Synthesis of Existing Structural Data for the Auckland Volcanic Field

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INTRODUCTION

Scope and limitations of this report.

The Auckland Volcanic Field (AVF) is an active intra plate basaltic lava field in northern New Zealand. The field has been active over at least the last 140,000 years, but activity may have has begun as early as 250,000B.P. (Magill et al, 2005). It has produced approximately 50 small volcanic vents over its history (Figure 1), the largest being the ca. 600 year old Rangitoto that forms a distinctive, almost circular, island a short distance off the east coast. Rangitoto produced approximately 59% of the lava present in the entire field (a total of approximately 3.4km^3) (Smith et al., 2007).

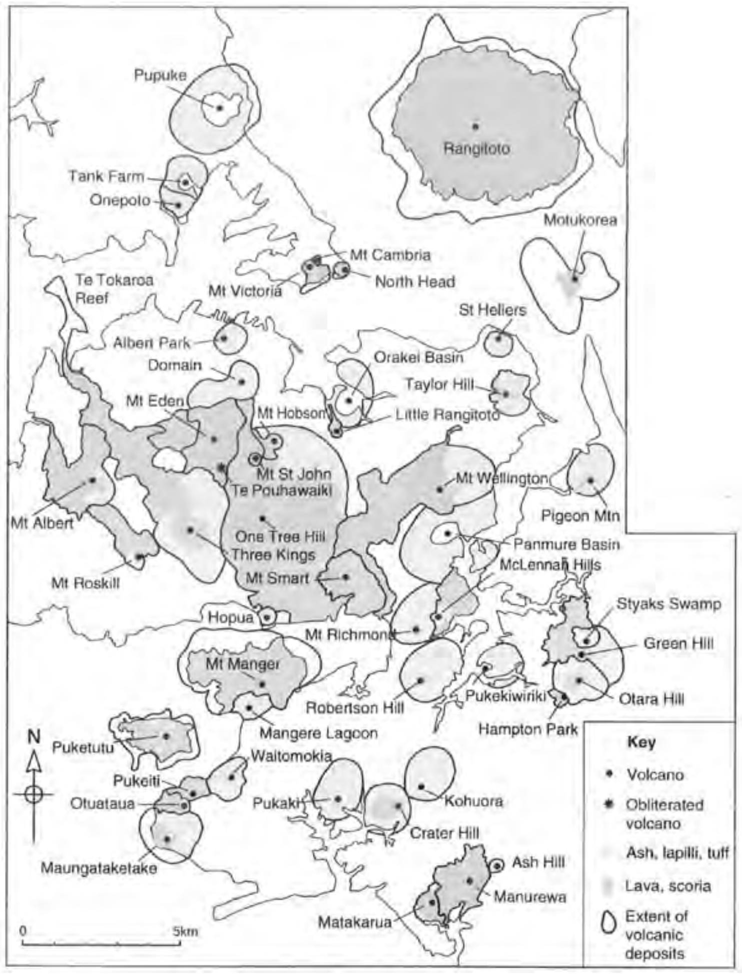


Figure 1: Location of volcanoes in the Auckland Volcanic Field. (Edbrooke, 2003)

The Auckland volcanic field also underlies the city of Auckland, New Zealand's largest city, which has a population of well over 1 million, and is also the focus of much of the country's commercial and economic activity.

The Devora (Determining Volcanic Risk in Auckland) Project seeks to better understand all aspects of the Auckland Volcanic Field and the volcanic processes that have occurred there in the past, in recognition that future events are likely to occur in a similar fashion. The project aims to enable risk minimisation in the run up to, and during, future volcanic eruptions, by understanding how to recognise as early as possible that an eruption is about to occur, if possible, to identify where it is likely to occur, and what the characteristics of the eruption are likely to be. Then strategies for managing such an emergency may be developed, based on the knowledge of 'what we are likely to be up against.'

One of the many aspects of the Auckland Volcanic Field that has a bearing on the style and location of eruptions is the structure of the underlying rocks, from the surface all the way down to the depths of magma generation (thought to be 80-100km beneath the surface in Auckland). Structures such as major crustal faults may provide easy pathways for ascending magma, and may ultimately control where the magma finally erupts. The better we understand the structural setting of the volcanic field, the better will be our understanding of how the magma is likely to rise, and perhaps we may gain a better estimate of where within the field an event is likely to occur -even if this is not until precursory seismic activity begins to give some clues about where the magma is at depth, and we can identify major crustal pathways in the vicinity that the magma is likely to follow.

This report is intended to summarise the structural information already known about the Auckland Volcanic Field, and to identify gaps in the knowledge that may hinder our ability to fully understand the mechanisms that are likely to occur.

A great deal of information on aspects of the structure of the AVF has been presented in many published articles and unpublished theses. There are over 70 unpublished theses lodged in the library of Auckland University alone, which describe studies within or close to, the AVF, and whilst few of them have the structural geology as their main focus, most have some structural information within them. The information is often very specific to an area. This is in contrast to many published articles, where information is typically presented in a much more generalised way, with structure not linked to specific outcrops. In any case there are also relatively few published articles dedicated to structural geology within the AVF, but whatever structural information is available has been extracted. Summaries of structural information taken from theses and notes from published articles are included in the appendices of this report. This limited structural picture has several contributing factors: the recent volcanic rocks blanket and obscure the underlying structure; the city itself, or bush on the outskirts of the city also covers structural information whilst on the coast the opposite may be true, with very complex structures being difficult to analyse and set in a regional context (too much information!).

In this context it is useful to study the information available about other, comparable volcanic fields in the area, as their subsurface structure and processes are likely to reflect many similarities with the AVF. In particular, the South Auckland Volcanic Field provides many insights into the regional structure of the area that is common to both fields. Many geophysical studies have been conducted in the area, enabling the identification of many large faults, which probably have equivalents within the AVF.

In addition it is also useful to study the AVF in its wider tectonic setting, to ascertain the influence, if any, of such regional features as the Hauraki Rift and the Junction Magnetic Anomaly.

The Auckland Volcanic Field is set in an area that has been subjected to a very dynamic tectonic environment over many millions of years. Each unit within the AVF has its own history and resulting structure. Overlapping events modify earlier ones, causing complicated structural patterns, which can be difficult to unravel. It is very useful to bear in mind the overall tectonic history of the region to provide a context within which to understand the local structure. This report begins with a description of the regional tectonic history, as it is relevant to the rocks that are present in the Auckland Volcanic Field and its environs.

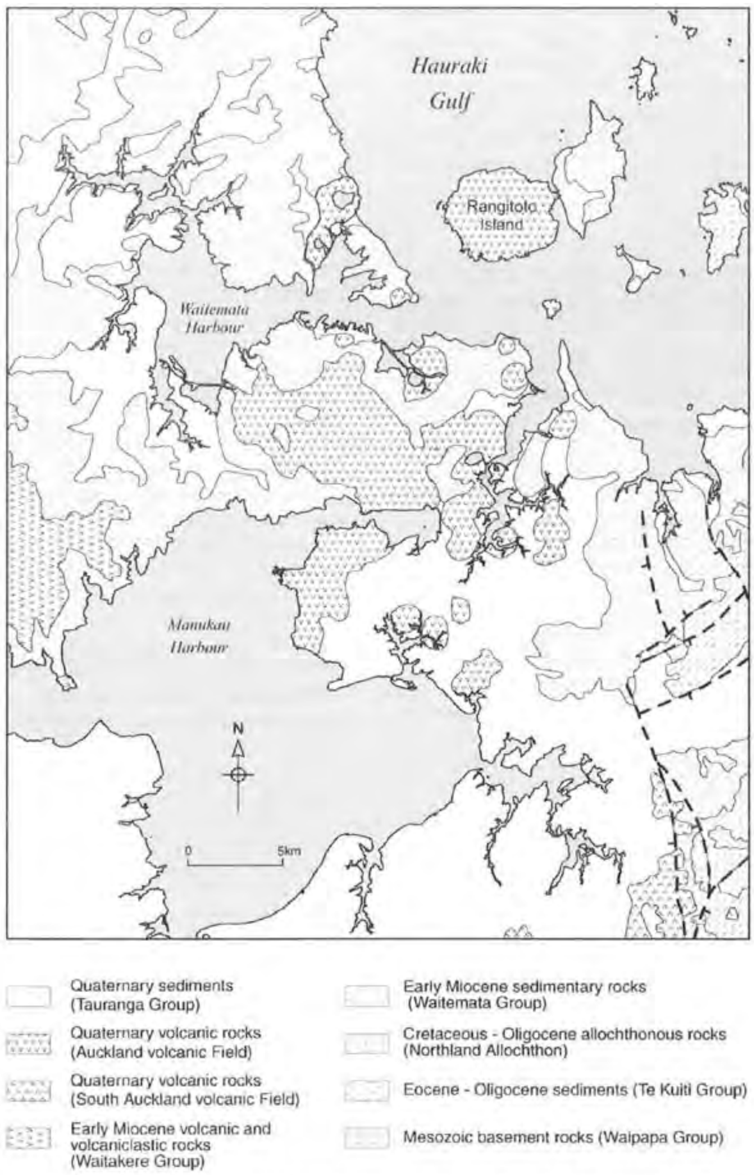


Fig. 5. Geology of the greater Auckland urban area and islands of the inner Hauraki Gulf.

Figure 2: Geology of the Auckland area.

(Edbrooke, 2003)

A Tectonic History of the Auckland Region.

The basement rocks of the Auckland area comprise three parallel, NNW trending belts: in the east, greywackes of the structurally complex Waipapa Terrane; in the middle a thin belt of ultramafic rocks, believed to be equivalent to the Dunn Mountain Ophiolite Belt and Matai Terranes of the South Island, now covered in the Auckland area, but represented at surface by the Junction Magnetic Anomaly; and in the west the structurally simpler Murihiku Terrane (Figs 3 and 4) (Isaac et al., 1994; Spörli, 1978).

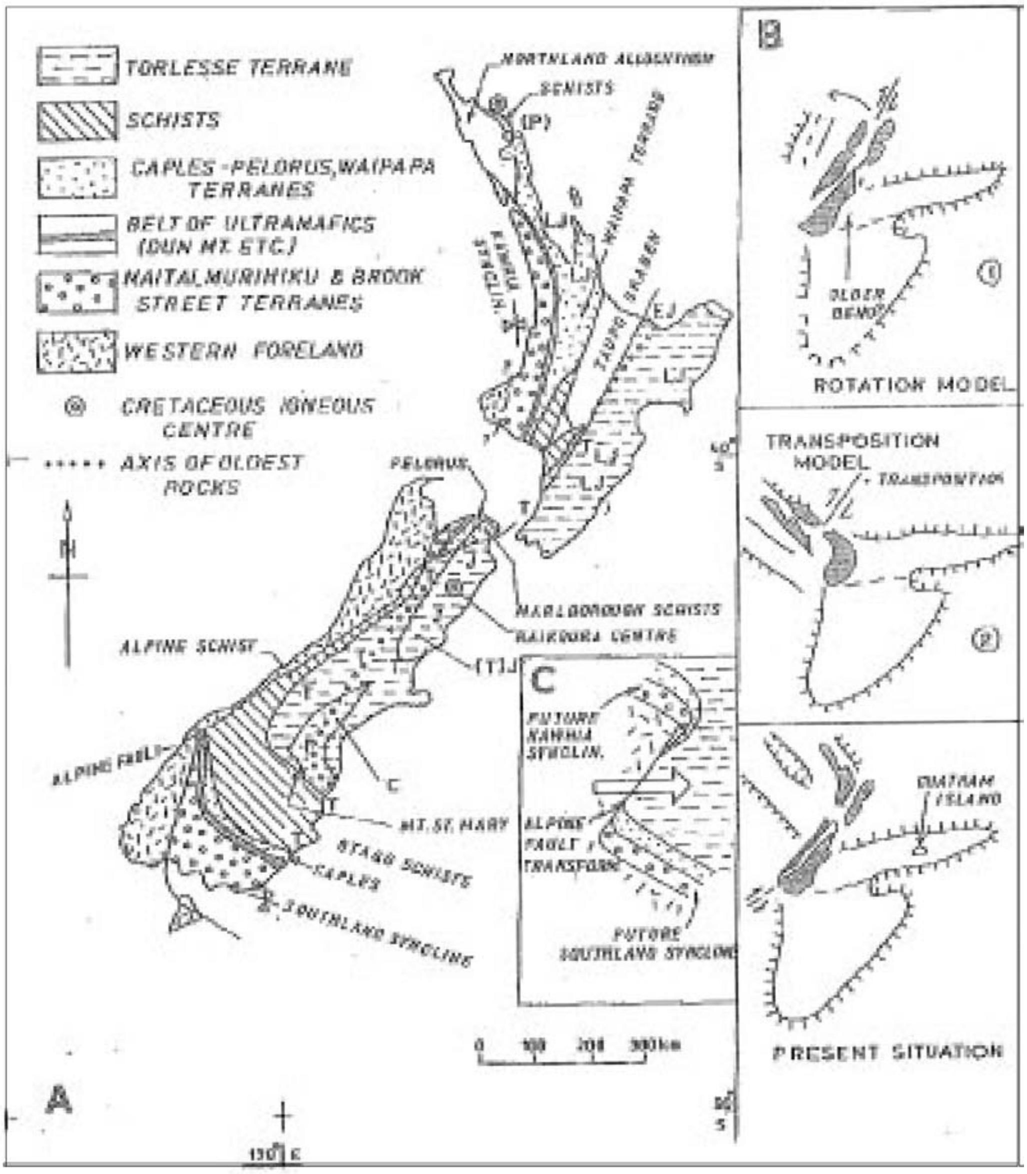


Figure 3: A) Tectonic-stratigraphic subdivision of New Zealand basement. B) Models for movement on Alpine Fault C) Transform fault model.
(Spörli, 1978)

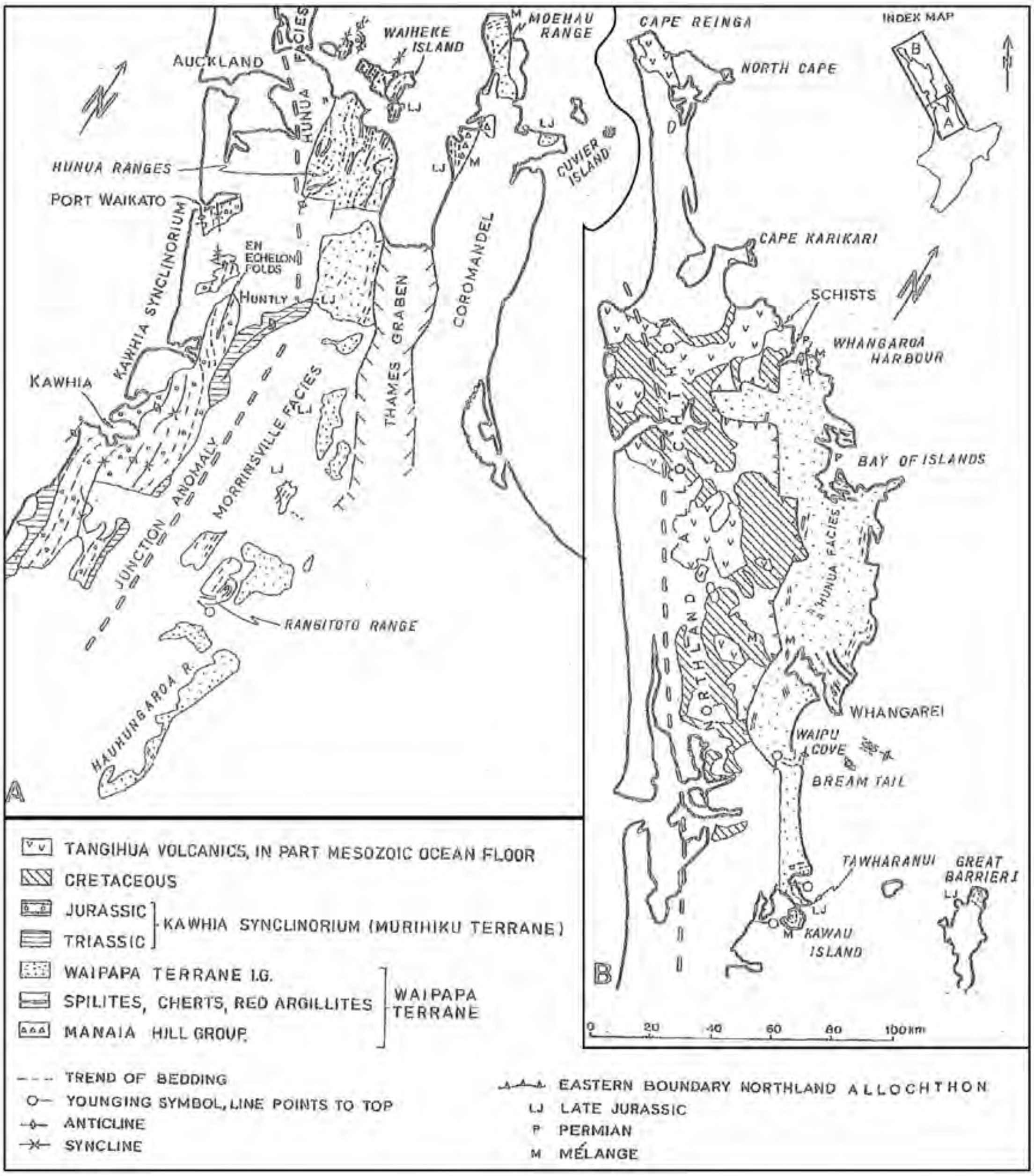


Figure 4: Geology of pre- Tertiary rocks of Auckland- Northland Peninsula. (Spörli, 1978)

During the late Palaeozoic and early Mesozoic, convergence and subduction east of Gondwana resulted in the deposition of sediments that now form the Waipapa Terrrane, in a dynamic arc-trench environment (Spörli et al., 1989). The sediments were then thrust westwards and accreted onto the edge of the overriding plate in an accretionary prism during the late Jurassic and mid Cretaceous. Formation of melange, imbrication of strata, faulting and 2-3 phases of folding occurred, resulting in complex structural fabrics (Spörli, 1978, 1982). Along with the Waipapa Terrane, the igneous rocks now represented by the JMA, thought to have formed on the deep seafloor in the forearc of the subduction zone (Sivell and McCulloch, 2000), and the less deformed Murihiku Terrane were also accreted (Isaac et al., 1994). The simpler structure of the rocks of the Murihiku sediments suggests that they formed in the tectonically quieter area of the arc-trench gap (frontal arc basin). The boundaries between the terranes are structural rather than sedimentary. Subduction ceased ca. 105Ma due to the collision of the Gondwana with the Phoenix Ridge (Raza et al, 1999).

An extensional regime was initiated during the late Cretaceous (ca. 80Ma), which eventually resulted in the separation of New Zealand from Gondwana, and the opening of the Tasman Sea. Associated with this rifting, block faulting deformed the basement rocks, forming hosts and grabens that are bounded by NE-ENE and NW-NNW trending major faults. There followed a period of quiescence, thermal subsidence and almost complete submergence of the New Zealand sub continent, during which time sediments were deposited throughout the region (Raza et al, 1999).

In the late Eocene, renewed extension produced the Challenger Rift System, in the west of New Zealand, including offshore. Some of the structural trends were inherited from earlier structures (Kamp, 1986).

Simultaneous with the faulting, deposition of the Te Kuiti Group began with the Waikato Coal Measures being deposited on the emergent land to the south of Auckland and the Kamo coal measure in the Whangarei Region (Kear and Schofield, 1959; Kear and Schofield, 1978; Isaacs et al., 1994). Initially coal deposits formed unconformably upon a deeply eroded basement in land-locked basins (Kear and Schofield, 1959). A N-NW flowing, anastamosed and meandering fluvial drainage system/delta developed, within a structurally controlled basin, and accumulation of Waikato Coal Measures (including thick peats) continued on an extensive alluvial plain, confined to the west by the hills of the Murihiku terrane basement and to the east by the hills of the Waipapa Group basement, but close to the sea (Edbrooke et al., 1994; Isaac et al., 1994). Earliest Oligocene transgression from the north, in response to tectonic subsidence and eustatic sea level rise, brought a change to estuarine and shallow marine sediments (calcareous muds, sands and limestones) across the region (Mangakotuku Fm) (Edbrooke et al., 1994; Kear and Schofield, 1978). Progressively more open marine conditions early-mid Oligocene (Glen Massey Fm) (Edbrooke et al., 1994; Edbrooke et al., 1998). Units in the Te Kuiti Group are generally flat-lying- usually 5-15º, averaging 10º except in close proximity to large faults, where even vertical dips may occur. The main block faulting and tilting episode, however, occurred post deposition, after the deposition of the Waitemata Group (Nelson, 1973; Nelson, 1978; Kear and Schofield, 1978).

At the end of the Oligocene the propagation of the Indo-Pacific Plate Boundary through New Zealand brought about a 10 million year period of compressional tectonics, that manifested itself in the Auckland-Northland region in several significant ways:

- Inception of the Alpine fault at ca 22Ma. Over its history it has a dextral strike slip offset within the North Island estimated at ca. 230km (Ballance, 1974).
- Initiation of subduction at ca.30-35Ma, led to the formation of two volcanic arcs 5-10 million years later, one running down the west of Northland and off the west coast (Herzer, 1995) and one running down the eastern part of Northland and the Coromandel Peninsula (Raza et al., 1999). The western arc initiated slightly before the eastern arc (25Ma and 22Ma respectively) and volcanism propagated southwards. The twin arcs were simultaneously active for at least 7 years (Ballance et al., 1982).
- Simultaneous with early subduction (24-22Ma), in a related but poorly understood mechanism (possibly related to subduction choking, but compression continuing), the sedimentary basin to the north east of New Zealand was uplifted and the sedimentary pile, along with thin slivers of igneous ocean floor, was pushed southwestwards in great nappes onto New Zealand (Hayward, 1993). These rocks form the Northland Allochthon, and comprise highly shattered and sheared mudstones with thin slivers of serpentinite. Internal structures and major thrust orientations imply that initial emplacement was from the NE, but later the allochthon changed direction to move south to southwestwards (Hayward, 1993). The main mechanism for transport is believed to be gravity sliding (Ballance and Spörli, 1979).
- Subsidence began in the Waitemata basin, the area between the two arcs, around 25Ma (Raza et al., 1999). The basin was bounded to the west by the volcanic arc, to the east by the eastern arc and high standing blocks of greywacke basement, to the north by a basement horst and the advancing allochthon and the south by another basement horst. Sediments within the basin were deposited in a very active tectonic environment (Ballance, 1974; Spörli,

1989). The basin subsided very rapidly- subsiding from zero to bathyal depths may have taken one million years, or less. Average subsidence rates of 1-2mm/year are suggested, so depths of 1-2km could be achieved in much less than 1 million years (Ricketts et al., 1989; Ballance, 1974). The main sedimentation occurred in the Otaian (23-19Ma). The long axis of the basin trended NNW-SSE, parallel to both arcs and earlier basement structures. Turbidity currents flowed ESE-SSE, diagonally across the basin, at about 45° to the axis, whilst other sediment types entered the basin in a NNE direction from the western margins and SW from the eastern margin (Ballance, 1974; Spörli, 1989; Allen, 2004). Volcaniclastic lahars and movement of conglomerate canyon-fill facies paralleled turbidity currents in the north and south and paralleled turbidity or longitudinal non-turbidity flows (i.e. SE or SSE) in the central part (Ballance, 1974). One of the chief sources of the sediment was the Northland Allochthon, which was still advancing, with sedimentation occurring at its toe being overridden or incorporated. Ahead of it the Waitemata sediments, under compression underwent soft sediment slumping and post consolidation thrusting in a southerly direction (Hayward, 1993; Kenny, 2008). The second significant source was the volcanoes of the active western volcanic arc, volcaniclastic debris interfingering with the sediments, particularly in the southern part of the basin, and lahars and volcaniclastic conglomerates spreading into the basin, provoking slumping of soft sediment and infilling subsea canyons (Brothers, 1954; Allen, 2004). A consequence of the very dynamic environment into which the Waitemata sediments were deposited is that, whilst there are large areas of horizontal to gently dipping strata, there are also zones of very complex deformation (e.g. Spörli, 1989; Spörli and Browne, 1982). The youngest preserved sediments are approximately 17Ma old; any younger sediments have eroded away. (Raza et al., 1999; Hayward and Smale, 1992).

- The western arc ceased activity around 15Ma. The eastern arc continued for at least another 10 million years, until subduction migrated to its current position and the activity began in the Taupo Volcanic Field ca. 2Ma (Cole, 1986).

Large-scale block faulting in northern New Zealand possibly began at ca. 15Ma, coinciding with the extinction of the Waitakere Arc (Ballance, 1974).

ENE trends tend to be truncated by N-NW trends. There is indirect evidence for block faulting within Auckland itself (Kenny, 2008b). Some faults in the Hauraki Plains and South Auckland lowlands are still active (e.g. Wise, 1999).

The Waitemata Basin was uplifted and the topmost sediments eroded. Pliocene and Pleistocene sediments occur only in infilled valleys in the relatively uplifted Auckland block (Affleck et al., 2001), whereas the south Auckland Lowlands represent a graben filled with such sediments (e.g. Berry, 1986; Allen, 1995).

Regional tilting occurred towards the west, although the regional tilt in the Coromandel area is towards the east, and there is some geophysical evidence for eastwards tilting in the covered Murihiku basement of the Auckland area (Williams, 2003).

Sometime during this period, the Hauraki Rift became active. This 250km long, 25->40km wide feature is still active and is considered to be akin to a continental rift (Hochstein and Nixon, 1979; Hochstein and Ballance, 1993). Whilst the timing of its initiation is unclear, it may have formed in response to an upwelling of the asthenosphere related to the NNW trending subduction zone of the eastern arc, and continued to open and subside because the regional tensile stress field continues to the present, albeit oriented 335º, some 40º clockwise from its orientation at 13Ma (Hochstein and Ballance, 1993). This results in dominantly dextral strike slip movement on the master faults of the Rift in recent times. It is possible that the uplift within the Auckland area is due to uplifting of the flanks of the rift. The westwards regional tilting to the west (Auckland) and the eastwards regional tilt in the east (Coromandel) may also support this.

The final stage in the history of Auckland involves the formation of the Auckland Volcanic Field itself. To the south of the AVF three earlier predominantly basaltic volcanic fields were formed: the Okete Basalts (2.69-1.80Ma); the Ngatutura Basalts (1.83-1.54Ma) and the South Auckland volcanic Field (1.59-0.51Ma) each field being progressively younger than those to the south (Heming, 1980). The activity in each field would last 0.3-1 million years, and after the field became extinct another field would develop 33-38km to the north (fig. 5)(Briggs et al., 1990; Briggs et al., 1994).

The 50 volcanoes of the Auckland Field exhibit a wide variety of eruptive styles from dominantly magmatic to dominantly phreatomagmatic. They are monogenetic, each resulting from a single eruptive episode and range in composition with tholeiite, transitional basalt, alkali basalt, basanite and nephelinite all represented (Rout et al., 1993).

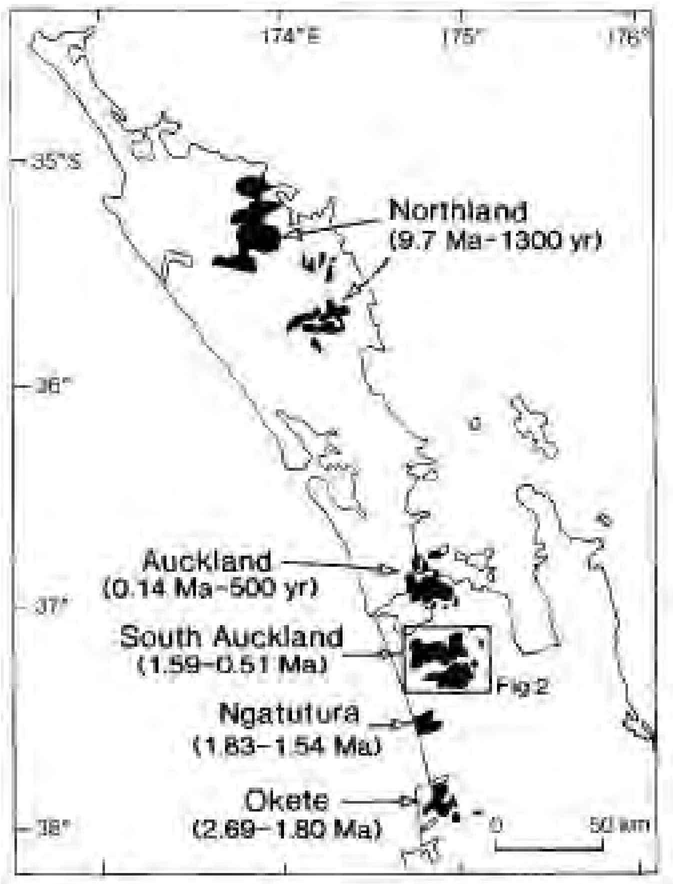


Figure 5: Location and age of volcanic fields of northern New Zealand. (Briggs et al., 1990)

Structural Geology in the Auckland Region.

Because all the rocks of the Auckland field formed in such a dynamic range of environments, each unit has its own individual structural characteristics. For this reason, the observed structure reported in theses and publications is presented in terms of the host rock as well as individual locations. The sections below present brief summaries of the structural geology for each unit. Two Appendices present much more detailed relevant information extracted from the theses and publications. Published data is kept separate from unpublished data.

Regionally important structural features such as the interformational block faulting and the Hauraki Rift are included in a later section. Areas north and south of Auckland are also described to gain a general regional picture of the structural geology, to help fill gaps in the data for the rocks underlying Auckland.

Structural Geology of the Waipapa Group Basement.

Waipapa Group rocks mainly outcrop southeast and northeast of Auckland, in the uplifted Hunua Block, the area from Leigh northwards and on the islands of the Hauraki Gulf. Although outcrop is relatively limited, these rocks form the basement of the AVF, and rising magmas would have to pass through them, so structural analysis of the greywacke rocks that are available near the AVF, and geophysical studies of the subsurface will enhance our understanding of processes. Some structures are more relevant than others- in particular major faults that also affect overlying strata- but, for the sake of completeness, a synopsis of other recorded structures is also included.

Bedding

Bedding within the basement greywackes tends to be very disrupted, discontinuous and intricately folded on many scales. The bedding at Whitford, in south Auckland is very difficult to discern, as it is in many areas, but generally trends 190-205º/55-85ºW (Boedihardi, 1990). One mile NE of Kawakawa Bay, also south of Auckland, bedding in the greywacke dips 60ºW (Brown, 1937). On Motutapu, an island off the North shore of Auckland, greywacke bedding mostly dips NNW/steep (65-80º) W or E (fold axis plunges towards 350º) (Milligan, 1977) and in Leigh, North of Auckland, basement broken formation is oriented NE/moderate south (Swain, 1993). NNW strikes, parallel to the regional trend, are the most commonly reported bedding orientations.

Anderson (1977) reports that in NW Manukau city, gravity surveys show the top surface of the greywacke dipping westwards. Similarly, Daly (1988) observed a similar deepening of the greywacke-Waitemata Group surface from the east coast to the west in the Leigh-Pakiri area, north of Auckland.

Folding

Bedding within the basement greywackes may be folded on many scales, and several phases are sometimes recognisable. Spörli (1978, 1982) reports that in the basement one can often recognise three phases of folding- the youngest (sinistral bending on steep axes) probably postdates the Rangitata Orogeny. The phases are:

1. Formation of melange and imbrication of strata with fold axes trending across the now-dominant basement grain and fold vergence predominantly towards the south. The sequence is several hundreds or even thousands of metres thick.
2. Strongly asymmetric folding and imbrication and further melange formation on horizontal axes parallel to the present structural grain; folds verge east and beds in the axial ranges have rotated to overturned and vertical attitudes. Fold axes often trend NW.
3. Open folding on steeply plunging axes. Dextral and sinistral present.

At Leigh, north of Auckland, the first phase of folding involves open to tight cylindrical chevron folds. Fold axes trend NNE-ENE, with sub horizontal fold axes. The second phase folds are NNW-SSE striking upright open cylindrical folds. (Swain, 1993). On Motutapu, Milligan (1977) records that the dominant fold axis observed in greywacke rocks plunges shallowly towards 350º. A major NNW- trending syncline is bounded by and parallel to, the Motutapu and Home Bay Faults. NNW trending minor faults and folds (anticlines) flank both sides of the syncline (figs. 6 and 7).

