkenhead Fault [4] is a new NNW-trending inferred fault that offsets topography along a strong lineament making up the western coastline of Birkenhead. A straight line of cliffs along this coastline separates the Birkenhead block, where the Waitemata Group erosion surface reaches an average height of 80 m, from coastal Hobsonville where the erosion surface barely reaches above sea level. This fault forms the northeastern boundary of the upper Waitemata Harbour depression. Many faults are visible in a Boomer seismic section traversing this area (Kenny, pers. obs. with B.Davy, GNS, 2011).

The Kaipatiki Fault [4] is a new NNW-trending fault to the northeast of the Birkenhead Fault. It downthrows topography 80 m to the west and truncates older cuspate faults. It cannot be traced northwards, but it may link southeastwards with a fault that has been previously mapped under the Auckland Harbour Bridge (Cornwell & High 1975, Hayward 1982).

The Glenfield Fault [3] is a new inferred fault composed of N–S-trending lineaments about 1 km east of the Glenfield ridge. The lineaments cut a series of easterly-jutting spurs, with a subtle topographic offset slightly downthrowing the eastern side by 10–20 m. Northwards it may curve to the northwest and link with the Alexandra Fault.

The Northcote Fault [3] is a new N–S-trending fault 1 km east of the Glenfield Fault. It is inferred to downthrow the same series of easterly-jutting spurs, with another subtle topographic offset of 10–20 m downthrowing the eastern side.

A NNW-trending fault mapped under the Auckland Harbour Bridge by Cornwell & High (1975) and discussed by Hayward (1982) was postulated to curve northwards to link with the East Coast Bays Fault [5], and also to extend southwards to be concealed under AVF deposits before emerging many kilometres further south as a potential northern extension of the Drury Fault. Like both these faults, it faces west, but it is now thought to continue in a more NNW direction, possibly to link up with the Kaipatiki Fault. It may also link southeastwards with the Newmarket Fault, then the Penrose Fault.

The East Coast Bays Fault has been described earlier, in the section on previously recognised regional faults. However, only one segment inland from Mairangi Bay is still located approximately in the same position as Schofield (1989) mapped it. The other segments, from north of the Okura River in the north to Shoal Bay in the south, have been repositioned according to subtle lineaments and lithologic offsets (sub-horizontal strata abutting contorted, sometimes steeply dipping strata; offset unknown) but no obvious topographic offset. They have been reassessed as inferred newly positioned sections of the East Coast Bays Fault and have been assigned a high confidence rating in Table 1.

The Ngataringa Fault [2] is a new fault inferred to be made up of two N–S-trending segments. The southern segment uplifts Stanley Point by about 20 m with respect to Devonport to the east. The northern segment is a subtle topographic offset of less than 10 m on Bayswater Peninsula. They are aligned with the southern limit of the East Coast Bays Fault, but have an opposite facing direction analogous to the Northcote and Glenfield Faults to the west and the Remuera Fault to the south. The fault is not specifically identified in seismic profiles of the Waitemata Harbour in this area (Davy 2008) and is only assigned a low confidence rating in Table 1.

Northeast Auckland

Three new faults have been postulated along the Whangaparaoa Peninsula, although this area is considered to be beyond the scope of this investigation. The Weiti Fault [3] is inferred to follow the NNW-aligned Weiti River that separates the Whangaparaoa Peninsula, upthrown 20–40 m from the rest of Auckland, forming an unusual elbow shape. A possible continuation of this fault further southeast, 300 m east of Long Bay, is delineated in an airgun seismic reflection line, where a multi-stranded major disruption involving deformed Waitemata Group sediments, downthrows basement strata by about 200 m to the west (Kenny, pers. obs. with B.Davy, GNS, 2011).

The Tindalls Fault [3] is a new NNW-trending fault inferred to cross Whangaparaoa Peninsula at eastern Tindalls Beach. It runs just to the west of Frenchmans Cap Island (Kotanui Island) off Matakatia Bay, uplifting the island and the eastern half of Whangaparaoa Peninsula by about 70 m. A possible continuation of this fault further southeast, 500 m east of Long Bay, is delineated in the same airgun seismic reflection line as Weiti Fault. It seems to affect cover sediments, but hardly seems to affect the basement (or it is just not visible in this profile).

Further east, the new N–S-trending Shakespear Graben [4] is inferred to downthrow the Whangaparaoa Peninsula at Army Bay through to Okoromai Bay (Shakespear Regional Park). The western fault has a throw of roughly 40 m; the eastern fault has a throw of about 80 m.

Northwest Auckland

A possible fault is mapped by Schofield (1989) as a dashed NNE-trending line along the middle reaches of Rangitopuni Stream, northeast of Riverhead. There is clearly a NNE-trending lineament here, but no obvious offset in topography. The sub-horizontal Okura Thrust (Edbrooke 2001) and local gently undulating conglomerate units within the Waitemata Group appear to be offset right-laterally by over 1 km. A relatively small vertical displacement, downthrown to the east, on a fault through this valley would give a similar apparent dextral offset. Thus the new NNE-trending Rangitopuni Fault [5] is inferred here, with a vertical offset of probably less than 50 m down to the east. It is compatible with lineaments mapped by Davidson (1990) and may be linked to the Brigham Creek Fault to the south.

The Riverhead Forest Fault [2] is a new NNE-trending lineament north of Riverhead. Its facing direction is unknown, but it is parallel to three nearby faults that are all down-thrown to the east.

Offshore seismic profiles

Offshore faults inferred from seismic profiles [2]
Airgun seismic reflection lines and Boomer seismic sections have been described in the main text. As a group, they are disappointingly vague and only reach a low confidence rating in this study.