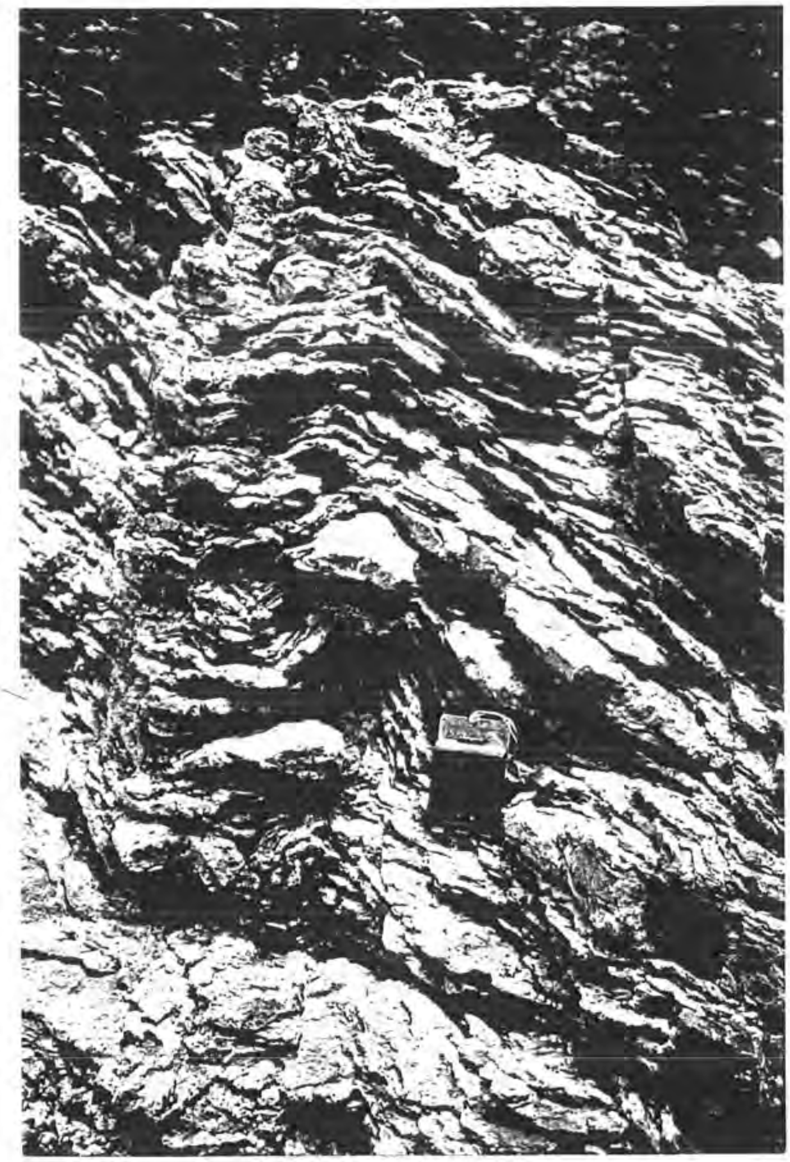


Figure 6 Folding in greywackes in the Leigh area. (Swain, 1993)

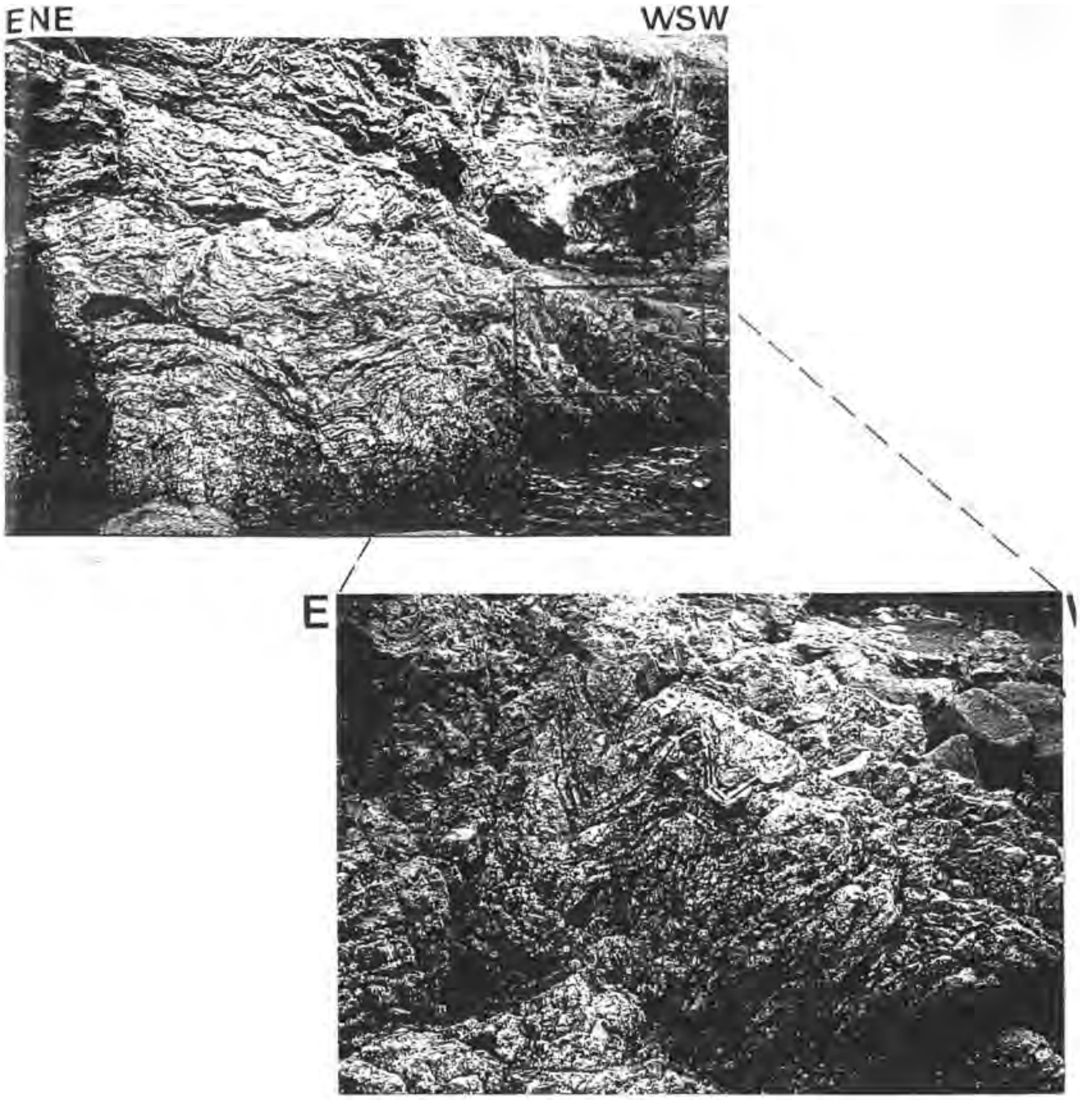


Figure 7 Folding in greywackes in the Leigh area.
(Swain, 1993)

Faulting

Major faults are probably the most significant structures available for focussing ascending magma as it travels through the crust. They tend to be more continuous than other fractures and may carry the magma from deep under Auckland to the surface or near-surface. Such faults cut through overlying Waitemata Group strata, as well as the basement. Some faults, however, ceased to move prior to the onset of Waitemata Group deposition and therefore do not extend beyond the unconformity surface. These may, nonetheless, be available to channel magma at depth.

- On Motutapu Milligan (1977) observed pre-Waitemata normal faulting oriented 140º/65ºE, conjugate strike slip (NE striking plane is dextral, E-ESE striking plane is sinistral), indicating a palaeostress regime with N-S extension and E-W compression, and then a NW-SE striking set of faults, including the major Motutapu Fault, that are also pre Waitemata Group. There may also have been a phase of low angle thrusting on faults oriented 080º/20ºN and S. Spörli and Anderson (1980) describe striations indicating N-S compression. Strike slip and reverse striations are both present, indicating that E-W and N-S orientations of principal stress axes were present and these were interchangeably occupied by compressions, extensions and intermediate axes.

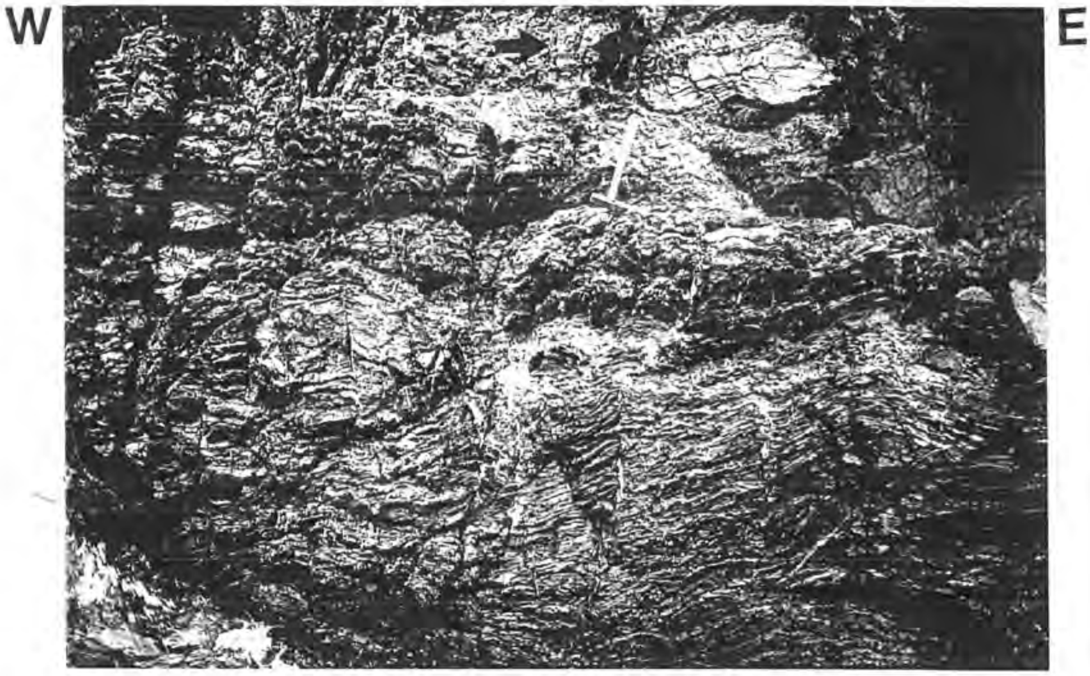
- At Whitford, in south Auckland, small scale normal faults trend E, NE, NW, and have undergone oblique-slip (striations pitch 50-60ºNE). Strike slip faults with dextral strike slip trend NE and dip towards the SW, striations pitch 20ºNE and SW. Reverse faults with an orientation of 300-345º/60º-vertical N+S are also present (Boedihardi, 1990). Spörli and Anderson (1980) calculated a statistical intersection line for similarly oriented thrust planes plunging moderately ENE. The same authors use fibre striations to interpret a palaeostress regime with ENE plunging compression. This is similar to the stress orientation inferred from large scale faults: NE trending faults have dextral displacements, NW trends are sinistral and N-S are reverse. The structures at Whitford are dominantly strike-slip, whilst those at Haliwells Quarry are more complex and dominantly reverse dip-slip. In other areas fibre striations indicate ENE or ESE compression.
- At Leigh, north of Auckland, late Cretaceous extensional block faulting affected the greywackes with NNW and ENE trends present. Thrusts indicate a phase of NW-SE compression.

Fig.3.35

a

b

Figure 8 En echelon veins in shear zone within greywackes in the Leigh area. (Swain, 1993)



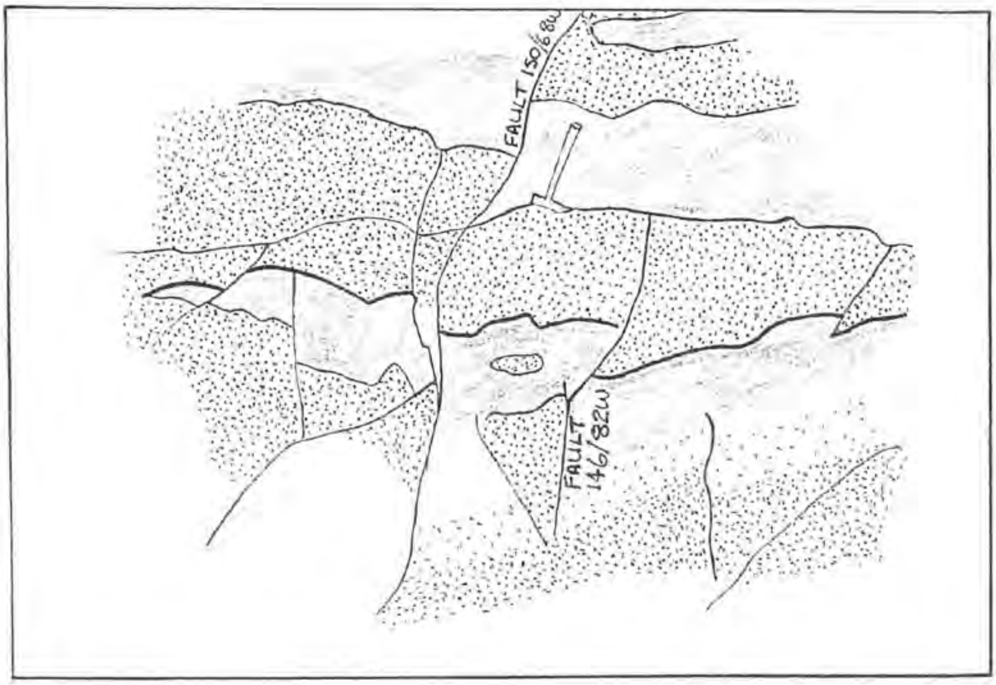


Figure 9 Small scale faulting in greywackes in the Leigh area.

(Swain, 1993)

- Major block faulting cut through the basement and overlying sediments, producing a series of horsts and grabens bounded by NNE and ENE trending faults. These will be discussed in more detail later.

Joints, veins and dykes

Although these fractures are present throughout the crust, they are usually only continuous over relatively small distances and are therefore less likely to be utilised by ascending magma than large-scale faults. It is possible that they may channel magmas over short distances. The margins of filled fractures (veins, dykes) may provide a locus for dilation, the crust cracking open more easily where a pre-existing weakness exists.

- At Whitford Quarry, NW trending fractures are most dominant. NE trending fractures are also present, and tend to be filled with quartz-chlorite, whilst NNW fractures often have thick gouges associated (Boedihardi, 1990).
- Joint sets at Peach Hill are mostly NE-ENE striking and dip moderately towards the SE or steeply NW.

Crosscutting relationships

The formation of the Waipapa Group greywackes in a dynamic accretionary prism environment means that each area has its own specific history, with many different phases of deformation present. These may not correspond exactly to outcrops in other areas. An example of the complexity of some areas is given below. Swain (1993) recognised 12 separate phases of deformation at Leigh in the Waipapa Group alone. (He also noted another 10 phases affecting the overlying Waitemata Group). Swain's sequence, in order of occurrence, for Leigh is as follows:

1) Broken Formation
2) Sub-isoclinal fold
3) Chevron folding with open NW folds

1) Prehnite veins
2) Pressure solution
3) Veining quartz albite-prehnite (Synchronous with NW folds)
4) Chevron NW plunging folds
5) Black ultracataclasite layers.
6) Slide plane at Ray Rock
7) Late Cretaceous extensional block faulting with NNW-ENE trends
8) Late veining-prehnite, quartz-chlorite-calcite

9) Striations

10) En echelon veins Dominant NW-SE compression, minor NE compression normal dip slip arrays.

11) Kink folds and thrusts indicating NW-SE compression

12) Jointing-ENE trends.

Topographic Lineaments

Topographic lineaments are sometimes surface expressions of structural features in the subsurface. Features such as streams may preferentially utilise fault planes, which may result in very straight-sided valleys, sometimes asymmetric in cross-section, with the steep side reflecting the dip on the causative fault. Straight-sided topographic ridges may reflect preferential erosion of the softer rock where two differing rock types are superposed by faulting.

The majority of topographic lineaments in the basement greywacke horsts parallel the NW-NNW and ENE-NE regional trends. The Hunua Range is a horst, raised up on N-NNW trending bounding faults. The Wairau North Fault, which is possibly still active, forms a prominent rangefront through the Hunuas, downfaulting greywackes to form the Wairau North Fault Angle Depression, which is filled with Pleistocene to recent sediments. There is also a prominent east trending set of lineaments, possibly representing faults, that crosses the Mesozoic boundary and may also offset the rangefront (Wise, 1999). Sibson (1968) notes that spurs on the flanks of the Maungamaungaroa Range trend NNE-NE, and interprets these as influenced by block faulting.

Depth to the basement

The depth at which the basement lies beneath the surface has been determined for some areas directly, by drilling boreholes that penetrate basement rocks, or indirectly using geophysical models. Most of the data available pertain to the South Auckland Volcanic field, since no boreholes have been drilled within Auckland city itself that are deep enough to penetrate basement, and fewer geophysical surveys are reported for the city, too.

Ormerod (1989) presents a table listing data on boreholes south of Auckland that did and did not reach the basement (Table 1). Depth to the unconformity ranges from 80m above sea level to 810m below sea level.

TABLE 1.2B

TABLE OF BOREHOLES

	Coordinates		Height	Depth in meters a.s.l.		
WVA#/REF#	mE	mN	m	Top of Waitemata G	Max Depth of B.Hole	Top of Basement
2290/1	6892	4398	100	65[illegible]	-20	
1930/3	6812	4404	56	n/r	-238	
1921/5	6860	4348	103	5	-180	
1208/7	6838	4349	56	n/r	-253	
1330/8	6795	4417	63	n/r	-300	
1429/9	6856	4433	172	100	-58	
1439/10	6866	4382	120	n/r	+40	
1450/11	6767	4410	109	n/r	-160	
1923/12	6862	4363	69	n/r	-246	
1427/13	6790	4465	20	-57		
2309/14	6806	4467	467	-36[illegible]4		
2308/15	6850	4456	~100	-21[illegible]		
453/16	6775	4450	~60	n/r	-141	
/17	6849	4428	140	91		
/18	6855	4414	120	10[illegible]		
/19	6850	4416	110	23[illegible]		
/20	6871	4419	220	16[illegible]		
/21	6871	4418	220	14[illegible]		
/22	6876	4414	200	15[illegible]		
2302/23	6802	4390	59	-26[illegible]	-318	
/24	6841	4400	80	n/r	3	
/25	6881	4398	120	120		
/26	6866	4391	160	11[illegible]		
/27	6861	4363	70	n/r	-180	
/28	6863	4359	70	4		
/29	6857	4348	60	2		
/30	6835	4349	65	n/r	-200	
/31	6819	4338	20	n/r	-141	
/32	6827	4325	10[illegible]	20		
/33	6880	4348	15[illegible]	[illegible]5		
/34	6878	4345	10[illegible]	-40		
/35	6878	4339	10[illegible]	-10		
2307/36	6889	4403	180	n/p	wc +88	80
1370/37	6782	4490	~60	-42		
1422/38	6919	4337	20	n/r	-100	
9140/39	6978	4402	27	n/p		-343
9141/40	6988	4425	20	n/r	-272	
9142/41	6967	4409	8	-170	wc -304	-470
9143/42	7005	4418	47	n/p	wc -57	-125
9144/43	6988	4405	15	n/p	wc -130	-179
9145/44	6978	4422	10	-291	-382	
9146/45	7008	4420	51	n/p	wc -32	-81
9147/46	6998	4424	21	n/p		-75
8064/47	6932	4314	6	-35	wc -266	-728
8078/48	6906	4369	8	-45	wc -451	-536
8088/49	6896	4369	22	-107		-475
[illegible]/50	6907	4385	31	-216		-309
[illegible]/51	6902	4311	82	-37	wc -501	
[illegible]/52	6894	4340	44	-39	wc -231	-810
[illegible]6/[illegible]	6919	4337	~10	-18	wc -220	
[illegible]8/[illegible]	6915	4363	20	13		

1 = n/r = not reached n/p = not present wc = depth to Coal measures
2 = driller unsure

Table 1. Borehole information from the South Auckland area.

(Ormerod, 1989)

In central Auckland, Williams (2003) and Eccles (2003) both summarise data for several boreholes in the central area (Table 2):

Borehole no	Location	Grid ref	Depth to basement (mbsl)	Greywacke terrane	source
1	Oratia	R11/558777	485	Not documented	W.Russell pers comm.2002
2	Grahams Beach	R12/564584	340	Murihiku	Waterhouse 1989
3	Mt Roskill	R11/644755	592-622	Not penetrated	Edbrooke et al 1998
4	Mt Eden	R11/675789	More than 590	Not penetrated	Isaac et al 1994
5	Orewa	R10/617127	Less than 876	Waipapa	Schofield 1989
6	Karaka-1	R12/789519	Less than 615	Murihiku	Isaac et al 1994
7	Ardmore	R11/883632	Less than317	Waipapa	Isaac et al 1994
8	Ardmore	R11/869622	Less than 322	Waipapa	Isaac et al 1994
9	Waiwera	R10/629163	424	Waipapa	Waterhouse 1968

Table 2. Borehole data from the Auckland area North of Auckland, in the Leigh-Pakiri area, Daly (1988) found from her geophysical studies that greywacke increases in depth from being sometimes 100m above sea level in the east to being maybe more than 4km deep on the west coast.
(from Eccles, 2003; Williams, 2003)

The depth to basement can vary greatly because of the presence of block faults with large displacements of several 100m or even kilometres (e.g. Hochstein and Nunns, 1976; Wise, 1999). A more comprehensive list of reported depth to basement is included in the Appendices.

Lower extent of the basement

Little is known of the thickness of the greywacke basement terranes. Williams (2003) quotes a significant change in seismic velocity (5.5-6.4 km/s) at approximately 6km depth under the Auckland region, recorded by a seismic refraction survey undertaken by Stern et al. (1987). She interprets this as the base of the greywacke rocks, or a fundamental change in the basement lithologies due to high temperatures and pressures. For each of these scenarios it is valid to consider 6km as the depth of the *geophysical* base of the basement rocks under Auckland.

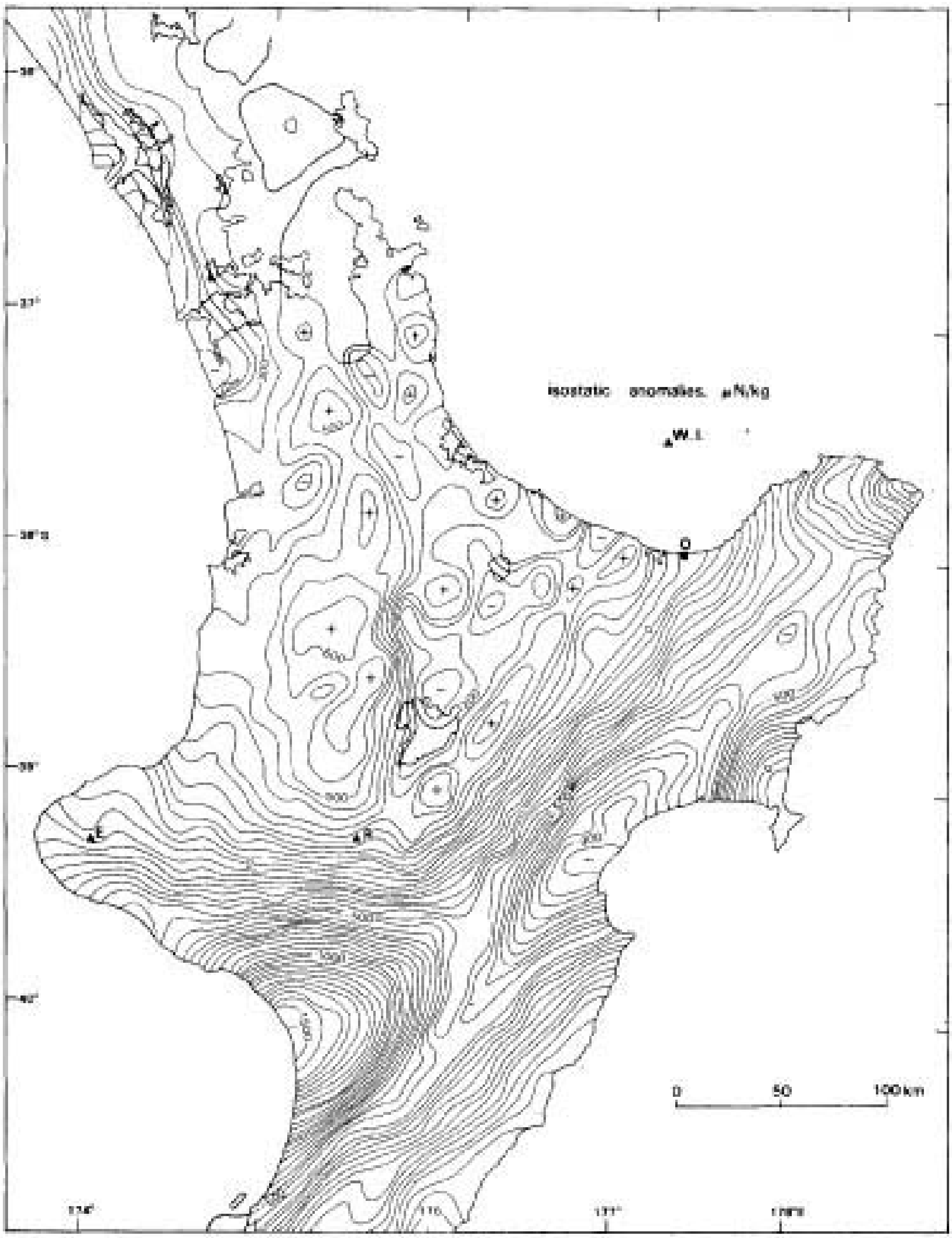


Figure 11. Isostatic (Airy–Heiskanen, T = 30 km) gravity anomalies of the central North Island. Contour interval = 50 µN kg^{-1} (5 mgals). After Reilly *et al.* (1977). E = Mt Egmont, R = Mt Ruapehu, O = Opotiki, W.I. = White Island.

Figure 10. From Stern et al. (1987)

The seismic velocity change reported at 25 km depth (an increase to 7.6km/s) is interpreted as representing the change from lower crust to upper mantle lithologies (Stern et al., 1987; Williams, 2003). This indicates a relatively thin continental crust, but Stern et al. (1987) interpret this as being the 'normal' thickness of New Zealand crust, rather than being due to stretching and thinning. Most of the New Zealand microcontinent- which includes the Lord Howe Rise and the Norfolk Ridge-is submerged, but the emergent land, which is coincident with the Australia-Pacific plate boundary, is subject to uplift due to injection of excess heat into the lithosphere.

Horspool et al. (2006) report a Moho depth of 29km+/-1km depth in the southern part of their array, near the Taupo Volcanic Zone, and decreasing to 26+/-1km on the edge of the continental shelf of northern New Zealand. Seismic velocities of 3.4-3.6 kms^{-1} are characteristic of the upper crust, whilst those of the lower crust are in the range 3.6-4 kms^{-1}. This study identifies a region of low shear velocity (4.2 +/-0.1 kms^{-1}) in the upper mantle beneath the Auckland Volcanic Field, at a depth of 70-90km, and extending approximately 10km further north than the current extent of volcanism. This is consistent with a zone of partial melting of a few percent, and is believed to be the source of magmas in the AVF. This could imply that future volcanism could migrate northwards.

The Junction Magnetic Anomaly

The Junction Magnetic Anomaly (JMA), marking the suture between the Waipapa and Murihiku Terranes and the variably serpentinised Dun Mountain and Maitai Terranes, passes through the Auckland region and right under the AVF itself. This represents a major discontinuity in the basement, and Spörli and Eastwood (1997) suggested that it could possibly be one of the contributing factors leading to the generation of magmas at depth. They postulated that dextral strike slip movement along the JMA could create a local field of higher tensile stress at a releasing bend, initiating decompressional melting.

Several of the geophysical theses lodged in the Auckland library have studied the JMA among other topics (e.g. Ormerod, 1989; Allen, 1995; Rout, 1992), whilst at least three theses in recent years have had the anomaly as a major part of their study. (Woollaston, 1996; Eccles, 2003; Williams, 2003). A summary of their work is presented in the Appendices, along with notes and quotes from published papers (e.g. Hatherton and Sibson, 1970, Locke et al., 2007). There are some important details that have emerged from these studies.

Hatherton and Sibson (1970) recognised a sinistral bend within the JMA north of Auckland and postulated that it was due to a 6km fault offset. Woollaston (1996) studied more detailed aeromagnetic data and discovered that at the bend the JMA, ca.1580m below the surface, was actually made up of a series of slivers, rather than being a single, discrete body. In addition she discovered that the magnetic field indicates that the rocks have been rotated anticlockwise by 55-135º above and beyond the rotation experienced by the rest of the North Island. She also observed that serpentinite bodies at the surface in the area showed no great magnetic anomaly and concluded that they were not part of the JMA, but part of the Northland Ophiolite, which was obducted and transported into the area along with the Northland Allochthon in the late Oligocene and early Miocene.

Eccles (2003) (and in Eccles et al., 2005; Locke et al., 2007) studied the JMA in more detail again and was able to delineate up to 10 slivers over a 40km distance. (Figure. 11). She suggests several mechanisms for this repetition, including faulting sub parallel to the JMA, strike slip duplex formation, and thrust repetition during accretion. She also postulates that if faulting were active along the JMA in the Miocene, as it was in some other segments, then this could be another factor contributing to the complexity of the Waitemata Group.

Williams (2003) (and Locke et al., 2007) discovered a blocky gravity anomaly over Auckland central, which she used to model a discrete body under the JMA. (Figure 12) The body strikes NW-SE, has a steep eastern boundary coinciding with the peak JMA, a flat upper surface within 500m of the ground surface, and a steep to vertical, NE-SW striking eastern boundary, directly below two vents, St Heliers and Taylor's Hill, that erupted exotic fragments of unaltered ultramafic and sedimentary rocks that were comparable to Dun Mountain and Maitai Terrane rocks (Searle, 1959). A recent BSc (hons) study by Jesse Jones (Jones, 2007) on these xenoliths has demonstrated clear similarities between these xenoliths and the rocks of the Dun Mountain –Maitai Terrane, in terms of trace elements, mineralogy and structural fabric, and also notes the scarcity of xenoliths of greywacke in the same area.

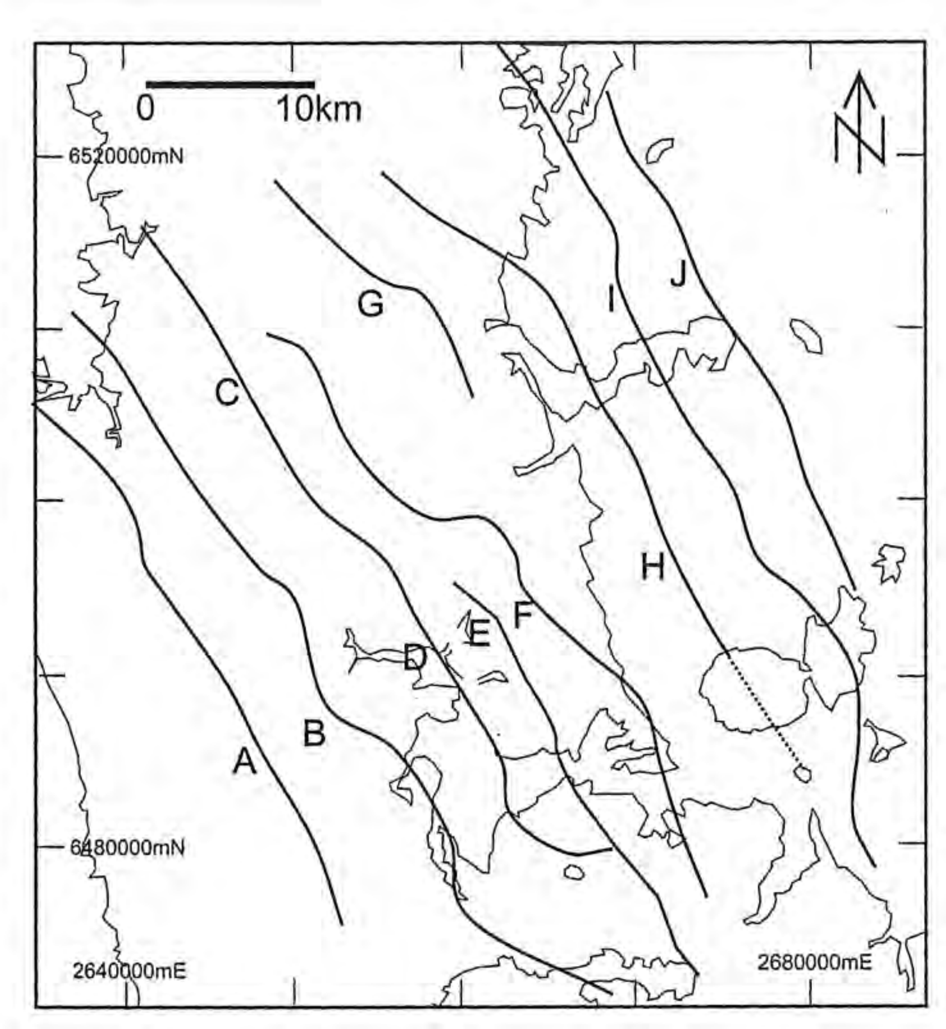


Figure 11. The Junction Magnetic Anomaly comprises a series of sub- parallel anomalies in the Auckland area.
(Eccles; 1993)

The western contact of the modelled body dips shallowly west and the southern boundary dips shallowly south. Williams (2003) postulates that the body underlies the whole central Auckland isthmus, and extends as far north as Orewa, including the area studied by Woollaston (1996) and Eccles (2003), and south along eastern shore of the Manukau Harbour. The body is comparable in size and shape to pods of Dun Mountain and Maitai Terrane found in the South Island.

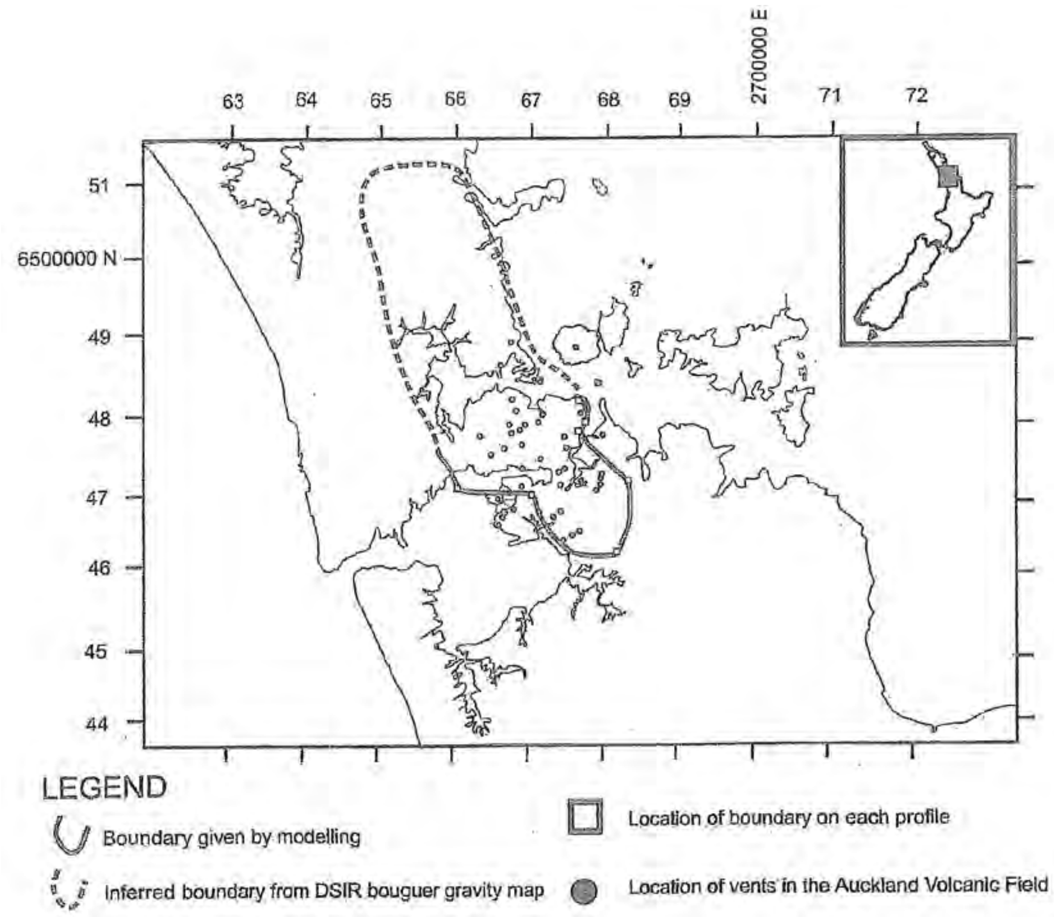


Figure 12. Blocky Gravity anomaly coincident with the Auckland Volcanic Field, and the complexity within the Junction Magnetic Anomaly. (Williams,1993)

It is worth noting that other authors have observed ultramafic-type exotic rocks in volcaniclastic rocks of the AVF, including at Shoal Bay, Smales Quarry (Pupuke), North Head and Mt Cambria on Auckland's North Shore, as well as in other nearby volcanic fields (Rodgers, 1966). Sibson (1968) reported unusual basement xenoliths from the Pukewairiki Tuff in the East Tamaki area.

Williams (2003) considers that the JMA is not connected with the AVF, even though it coincides with it, because magma generation is believed to occur at much greater depths than the 500m +/- 100m occupied by this modelled body. Nonetheless, it seems possible that a significant proportion of the basement underlying Auckland comprises neither Waipapa nor Murihiku Terrane, as previously believed, but Dun Mountain and Maitai Terrane. The basement rocks may have been sliced by faulting into a series of NNW-tending slivers that, incidentally, are paralleled by lava flows from Three Kings/Mt

St John and Mount Eden. This could indicate that the palaeovalleys that channelled the flow were also fault controlled.

Some authors interpret the volcanism of the AVF, and those to the south as forming at the tip of a northwards propagating lithospheric fracture (Briggs et al., 1994; Spörli and Eastwood, 1997; Locke et al., 2007). If the magnetic and gravity anomalies described by Eccles (2003), Williams (2003) and Locke et al. (2007) do, indeed, represent a large non-sheared ultramafic block, then such a dense, competent unit could cause the temporary arrest of the northward propagating lithospheric fracture. The complex stress field at the fracture tip may be responsible for joint arrays and decompressional melting in the upper mantle, allowing magma to be mobilised (Locke et al., 1007; Spörli and Eastwood, 1997).

Structural Geology of the Te Kuiti Group

The Te Kuiti Group has no known outcrop between the Brynderwyn Range, south of Whangarei and the Clevedon Fault Angle Depression, 28km south of Auckland (Isaac et al., 1994). Prior to 1998 the furthest north Te Kuiti Group was known was in a drillhole at Ardmore (d8427 in the National Coal Database) where thin late Eocene coal measures underlie early Miocene Waitemata Group. Thin remnants of Te Kuiti Group are locally present east of the Drury Fault on the western flanks of the Hunuas, between Ardmore and Pokeno. Thick Te Kuiti Group is present in the Lower Waikato Basin (Edbrooke et al., 1998).

However, Edbrooke at al. (1998) reported that a 592 m deep borehole in Mount Roskill, within the Auckland Volcanic Field, intersected Te Kuiti Group at depths of 475-492m, and estimated that the greywacke basement was probably less than 30m from the termination of the borehole. Davy (2008) also interpreted Te Kuiti Group as underlying Waitemata Group in seismic sections within the Waitemata Harbour, which also lies within the AVF. A summary of the structure of these sediments, as represented by the outcrops south of Auckland is therefore included, as these are likely to be similar to the structure of the same sediments underlying the Auckland Volcanic Field.

The Te Kuiti Group was mostly formed during a period of relative tectonic quiescence, and this is reflected by the mineralogy of the sediments as well as their structure. Millions of years' emergence led to chemical weathering in a warm to sub-tropical climate, on a generally low relief topography, though locally 100m relief or more was present (Nelson, 1973) and the resulting thick, chemically weathered regolith, rather than the underlying unweathered greywackes, became the parent rock of the Te Kuiti sediments, which were quartz and kaolin rich and feldspar poor (Nelson and Hume, 1987).

The main controls on the outcrops and isopachs of the group are the palaeotopography, which was influenced by block faulting that had occurred during the earlier rifting phase, and the mainly post-depositional block faulting, which inherited the same structural trends (Kear and Schofield, 1978; Nelson, 1973; Nelson, 1978; Edbrooke et al., 1994). The earliest sediments, the Waikato Coal Measures formed unconformably on the deeply eroded basement in largely landlocked basins. The unconformity locally dips up to 40º, in steep-sided basement depressions, rather than being fault controlled (Nelson, 1973). Isopachs are elongate N-S and parallel major fault trends (Nelson, 1978; Kear and Schofield, 1978).

Coal measures were therefore deposited in a structurally controlled, pre coal-measures, relatively narrow, N-NNW trending basin, which was best developed in the north. Cret-late Eocene, intervals of faulting and prolonged periods of weathering. A phase of late Cret- early Palaeogene strike-slip faulting preceded normal block faulting, which was major control on the coal measures depositional valley. Topographically low, NNW trends in broad inland valleys and ridges, mostly formed pre coal measures. (Edbrooke et al., 1994; Kear and Schofield, 1978; Nelson, 1973).

Throughout the Eocene slow regional subsidence occurred. Some (relatively rare and mostly in south) deformation with syn- depositional faulting. Most observed internal deformation is due to differential compaction over basement topography, with increasing sediment loading, including some slumping/faulting/ bedding parallel shears (Edbrooke et al., 1994; Kear and Schofield, 1978).

Regional subsidence occurred through Te Kuiti deposition (Edbrooke et al., 1994).

Bedding

Bedding within the Te Kuiti Group is generally flat-lying. Nelson (1973) reports dips rarely exceeding 5º, whilst Kear and Schofield (1978) observed dips ranging 5-15º, averaging 10º. Locally greater dips occur in close proximity to large faults, where even vertical dips may occur. Other anomalies are due to uneven pre-Tertiary topography and differential compaction (Nelson, 1973; Kear and Schofield, 1978). Dips are steeper on the eastern side of the Herangi Range, averaging 15º and increasing to 40º in the south. This is due to faulting, and the intrusion of the Wairere Serpentinite-near which the Otarohanga limestone is near vertical (Nelson, 1973).

Tilting, uplift and erosion of the Te Kuiti Group prior to Waitemata Group deposition resulted in a regional angular unconformity- reflected by observed regional dip differences of 3-4º W-SW between two Groups, but also coal rank variation, which is higher in the west. Post Waitemata Group tilting resulted in the dips of up to 15º.

Folding

Folding in the Te Kuiti Group is almost non- existent. Rather than folding, the block faulting and gentle westwards tilting of the fault blocks have occurred. (Kear and Schofield, 1978; Edbrooke et al., 1994) Most internal deformation is due to differential compaction over basement topography, with increasing sediment loading, and includes some soft sediment slumping-possibly associated with faulting/ bedding parallel shears (Edbrooke et al., 1994).

There are a couple of recorded exceptions. The first is the steepening of the Otorahanga Limestone close to the Wairere Serpentinite, as mentioned above. In the quarry at Aria, small-scale overfolding is locally evident (Nelson, 1973). Secondly, Davy (2008) interprets a larger-scale anticline affecting both the Te Kuiti Group and the overlying Waitemata Group in the mouth of the Waitemata Harbour, south of the North Head volcano. This fold, which has a half-wavelength of approximately 600m and an amplitude of about 50m, is interpreted as being associated with previously unrecognised strike-slip faulting, and then intrusion of an igneous body during the activity of the Auckland Volcanic Field (Davy, 2008) (fig 13).

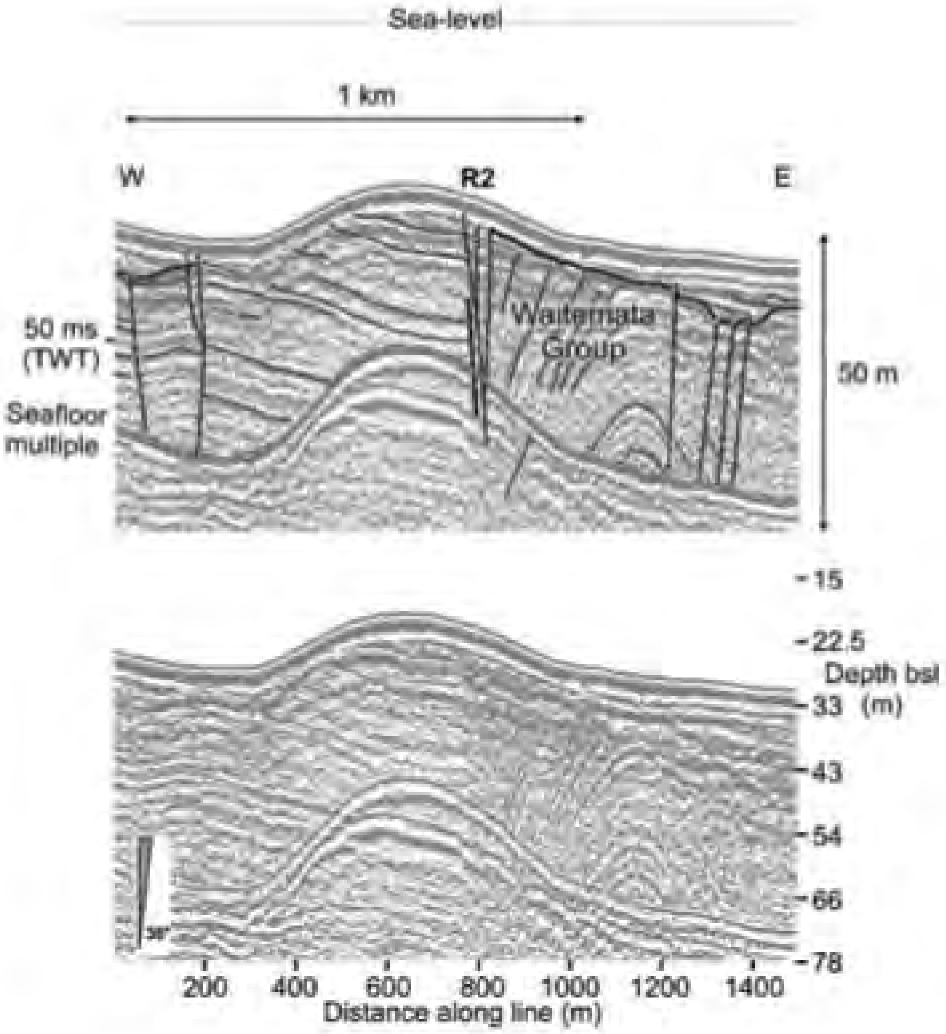


Figure 13. Seismic section south of North Head in the Waitemata Harbour showing folding of the Waitemata Group and the underlying Te Kuiti Group.
(Davy, 2008)

Faulting

There is some evidence for syn-depositional faulting during the early stage of Waikato Coal Measures Deposition, particularly in the "Rotowara Deep" area of the Rotowara Coalfield (Kear and Schofield, 1978). The coal measures apparently formed in a fault-angle depression running parallel to the main fault strike (N-NNW). This must have been young at the time of deposition (Kear and Schofield, 1978; Isaac et al., 1994). Basal conglomerates in some areas near faults have very angular clasts, implying steep, scarp-like topography, and coal becomes thinner and dirtier towards N-S trending faults, implying topography was irregular roughly coincident with faults (Kear and Schofield, 1978). Lateral variations in facies and rapid changes in the thickness of units may also be in part due to differential tectonic movements of areas of deposition, source area and dispersion path (Nelson, 1978).

On a small scale, structural features in coal measures include bedding-parallel shears (most commonly associated with coal seams and shale beds) and related faults, calcite-cemented crush zones and feather veins. Shears within coal seams can be up to 1m thick, composed of shattered and powdered coal, and some also produce small, flat, polished, striated lozenges of coal. Multiple movement phases are indicated by more than one lineation set. Faults of moderate dip (35-60º), without associated gouge, commonly terminate at bedding-parallel shear zones (some in both directions). These tend to be less than 5m long. The bedding-parallel shears and joining faults appear to have formed during burial, with flexural slip occurring during compaction, especially over basement highs (Edbrooke et al., 1994).

Most of the major faults run NNW in the north and N-S in the south. Minor faults are NE (050-031º) (Kear and Schofield, 1978). Nelson (1973) notes that in the Waitomo County, the major fault orientation is 011º and minor faults trending 032-079º, with average strike being 056º. These faults are steep and normal, although many faults had and earlier history including considerable dextral strike-slip. The faults of the NE trend are generally far less laterally persistent than those of the N-trend, and tend to have greater vertical throw at the middle rather than at the end (Nelson, 1973). N-NNW striking faults dominate-they are fewer but longer than E-ENE sets, and have larger displacements. Most of the movement occurred during the Miocene, although most N-trending sets were probably reactivated from late Cretaceous-early Paleogene faults. Many have displacements of 500m, but frequently they have no surface expression due to overlying Tauranga Group and volcanics. Some ENE faults were reactivated from pre coal measures, but most formed during the mid-late Miocene and terminate against N-NNW faults. Displacements on these faults vary inconsistently along the lengths, up to 250m and tend to downthrow SE. The nearly rectangular fault pattern reflects a crustal stress field that had principal horizontal axes oriented N-S and E-W- an orientation that persists to the present. (Edbrooke et al., 1994, Spörli, 1989).

The present pattern of block faulting and tilting (towards the north and northwest) was formed mainly in the late Tertiary Kaikoura Orogeny (Nelson, 1973; Kear and Schofield, 1979). It affects the Te Kuiti and Waitemata Groups, but mostly occurred prior to the Pliocene Kaawa Group sediments (Kear and Schofield, 1978).

Joints and Veins

There is little published information on joints and veins within the Te Kuiti Group.

Within the coal measures, feather veins are rare, feathery aragonite masses up to 1m in diameter, They are approximately circular, flat discs, which formed in two stages: firstly as tension gashes in vertical shear zones, followed by horizontal extension (Edbrooke et al., 1994).

Late Neogene tectonism produced extensive jointing in coals (know as cleats). At the Huntly Coalfield there are two well-defined cleats, perpendicular to the seam and each other. The dominant set follows the regional strike of 070º, with 90% of cleats falling 040º-100º. This is aligned with least principal horizontal stress. Many joints have thin coating of Kaolinite or pyrite-no calcite and therefore interpreted as post Oligocene/early Miocene deep burial (Edbrooke et al., 1994).

Topographic Lineaments

The Te Kuiti Group formed in a landscape where ridges and valleys ran NNW-N (Nelson, 1973; Edbrooke et al. 1994). Present day lineaments tend to parallel these trends, often marking the presence of reactivated block faulting. Fault scarps are present in some instances, but elsewhere even major faults have no surface expression at all, due to overlying Tauranga Group sediments or later volcanics (Edbrooke et al., 1994).

Structural Geology of the Rocks of the Northland Allochthon

During the Oligocene, at the same time as the Te Kuiti Group was accumulating south of Auckland and in the Whangarei District, shallow- bathyal marine sediments were also accumulating in a basin to the northeast of New Zealand (Isaac et al., 1994). These sediments were subsequently obducted onto Northland, during the Miocene, as a series of nappes and travelled hundreds of kilometres southwestwards on basal thrusts, and by gravity flow (Hayward, 1993; Ballance and Spörli, 1979). The movement of the “Northland Allochthon”, which is up to 3km thick, but averages 2km (Hayward, 1993), was responsible for some of the structural complexity of the Miocene Waitemata Group, which was, in part, carried along in a piggy back basin, and in part interfingers with the Northland Allochthon at the periphery of the basin (Ballance and Spörli, 1979; Spörli, 1989; Hayward, 1993).

Northland Allochthon rocks outcrop to the north of Auckland. They are structurally the most complex rocks of all those present in the region.

Their southernmost known outcrop is at Coatesville, 18km northwest of Auckland (Isaac et al., 1994). Earlier work suggested that the Northland Allochthon may extend beneath the Waitemata group as far south as the Waikato Fault (Ballance and Spörli, 1979) and that it may be present within the Karaka 1 well drilled on the Manukau Lowlands. However, this was contentious, due to several factors including known contamination of drill cuttings (Isaac et al., 1994; Edbrooke et al., 1998). A drillhole in Mount Roskill, within the AVF itself extended down to 593m, and passed through Waitemata Group straight into underlying Te Kuiti Group sediments, terminating an estimated 30m above basement rocks. Northland Allochthon was not present (Edbrooke et al., 1998). Davy (2008) reported that seismic sections from the Waitemata Harbour, within the AVF, have no reflectors consistent with the Northland Allochthon, and concludes that this unit is not present beneath the Auckland area.

This report does not, then, attempt to summarise the complex structure of the Northland Allochthon, as there is no clear indication that they are present within the AVF, and so it is deemed to be outside the scope of this summary.

Structural Geology of the Waitakere Group Volcanogenic Rocks.

As the rocks representing the Miocene Waitakere Arc outcrop to the west of the AVF, a brief synopsis of their observed structure is presented.

Bedding

Hayward (1975) observed that bedding in volcaniclastic sediments within the Waitakere Ranges, and on the west coast, tends to dip shallowly towards the W or NW (typically 0-20°NW, rarely exceeding 50°). He also noted that the oldest outcrops occur in the east and there is a steady decrease in age towards the west. He infers that post depositional tilting has produced this pattern.

Pohlen (1934) noted slumping in the Waitakere Group, with beds above the slump dipping 5ºSE and those below it dipping 20ºSE.

Searle (1932) described interfingering of the Manukau Breccia of the Waitakere Group and stated that the two were generally conformable.

Brothers (1954) described bedding along the west coast as mostly striking NW-NNW and dipping shallowly west, occasionally east. Travelling westwards up the Anawhata stream, strikes are mostly NW, dips alternate, 45ºNE, 20ºSW, 24ºNE, 20ºSW before the strike swings west-east. i.e. there is a series of horizontal NW-striking folds. He observes that severe folding of the Manukau Breccia on a minor scale is not infrequent, with very varied structural axes. He interprets this as widespread slumping in Manukau Breccias brought on by gravity slides of varying magnitude and intensity. In areas where severe folds are absent, the general structure is simple, with strikes trending E-W or NW-SE. This is a very similar picture to that seen in the coeval Waitemata Group. In fact Brothers (1954) recognises the Manukau Breccias share a common origin with the Parnell Grit of the Waitemata Group, noting at the same time that Waitemata beds that are associated with the Parnell Grits are usually highly deformed/slumped.

Folding

Hayward (1975) describes the following folds in the Waitakere Group:

- A very open N-S trending horizontal anticline at Otakamiro Bay,
- A broad ENE trending anticline plunging towards the ENE at Maori Bay,

- A series of small-scale horizontal E-W trending synclines and anticlines in the south of the area.

Brothers (1954) reported the series of horizontal NW-striking folds in the Anawhata stream, as mentioned above. The severe folding with varying axis orientation interpreted as slumping in the Manukau Breccia should also be noted here.

George (1993) observed low angle plunges to fold axes, 2-5º in a variety of orientations in the South Waitakere ranges

Faulting

Large scale WNW and NE trending faults in a grid pattern, with many tilted blocks, and NW downthrows are reported by Hayward (1975). He states that the Waitakere Ranges are NOT a raised horst, but are at a higher elevation than the surrounding Waitemata Group due to hard cap of resistant Lone Kauri/Piha formation, and in fact the rocks of the Waitakere Group are downthrown with respect to the Waitemata Group on a major fault on the eastern flank of the ranges, which drops them down 80-120m to west. Searle (1932) also noted this scarp-like contact between the Waitakere Hills and that nearby the bedding is tilted to NE-striking and vertical in the Manukau Breccia.

In the coastline from Muriwai to Te Waharoa 3 major NE faults are observed, with many sub-parallel minor faults. Blocks are thrown progressively down to south, with bedding dipping westwards at a low angle.

Filled canyons intercepting the coastline, and in the Albany area are very steep sided, and deep therefore of tectonic origin (syn depositional), but block faulting also occurs post deposition (Hayward, 1975) (fig 14).

Inland faults are often inferred from lineaments- some are concentric or radiating around volcanic centres, some formed during deposition and eruption-active mid Miocene. Andesite intrusives align along large fault structures, as do volcanic neck/crater complexes and dykes (Hayward, 1975).

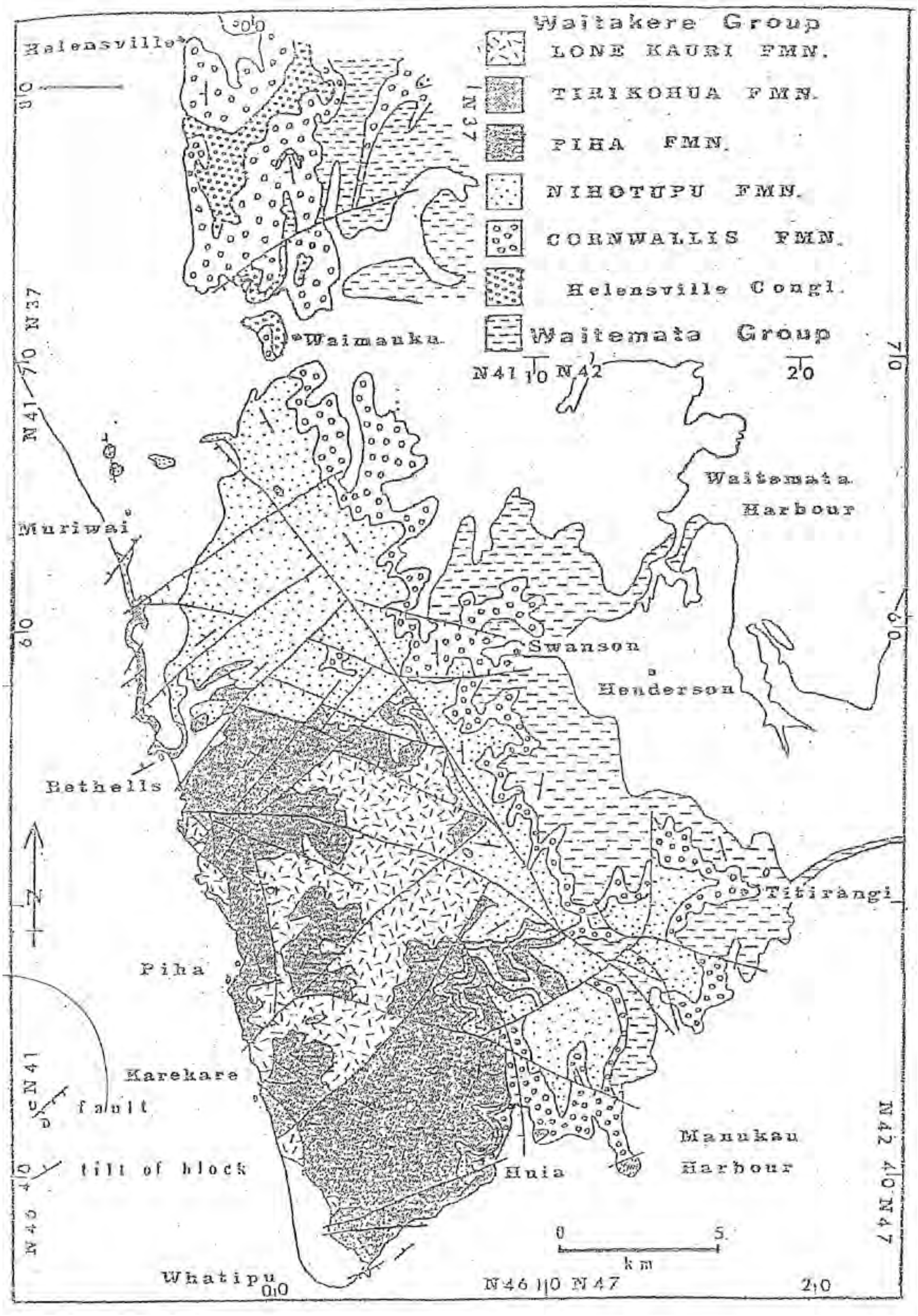


Figure 14. Block Faulting in the Waitakere Group west of Auckland. (Hayward, 1976)

In the South Waitakere ranges, George (1993) reports that steeply dipping (60-80º) normal faults are dominant, whilst more shallowly dipping (15-30º) normal faults are also present, sometimes in fault zones. He does not record strike orientations. Thrust faults, associated with soft sediment deformation occur at Cornwallis. They are several metres long.

Joints, veins and dykes

14 dykes are present at one location in the Waitakere Group; one trends 040-010º/SE, one 170º/E and 12 dykes are oriented 040-120º/10-48ºS. A rose plot of 153 dykes in the whole Waitakere area shows that the dominant strikes are N-NNW, and NE-E, which are parallel to the trends of major faults, and are comparable to orientations measured in the Tokatea area of Coromandel where Black (1964) reports two main directions in bosses dykes and sills: NNW and ENE (these are again parallel to the main structural trends of Northland (Hayward, 1978).

George (1993) reports that in the Piha formation, basaltic andesite dykes 5-50cm wide, 10m long, dip 5-40º but again he records no strike orientations. Sedimentary dykes 30-100mm wide dip 60-90º (no strikes recorded). Joints dip steeply (more than 70º), with dominant sets trending N, W and NNE.

Topographic Lineaments

Topographic lineaments in the Waitakere Ranges come in a number of guises. Hayward (1975) describes the following:

- Volcanic eruptions occurred along two NNW trending lines (fig 15).
- Of these the western belt, runs along coast, with 8 craters and volcanic neck complexes lining up on a bearing of 345°.
- The eastern belt, which is 12km long and 2km wide with a strike of 330° also, coincides with the major fault that downthrows the Manukau subgroup 100m with respect to Waitemata Gp. Andesite intrusions, dykes and volcanic neck/craters all fall along the line of the fault.
- The above-mentioned fault forms the straight, scarp-like edge to the Ranges, where downthrown, but more resistant Waitakere Group rocks were juxtaposed against the more easily eroded Waitemata Group.
- Air photo lineaments, interpreted as faults, are present in a strong, grid-like pattern with NE and ESE orientations present (fig 14).

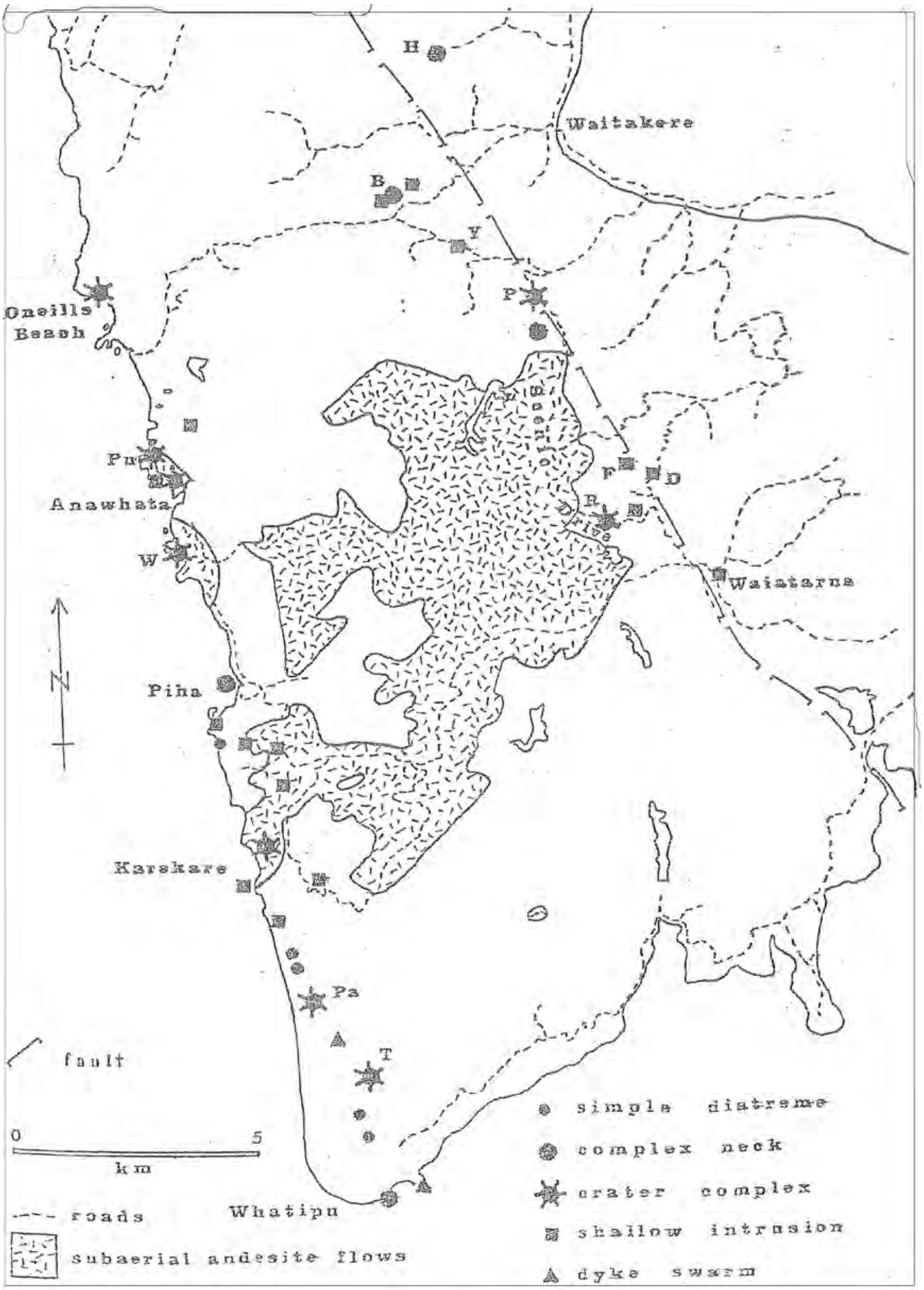


Figure 15. Alignment of vents in the Miocene Waitakere Group, west of Auckland, in two NNW-running belts.

(Hayward, 1976)

Structural Geology of the Waitemata Group Rocks.

The rocks of the Waitemata Group underlie most of the AVF, with a thickness of around 500-600m, as indicated by boreholes and geophysical surveys. The last few hundred metres of ascent of magma, and the eventual location of a new vent is likely to be largely controlled by structures in the Waitemata Group.

Bedding

In general the rocks of the Waitemata Group are separated into zones where the structure is very simple, with horizontal or very gently dipping strata, and zones with extreme structural complexity. (fig 16). This simple zone: complex zone partitioning has been noted throughout Auckland by many published authors (e.g. Turner and Bartrum, 1924; Brothers, 1954; Spörli, 1989; Hayward, 1993, Allen, 2004; Spörli and Rowland, 2007; Strachan, 2008) and in many theses (e.g. Morris, 1983; Berry, 1986; Swain, 1993; Patterson, 2002). This pattern is again a product of the dynamic environment into which these beds were deposited. Simple zones apparently represent deposition and burial within a relatively quiet period in the basin, whilst complex zones are interpreted as due to disruption, often when the beds were still unconsolidated. Several authors note a relationship between intense folding, faulting and shearing and the presence of Parnell Grits, which are interpreted as submarine lahars (Turner, 1924; Brothers, 1954; Hayward, 1993). Transition between simple and complex zones is often very abrupt, with beds immediately above and below the slumped horizon being unaffected, but may be more gradual.

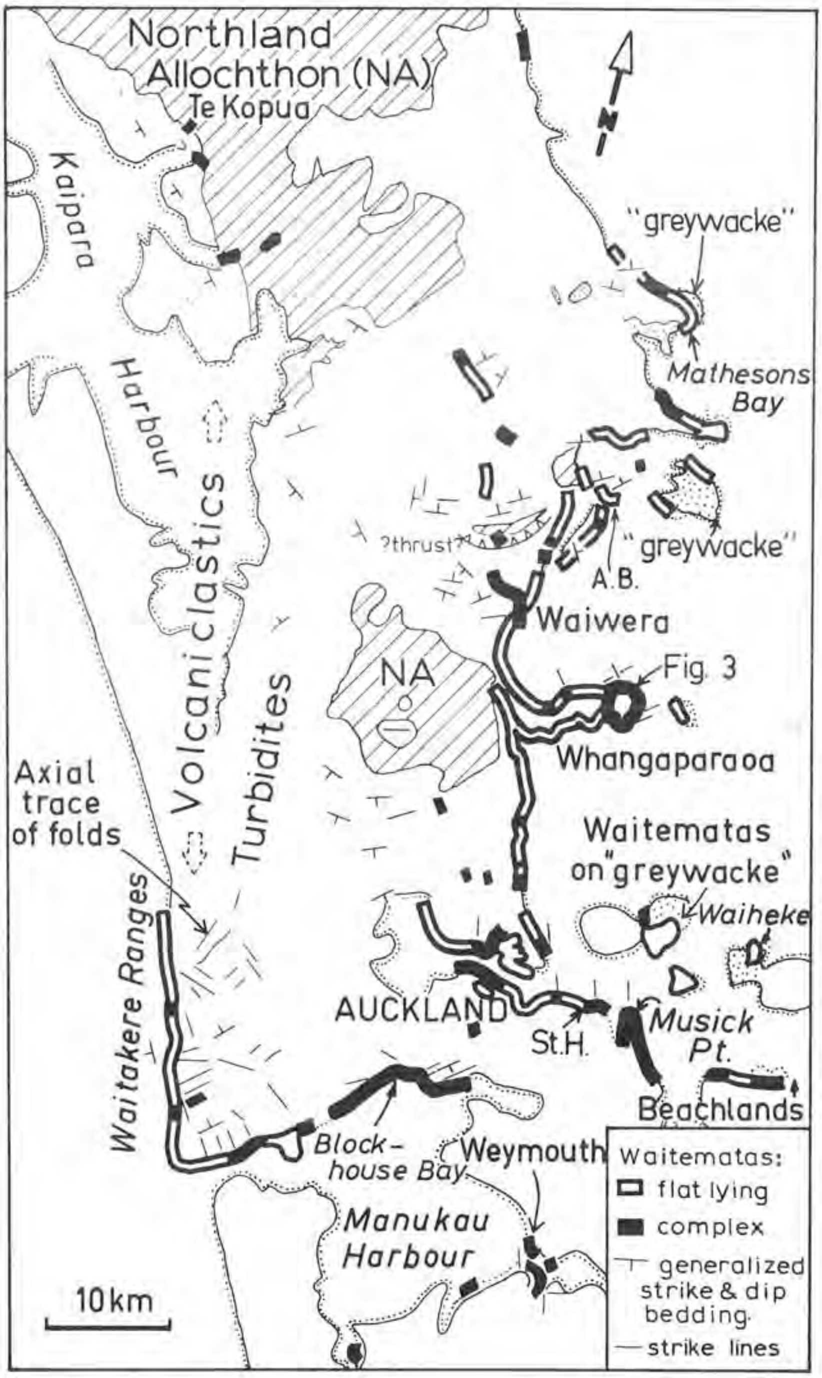


Figure 16. Extent of simple and complex structural zones in the Waitemata Group of the Auckland area.

(Spörli, 1989)

Slumped horizons may be quite thick. At Tarihunga, there is a slump sheet with minimum thickness of 30-45 feet. At Stanmore Bay there is one ca. 40ft thick, West of Red Beach, another one 40 ft thick. From Army Bay to Whangaparaoa Head deformation becomes progressively more complex until at Whangaparaoa Head, a minimum of 300ft of steeply dipping and locally overturned strata is exposed in the cliff-face and platform. The total amount of strata involved in the slumping probably >400ft (Gregory, 1969).

The disruption of the complex zones is thought to have occurred ahead of and/or on top of the advancing Northland Allochthon (Spörli, 1989; Hayward, 1993) and may have been initiated by seismic activity. The presence of the Parnell Grits indicates a volcanic influence, with the incoming lahar becoming involved with disruption of the previously deposited flysch.

Bedding strike orientation varies widely throughout the Waitematas, partly because the near horizontal sections of strata may dip very gently in any direction, and partly because of the almost random nature of the folding and faulting within the slumped zones. Nonetheless, very general patterns may be discerned in the bedding. NNW and NNE-ENE orientations are most common, as are dips towards the west.

A good example of how the bedding attitude may vary is given by Turner (1928) for the Takapuna-Silverdale section:

On the north side of the Wairau Creek, Waitemata beds dip at 30 west, and from there to Castor Bay the beds are very disrupted. North of Castor Bay strata dip gently north, with the dip rapidly increasing northwards until half way to Red Bluff, where the beds are vertical. The beds then turn in on a fault, the other side of which they are again gently dipping. Near Red Bluff the strata have a steep SW dip. Whilst most of the strata on Whangaparaoa are gently dipping, those at Whangaparaoa are intensely deformed.

The sediments were probably mostly deposited on a gently southwards sloping seafloor. Palaeocurrent indicators in the turbidites commonly show flow occurred towards the ESE-SSE (Ballance, 1964; Gregory, 1969; Allen, 2004) (fig 17).

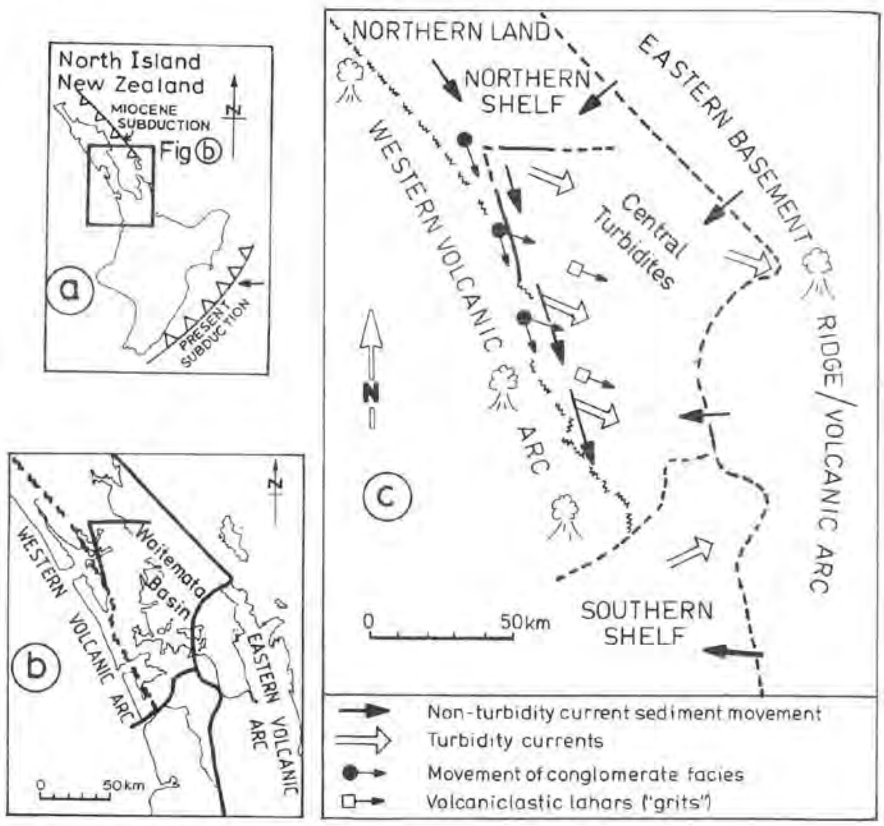


Figure 17. Palaeocurrent directions in the Waitemata Group.
(Spörli, 1989)

At Whangaparaoa, Gregory (1966) observed the following:

- In turbidites, flow was predominantly from the NW (290-300º) in the early stages, but possibly swinging to 230º in the later stages.
- The Whangaparaoa grits were emplaced by N or NE flowing submarine volcanic mud flows.
- The turbidites at Whangaparaoa and Takapuna suggest almost horizontal deposition where currents had lost their ability to erode (axial basin); SE and SSE flowing currents are indicated.

Strachan (2008) not only reports sediment sources to the NW and W, as in previous studies, but also, from cross-bedding in turbidites at Little Manley, Whangaparaoa, has palaeocurrents to the NE and SW, indicating additional hinterland emergent in the SW and NE. Average current direction was to the SW. Northland Allochthon and Waipapa basement were important sediment sources. Average movement directions in slump beds are towards 230º.

Sprott (1997) and Lipman (1993) both observed interpreted flow direction within the Albany conglomerate as being towards the SSE, and these may have been channelled within submarine canyons.

Folding

Folding within the Waitemata Group also ranges from very simple to very complex, where soft sediment deformation is involved. Flexural slip mechanisms are very common, sometimes kink folding. A wide variety of orientations are again present, but NNW-N and NE trending axes are most frequently reported, with gentle plunges to both the north and the south. Below some examples of simpler folding are given.

- At Musick Point Morris observed a1.5-2km long, NNW trending anticline that is refolded on an (?) E-W- trending axis so that it plunges gently northwards in the north and gently southwards in the south. The fold verges westwards.
- In the upper Waitemata Harbour, Davidson (1990) also observed that N-S folding predates E-W folding, the latter of which is isoclinal.
- Geelen (1973) described a NNW trending ‘major regional anticline’ affecting the Waitemata Group on the north coast of the Manukau Harbour. Minor folds tend to be parallel or perpendicular to the large anticline, parallel folds plunging shallowly either NNW or SSE, although plunges up to 50º are present. Axial planes are mostly vertical and vergence is to the west. NNW tending folds again predate ENE trending folds.
- Alldred (1980) reported mostly E-W trending folds in the Pakiri Formation, with fold axes plunging westwards. The mean fold axis is 260º/15º.
- Wise (1999) observed a series of NNE trending folds, subparallel to the Wairau North Fault.

Where slumping is involved, folding can seem very chaotic and orientations vary widely. Nonetheless, patterns emerge with fold axes tending to be NE-SW, perpendicular to the palaeoslope (Ballance, 1964; Allen, 2004; Strachan, 2008; Spörli and Rowland, 2007) (fig 18).

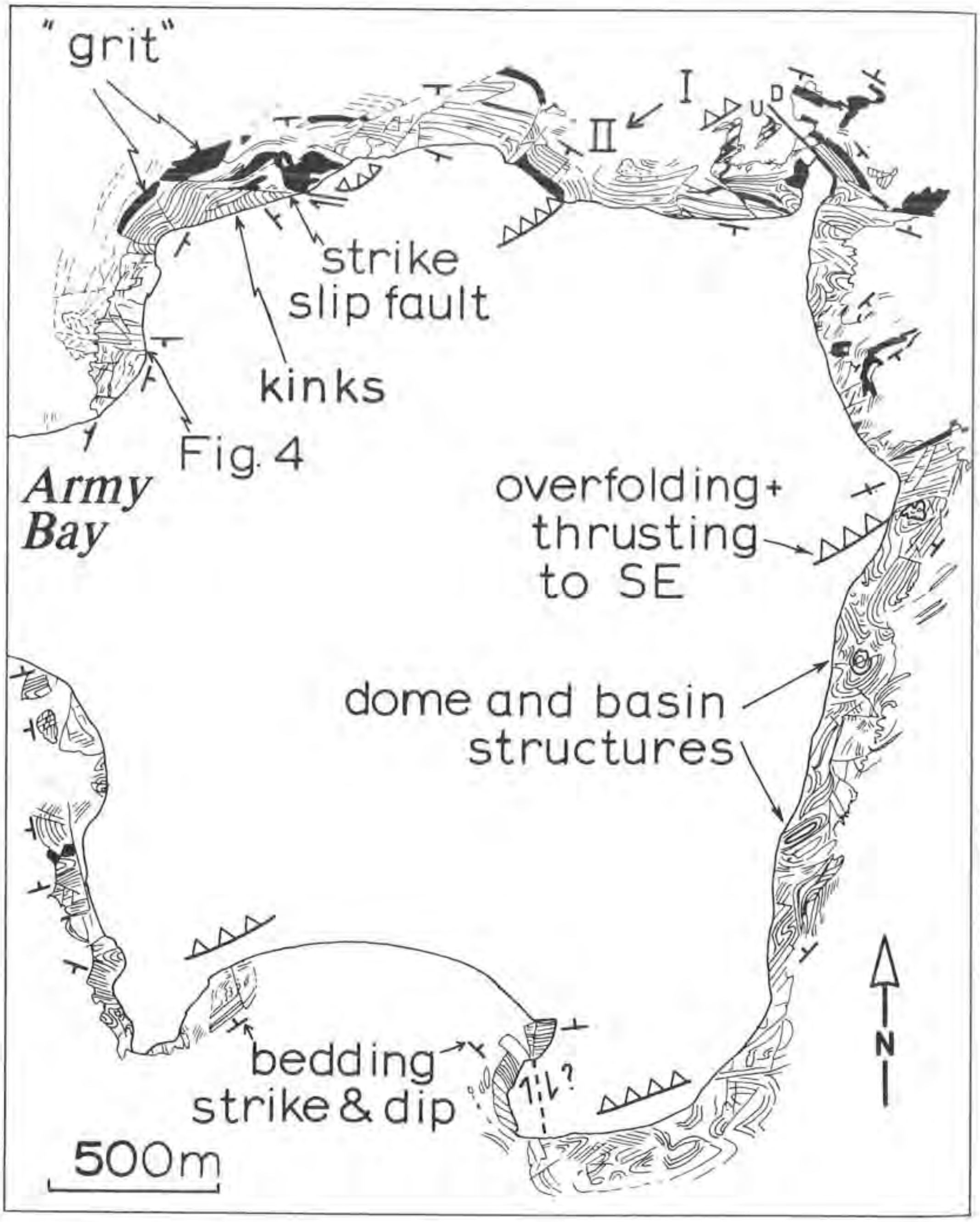


Figure 18. Small scale complex folding and faulting within the Waitemata Group at the east end of the Whangaparaoa Peninsula.
(Spörli 1989)

Recent papers on Whangaparaoa present very comprehensive summaries of the slump-associated folding, and are good examples of the complexity that can occur within a slump. Such features formed instantaneously in geological terms, but their development from other flow types can sometimes be traced across the outcrop, and processes interpreted- for example, at Little Manley the slump motion appears to have been unsteady, non uniform, and arrested rapidly (Strachan, 2008).

Within the slump at Little Manley, folds are recumbent to upright, similar or parallel and on a decimetre to sub-centimetre. Three phases are present: with progressive slumping: 1) flat-lying, long wavelength (up to 5m) isoclinal folds, usually in coarse sandstone and often only limbs are preserved. 2) south verging. 3) upright folds with vergence to the SW (dominant) and to the E (locally, at the SE end of the exposure). The following patterns of folding emerge:

- Facing is consistently SW.
- Fold hinges are NW-SE/ subhorizontal, with axial plane fanning about the trend.
- Axial planes that strike NE-SW have greater hinge pitch angle and gentler dip than those with axial plane striking NW-SE.
- NE-SW folds have smaller inter-limb angles than NW-SE.
- Fold hinges that pitch >40º on the axial plane have a small interlimb angle (<35º).
- SE and S –striking axial planes tend to have greatest dip angle and greatest interlimb angles (Strachan, 2008).

Spörli and Rowland (2007) interpreted the following sequence for the slumped beds at Army Bay- Whangaparaoa:

- D1 syn-sedimentary slumping and grit emplacement;
- D2 large scale, deeper seated sliding extensional and low-angle shearing associated with generation of boudinage and broken formation;
- D3 thrusting and folding with transport mostly to the SE-S;
- D4 thrusting and folding to the N-NE;
- D5 further folding, including a) N-S trending folds, b) E-W trending folds and c) sinistral shear;
- D6 steep faults, initially strike slip and then normal.

The authors infer intermittent or continuous SE-wards transport of units with increasing sedimentation and structural burial. By D3 the sediments had low levels of consolidation, and whilst the lack of cleavage is taken to indicate formation by slumping, this is interpreted as having been influenced by tectonics-especially by the movement of the Northland Allochthon (Spörli and Rowland, 2007).

Davy (2008) interprets a larger-scale anticline affecting both the Te Kuiti Group and the overlying Waitemata Group in the mouth of the Waitemata Harbour, south of the North Head volcano (fig 13). This fold, which has a half-wavelength of approximately 600m and an amplitude of about 50m, forms a raised flank to an interpreted igneous body at the unconformity between the Te Kuiti Group and the Waitemata Group. He interprets it as being associated with previously unrecognised strike-slip faulting, and then intrusion of the igneous body during the activity of the Auckland Volcanic Field.

Faulting

The most obvious faults in the Waitemata Group are those involved with late stage block faulting. This will be described in a later section. However, where outcrop is good, it is common to observe a multitude of faults of varying scale: usually most are a few metres long with a few centimetres offset, several extend for several tens of metres with up to a couple of metre's separation and a few major faults, often with steep dips, have offsets that are too great to match beds in the cliff or the wavecut platform. Smaller faults often parallel the larger faults, with NW-NNW and NE-ENE trending normal faults often present (e.g. Gregory, 1964; Berry, 1986).

Kenny (2008) postulates the presence of many large-scale arcuate thrusts in the Waitemata Group, trending in a generally ENE-NE striking, north dipping orientation, indicating south to south eastwards transport direction. She suggests that these thrusts may be connected with the emplacement of the Northland Allochthon in the north, as they appear to fan out from an area just north of Albany, corresponding with the toe of the allochthon (Hayward, 1993).

The authors of many theses also note thrusting towards the south on E-W or SE-NW trending faults, throughout the Auckland area. These include Davidson (1990) (Upper Waitemata Harbour), Jugum (2000) (Timber Bay); Swain (1993) (Leigh); Johnston (1999) (Albany); Geelen (1973) and Manning (1983) (both along the north Manukau Harbour coast); Tejaksuma (1998) (Beachlands) and Berry (South Manukau Lowlands). This thrusting is often present as an early phase of deformation. Davidson (1990), Manning (1983) and Geelen (1973) also record thrusting on N-NNE trending planes in the upper Waitemata Harbour and North Manukau coast.

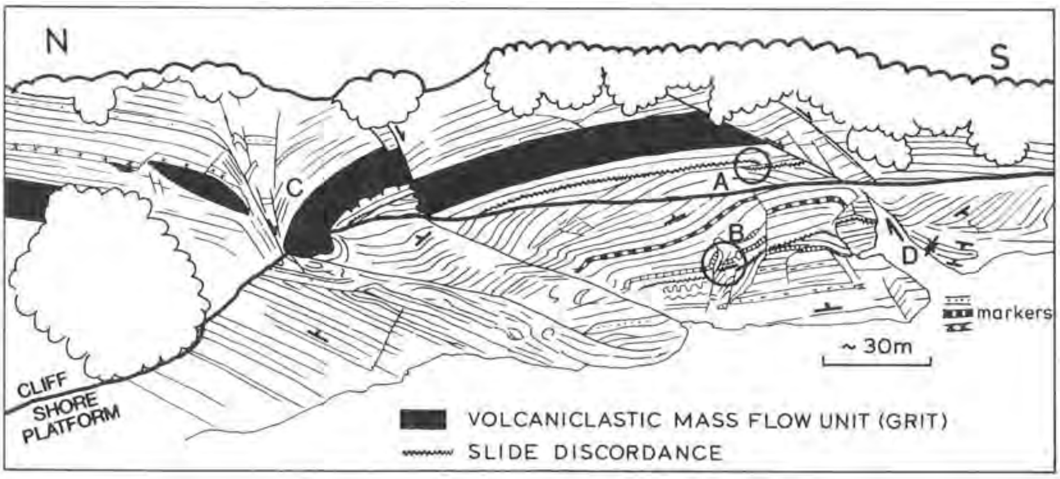


Figure 19. Faulting within the Waitemata group on the Whangaparaoa Peninsula. (Spörli, 1989)

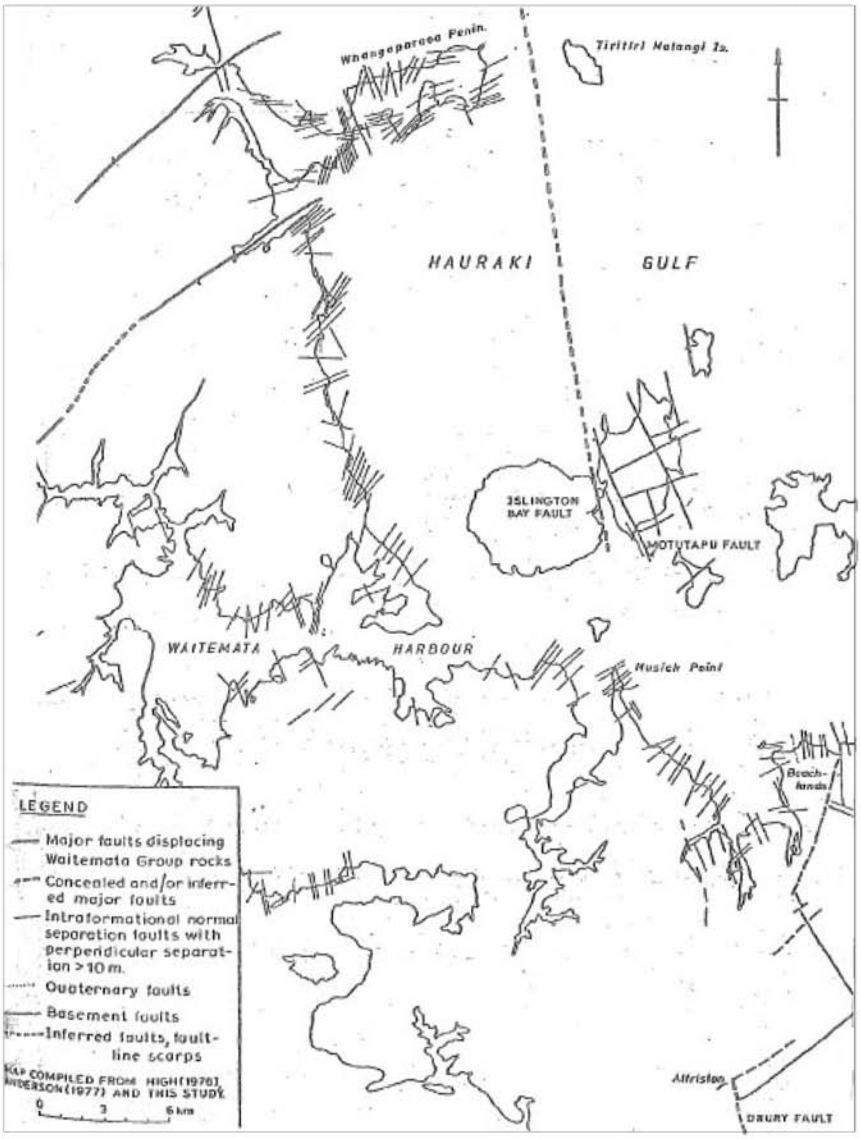


Figure 20. Summary of observed and inferred fault orientations for the Auckland area. (Milligan, 1977)

Thrusting is very often crosscut by later northeast or northwest trending, mostly normal, faults, although reverse faults are also present in some areas- for example, at Albany (Johnston, 1999); on the east coast (Simpson, 1988); on the north Manukau coast (Manning, 1983); and in the South Manukau Lowlands (Berry, 1986). Gregory (1964) notes that whilst ENE trends are most common, major faults with an unmatchable displacement are most likely to have a NNW or ENE trend and a steep dip. These are parallel to the regional block faults.

At Little Manley Strachan (2008) notes that faults range from 5-0.05m long but faults that are >2m long are always compressional, whilst those that are <2m long may be normal or reverse. Thrusts that are >2m long cross-cut all other deformation and are characterised by curved, ramping geometry. She interprets these last phase thrusts as indicating a rapid arresting of the slump. Poles to faults trend around a SE-NW girdle, with a secondary NW-SE girdle also present**.**

Conjugate thrust or normal faults are present in many places. Examples of these are:

- Tilsley (1993) interprets a shallow to moderately SE plunging compression on NNE trending conjugate normal faults in the Howick-Alfriston area.
- Morris (1983) observed conjugate thrusts at Musick Point with NNW strike, dipping towards the east and the west, as well as four sets of normal faults that operated simultaneously: two sets trending E-W and dipping steeply north and south; two sets trending NE-SW and dipping steeply NW or SE. There are more of the east-west striking faults, but the NE-striking, SW dipping set has the best developed faults with the largest slips. These four mutually offsetting fault sets represent orthorhombic three dimensional strain with NNW main extension direction (Krantz, 1988) (although Morris does not interpret the pattern in this way).
- At Manley Christie (1986) calculated tension axes for 28 conjugate pairs of faults, which clustered in four different orientations: 020º/20; 333º/15º; 295º/15º; 215º/07º. The relative timing of different fault sets is not recorded.

Whilst the throws on many faults is relatively small, the combined throw of many faults within a fault zone can lead to very significant offsets. Geelen (1983) suggested that the Manukau Fault, one of the major regional block faults forming the boundary between the upstanding Auckland and Waitakere Blocks and the South Manukau Lowland Block, is actually a fault zone. He observes many smaller scale faults with displacements of 20m-40m, which he estimates combine to give a total throw of 100-800m, within a fault zone that is at least 1km wide (the length of the Cornwallis Peninsula).

It is interesting to note that there are almost no reports of primary strike slip faults within the Waitemata Group, although some faults may be reactivated with dextral oblique-slip (Wise, 1999).

Joints, veins and dykes

Joints are sometimes the most common structure in an area (e.g. McManus, 1982; Albany-Paremoremo). In the Waitemata Group they often form in two orthogonal sets within sandstones, at a high angle to bedding i.e. close to vertical within the simple structural zones. Tilsley (1993) noted that N to NNW trending joints mutually offset/truncate ENE trending joints, indicating that they were formed at the same time. Many joints affect just one bed (Simpson, 1988). Some form parallel to faults in the area –for example, at Leigh where ENE, NNW and NNE trending joints all parallel fault sets, the NNE set being the most strongly represented set (Swain, 1993). NW-SE and NE-SW trending sets are most commonly reported. Tejaksuma (1998) noted that at Beachlands, whilst joints are common in the Waitemata Group, they are rare in the overlying Quaternary rocks, indicating that they formed early.

Veins usually parallel joints, Simpson (1988) recorded four sets: two strong sets striking NW and NNE, with two weaker sets striking NNW and ENE, all sets dipping at more than 70º.

Some authors note the presence of clastic dykes, but usually orientations are not given (e.g., Jugum, 2000; Gregory, 1964).

Crosscutting relationships

Hayward (1993) summarised age relationships of structures in the Waitemata Group as follows:

1. an early syn-basinal phase of thrusting and folding with east vergence (as seen

in the east East Coast Bays Formation).

2. a later syn-basinal phase of thrusting with S and SE vergence (refolding earlier folds, but not affecting eastern ECBF), more complicated near Kaipara
3. a post-basinal phase of gentle regional tilting of western areas towards the west and open folding on NE and NW axes.
4. later phase of normal faulting NE first then NW.

Observations at an outcrop scale do not necessarily follow this order, or orientations may vary from those quoted above. For example Berry (1986) observes NNW trending normal faults as being older than those trending ENE, and some authors report steep reverse faults paralleling normal faults, which are not mentioned above (e.g. Davidson, 1990; Manning 1983; Johnston, 1999). Generally, however, this order of events is compatible with what is observed at most locations.

Topographic Lineaments

In almost every case topographic lineaments within the Waitemata Group are parallel or sub parallel to the regional trends. Some lineaments may be the surface expression of major faults that carve the whole area into horsts and grabens. Others may be smaller faults that formed in the same time period as the major faults. There is evidence that some of these faults may still be active (e.g. Wise, 1999). It should be noted, however that even major faults may not produce a topographic lineament, and it may be unclear exactly where they run, even where their presence is obvious from differences in stratigraphic heights observed in boreholes (e.g. Gregory, 1964).

Reported lineament trends are: N-NNW, NNE-NE, ENE-E (e.g. Davidson, 1990) and are manifested as straight sided streams and ridges, sometimes asymmetric valleys, topographic depressions and straight, steep scarps and cliffs. (e.g. Tilsley, 1993).

Structure of the Volcanics of the AVF.

Because of the young age of the volcanic rocks of the AVF, most structures observed within them are primary or occurred during compaction. For example, Bryner (1991) studied faults in the tuff ring of Brown's Island (Motukorea), measuring 160-200strikes. Most faults were normal, a few reverse. Some conjugate normal faults have a N-S strike, indicating E-W extension; other conjugate normals strike E-W indicating N-S extension (or if all four fault sets are simultaneous they could represent a type of orthorhombic three dimensional strain). The faulting may be due to volcanic disruption, compaction, slumping of tuff ring rim, or differential compaction on undulating surface (or possibly tectonic, although this is considered unlikely.) The largest offset is 4m.

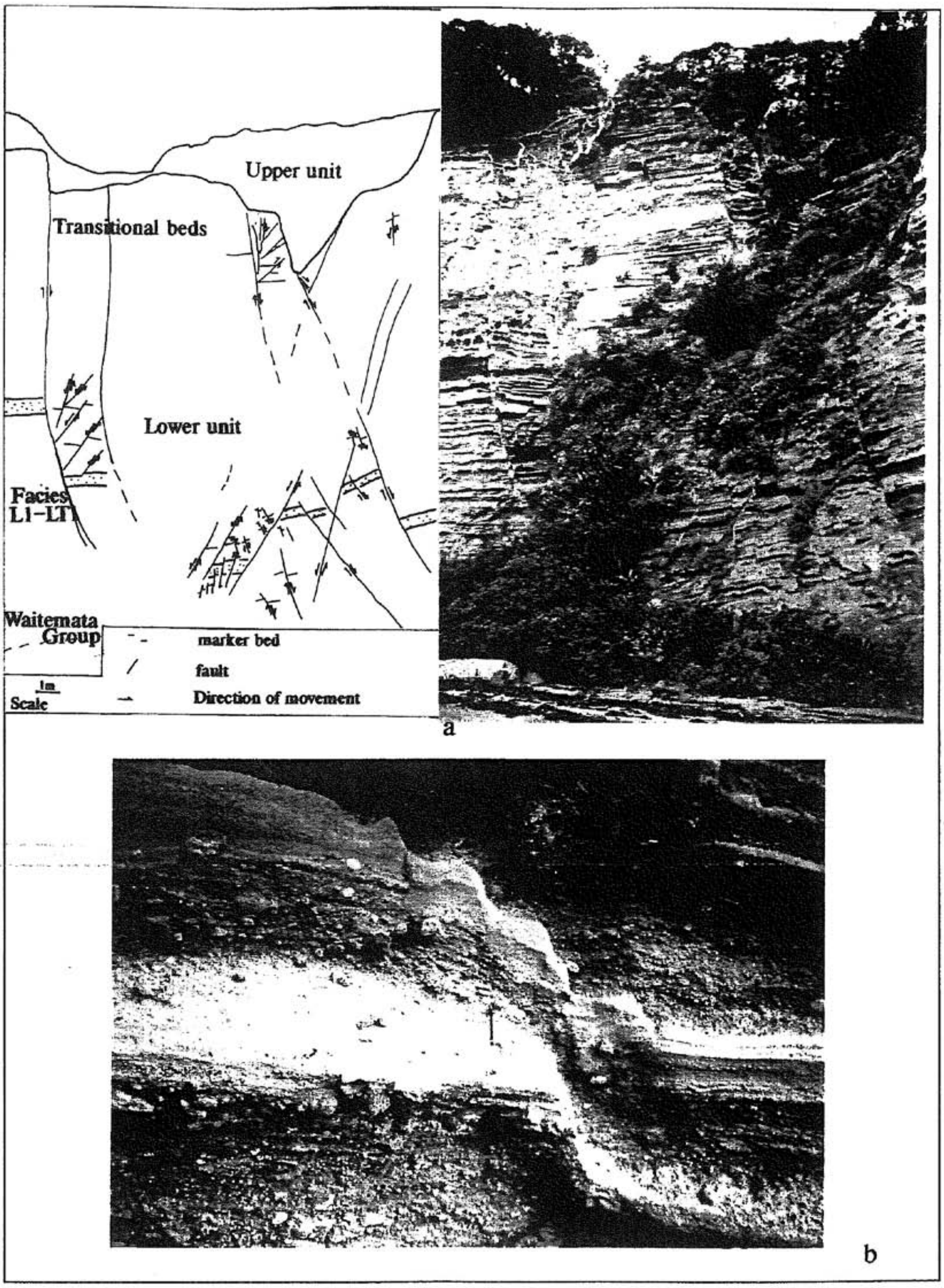


Figure 21. Faulting in the volcanic rocks of Motukorea Island, east of Auckland. (Bryner, 1991)

Several of Auckland's volcanoes have been the subject of geophysical studies to determine their subsurface structure. (e.g. France, 2003; Jukic, 1995; Miller, 1996; Cassidy et al., 1999; Affleck, 1999; Roberts, 1981; Rout, 1992). Examples are given below, from Rout (1992), and a more comprehensive summary is given in the appendix.

- Pukaki Crater has a negative gravity anomaly and no magnetic anomaly indicating the presence of low density mud/colluvium. No subsurface plug is present beneath the crater-a low density cone is modelled with a top surface 650m diameter and depth of 25m.
- Crater Hill has a positive gravity anomaly and a strong magnetic anomaly indicating a solid lava body infilling a crater and a pipe is modelled down to 110m, which is cylindrical in the upper 65m and conical in the lower 45. The body sits between 100m a.s.l. to 110m b.s.l. and has a diameter of 100m.
- Wiri Mt has a positive gravity anomaly with a broader gravity low. There is no sharp magnetic anomaly, only a broad, weakly negative anomaly, associated with the vent. The volcano probably erupted eruption into an alluvium filled river channel, which was filled by later lava flows. The geology shows more than 15 phreatomagmatic explosions then Strombolian and Hawaiian eruptions forming a 90m high scoria cone and lava flows. There is a small plug from 7m a.s.l. to 25m depth, with a diameter of 50m, that tapers within this valley.
- McLaughlins Mountain has a classical dipolar magnetic anomaly, but gravity is subdued and variable. This represents scoria cones and surface lavas with no significant subsurface structure.
- Ash Hill-magnetic anomaly shows a body of magnetised rock beneath it. One possible model for this is a cone with 100m diameter at sea level, decreasing to 50m diameter at 40mbsl. This is not a well-defined model.

Some vents appear to be aligned, possibly indicating the influence of subsurface faults:

- The three Wiri Group volcanoes lie on a line bearing 050º. Wiri is the youngest, and the relative ages of McLaughlins and Ash Hill are unknown, but distinct. There is no geophysical evidence for a major basement fault causing this alignment (although it is possible that they are on a small offset fault or a strike slip fault, which would have little difference in elevation of greywacke either side of it) (Rout, 1992).
- There is a possible NW-SE alignment of Crater Hill-Wiri-Puketutu volcanoes and Hampton Park- Otara Hill- Mclennan Hill (Miller, 1996).
- The Domain central crater is oval and elongate N-S. The Domain and Redhill volcanoes are on a line running NE-SW (Redhill tuff ring is also elongate NE-SW) but the two are distinct, different magma bodies (France, 2003).

- Houghton et al (1999) report that at Crater Hill four simultaneously active vents were aligned along a 600m NE-trending dike, again sub parallel to the regional structure.
- Larger scale alignments are sometimes observed in NE-NNE or occasionally NNW directions, sub-parallel with the structural block faulting trends, and the Hauraki Rift (Searle, 1961; Sibson, 1968; Magill et al., 2005).
- Houghton et al. (1999) report that at Crater Hill four simultaneously active vents were aligned along a 600m NE-trending dike, again sub parallel to the regional structure.

Geophysics has also been used in dating some volcanoes. Palaeomagnetic studies, measuring the palaeomagnetic declinations at each site, and comparing these with historically recorded declinations indicates that Rangitoto was active between AD 850 and AD 1800, with a maximum of activity between AD 1200 and 1500. This agrees with results earlier obtained from ^{14}C dating. Sites that are currently situated in the intertidal zone also have higher than usual magnetism, probably due to formation of small magnetite grains by quenching. This indicates that sea level was roughly the same at the time of eruption as it is today (Robertson, 1986).

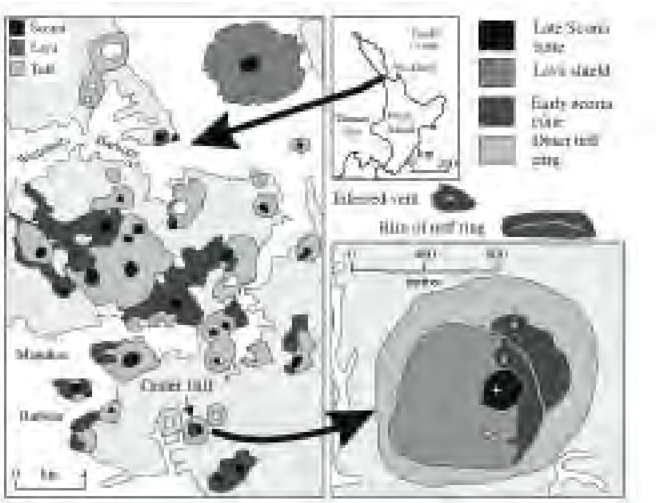


Figure 22. Concentric structure of Crater Hill.
(Smith et al., 2007)

REGIONAL SCALE STRUCTURES

The Hauraki Rift.

The Hauraki Rift is a major active tectonic feature that lies to the east of Auckland, occupying the Hauraki Gulf as far north as Whangarei and the Hauraki Plains as far south as Matamata- a distance of more than 250km. The Rift trends NNW (striking at approximately 70º to the currently active Taupo Volcanic Zone), and its width varies from 25 to >40km- the widest part being in the north (Hochstein and Nixon, 1979). The location of the AVF on the flanks of the Rift mean it is potentially an important tectonic influence on the field, even though geochemical and isotopic evidence suggests that the AVF has formed in an intraplate rather than a rift environment (Briggs et al., 1994).

Several geophysical studies of the Hauraki Rift have been undertaken by students at Auckland University, and the structure of the Rift has become fairly well defined (Fergusson, 1974; Rawson, 1980; Tearney, 1980; Backshall, 1982; Davidge, 1982; Grieg, 1982).

The structure of the rift is apparently fairly consistent along its full length. In W-E section it is made up of a fault-angle depression, a median horst, and a graben. A maximum thickness of c. 3km of Quaternary and Tertiary fill the two depressions. The fault angle depression and the graben are bounded on eastern side by major normal faults dipping 70º+/-10º W (the Kerepehi fault in the centre and the Hauraki Fault, forms eastern boundary of the depression). Minor hinge fault (Firth of Thames Fault) probably runs along western boundary (Hochstein and Nixon, 1978). Apparent offsets of the central horst and graben may actually be due to en echelon formation (Hochstein and Ballance, 1993).

The flanks of the rift are uplifted, which may have contributed to the westwards tilt observed in the Auckland region and the Eastwards tilting observed in the Coromandel Peninsula. Anomalously high heat flow is observed within the Rift and along its flanks, with the presence of hotsprings whose chemistry indicates anomalously high temperatures (250-250ºC) at less than 5km depth and all measured earthquakes having focal depths of less than 12km. A geothermal gradient of >30ºC/km is suggested. (Hochstein and Nixon, 1978).

The age of the Rift is not well defined with authors expressing differing opinions e.g.:

Hochstein and Nixon (1979)	upper Miocene age
Skinner (1976)	late Mesozoic init, but main subsidence late Tertiary
Ballance (1976)	Pliocene
Schofield (1967)	upper Pliocene
Davidge (1982)	3-2 million years ago
Tearney (1980)	less than 2 million years ago.
Brothers and Delaloye (1982)	Pliocene-Quaternary (2my or less) after late Cenozoic warping above upper mantle swell and rift collapse in late Pliocene

Hochstein and Ballance (1993) believe that precursory uplift may have begun ca. 10Ma ago, and sedimentation was probably occurring in the Rift by 5-7Ma. They propose a model in which the rift formed due to arching of the crust, which was induced by asthenospheric upwelling in response to subduction in the NNW trending Miocene arc that ran through the Coromandel Peninsula (although the Rift is not a classical behind-arc rift). The asthenosphere, they propose heated the whole lithosphere beneath the rift and although there was probably insufficient time to develop a full plume, but rifting continued, driven by the tensile palaeostress field that affected the whole Northland plate segment. Tensile stress continues in the area into the present, now rotated to where the principal horizontal stress is oriented 335º, which tends to cause dextral strike slip rather than simple extensional faulting on NNW trending features.

Regional Block Faulting Pattern.

During Miocene-Pliocene times (7-2Ma), uplift occurred, everting the Waitemata Basin, and a switch from compressional tectonics to oblique extensional tectonics led to block faulting. This marked the beginning of the Kaikoura Orogeny and formed the present relief.

Block faulting is present throughout the region, comprising a series of horsts and grabens, bounded by steep NNE-NE (e.g. Drury and Wairoa North Fault) and ENE-NE (e.g. Waikato and Glenbrook Faults) trending major normal faults (Figs 14, 23, 25). Large scale horsts include the high-standing basement blocks in the east of the area, such as the Hunua and Moehau Ranges, whilst the South Manukau Lowlands, and the Manukau Harbour itself are underlain by a series of ENE, elongate graben. The AVF lies on a block that stands at a height midway between the Hunuas and the South Manukau Lowlands (Wise, 1999). Another fault separates the Auckland block from the Waitakere Ranges, although the latter is actually the downthrown block, but maintains a higher elevation than the upthrown Waitemata Group due to the more resistant nature of its rocks (Hayward, 1978). These fault trends extend throughout the Northland area, and are inherited from basement structures that formed during the rifting of New Zealand from Gondwana ca. 80Ma. (Spörli, 1982; Kamp, 1986). Patterns of faulting in areas underlain by Murihiku Terrane basement are similar to those for areas underlain by Waipapa Terrane. (Barter, 1976; Wise, 1999). Similarly, comparable trends occur within the surface Waitemata Group and Kaawa Group rocks north of Auckland, in the South Auckland area and the Waitakere Group of the Waitakere Ranges west of Auckland (Berry, 1986; Hayward, 1978).

The block faulting pattern in Auckland itself is very poorly defined. Faults almost certainly parallel those north, south and west of the area, but their locations are mostly unknown. Kenny (2007, 2008, 2008a) have maps showing the possible location of some faults, based on height differences on the post Waitemata Group erosional surface, which is virtually the only marker horizon in the area (Figure 23). Eccles (2003) shows the JMA in the area as being separated into 10 subparallel NNW- trending lineaments, which, she suggests, could be repetition due to faulting. Even if such faults formed at an earlier stage, they could have been reactivated as part of the Miocene-Pliocene block faulting.

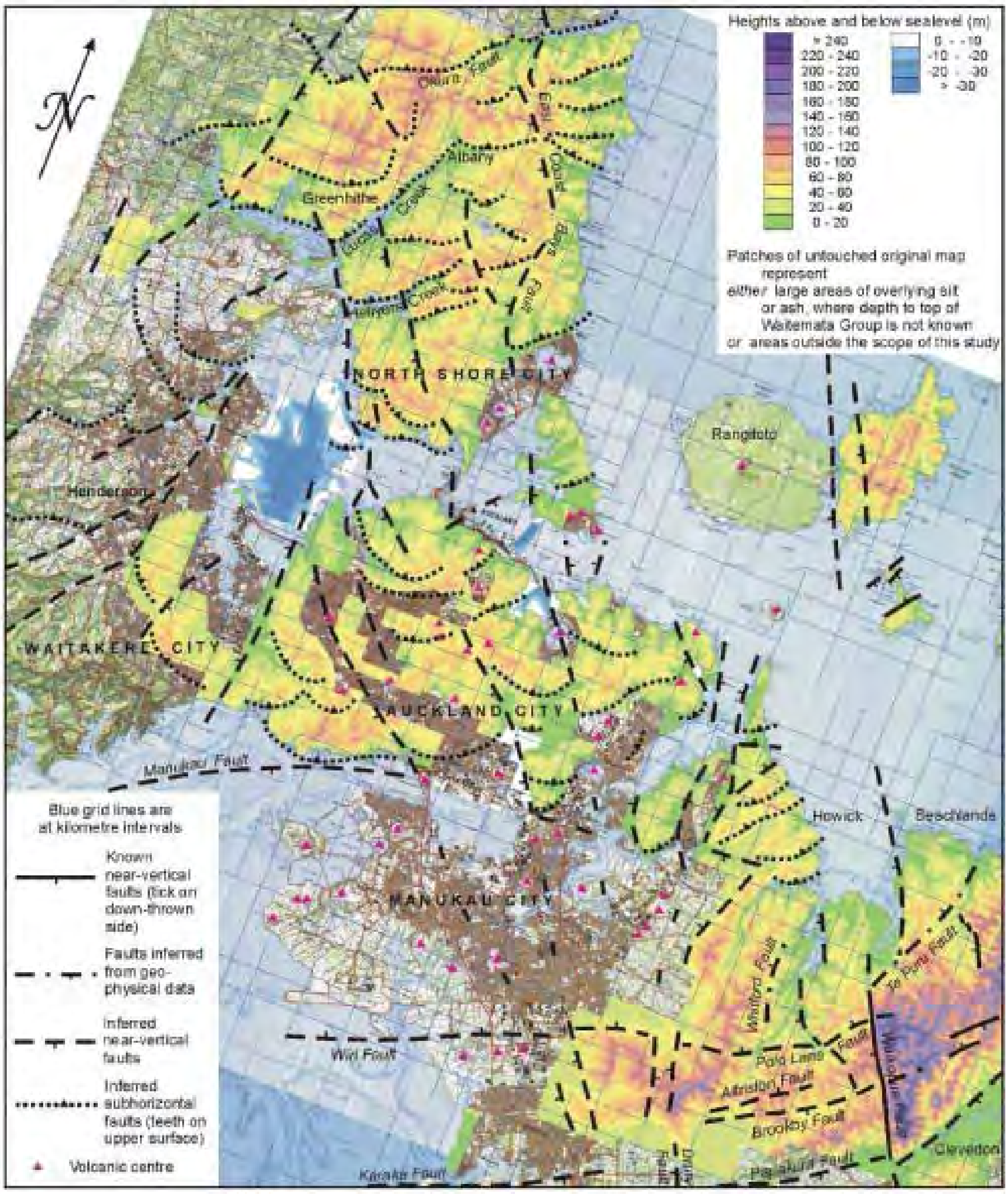


Figure 23. Block faults/ thrusts interpreted from photolineaments and displacement of the post Waitemata Group erosional surface.

(Kenny, 2008)

Very few large faults, though, are actually located with any certainty. This is the most crucial gap in the current understanding of the structural geology of the AVF. These major faults affect all geological layers from the basement to the surface. They are steep and form major structural discontinuities in the crust. They provide an ideal pathway for magmas rising through the crust, and are likely to be a very important factor in the eventual location of a volcanic eruption. In both the South Auckland Volcanic

Field and the Ngatutura Field, further to the south again, vents are often observed to be associated with similar faults (Jukic, 1995; Wise, 1999; Briggs et al., 1990; Briggs et al., 1994).

In contrast, the pattern of faulting is very well known for the area south of Auckland, where many geological and geophysical investigations have helped to define the location of faults and in many cases estimate their vertical throw. (Barter, 1976; Anderson, 1977; Berry, 1986; Ormerod, 1989; Tilsley, 1989; Allen, 1995; Jukic, 1995; Wise, 1999; Hochstein and Nunns, 1976). It is useful to study these patterns. The South Auckland Volcanic Field lies in this area, and provides a very relevant analogue to the nearby AVF.

A brief summary of the characteristics of some of the major faults in the South Auckland volcanic Field is provided below, whilst a more exhaustive summary is provided in the Appendices.

- Gravity surveys in the Manukau Block, from Port Waikato to Manukau Head, indicate that the throw on several faults increases westwards (blocks dip westwards). NNW trending faults tend to be downthrown to the east, with the exception of the Waiuku River Fault. NE trending faults appear to be truncated by NNW trends, and in some instances NNW trending faults appear to act as passive transforms for the extension on the NNE trending faults rather than as active strike slip faults, with Mesozoic structures compatible with dextral strike slip (Berry, 1986).
- There are several prominent faults in the Awhitu area with known throws. The Glenbrook Fault has 200m vertical offset, downthrown to the south; the Waiau Fault has a 130m downthrown vertical offset to the north; the Karaka has an 80m vertical offset, downthrown to the south, and the Wiri Fault has a 120m vertical offset, downthrown to the north. All these faults strike ENE, are tens of kilometres long and are constrained by boreholes. They cut Quaternary deposits. In addition, along the coast there are at least four smaller ENE trending faults with vertical offsets of 10m, 24m, 25m 60m (Barter, 1976).
- Wise (1999) used geophysics to define the fault plane of the Wairau North Fault, and determined that it is a normal fault, with an orientation of NNW/50-70W and a displacement of at least 120m, suggested by borehole data, but Wise

conservatively estimates a total displacement of 140m. Williams (2003) quotes the actual displacement on the fault as 4.7km of vertical movement, downthrown to the west, as defined by gravity surveys. She suggests that Wise's 120m displacement may just represent more recent movement). A fault scarp of 70m is hidden beneath the Happy Valley sediments, which formed in the fault angle depression. The fault is traceable for 24km in three offset (or en echelon) segments, each stepping progressively eastwards moving towards the south. By noting offsets of topographic features and logging of trenched surfaces Wise ascertained that the fault may be considered to be active.

- The Waikato Fault runs ENE/75+/-15N and is a large scale normal fault, with Murihiku basement displaced vertically down at least 2.7km to the north in the west near Port Waikato, the offset decreasing eastwards to 0.7km near Tuakau, where the fault appears to be offset by 2km to the north. The offset could be due to a crosscutting later fault, flexure or en echelon formation. This northern fault trace is aligned with the Pokeno Fault and the two faults possibly merge. The Pokeno fault downthrows southwards, which would indicate a scissor-type fault. Movement on the fault was probably caused by a regional west-southwest tilt of the large block of greywacke, at least 60km wide, pivoting in the region of the western foothills of the Hunua block. It is possible that the Waikato Fault extends to the western edge of the continental shelf (Hochstein and Nunns, 1976).
- The Drury Fault is a NNW trending normal fault, downthrown to the west, with a throw of 2.7km in the south at Ramarama, 0.5km in the middle, west of Ardmore, decreasing to zero north of Alfriston, (Ormerod, 1989).

North of Auckland, faulting is also better defined than for the AVF itself. A major N-S trending normal fault runs between Tiritiri Matangi Island and Whangaparaoa Peninsula, upthrowing basement and Waitemata rocks to 80m above sea level to the east (Spörli and Rowland, 2007). The Silverdale fault is known to downthrow to the north as observed in boreholes and Gregory (1965) interprets it as reaching the coast where it is upthrown to the south by at least 125 ft. The E-W trending Waiwera Fault has an offset of more than 50m as observed in cliff sections, where the offset is more than twice the height of the cliff, and boreholes show the basement stepping down 50m to the north across the fault. Hotspots and geochemical concentration maxima also along trace of fault (Alldred, 1980). The basement also drops 470m to the south across Stingray Bay

Fault, as deduced from boreholes (the north end of Stingray Bay is fault controlled) (Alldred 1980). Daly (1988) described block faulting in the Te Arai-Leigh area. In this area a significant amount of the basement is above sea level but often has Waitemata Group cover. Greywacke is sometimes more than 100m above sea level, and where it is above sea level in the south and east of the area, it is fault controlled.

In the west of the area a normal fault oriented NNW/20-40W drops basement westwards from 200m to 500m below sea level. In the south of the area, an ENE trending normal fault drops basement from 0 to 200m below sea level to the south. In the southeastern part of the area a NE-ENE striking fault drops basement from 100m above sea level to 100m below sea level towards the east. A further fault controlled thickening of up to 300m occurs in the west of the area on a fault that dips 20-40°W. The greywacke surface slopes down to west at 3°, so Waitematas thicken westwards, and published data has greywacke increasing in depth E to W, possibly 4km deep on the west coast (Daly 2008).

In the Hauraki Gulf, the Motutapu Fault cuts right across Motutapu Island. This NNW striking normal fault, which throws down to the west at least 90m affects the greywacke basement but not the overlying Waitemata Group (Milligan, 1977).

A gravity survey indicates a major post Waitemata Group fault some distance west of the Motutapu Fault, named the "Islington Bay Fault " by Milligan (1977). His best-fit model has a vertical, NNW (168-171º) striking fault, downthrow 120m to the west. There is no evidence of the fault on Motutapu Island, and so it probably follows the trend of Islington Bay and passes East of Musick Pt. It may be an extension of the Wairoa North Fault.

There has been some speculation that the Motutapu fault or the Islington Bay Fault could be a northern continuation of the Drury Fault, or that the Drury Fault extends northwards into the central Auckland area (e.g. Kenny, 2008b). However, Anderson, (1977) was unable to define a fault continuing north from the Drury Fault at Ardmore, and concluded that the fault was probably truncated by an E-W trending fault less than 1.5km north of Ardmore. It is unknown whether there is any connection of the Wairoa North Fault and the Islington Bay Fault.

Kenny (2008b) interprets faulting as being responsible for the current shape of the post-Waitemata erosional surface (fig 23), and therefore speculates that faulting and uplift continued into the Pliocene, as suggested by Ballance (1968), and is possibly still occurring, Samsonov and Tiampo (2008) observed areas of relative uplift and subsidence within the AVF using SAR interferometry (fig 24).

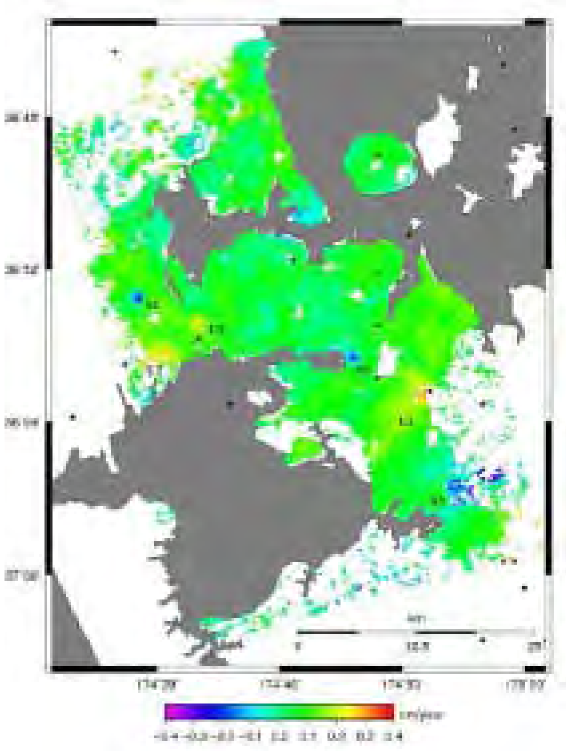
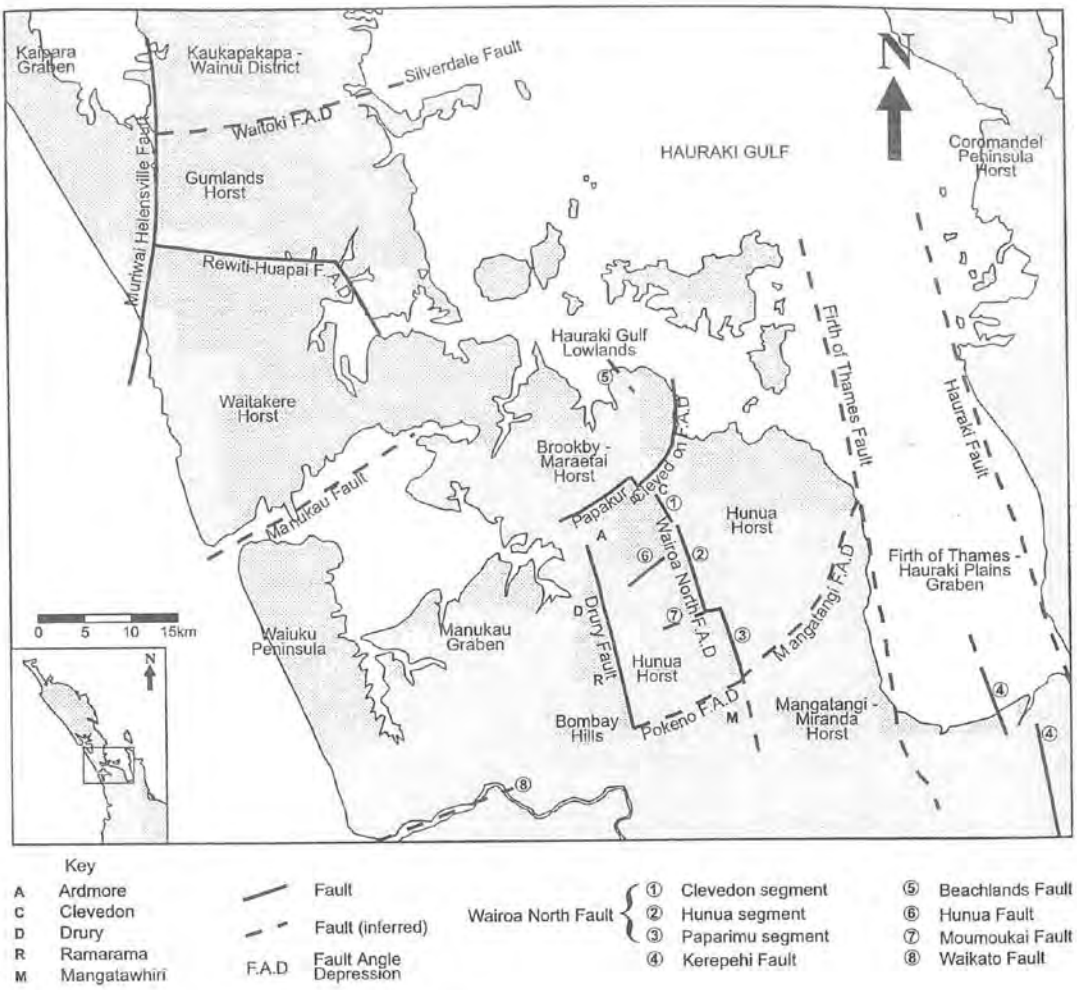


Figure 24. Stack of 117 differential interferograms. Areas of subsidence appear blue, areas of uplift yellow-orange.
(Samsonov and Tiampo, 2008)



A

B

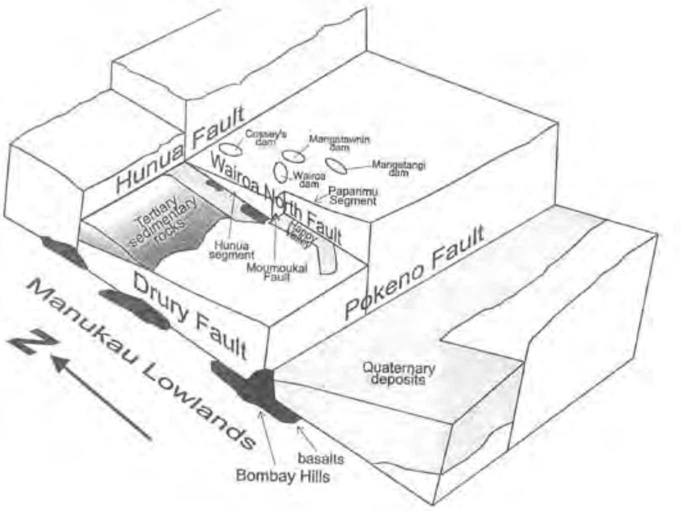


Figure 25A. Block faulting in the Auckland area

Figure 25 B. Block model of the Drury, Wairoa North, Hunua and Pokeno Faults.

(Wise, 1999)

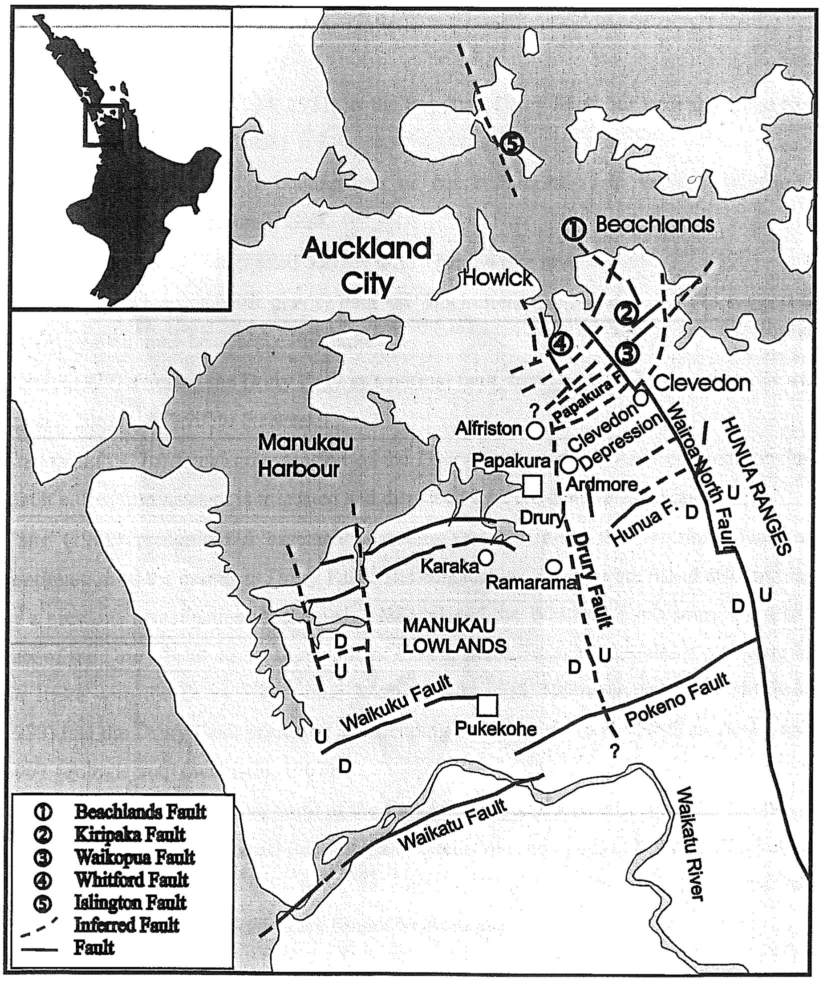
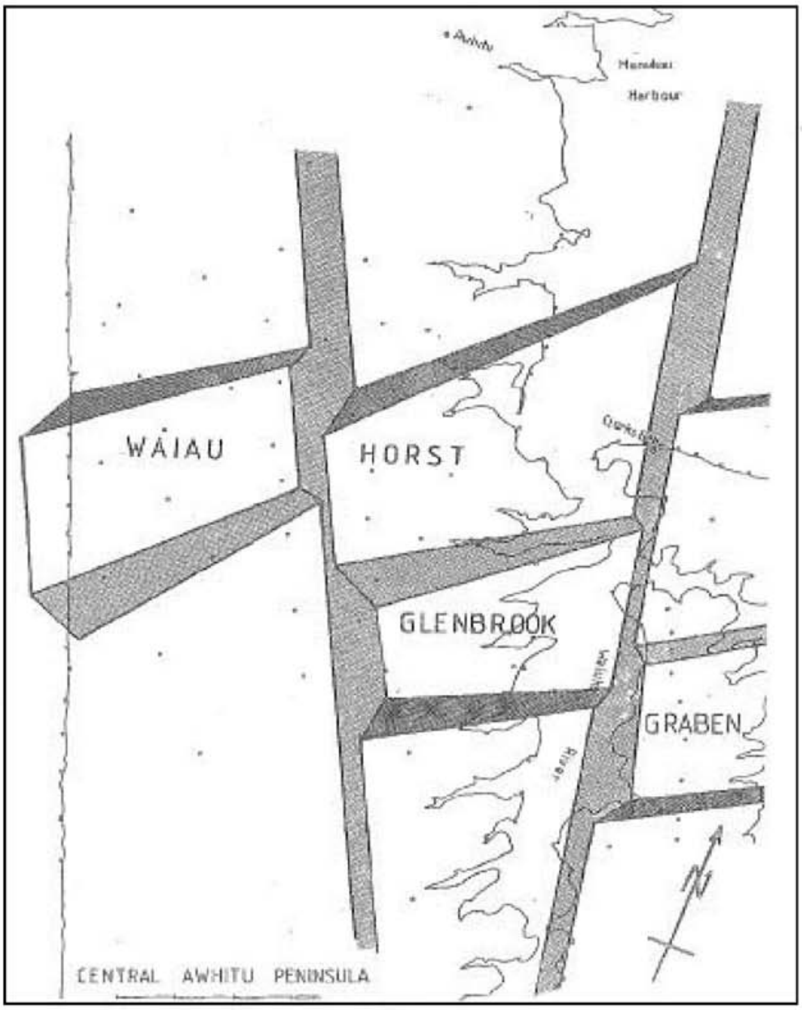
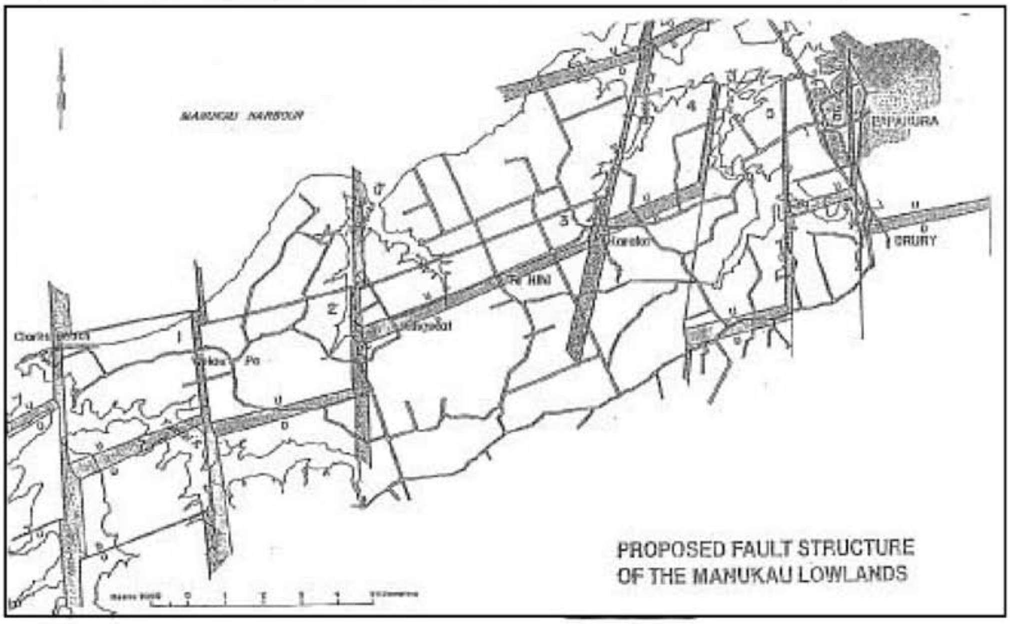


Figure 25C Large scale faults in the South Auckland area. (Wise, 1999)





Figures 25 D from Berry (1986) (top) and 25E Allen (1995) (bottom). 3d block fault models for the South Auckland area.

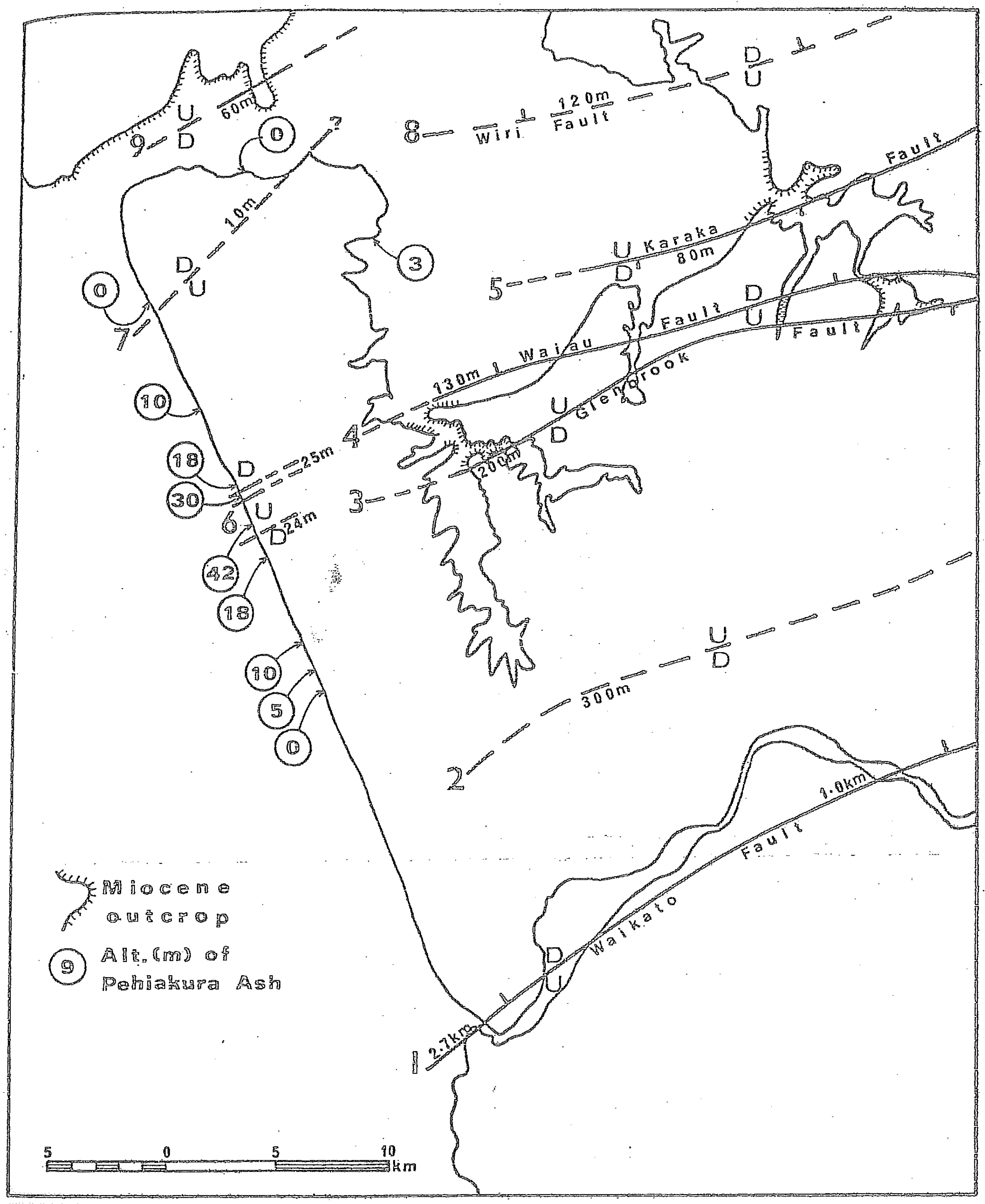


Figure 25 F. Large faults in the Southwest Auckland- Awhitu Peninsula area. (Barter, 1976)

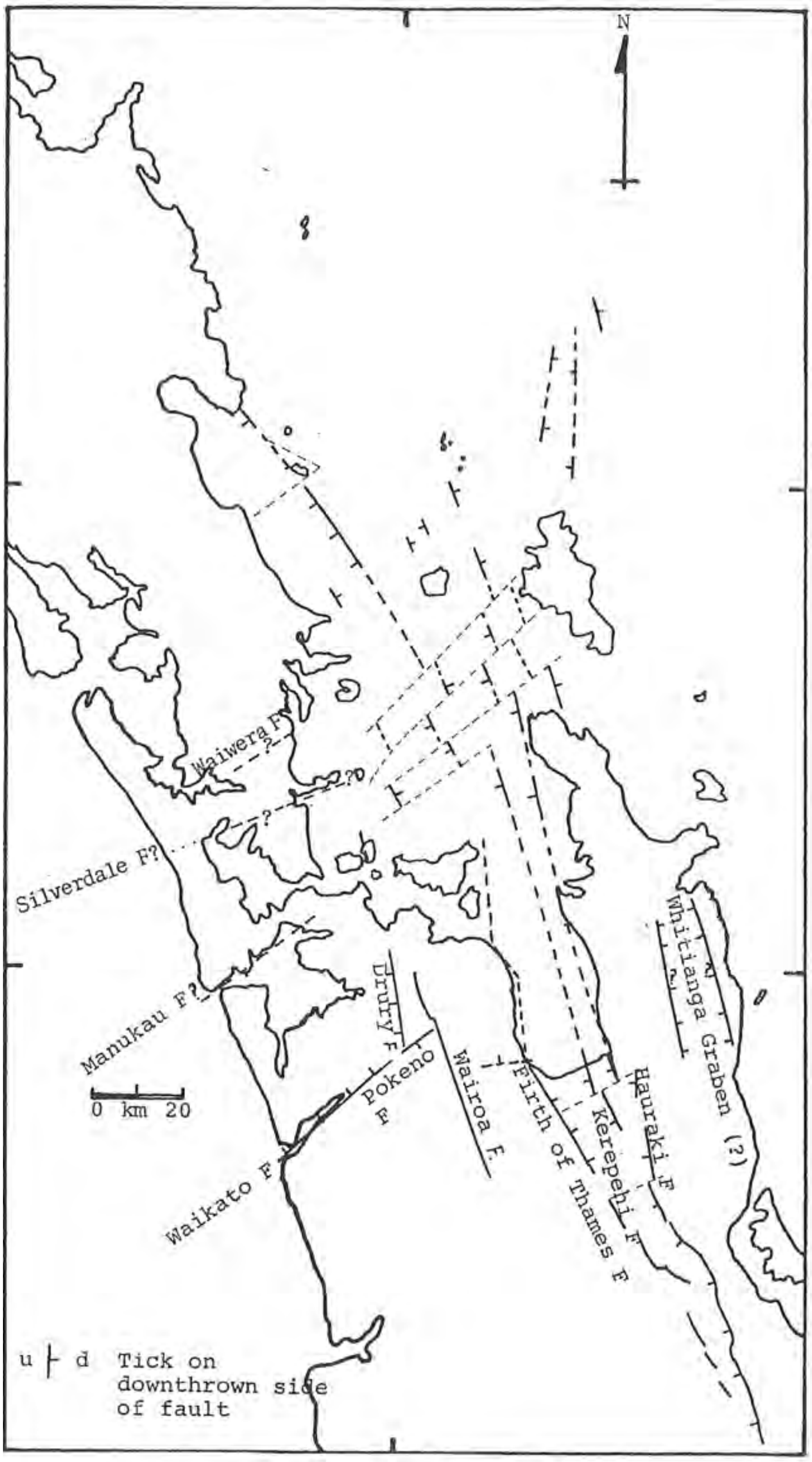


Figure 25G Block faulting in the Hauraki Rift.
(Rawson, 1983)

Active Faulting and Seismicity.

Whilst the Auckland area is generally taken to be tectonically stable, there is evidence that several major faults were active into the Quaternary, some up until very recent times. In the latter case it can be assumed that activity is ongoing (Wise, 1999; Tejaksuma, 1998). There have also been studies into the seismicity of the region (Eiby, 1955, 1964; Backshall, 1982; Sherburn et al., 2007), again confirming present activity.

Active faults include the Port Waikato Fault (Smith, 1981) the Kerepehi Fault (Hochstein et al., 1986; DeLange and Lowe, 1990; Tilsley, 1993), the Beachlands Fault (Tejaksuma, 1998), the Wairoa North Fault (Wise, 1999; Wise et al., 1999) and the Wynyard Fault (Davy, 2008). North of the Papakura Fault a possible fault scarp, which is aligned with Drury Fault, seems to truncate an overlying terrace of recent sediments. This suggests possible ongoing movement on what may be a northern extension of the Drury Fault (Al Salim, 2000).

Tejaksuma deduced a vertical movement rate of 0.827mm/1000years on the Beachlands Fault and an uplift rate of the Beachlands Block of 0.0169mm/yr, which he compares to Port Waikato where the uplift is 0.0554mm/yr. Wise (1999) deduced the movement on the Wairoa North Fault to be 3.2cm/1000yrs and compares it to a rate of 13cm/1000years on the Kerepehi Fault, which lies within the Hauraki Rift.

Davy (2008) identified a NNE-trending fault in the Waitemata Harbour, extending from Wynyard Wharf, where there is a 2m scarp, into middle of Harbour Channel. The fault is upthrown to the west, and is normal, possibly with some dextral strike slip.

Faults that were active into the Quaternary include: the Drury Fault, the Polo Lane Fault, the Brookby Fault, and possibly the Wiri Fault, the Karaka Fault, the Waioa Fault and the Glenbrook Fault, as well as several unnamed basement faults (Tilsley, 1993; Barter, 1977; Wise, 1999; Al Salim, 2000).

A summary of reported earthquakes in the region is presented below:

- Backshall (1982) studied the seismicity of the Hauraki Rift and reported a swarm of earthquakes that occurred 20km north of Thames in August and September 1970. The swarm started with a main shock of M 4.6 on 26 August, a second shock of M3.7 on 12 September, and over the next 42 days there were more than 50 shocks of M3 or less. A second swarm of earthquakes occurred south of Te Aroha in January 1972. The epicentre of the main shock, which occurred on 8

January and had a magnitude of M5.1, was 4km south of Te Aroha. Over the next 33 days there were 213 aftershocks, with the largest (M4.1) occurring 3 minutes after the main shock. Backshall deduced NNW trending modal planes oriented 336/60W and 332/30E. Faulting was normal. All focal depths were 12km or less.

- Eiby reported earthquake swarms near Great Barrier Island in June 1953 and near the Moko Hinaus in June 1957 (Eiby 1955,1964). Eiby (1968) also published historical reports of earthquakes including one in 1891 with magnitude MM 8 and epicentre just offshore off the Waikato River Mouth, which may indicate that the Waikato Fault is still active.
- Of the Seismic activity recorded in the Auckland region between 1960 and 1983, all 51 events were in the Hunua or Coromandel area. (Wise, 1999).
- During 1998 three earthquakes occurred close to Auckland. These were:
    - January 30, 5km east of Papakura, magnitude 2;
    - April 9, 4km south of Clevedon, magnitude1.5;
    - May 16, (?) north of Waiheke, magnitude 2.5 (www.igns.cri.nz);
    - November 30, 2005 six small earthquakes, 3 of which were felt, occurred off Waiheke Island, They all were focussed in the same location, had magnitudes of 2.5-3 and focal depth of approximately 8km.Another earthquake, magnitude 2.4 and 7km deep occurred in the same general area on 14 December, 2005. There is no known fault in the area, (www.igns.cri.nz).
- On February 21, 2007 there were three earthquakes focussed 30km east of Orewa, at depths ranging 7-15km and magnitudes of 4.5, 3.7 and 3.8 Richter. These were in the same area as 2 tiny tremors on 30th January 2007. Modified Mercalli magnitudes of up to V were experienced in the Orewa area, resulting in damage to some buildings (www.igns.cri.nz).
- The most recent earthquakes have been located to the north, just offshore within the Hauraki Gulf (B. Davies, pers. comm.; Sherburn et al., 2007).

DISCUSSION

Tectonic, Structural and Other Influences on Quaternary Volcanism in the AVF.

The exact mechanism for the formation of the AVF is debatable. A hot spot mechanism has been proposed, as has a mechanism involving convection over a subducting slab and another where the AVF is a back arc to the TVZ, but all the above have limitations (Heming, 1980). The Auckland magmas have geochemical signatures that indicate formation in an intraplate setting (e.g. Hodder, 1994). Spörli and Eastwood (1997) suggested a very small upper mantle dome or a lens of asthenospheric material intruding into the neck of an extensional structure, or an area of tensional stress leading to decompressional melting. The tensional field could be caused by a releasing structure during deep strike slip along the Dun Mountain Ophiolite Belt, or may represent the tip of a fracture along which the Auckland field is propagating northwards.

Another possibility is that the asthenospheric upwelling associated with the formation of the Hauraki Rift is still present and affects the flanks of the rift, producing high heatflow as well as uplift (Hodder, 1994; Hochstein and Ballance, 1993). There is evidence in Auckland that uplift may still be occurring- with recent movement on small faults and the presence of several terraces indicating changing sea level in recent times (Tejaksuma, 1998; Kenny 2008). Samsonov (2008) used SAR interferometry to identify three areas of uplift, one of which was coincident with the epicentre of a small earthquake hat was recorded on 15 March, 1995, as well as three areas of subsidence in the greater Auckland area.

Horspool et al. (2006) identified a low velocity zone beneath the Auckland field at a depth of 70-90km. This is inferred to be a zone of partial melting in the upper mantle and possibly the source zone for the AVF magmas. This is compatible with depth calculations using U-Th isotope signatures, which suggest a source that lies at a depth of 80-140km (Huang et al., 1997; Smith et al., 2007). It is possible that this low velocity zone may represent the high heat flow and remnants of asthenospheric upwelling that caused subsidence of the Hauraki Rift and uplift in its flanks.

There is some evidence for influence of rising magma by underlying faults. Vents are sometimes aligned NE-NNE or occasionally NNW, sub-parallel with the structural block faulting trends, and the Hauraki Rift (Searle, 1961; Sibson, 1968; Magill et al., 2005) (fig 26), even where there is no temporal link, indicating that major faults may be present and providing a pathway for rising magmas at various distances along their length. Houghton et al (1999) report that at Crater Hill four simultaneously active vents were aligned along a 600m NE-trending dike, again sub-parallel to the regional structure.

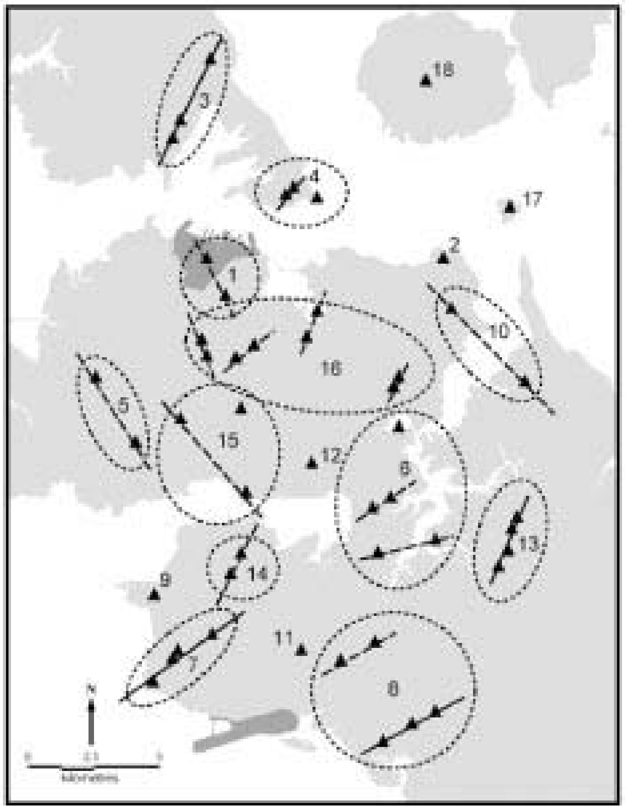


Figure 26. Possible vent alignments within the AVF (Magill, 2005)

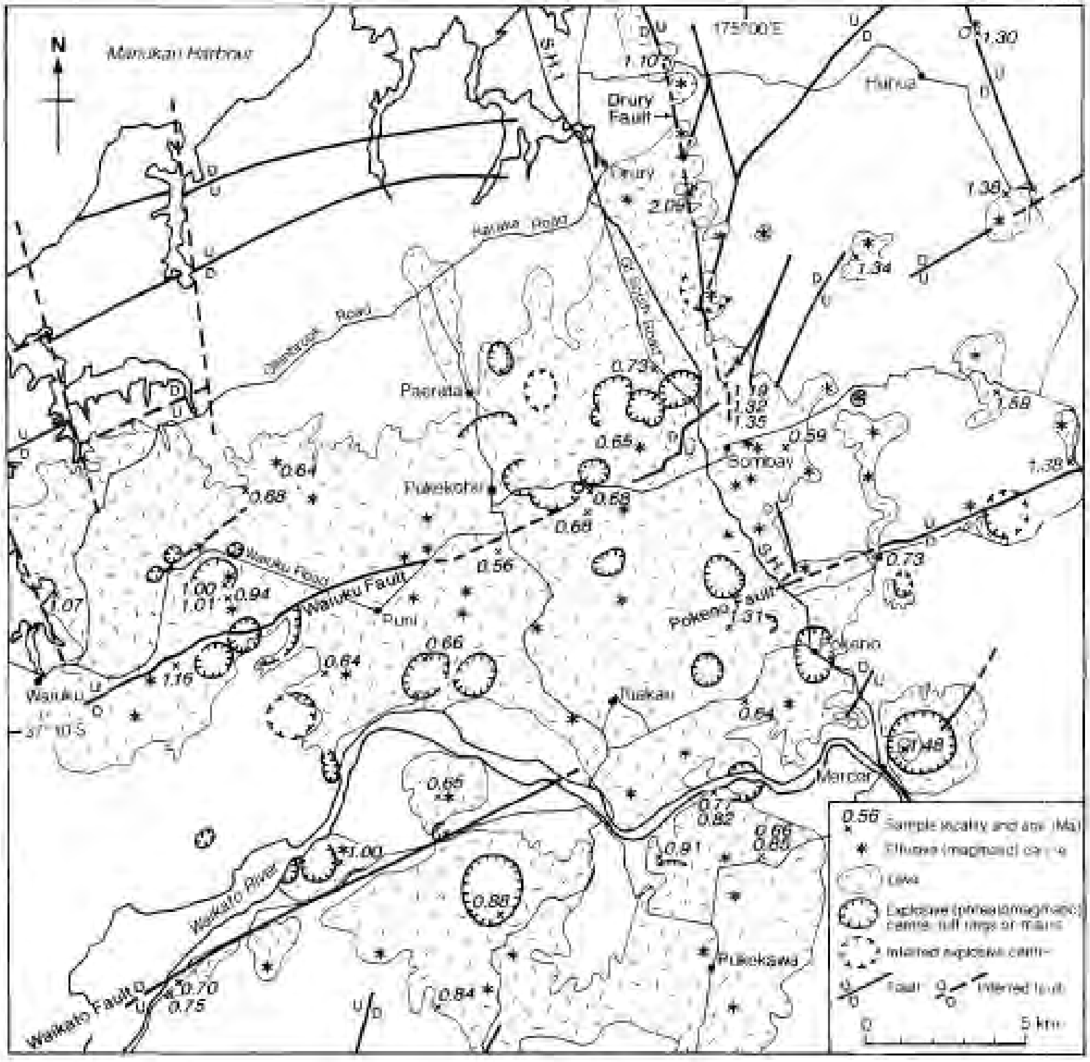


Figure 27 Alignment of vents in the South Auckland Volcanic Field. (Briggs et al., 1994)

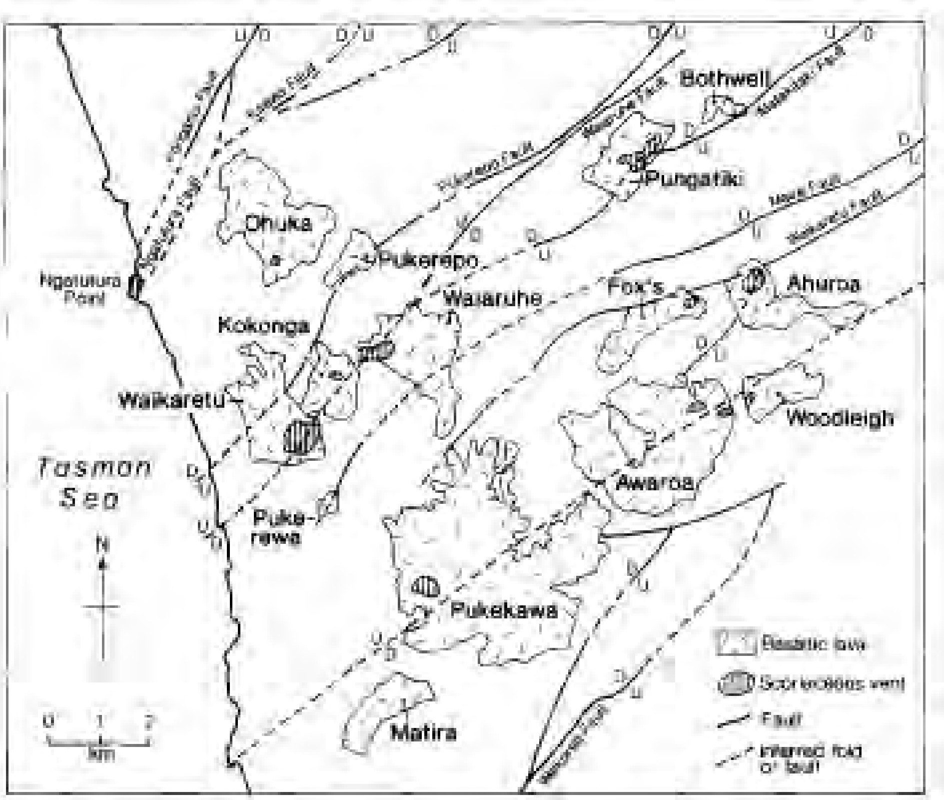


Figure 28. Alignment of vents in the Ngatutura Volcanic Field (Briggs et al., 1990)

This is also compatible with observations in the South Auckland Volcanic Field and the Ngatutura Field, where many vents are aligned on and are seen to have utilised major faults as a route for magma ascent (Jukic, 1995; Briggs et al., 1990; Briggs et al., 1994).

Other authors noted the following patterns of eruption:

Allen (1991) reported that of the 50 volcanoes in the AVF:

- 25 erupted through a country rock of Waitemata group ± alluvium
- 1 (Rangitoto) erupted through Waitemata Group and mudstone/mud
- 3 erupted through Waitemata Group + Kaawa Group
- 18 erupted through Kaawa formation
- Only one (Motukorea) erupted through Greywacke + Waitemata Group
- None erupted into just greywacke.

She also noted a wide variation in height above sea level at the time of eruption. For dated eruptions she notes:

- One Tree Hill, Mt Eden and Three Kings all 115-135m a.s.l.
- 5 dated volcanoes 60-85m a.s.l.
- 6 dated volcanoes 40-55m a.s.l.
- 2 (Motukorea and Rangitoto below sea level (-5 and –14 respectively).

Interestingly, Te Pouhawaiki and Three Kings, both formed on a ridge yet still have some associated phreatomagmatic activity (Affleck et al., 2001)

Figure 29. Location of volcanic centres in the AVF showing symbolic palaeomagnetic directions. Black arrows and triangles denote anomalous downwards inclinations and approximate north-pointing declinations. Volcanoes with these palaeomagnetic signatures, Mt St John, Taylor Hill, Puketutu (4), Crater Hill (5) and Wiri (6), are inferred to have formed during a geomagnetic excursion and may have erupted within a time period of a few hundred years of one another. (Cassidy et al., 2004)

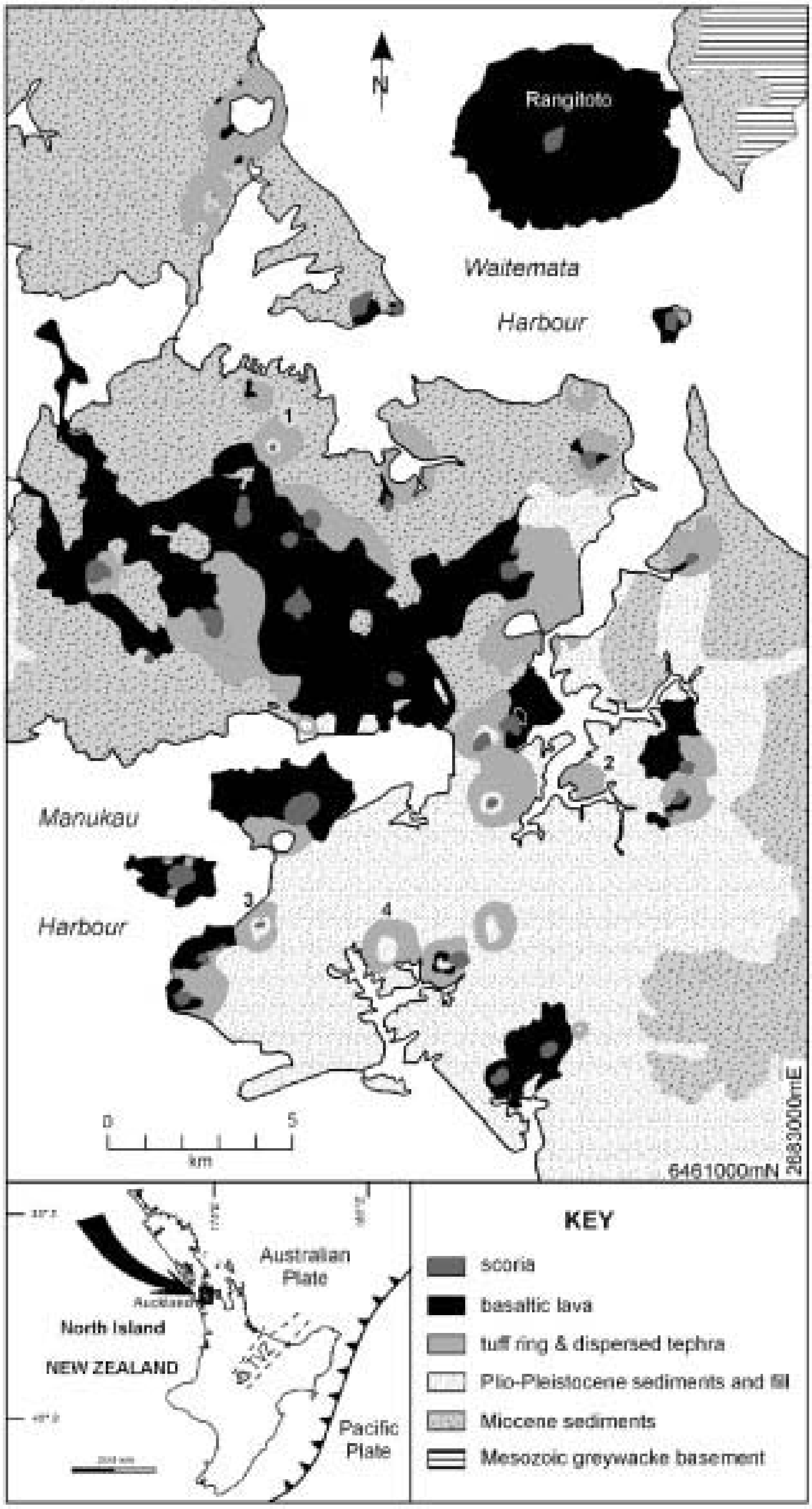


Figure 30. Volcanoes and associated deposits of the Auckland Volcanic Field. Notice NW-NNW and NE alignment of lava flows and parts of the coastline, parallel to large scale block faults. This may imply fault control of palaeovalleys and current coast.

(Cassidy et al., 2007)

Eccles (2003) noted that the large lava flows from Mt Eden and Three Kings follow the NNW trend of the basement structures, including the JMA. (Figure 30, 31). This may mean that the palaeovalleys were structurally controlled, and the site of significant faults, although there is now some question as to whether the lava flow at Meola Reef came from Mount Eden- it may have come from Mt St John (Eade, MSc in prep.). Affleck et al. (2001) and Affleck (1999) used gravity surveys to identify a major steep, sided ridge in the buried Waitemata Group. The steepness of the slopes may indicate a structural influence (and/or deep incision due to rapid uplift.) The ridge represents the divide between the ancestral Waitemata and Manukau Rivers. The NNE and NW trends observed in the buried ridge and a side spur are subparallel to the trends in alignment of volcanic vents, and to regional structural trends.

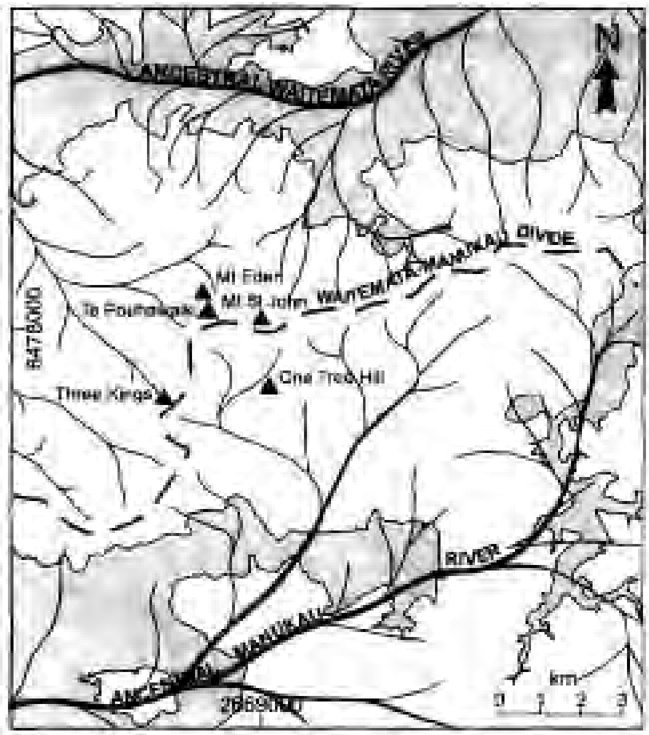


Figure31A. Palaeotopography of the central Auckland area. (Affleck et al., 2001)

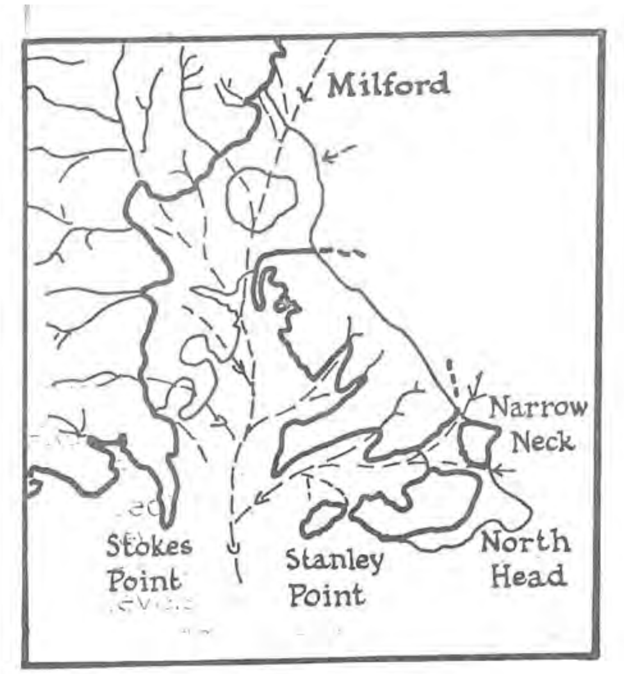


Figure 31B Palaeotopography of Auckland's North Shore.
(Milligan, 1977)

Geographically, Magill et al. (2005) suggested that the eastern greywacke block is the limit of the AVF. Horspool et al. (2006) reported that the zone of partial melting they identified in the mantle beneath the AVF extends 15km north of Auckland, and suggest that volcanism could therefore migrate northwards. Spörli and Eastwood (1997) define an ellipse, which runs through Pupuke and Rangitoto in the north, Pigeon Mountain in the east, Otara Hill and Ash Hill in the southeast and Mount Albert in the west. They interpret this ellipse as delineating the current extent of the AVF, and infer that for a period of time in the future, volcanism can be expected to take place within or on the boundary of the ellipse (fig 32).

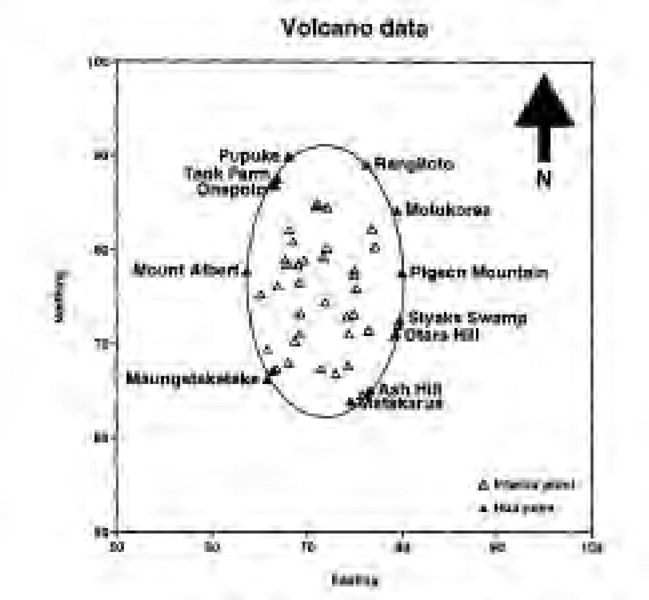


Figure 32. Elliptical boundary of the Auckland Volcanic Field. (Spörli and Eastwood, 1997)

CONCLUSIONS

The structure underlying the Auckland Volcanic Field is very complex and varied, due to the very dynamic history of the region, which continues to this day.

Past events have tended to occur in locations underlain by Waitemata Group rocks (Allen, 1992), but it is unclear whether that is because of processes leading to the partial melting (perhaps the decompressional melting is easier here than in areas overlain by denser greywacke rocks?) or whether it is due to transport processes (perhaps the faults are 'tighter' in the basement rocks?), or possibly a combination of the two.

In terms of structural controls causing channelling of ascending magmas, the most significant features identified are the post Waitemata Group normal faults (Kenny, 2007). These provide significant discontinuities in the crust, and, in the prevailing tensional field (prevailing tension is oriented 335º, which tends to cause a component of dextral strike slip on NNW trending faults, rather than purely normal movement (Hochstein and Ballance, 1993; Wylie, 1989), could provide an easy route for transport of magmas from the basement to the surface.

The exact location of a vent would be due to a combination of these deep faults, local near-surface geology and topography. It should be noted, however, that elevation per. se. does not seem to be a major control on the location of vents. Volcanoes are as likely to form on a ridge as they are in a valley: Some of the largest volcanoes (Mt Eden, Three Kings, One Tree Hill) all formed on a ridge, whilst others were formed on the sea floor (Rangitoto, Motukorea) (Allen, 1992).

In the event of an impending volcanic eruption, it would be impossible to predict exactly where the magma would finally break surface, even if the subsurface geology were well known. The location of precursory earthquakes could be traced, but it would not be clear exactly which route the magma would carry on to follow. Best estimates would probably be difficult until the magma was within a few hundred metres of the surface (Blake et al., 2006). As it is, estimating the location of an eruption is even more difficult.

Suggested Further Work.

The single most crucial gap in the knowledge of the structure of the AVF is the location of major block faults. Very few large faults, though, are actually located with any certainty. These major faults are important in several ways:

- They affect all geological layers from the basement (at least) to the surface.
- They are steep and form major structural discontinuities in the crust.
- They provide an ideal pathway for magmas rising through the crust,
- They are likely to be a very important factor in the eventual location of a volcanic eruption.
- In both the South Auckland Volcanic Field and the Ngatutura Field, further to the south again, vents are often observed to be associated with similar faults (Jukic, 1995; Wise, 1999; Briggs et al., 1990; Briggs et al., 1994).

Kenny (2007, 2008, 2008a) has begun to address this using the Waitemata Group erosional surface as a marker horizon, but more work is needed. Unfortunately geophysical measurements are affected by ash from the AVF, the shallowness of the Waitemata and Manukau Harbours and the background noise of the city (Kenny, 2008, Davy, 2008). Nonetheless, delineating these structures should be a priority.

Other areas that could be addressed include:

- Structural studies on individual centres could be illuminating- especially where alignment of vents, possibly representing localised dykes, within a centre can be identified (Houghton et al., 1999).
- Further work on alignment of separate centres to ascertain whether the alignments reflect regional structures: do they reflect dykes, and what length of a regional fault may open out as a dyke (Magill et al., 2005)?
- Temporal connections between adjacent volcanoes: can these be identified, and, if so, is there a clear structural link (Rout et al., 1993)?
- Identification of any structural link between the several eruptions that occurred in different parts of the field ca. 30Ma, or any significant tectonic event that may have caused them (Cassidy, 2006).
- In contrast, is there a tectonic event that caused Rangitoto to pour out large quantities of magma in basically the same spot, over a period of 950 years (Robertson, 1986)? What are the tectonic differences causing this contrast?

- More marine seismics may help delineate regional structures in the offshore AVF. Is it possible to define more detail in the Waitemata Harbour? The Manukau Harbour? The area between Rangitoto/ Motutapu and St. Heliers/ Musick Point/ Beachlands (Davy, 2008)?
- Can heat flow studies help identify structures? The Waiwera Fault is the locus of high heat flow and maxima of geochemical concentrations, (Alldred, 1980) as are faults in the Hauraki Rift (Hochstein and Nixon, 1979). Is anything akin to this present within the AVF?
- Analogue or numerical modelling of the field, or parts thereof. Other techniques (e.g. Samsonov et al., 2008)?

REFERENCES

Affleck, D. K. (1999). A geophysical delineation of basaltic flows and tuffs in the central Auckland isthmus., University of Auckland. **MSc**.

Affleck, D. K. (2002). A three-dimensional gravity survey of the pre-volcanic topography in Epsom, Auckland. 5th Australia-New Zealand young geotechnical professionals conference., Rotorua, New Zealand, New Zealand Geotechnical Society.

Affleck, D. K., J. Cassidy, et al. (2001). "Te Pouhawaiki Volcano and pre-volcanic topography in central Auckland: volcanological and hydrogeological implications." New Zealand Journal of Geology & Geophysics **44**: 313-321.

Alldred, H. B. (1980). Sedimentology and structure of the Waitemata Group Wenderholm-Orewa section, North Auckland, University of Auckland. **BSc (hons)**.

Allen, J. R. (1995). A geological model of the Northern Manakau lowlands, New Zealand, University of Auckland. **MSc**.

Allen, S. R. (1992). Volcanic hazards in the Auckland volcanic field. Auckland, University of Auckland. **MSc:** 153.

Allen, S. R. (2004). "The Parnell Grit beds revisited: are they all the products of sector collapse of western subaerial volcanoes of the Northland Volcanic Arc?" New Zealand Journal of Geology & Geophysics **47**: 509-524.

Al-Salim, M. A. (2000). A geophysical and geological investigation of the Drury Fault and related block faulting, Southeast Auckland, University of Auckland. **MSc**.

Anderson, H. J. (1977). gravity survey of north-west Manukau City, Auckland, University of Auckland. **BSc (hons)**.

Ashcroft, J. (1983). "The Kerikerei Volcanics: A basalt-Pantellerite Association in Northland." Royal Society of New Zealand **23**: 48-63.

Backshall, D. T. (1982). A microearthquake study of the Hauraki Depression., University of Auckland. **MSc**.

Ballance, P. F. (1964). "The Sedimentology of the Waitemata Group in the Takapuna Section, Auckland." New Zealand Journal of Geology & Geophysics **7**: 466-499.

Ballance, P. F. (1974). "An inter-arc flysch basin in Northern New Zealand: Waitemata Group (Upper Oligocene to Lower Miocene)." Journal of Geology **82**: 439-471.

Ballance, P. F. (1976). "Evolution of the Upper Cenozoic Magmatic Arc and Plate Boundary in Northern New Zealand." Earth and Planetary Science Letters **28**: 356-370.

Ballance, P. F. (1976). "Stratigraphy and Bibliography of the Waitemata Group of Auckland, New Zealand." New Zealand Journal of Geology and Geophysics **19**(6): 897-932.

Ballance, P. F. (1995). "Neogene Sandstone Provenance, North Island, and its Tectonic Significance." Geological Society NZ Miscellaneous Publication **81A**: 74.

Ballance, P. F. and J. R. Pettinga (1982). "A model of the Cenozoic evolution of northern New Zealand and adjacent areas of the Southwest Pacific." Tectonophysics **87**: 37-48.

Ballance, P. F. and K. B. Spörli (1979). "Northland Allochthon." Journal of Royal Society of New Zealand **9**(2): 259-275.

Barter, T. P. (1976). The Kaihu group (Plio-Quaternary) of the Awhitu Peninsula, South-West Auckland. , University of Auckland. **PhD**.

Berry, K. A. (1986). Stratigraphic, structural and geophysical studies of Neogene sediments of the Manukau lowlands., University of Auckland. **MSc**.

Black, P. M., R. M. Briggs, et al. (1992). "K-Ar age data and geochemistry of the Kiwitahi Volcanics, western Hauraki Rift, North Island, New Zealand." New Zealand Journal of Geology & Geophysics **35**: 403-413.

Blake, S., C. J. N. Wilson, et al. (2006). Lead times and precursors of eruptions in the Auckland Volcanic Field, New Zealand: Indications from historical analogues and theoretical modelling. GNS Science Report**:** 22.

Boedihardi, R. M. (1990). Structural, resistivity and temperature surveys of basement fracture zones in the greater Whitford area (South Auckland). , University of Auckland. **MSc**.

Briggs, R. M., T. Okada, et al. (1994). "K-Ar ages, paleomagnetism, and geochemistry of the South Auckland volcanic field, North Island, New Zealand." New Zealand Journal of Geology & Geophysics **37**: 143-153.

Briggs, R. M., A. J. Utting, et al. (1990). "The origin of alkaline magmas in an intraplate setting near a subduction zone: the Ngatutura Basalts, North Island, New Zealand." Journal of Volcanology and Geothermal Research **40**: 55-70.

Brothers, R. N. (1948). Geology of the NW portion of Waitemata County, Auckland, University of Auckland. **MSc**.

Brothers, R. N. (1954). "The Relationship of Waitemata Formation and the Manukau Breccia, Auckland, New Zealand." Transactions of the Royal Society of New Zealand **81**: 521-538.

Brothers, R. N. and M. Delaloye (1982). "Obducted ophiolites of North Island, New Zealand: origin, age, emplacement and tectonic implications of Tertiary and Quaternary Volcanicity." New Zealand Journal of Geology & Geophysics **25**: 257-274.

Brown, D. A. (1937). Geology of the Clevedon area, Auckland, University of Auckland. **MSc**.

Bryner, V. (1991). Motukorea: the evolution of an eruption centre in the Auckland Volcanic Field. Auckland, The University of Auckland. **MSc:** 126.

Carter, L. (1971). "Stratigraphy and Sedimentology of the Waitemata Group, Puketotara Peninsula, Northland." New Zealand Journal of Geology & Geophysics **14**(1): 169-191.

Cassidy, J. (2006). "Geomagnetic excursion captured by multiple volcanoes in a monogenetic field." Geophysical Research Letters **33**(L21310): 1-5.

Cassidy, J., S. J. France, et al. (2007). "Gravity and magnetic investigation of maar volcanoes, Auckland volcanic field, New Zealand." Journal of Volcanology and Geothermal Research **159**: 153-163.

Cassidy, J. and C. Locke (2004). "Temporally linked volcanic centres in the Auckland Volcanic Field." New Zealand Journal of Geology & Geophysics **47**: 287-290.

Cassidy, J. and C. A. Locke (2002). "Geophysical data from the Auckland Volcanic Field: structural and temporal implications." Eos Transactions AGU **83**(22 (Supplement)): WP124.

Cassidy, J., C. A. Locke, et al. (1999). "The Auckland Volcanic Field, New Zealand: geophysical evidence for its eruption history." Geological Society, London, Special Publications **161**: 1-10.

Christey, G. R. (1986). Structure and setting of a synsedimentary slide at Little Manly, Whangaparoa Peninsula, New Zealand. , University of Auckland. **MSc**.

Clark, L. N. (1959). Stratigraphy of the Mesozoic rocks of the Hautura area, SW Auckland. , University of Auckland. **MSc**.

Clark, R. H. (1948). The evolution of drainage of the area between the South Kaipara and Waitemata Harbours. , University of Auckland. **MSc**.

Codling, A. P. (1970). Waitemata rocks of Hobson Bay-Mission Bay area, Auckland, University of Auckland. **BSc (hons)**.

Cole, J. W. (1986). "Distibution and tectonic setting of Late Cenozoic Volcanism in New Zealand." Bulletin of the Royal Society of New Zealand **23**: 7-20.

Cong, S. (1992). Engineering geology of Rhyolitic silts in the Upper Waitemata Harbour, Auckland, NZ. , University of Auckland. **MSc**.

Cook, C., R. M. Briggs, et al. (2005). "Petrology and Geochemistry of Intraplate Basalts in the South Auckland Volcanic Field, New Zealand: Evidence for Two Coeval Magma Suites from Distinct Sources." Journal of Petrology **46**(3): 473-503.

Daly, M. (1988). A Regional Geophysical Study of part of the Waitemata Sedimentary Basin and basement structure, Pakiri, Northland, University of Auckland. **MSc**.

Davey, F. J. (1974). "Magnetic Anomalies off the West Coast of Northland, New Zealand." Journal of The Royal Society of New Zealand **4**(2): 203-216.

Davidge, S. C. (1982). A geophysical study of the South Hauraki lowlands, University of Auckland. **MSc (hons)**.

Davidson, K. J. (1990). Sedimentology, structure and petrology of the Waitemata Group. Upper Waitemata Harbour, Auckland, University of Auckland. **MSc (hons)**.

Davy, B. Marine seismic surveying of the Auckland Volcanic Field Proposal.

Eccles, J. D. (2003). Structural and Tectonic implications of the JMA in the Auckland area, University of Auckland. **MSc**.

Eccles, J. D., J. Cassidy, et al. (2002). The Junction magnetic anomaly in the Auckland region. Geological Society of New Zealand annual conference, Northland 2002 Whangarei New Zealand, Geological Society of New Zealand

Eccles, J. D., J. Cassidy, et al. (2005). "Aeromagnetic imaging of the Dun Mountain Ophiolite Belt in New Zealand: insight into the fine structure of a major SW Pacific terrane suture. ." Journal of the Geological Society of London **162**: 723-735.

Edbrooke, S. W., E. M. Crouch, et al. (1998). "Late Eocene-Oligocene Te Kuiti Group at Mount Roskill, Auckland, New Zealand." New Zealand Journal of Geology & Geophysics **41**: 85-93.

Edbrooke, S. W., C. Mazengarb, et al. (2003). "Geology and geological hazards of the Auckland urban area, New Zealand." Quaternary International **103**(1): 3-21.

Edbrooke, S. W., R. Sykes, et al. (1994). Geology of the Waikato Coal Measures, New Zealand. Institute of Geological and Nuclear Sciences monograph, Institute of Geological and Nuclear Sciences. **6:** 53-101.

Eiby, G. A. (1955). "The Seismicity of Auckland City and Northland." New Zealand Journal of Science and Technology **B36**: 488-494.

Eiby, G. A. (1964). "The Northland Earthquakes of 1963 November-December and the Seismicity of Northland." New Zealand Journal of Geology & Geophysics **7**: 745-765.

Ferguson, S. R. (1974). The velocity structure of the seabed between Leigh and the Moko Hinau Islands, University of Auckland. **MSc**.

Ferguson, S. R., M. P. Hochstein, et al. (1980). "Seismic refraction studies in the northern Hauraki Gulf, New Zealand." New Zealand Journal of Geology & Geophysics **23**(1): 17-25.

Firth, C. W. (1928). Geology of the NW portion of the Manukau County, University of Auckland. **MSc**.

France, S. F. (2003). Geophysical and Petrological Study of the Domain and Pukekiwiriki Volcanoes, Auckland. MSc Thesis, University of Auckland.

Franklin, J. (1999). "Little Rangitoto Volcano." Historical Studies Group, Geological Society of New Zealand Newsletter **18**: 13-18.

Geelen, J. N. (1973). The stratigraphy of the north Manukau Harbour coastline, University of Auckland. **MSc**.

George, A. K. (1993). The engineering geology, with aspects of sedimentology of the Southern Waitakere Ranges, New Zealand., University of Auckland. **MSc**.

Glading, A. V. (1987). Aspects of the engineering and Quaternary geology, Whitford-Brookby-Beachlands, Auckland, University of Auckland. **MSc (hons)**.

Gregory, M. R. (1966). Rocks of the Waitemata group, Whangaparoa Peninsula, Northland., University of Auckland. **MSc**.

Gregory, M. R. (1969). "Sedimentary Features and Penecontemporaneous slumping in the Waitemata Group, Whangaparaoa Peninsula, North Auckland, New Zealand." New Zealand Journal of Geology & Geophysics **12**(1): 248-282.

Greig, D. A. (1992). Sediments and recent geological history of the Hauraki Gulf, Firth of Thames and Colville Channel, North Island, New Zealand. , University of Auckland. **MSc**.

Halcrow-Nicholson, H. (2003). The New Zealand Greywackes. A Study of associated geological concepts., University of Auckland. **PhD**.

Hasibuan, F. (1980). The Mesozoic sequence in the Waikawau area, Southwest Auckland, New Zealand, University of Auckland. **MSc**.

Hatherton, T. and R. H. Sibson (1970). "Junction Magnetic Anomaly North of Waikato River." New Zealand Journal of Geology & Geophysics **13**(3): 655-662.

Hayward, B. (1975). Lower Miocene geology of the Waitakere Hills, West Auckland, with emphasis on the paleontology. , University of Auckland. **PhD**.

Hayward, B. (1993). The tempestuous 10 million year life of a double arc and intra-arc basin--New Zealand's Northland Basin in the Early Miocene. South Pacific Sedimentary Basins, Sedimentary Basins of the World. P. F. Ballance. New York, Elsevier. **2:** 113-142.

Hayward, B. (2004). "Foraminifera-based estimates of palaeobathymetry using modern Analogue Technique, and the subsidence history of the early Miocene Waitemata Basin." New Zealand Journal of Geology & Geophysics **35**: 223-242.

Hayward, B. W. and F. J. Brook (1984). "Lithostratigraphy of the basal Waitemata Group, Kawau Subgroup (new), Auckland, New Zealand." New Zealand Journal of Geology & Geophysics **27**: 101-123.

Hayward, B. W. and D. Smale (1992). "Heavy minerals and the provenance history of Waitemata Basin sediments (early Miocene, Northland, New Zealand)." New Zealand Journal of Geology & Geophysics **35**: 223-242.

Heming, R. F. and P. R. Barnet (1983). "The Petrology and Petrochemistry of the Auckland Volcanic Field. ." Royal Society of New Zealand **23**: 64-75.

Herzer, R. H. (1995). "Seismic stratigraphy of a buried volcanic arc, Northland, New Zealand and implications for Neogene subduction." Marine and Petroleum Geology **12**(5): 511-531.

Hochstein, M. P. and P. F. Ballance (1993). Hauraki Rift: A young active intra-continental rift in a Back-Arc Setting. South Pacific Sedimentary Basins, Sedimentary Basins of the World. P. F. Ballance. New York, Elsevier. **2:** 295-305.

Hochstein, M. P., J. A. Milligan, et al. (1980). Geophysical structure of Rangitoto Volcano. 1st New Zealand geophysics colloquium. Wellington NZL New Zealand, Wellington, New Zealand, Victoria Univ. at Wellington, Inst. Geophys.

Hochstein, M. P. and I. M. Nixon (1979). "Geophysical study of the Hauraki Depression, North Island, New Zealand." New Zealand Journal of Geology & Geophysics **22**(1): 1-19.

Hochstein, M. P. and A. G. Nunns (1976). "Gravity Measurements across the Waikato Fault, North Island, New Zealand." New Zealand Journal of Geology & Geophysics **19**(3): 347-358.

Hodder, A. P. W. (1984). "Late Cenozoic Rift Development and Intra-Plate Volcanism in Northern New Zealand inferred from Geochemical Discrimination Diagrams." Tectonophysics **101**: 293-318.

Hoernle, K., White J. D. L., et al. (2006). "Cenozoic intraplate volcanism on New Zealand: Upwelling induced by lithospheric removal." Earth and Planetary Science Letters **248**: 350-367.

Hookway, M. (2000). The Geochemistry of Rangitoto. Department of Geology. unpublished BSc (hons) thesis, University of Auckland.

Horspool, N. A., M. K. Savage, et al. (2006). "Implications for intraplate volcanism and back-arc deformation in northwestern New Zealand, from joint inversion of receiver functions and surface waves." Geophysical Journal International **166**: 1466-1483.

Houghton, B. F., C. J. N. Wilson, et al. (1996). "Mixed deposits of complex magmatic and phreatomagmatic volcanism: an example from Crater Hill, Auckland, New Zealand." Bulletin of Volcanology **58**: 59-66.

Houghton, B. F., C. J. N. Wilson, et al. (1999). "Shallow-seated controls on styles of explosive basaltic volcanism: a case study from New Zealand." Journal of Volcanology and Geothermal Research **91**(1): 97-120.

Hunt, T. (1978). "Stokes Magnetic Anomaly System." New Zealand Journal of Geology & Geophysics **21**(5): 595-606.

Isaac, M. J., R. J. Herzer, et al. (1994). Cretaceous and Cenozoic sedimentary basins of Northland, New Zealand. Lower Hutt, GNS, Gracefield Research Center.

Johnston, G. I. (1999). Geophysical and structural aspects of the Albany Conglomerate, North Auckland, New Zealand, University of Auckland. **MSc**.

Jones, J. (2007). The Amphibolite Xenoliths of St Heliers: Auckland, New Zealand, University of Auckland. **BSc (hons)**.

Juggernaut, L. S. (2008). Paleolimnology of an Auckland maar crater paleolake Hopua Maar (Gloucester Park), Onehunga Auckland, University of Auckland. **MSc**.

Jugum, D. (2002). The geology of the Hoteo Beds, Waitemata Group, North Auckland, University of Auckland. **MSc**.

Jukic, M. F. (1995). A geological investigation and geophysical subsurface investigation of the South Auckland Volcanic Field, University of Auckland. **MSc**.

Kamp, P. J. J. (1986). "The mid-Cenozoic Challenger Rift System of western New Zealand and its implications for the age of Alpine fault inception." Geological Society of America Bulletin **97**: 255-281.

Kandharrosa, W. (1989). Sedimentology-stratigraphy of the Te Akatea formation, Port Waikato to Raglan district, South Auckland, New Zealand, University of Auckland. **MSc**.

Kear, D. (1959). "Rock Units." New Zealand Journal of Geology & Geophysics **2**: 689-717.

Kear, D. (2004). "Reassessment of Neogene tectonism and volcanism in North Island, New Zealand." New Zealand Journal of Geology & Geophysics **47**: 361-374.

Kear, D. and J. C. Schofield (1978). "Geology of the Ngaruawahia Subdivision." New Zealand Geological Survey Bulletin **88**: 131-138.

Kenny, J. (2008). "JAFfa--Just Another Fault for Auckland." Geological Society NZ Newsletter **145**: 3-11.

Kenny, J. (2008). "Northland Allochthon-related slope failures within the Waitemata Group." Geocene **March 2008**(3): 5-7.

Laird, M. G. (1962). Geology of the Whatawhata district, Auckland, University of Auckland. **MSc**.

Laws, C. R. (1924). The geology of the Papakura-Hunua district, University of Auckland. **MSc**.

Lentfer, K. (2007). Engineering geology of the Northland Allochthon, Silverdale, North Auckland, New Zealand, University of Auckland. **MSc**.

Lipman, M. (1993). Engineering geology and hydrogeology of the proposed Campbell Road Dam Site, North Auckland, University of Auckland. **MSc**.

Locke, C., J. Cassidy, et al. (2007). Auckland Volcanic Field, New Zealand: Geophysical characteristics and regional structure. IAVCEI IUGG XXIV General Assembly, Perugia, Italy.

Magill, C. R., K. J. McAneney, et al. (2005). "Probabilistic Assessment of Vent Locations for the Next Auckland Volcanic Field Event." Mathematical Geology **37**(3): 227-242.

Malpas, J., K. B. Spörli, et al. (1991). "Northland ophiolite, New Zealand, and implications for plate-tectonic evolution of the southwest Pacific." Geology **20**: 149-152.

Manning, P. A. (1983). Engineering geology of a section along the northern coast of the Manukau Harbour, Auckland, University of Auckland. **MSc**.

Mayer, W. (1965). The geology of the islands of Motutapu, Rakino and the Noisies group in the Hauraki Gulf near Auckland, University of Auckland. **MSc**.

McManus, D. A. (1981). Aspects of the engineering geology including mass movement of the Albany Basin and Paremoremo area, University of Auckland. **MSc**.

Miller, C. (1996). Geophysical and geochemical characteristics of the Auckland Volcanic Field. Auckland, The University of Auckland. **MSc**.

Milligan, J. A. (1977). A geophysical study of Rangitoto volcano. Auckland, The University of Auckland **MSc**.

Molloy, C. (2008). Tephrostratigraphy of the Auckland Maar Craters, University of Auckland. **MSc**.

Moore, C. L. (1989). Rhyolytic tephra in the Auckland Region, University of Auckland. **BSc (hons)**.

Morris, J. C. (1983). The structural geology of the Waitemata Group at Musick Point, Auckland, NZ, University of Auckland. **MSc**.

Namjou, P. (1997). Hydrogeological evaluation of proposed landfill sites in the greater Auckland area (N.Z.) : Mt Wellington and Peach Hill valley, University of Auckland. **PhD**.

Nelson, C. S. (1973). Stratigraphy and sedimentology of the Te Kuiti group in Waitomo County, South Auckland. Geology Department. Auckland, University of Auckland **Doctor of Philosophy in Geology:** 877.

Nelson, C. S. (1978). "Stratigraphy and paleontology of the Oligocene Te Kuiti Group, Waitomo County, South Auckland, New Zealand." New Zealand Journal of Geology & Geophysics **21**(5): 553-594.

Nelson, C. S. and T. M. Hume (1987). "Paleoenvironmental controls on mineral assemblages in a shelf sequence: Te Kuiti Group, South Auckland, New Zealand." New Zealand Journal of Geology & Geophysics **30**: 343-362.

Newson, A. M. (2003). Alteration and landslides on the Paeroa fault at Te Kopia, TVZ, New Zealand, University of Auckland. **MSc**.

Nowak, J. F. (1995). Lava flow structures of a basalt volcano, Rangitoto Island, Auckland, New Zealand. Auckland, The University of Auckland. **MSc**.

Nunns, A. G. (1975). A geophysical investigation of Auckland explosive craters. Auckland, The University of Auckland. **BSc (Hons)**.

Ormerod, M. P. (1989). A geophyscial study of basement structure in South Auckland, University of Auckland. **MSc**.

Patel, J. (1997). Engineering geology of coastal cliff stability along the northern Manukau Harbour, University of Auckland. **MSc**.

Patterson, R. (2002). Engineering Geology and coastal cliff erosion of Takapuna University of Auckland. **MSc**.

Pohlen, I. J. (1934). Geology of the middle portion of the Waitemata County, University of Auckland. **MSc**.

Rait, G., F. Chanier, et al. (1991). "Landward- and seaward-directed thrusting accompanying the onset of subduction beneath New Zealand." Geology **19**: 230-233.

Rait, G. J. (2000). "Thrust transport directions in the Northland allochthon, New Zealand." New Zealand Journal of Geology & Geophysics **43**: 271-288.

Rawson, S. J. (1983). A marine geophysical survey of the Hauraki Gulf, University of Auckland. **MSc**.

Raza, A., R. W. Brown, et al. (1999). "Thermal history of the early Miocene Waitemata Basin and adjacent Waipapa Group, North Island, New Zealand." New Zealand Journal of Geology & Geophysics **42**: 169-188.

Ricketts, B. D., P. F. Ballance, et al. (1989). "Basal Waitemata Group lithofacies: rapid subsidence in an early Miocene interarc basin, New Zealand." Sedimentology **36**: 559-580.

Roberts, G. W. (1980). A geophysical-hydrological study of the Mount Wellington area. Auckland, University of Auckland. **MSc**.

Rodgers, K. A. (1966). Ultrabasic and basic nodules from the basalts of the Auckland Province, University of Auckland. **MSc**.

Rout, D. A. (1991). A geophysical and volcanological study of the Wiri and Papatoetoe volcanoes, Auckland. Auckland, University of Auckland. **MSc:** 132.

Rout, D. J., J. Cassidy, et al. (1993). "Geophysical evidence for temporal and structural relationships within the monogenetic basalt volcanoes of the Auckland volcanic field, northern New Zealand." Journal of Volcanology and Geothermal Research **57**: 71-83.

Samsonov, S. V. and K. F. Tiampo (In Press). "DRAFT Deformations occurring at the city of Auckland, New Zealand as mapped by SAR interferometry." Geophysical Research Letters **DRAFT**: DRAFT.

Searle, E. J. (1932). Geology of the Southern Waitakeres and West Auckland area, University of Auckland. **MSc**.

Searle, E. J. (1959). "Schistose Rocks from St. Heliers Bay, Auckland " New Zealand Journal of Geology & Geophysics **2**: 368-379.

Searle, E. J. (1960). "Petrochemistry of the Auckland Basalts." New Zealand Journal of Geology and Geophysics **3**: 23-40.

Searle, E. J. (1961). "Studies in the Auckland Volcanic Field."

Sheehy, A. (2002). A study of the perceived risks of tephra fall hazards in Auckland, New Zealand. , University of Auckland. **MSc**.

Sherburn, S., B. J. Scott, et al. (2007). "Monitoring seismic precursors to an eruption from the Auckland Volcanic Field, New Zealand." New Zealand Journal of Geology & Geophysics **50**: 1-11.

Simpson, K. A. (1988). Rock properties and slope processes in the Waitemata Group soft rock, along sections of the East Coast of Auckland, New Zealand University of Auckland. **MSc**.

Sivell, W. J. and M. T. McCulloch (2000). "Reassessment of the origin of the Dun Mountain ophiolite, New Zealand: Nd-isotopic and geochemical evolution of magma suites." New Zealand Journal of Geology & Geophysics **43**: 113-146.

Skinner, D. N. B. (1986). "Neogene Volcanism of the Hauraki Volcanic Region." Bulletin of the Royal Society of New Zealand **23**: 21-47.

Smith, I. E. M., S. Blake, et al. (2008). "Deep-seated fractionation during the rise of a small-volume basalt magma batch: Crater Hill, Auckland, New Zealand." Contributions to Mineralogy and Petrology **155**: 511-527.

Spargo, S. (2007). The Pupuke volcanic centre: polygenic magmas in a monogenetic field. unpublished MSc Thesis, University of Auckland.

Spoerli, K. B., M. P. Hochstein, et al. (1989). Post Rangitata faulting in the greater Auckland area. Geological Society of New Zealand Miscellaneous Publication, Auckland, New Zealand, Geological Society of New Zealand.

Spörli, K. B. (1978). "Mesozoic tectonics, North Island, New Zealand." Geological Society of America Bulletin **89**: 415-425.

Spörli, K. B. (1982). "Review of the paleostrain/stress directions in Northland, New Zealand, and of the structure of the Northland Allochthon." Tectonophysics **87**: 25-36.

Spörli, K. B. (1989). Exceptional structural complexity in turbidite deposits of the piggy-back Waitemata Basin, Miocene, Auckland/Northland, New Zealand. Geology of Northland. K. B. Spörli and D. Kear. Wellington, The Royal Society of New Zealand. **26:** 183-194.

Spörli, K. B. and H. J. Anderson (1980). "Paleostress axes from mineral striations in faulted Mesozoic basement, Auckland, New Zealand." New Zealand Journal of Geology & Geophysics **23**(2): 155-166.

Spörli, K. B. and G. H. Browne (1982). "Structure in a Miocene interarc basin; Waitemata Group at White Bluff, Auckland, New Zealand." Journal of The Royal Society of New Zealand **11**(2): 87-92.

Spörli, K. B. and V. R. Eastwood (1997). "Elliptical boundary of an intraplate volcanic field, Auckland, New Zealand." Journal of Volcanology and Geothermal Research **79**(3/4): 169-179.

Spörli, K. B. and J. V. Rowland (2007). "Superposed deformation in turbidites and syn-sedimentary slides of the tectonically active Miocene Waitemata Basin, northern New Zealand." Basin Research **19**: 199-216.

Sprott, A. (1997). Aspects of the Albany Conglomerate, Waitemata Group, North Auckland, University of Auckland. **MSc**.

Strachan, L. J. (2008). "Flow transformations in slumps: a case study from the Waitemata Basin, New Zealand." Sedimentology **55**: 1311-1332.

Swain, A. (1993). Structure in Waipapa and Waitemata Group rocks near Leigh, University of Auckland. **MSc**.

Tang, J. (1999). Environmental geology study on Panmure Basin, New Zealand, University of Auckland. **MSc**.

Tearney, K. (1980). A Marine Geophysical study of the Hauraki Depression, North Island, New Zealand, University of Auckland. **MSc**.

Tejaksuma, I. G. (1998). Slope movement and faulting in Quaternary deposits and Miocene weak rock at Beachlands, Auckland, New Zealand, University of Auckland. **MSc**.

Thompson, S. A. (1975). Waitemata Harbour - selected sedimentary topics, University of Auckland. **MSc**.

Thrasher, G. P. (1986). "Basement structure and sediment thickness beneath the continental shelf of the Hauraki Gulf and offshore Coromandel region, New Zealand." New Zealand Journal of Geology & Geophysics **29**: 41-50.

Tilsley, S. (1993). Engineering Geology and mass movement of the Howick-Alfriston-Whitford district, South-east Auckland, New Zealand, University of Auckland. **MSc**.

Turner, F. J. (1925). Geology of the Takapuna-Silverdale district, University of Auckland. **MSc**.

Viljevac, Z. (1998). Western Springs aquifer. Hydrogeological characteristics and computer model., University of Auckland. **MSc**.

Weigel, V. H. (1976). The Waitemata Group in southwest Auckland, University of Auckland. **MSc**.

White, S. R. (1989). Structural geology of the Mahurangi limestone at Dairy Flat, North Auckland, University of Auckland. **BSc (hons)**.

Whyte, D. E. (1982). Aspects of the engineering geology of the Rangitopuni catchment, Auckland, University of Auckland. **MSc (hons)**.

Williams, A. L. (1989). Lithologic properties, defects and slope movements in weak rocks of the Pakiri Formation, Leigh, University of Auckland. **MSc**.

Williams, H. A. (2003). Geophysical and structural investigation of basement greywacke in the Auckland region, University of Auckland. **MSc**.

Williams, H. A., J. Cassidy, et al. (2002). Geophysical and structural investigation of basement greywacke in the Auckland region. Geological Society of New Zealand annual conference, Northland 2002 Whangarei New Zealand, Geological Society of New Zealand.

Wise, D. J. (1999). Geophysical and geotechnical study of the Wairoa North Fault, South Auckland. Department of Geology. Auckland, New Zealand, University of Auckland. **MSc:** 128.

Wise, D. J., J. Cassidy, et al. (2003). "Geophysical imaging of the Quaternary Wairoa North Fault, New Zealand: a case study." Journal of Applied Geophysics **53**: 1-16.

Wise, D. J., J. Cassidy, et al. (1999). A geological and geophysical and engineering geological study of the Wairoa North Fault, Auckland. Geological Society NZ Miscellaneous Publication. C. Wallace. GSNZ 1999 Annual Conference. **107A**.

Wong, P. C. N. (1946). Aspects of post-Tertiary volcanism at Auckland, University of Auckland. **MSc:** 97.

Woollaston, M. (1996). The Junction Magnetic Anomaly in the Auckland region, University of Auckland. **BSc (hons)**.

Wylie, C. (1989). Engineering geology of a soft, weak rock tunnel: ARA Redoubt Road No. 2 inlet tunnel, University of Auckland. **MSc**.

APPENDIX 1: SUMMARY OF STRUCTURAL DATA FROM UNIVERSITY OF AUCKLAND THESES.

Bedding

South Auckland

<u>Boedihardi (1990) Whitford-basement fractures</u>

Bedding in greywacke is hard to discern but generally 190-205º/55-85ºW
l

<u>Anderson (1977) NW Manukau city gravity</u>
Greywacke surface dips west

<u>Brown (1937) clevedon area</u>
1 mile NE of Kawakawa Bay, bedding in greywacke dips 60ºW

<u>Berry () Manukau Lowlands</u>
Park Estate to Drury The bedding dips shallow west in east and east in west, N-strike
Hingaia Bridge Bedding varies NNE-N/ 30-40ºE in west or westwards in east
Glassons Creek- bedding NNE/mod west
Whatapaka strike N/dip shallow –mod east
Kahawi Pt to Glenbrooke Beach bedding mostly N/10-25º W

<u>Wiegel (1978) Port Waikato (Miocene)</u>
NW strike /shallow SW dip
To south, Te Akau, NE strike /shallow N dip mostly

<u>Wylie, (1989) redoubt Road (Waitemata gp)</u>
Beds dip 4-15°W, no strike recorded

<u>Tilsley, 1993. (Howick-Alfriston, Whitford) Road (Waitemata gp)</u>

In simple domains, dip 0-20°) variable strike WNW-NW, NE common
Complex domain dip 10-85°) “

North Auckland

<u>Mcmanus, 1981 (Albany to paremoremo)</u>
WAITEMATA GROUP
Hochstetter(1864)”horizontal beds of sandstones and muds which form the cliffs of the Waitemata Harbour”
Park (1889) noticed sub-horizontal nature of bedding and recognised zones of complex folding/tilting
Strike EW near Paremoremo, swings NE in east of study area, dips generally S-SE/ mod, some up to 80º

<u>Turner (1929) takapuna to silverdale</u>
WAITEMATA GROUP

Beds mostly very gentle dips or horizontal, very deformed strata Milford Beach to Red Bluff and east coast Whangaparaoa

North side Wairau Creek beds dip 30ºW, and from there to Castor Bay, beds are disrupted. North of Castor Bay, strata dip gently north, dip rapidly increases as go further north until half way to Red Bluff, where they are vertical. Beds then turn in on a fault, the other side of which the beds are gently dipping again. Near Red Bluff strata steep SW dip. Maori Bay area dips gently undulating but maintain a strike of 250º

Patterson(2002) Takapuna)
(Waitemata gp)
Simple domains NE/10ºS
Complex domains variable 25°-vertical

Johnston (1999) Geophysics of the Albany Conglomerate
(Waitemata gp)
Bedding generally 115-112/40-68S, avge 115º/66ºS
Mudstones may dip up to 85ºS

Alldred (1980) Wenderholm-Orewa
(Waitemata gp)
Wenderholm-Waiwera 5-10°NW dip
Waiwera- Cooks Beach NW dips on beds
Stingray Bay- Hadfields SW dips
Hadfields to Orewa NW dips

Suggests westwards tilting of the whole area of 5-10°, also fold axis plunging westwards.

Lipman 1993 (Albany Riverhead-Kumeu)
(Waitemata gp)
Albany conglomerate
In west bedding dips 20-40ºW
Fold axis plunges NW
In east bedding dips 70-90ºE

Jugum (2000) Timber Bay (North Wait Basinequiv ecbf)
(Waitemata gp)
Regional dip SW, top allochthon/bottom Waitemata SW dip

Swain (1993) Leigh
In basement broken fmn NE/mod S

Gregory (1966) Whangaparaoa
sub horizontal or gentle (usually 5-8ºW)

Swhite (1989) Redvale Quarry-Allochthon (Mahurangi lst)
35-45ºW dip on top limest-bottom allochthon contact
Mahurangi limest NNW-NNE strike/ shallow-mod E, steep in SW of quarry

West Auckland

Davidson, (1990) (upper Harbour)
WAITEMATA GROUP
Upper Waitemata ECBF, EW-ESE strikes, mostly shallow S but varies to steep N and steep S
Possibly broad horizontal fold axis

Hayward (1975) Waitakeres
Shallow dips to W or NW usually 0-20°NW, rarely exceed 50°
Oldest outcrop in E to youngest in west
Not original dip since little evidence for shallowing W-NW/source

Searle (1932) Geol of s Waitakeres
Bedding in Wait Gp 050º/45º NW Little Muddy Creek
ENE/50ºNNW Duck Creek
155/40ºENE Shag Pt-SW of Titirangi beach
interbedded silts dip 70º towards WSW S of Pararaha Stm
Manukau breccia- Wait Gp generally conformable

Pohlen (1934) Mid Waitemata County (west Auckland PiHA,Titirangi, Hobsonville, Muriwai
WAITEMATA GROUP
Beds mostly very gentle dips or horizontal, very deformed zones present SE of New Lynn. Most strata in the Waitematas of the area are horizontal, with local very complicated zones.
Waitakere slumping, with 5ºSE dip above slump and 20ºSE below slump
Horizontal strata Te Atatu Peninsula, Hobsonville 20ºN and then curved by folding or faulting

Central and eastern Auckland

Tejaksuma () Beachlands
WAITEMATA GROUP
Two domains of bedding: ECBF NW, N and NE strikes, dips mostly 2-20º, with some 21-35º
Quat beds (Tauranga Gp) sub horizontal

Morris, 1983 (Musick point)
WAITEMATA GROUP
N-S strikes E-W dips
Slumping and complex folding

Codling (1970) . (mission bay -orakei)
WAITEMATA GROUP
Mostly gentle dips less than 8°
West shore of Hobson Bat 20°dip,
East of Orakei Basin more variable dips, up to 80°
Strikes predom NNW-N

Geelen, (1973) Wait Gp, N Manukau coastline

WAITEMATA GROUP
Waikowai-Pukeha Ck-20ºEdip
Pukeha- Taylors Bay5º-ESE dip
Taylors Bay-Wesley Bay-5º-20SE dip some 50º above unconf
Wesley Bay-Cape Horn-20ºSE
Cape Horn-Duck Creek-no bedding quoted
Duck Creek-Flounder Bay-“
Flounder Bay-Green Bay-
Green Bay-Oatoru Bay 20º
Oatoru Bay-French Bay-
French Bay- Davies Bay-
Davies Bay-Little muddy creek
Little Muddy Creek- Big Muddy Creek-
Big Muddy creek-Mill Pt
Mill Pt- Cornwallis Beach
Cornwallis beach-Kakamatua Stream
Kakamatua Stream-Kaitarakiki Point
Kaitarkiki Point-Little Hunua

Gulf and islands
Milligan-Geophysics of Rangitoto (actually more Motutapu)
Bedding in Wait gp from map generally NW-NNW a/very shallow S (3-5º)
In greywacke mostly NNW/steep (65-80º)W or E (FA pl 350º)

Faults

South Auckland

Al Salim , M.A. (2000)

. He says Drury fault poss still active from recent seismic mapping IGNS-v little evidence from geomorph

Topo expression and surface throw decrease from south to north,

North of Papakura Fault possible scarp aligned with Drury Fault seems to truncate overlying terrace of recent seds.

Normal, dip NNW/65-90º W

Some complexity in linkage of Drury and Papakura Faults.

Anderson, 1977. NW Manukau City, Grvuty

Clevedon-Waikopu Fault NNW/ 65-70º but eroded to 20º.

Drury Fault at Atdmore steeply dipping 65-70º, normal, downthrown W by 500m.

1.5km north of this no fault present- probably truncated by E-W trending fault Parallel to Papakura Valley Fault.

Kiripaka Fault delineates north boundary of Kiripaka basain-truncated by Te puru Fault. (this has eroded fault scarp)

Oblique- slip on Clevedon-Waikopu Faults sinistral/normal (from mineral striations) Other major fault set 45º NW, dextral strike-slip. This in greywacke.

Also in greywacke, post –striation deformation includes NW-SE (120)/downthrown SW, NE (030) Downthrown NW (c.f. Te Puru Faul) and 155/downthrown W +E, horst and graben, paralleling the Clevedon-Waikopu Fault.

No fault defined lining up with Drury Fault and Islington Bay Fault- i.e. unable to prove whether they are the same fault.

Barter (1976) Awhitu Peninsula and Manukau Lowlands

Manukau Lowlands downfaulted Block.

Cretaceous- Eocene found at depth in Karaka Borehole, similar to blocks included in Waitematas at Blockhouse Bay, which are also similar to “Onerahi Formation” (Northland Allochthon). Borehole stopped and didn’t penetrate far into it, so unclear whether included blocks or in situ.

Some evidence of late Tertiary to Quaternary movement on faults in the area. Waikato Fault (2.7km downthrown vertical offset), and at least three other faults with downthrows of 300m S, 25m S and 10m N cut Pleistocene sediments at least, and Glenbrook (200m S vertical offset), Waiau (130m N downthrown vertical offset), Karaka (80m S downthrown vertical offset), and Wiri Faults (120m N downthrown vertical offset), all cut Quaternary.

All these faults strike ENE and are constrained by boreholes.

Waikato Fault began to move in Miocene and continued until mid-upper Pliocene.

Eiby (1968) reported an earthquake in 1891 with magnitude MM 8 with epicentre just offshore off the Waikato River Mouth, which may indicate that the Waikato Fault is still active. At least 300m has occurred since Pleistocene and Hochstein and Nunns deduced that 750m movement has occurred during the Quaternary.

Small fault 10km N of Waikato Fault has 300m+ of downthrow

Drury Fault (NNE strike) has 700m?? of movement.

Manukau Fault- unknown exactly where it is but big altitude difference between crest of Waitakere Hills and Manukau Lowlands.
Geelen proposed a whole series of small faults with a cumulative throw of 100-800m.
Gravity surveys across the Manukau entrance do not show a big fault- displacement is likely to be about 100m at the west coast, taken up on small fractures.

Berry () ManukauLowlands
Large scale faults horst and graben blockfaulting. On Manukau Wiri Karaka, Waiau, Glenbrooke, Pukekohe, Waikato, Pokeno Faults ((ENE trends) and Ponganui Tuakau and Drury Faults (NNW-NNE)
Smaller scale faults at Hingaia Bridge alos ENE, NW dip, normal and N-NNE

NE fracture zone with drag indicating dex strike slip(or NW down normal faulting)
Mouth of Glassons Creek-reverse faults oriented NNE-N, SE down separation and WNW to NW with NE separation

Numerous N-NNE steep extensional faults
NE-ENE faults-NW up dip slip

Karaka Point has early bedding parallel thrusts, then folding, then ENE extensional faulting.

Whatapaka NNW extensional faults, ENE trending extensional faults

Kahawai Pt to Glenbrooke beach-NE-ENE/SE and Nwstrike/NE dip normal faults

Summary of Waitemata Faulting in the area:-

1) NE and WNW-NW trending small normal and reverse faults, sometimes associated with low angle bedding parallel thrusts
2) N-NNE trending steep extensional faults
3) NE-ENE extensional faults last phase

Not much structure in seds overlying Waitemata Group-most apparently due to draping/ compaction
Pliocene to recent structures have NNW-N and NE-ENE orientations dominant.

Geophysics shows throws on faults tend to increase westward
Gravity survey N-S traverse of the Manukau Block Port Waikato to Manukau head to investigate ENE trending faults
NNW faults tend to be west up in basement, but West down movement sense in Waiuku River fault (NNW trend) therefore maybe a reversal in movement sense in Miocene
3D block model of horst and grabens developed.
West dipping blocks separated by NNW trending faults
NE faults apparently younger
Changes in throw occur in NE trending fault segments between the NNW faults
Glenbrook Graben terminates at the Awhitu Bisecting Fault: NNW faults acted as passive transforms for the extension on the NE faults rather than active strike slip faults.

Ratio of offset at base of Plio-Pleistocene layer to that of the mid-Tertiary layer increases from approx 0.5 in the west to nearly 1.0 in the east. (eastwards younging of faults?)
Throw on Drury Fault increases southwards, and on Waikato Fault decreases eastwards Scissors-type movement on the Waikato Fault linked to southerly tilting on north side of western fault segment oriented NE.

Early phase mesoscopic faults in Waitemata Gp NE and SE trending reverse and normal faults and N-S normal faults
Gravity anomalies show NE and NNW large scale faults present
Basement-Waitemata NE trends terminate at NNW faults, maybe because NNW trends are passive transforms
Mesoscopic structures compatible with dextral strike slip.
Latest phase mesoscopic features are ENE trending faults.(extensional)
N-S and ENE trends in structures in Plio-recent
NNW and ENE extension has occurred since Miocene at latitude immediately south of Auckland, cf NE and NW for Northland
Possible change in tect grain (cf 10-15º clockwise swing in JMA)
Or possible rotation of strain axes Miocene to pliorecent extensional faulting- possibly with or predated by dex strike slip on NNW faults

Wise (1999) Wairau North Fault

Regional Block Faulting post Waitemata Group, uplift, switch to oblique extensional tectonics leading to block faulting. This beginning of Kaikoura orogeny, mostly active late Miocene-Pliocene (7-2ma) forming present relief. Patterns inherited from basement upper Mesozoic Rangitata orogeny

N-NNW bounding faults: Coromandel and Hunua are elevated horsts, Firth of Thames/ Hauraki Plains and Manukau Lowlands are grabens. Auckland city midway-higher than the lowlands, lower than Hunuas
Several faults transverse to or parallel to main trends, (ENE and NNW resp.) subdivides Hunua block, causing tilting to N, NE or E., and forming fault angle depression. Series of sub parallel folds trend ENE, Parallel to transverse faults

Seismic activity in Auckland region- all 81 events (all less than M5.0) recorded between 1960 and 1983 were in Hunua/ Coromandel area.
Wairau North Fault is prominent range front through Hunuas, downfaults greywackes and forms W. N. Fault angle depression (filled with Pleistocene to recent sediments.

There are also prominent East trending lineaments (faults/other defects) may offset range front.

Geophys used to define fault plane of Wairau North Fault-including prominent reflector that terminates at the fault
NNW/50-70W, normal fault with approx 70m of fault scarp concealed by Happy Valley sediments. Traceable for 24km, in three offset (or en ech?) segments, steps progressively eastwards as move south

Conservative estimates has vert displ of 140m (ie considerably less displacement than Hunua fault which has o.4 to2.7km throw)
Quat displaced (from trenching) probably no later than 25000 yrs ago:
Min combined displacement 4m in Paparimu formation gives quaternary slip of 3cm/1000yrs

Dating fault movement: -Fault sag ponds/offset ridges and streams show possible Quat movement.

-Boreholes suggest 120m displacement in last 20ma
-Basalt only on downthrown side (1,3ma) possibly means most movement predates this. Basalt in contact with greywacke on the upthrown side.
Palaeoseismic study using field relationship and SEM of quartz grains indicates that Wairoa North Fault has been active in the last 10ma, probably the last 0.5ma
-possible deformation of terraces suggests two movements, in last 40,000 years, most recent 0.7m dip slip in last 10,000 years.
-No movement in last 330years.

Trenching -to identify and quantify quaternary movement
-faults in trench steep 55-90º, sometimes steepen upwards
-clay units faulted (dated 50,000yrs)
-probably some unfaulted terrace above: soils NOT faulted (soils post glacial ie movement is older than 25500 to 18000yrs)
-4m min displacement vertical over this time
3.2cm/1000yrs postulated for Wairau North Fault
compared to 13cm/1000years on Kerepehi Fault (part of active Hauraki Rift)
and 0.08cm/1000years on Beachland fault (which has no apparent fault scarp and therefore must be young or low def rate but offsets tephra beds by 0.6m)
therefore 3.2cm/1000years seems reasonable for Wairau North Fault.

In Manukau block N faults offset E faults
In the Hunua block, East faults offset NNW faults,
But in Hunua block there is no evidence for Pleistocene movement on NE-E faults, but evidence for movement on some NNW faults (eg Wairau North Fault)

<u>Boedihardi (1990) Whitford-basement fractures</u>
Major Faults-NNW trending Waikopu and Whitford faults (downthrown W)
NE trending Alfriston-Brookby- Papakura fault system.
Smaller scale faults, Normal faults trend E, NE, NW, oblique-slip (striations pitch 50-60ºNE)
Strike slip faults dex str slip, NE/dip SW, striations pitch 20ºNE and SW

Reverse 300-345º/60º-vertN+S

Anderson (1977) NW Manukau city gravity

Waitemata Gp infills Deep basin in greywacke, steep sided, fault controlled ridge in centre
(JMA causes difficulty modelling western basin)
Eastern boundary segmented, avge dip 25°,
Some Faults are eroded to low angles
Kiripaka Fault delineates northern boundary of Kiripaka Basin- truncated by Te Puru Fault- (also delin N-boundary)
Edge basin dips 21°

ProfileB:- NNW in Eastern boundary Clevedon-Waikopu Fault 65-70°E, but eroded to about 20°-possibly two periods of fault movement

Profile C:-is 1.5 km north of this and there is no fault there- it is probably truncated by an E_W trending fault parallel to the Papakura Valley fault.
Oblique slip on the Clevedon-Waikopu Fault (Sin-normal) (numerous striations)
Other major fault set 45°NW dex strike slip

Post striation deformation
NW_SE trend /downthrow SW
NE trend /downthrow NW (cf Te Puru Fault)
NNW trend/downthrow W and E-horst and Graben (parallel to Clevedon –Waikopu fault)
Main Faulting in in Waitemata Gp in the region is NE-SW (ie NW extension) – inherited from the greywacke)

Brown (1937) clevedon area

NE-SW and NNW-SSE (western boundary of Hauraki Graben is NNW)
Wairoa fault NNE –1300' throw
Miranda fault NNE-2200'throw
Mangatangi Fault ENE trend 500-600'throw

J Allen (1995) North Manukau Lowlands(geophys)

3 Large scale ENE-WSW trending faults "southern Glenbrook(220m+ downthrow south, normal), Waiau(130m+ downthrow N, Normal) and Karaka(in north, downthrow 80m+ normal downthrow south)" these quoted from Berry

Glenbrooke fault in Vertical plane, south downthrow increases to the west from 0 in east to 200m in west over 10km distance. Pre Pliocene-low angle fault plane due to erosion
He says Wairau Fault doesn't seem to exist and then you do not nee Karaka fault,
Drury fault to E Waikato fault to S
Horst and graben structure geophys and borehole data consistent, but this only in Kawaa and Waitemata- doesn't go into basement.

Marija Jukic (1995) Subsurface of South Akl Volcanic field

Hunua- Ramarama relationship of early faulting and volcanics, esp. Drury Fault. Coarse/fine lavas relate to final stages of faulting (Healey 1935). Close assoc of vents with faults in Pokeno region esp Pokeno fault (Kear 1961), Schofield- Mangatawhiri locn eruptive sites on fault extensions

<u>Miller (1996) South auckland (mangere)</u>
Crater Hill-Mangere mountain, Puketutu, Hampton Park, Otara Hill
No geophysical evidence for faulting
Possible NW-SE alignment of some centres.

<u>Wiegel (1978) port waikato</u>
See diagram
Kauiwhauha, Pirongia, N and NNE faults
S port Waikato, to Te Akau, NE trending faults, postdates volcanics in N of map

<u>Wylie, (1989) redoubt Road</u>
Normal NE (NNE-ENE)/ steep E (some steep W)
Reverse NNE-NE/ steepE one NW/steep W
Thrust almost horizontal.

<u>Tilsley, 1993. (Howick-Alfriston, Whitford)</u>
ECBF Faulting predom steep NNW trend ,mod ESE trend
Steep NNE trend, steep NE

Conjugate normals give $\sigma 1$ shallow-mod SE
$\sigma 3$ mod NNW
Normal, reverse, thrust and complex faulted sequences observed.

First set NNW or NS tend on major basement faults in the area.
Beachland Kirpaka, Wairoa North –quaternary movement
Waikopua 3km east of area may be extension of Wairoa fault

Second set, NNE to ENE includes lower Wairoa, Papakura fault

In this area, Drury, Polo Lane Brookby, and several others. No direct evidence of recent movement in the area (though Quaternary movement noted on Drury Fault SE of Drury), nor clear surface displacement. No clear plane in ECBF. Rather, N-S topographic lineament intensity, increased fracturing and calcite veining in a NNW direction, ANNW trending persistent crush zone, evidence for displaced basement at depth in boreholes and gravity surveys, different depths either side of fault zone (in W 262m, in E 53m)
Ie indirect evidence of faulting in Waitematas as a continuation. Of Drury Fault.
Possibly 0.5-1.5km wide zone. Geophysically modelled fault in basement overlain by fractures in overlying sediments

Quaternary movement observed in offsets in silt/clay. 102º/v fault downthrown 300-400mm to S

ACTIVE FAULTING: two known, Port Waikato Fault (Smith1981) and Kerepehi Fault (Hochstein et al, 1986 De Lange and Lowe, 1990)

Quaternary Faulting movement on several faults- Drury Fault, Polo Lane fault, Brookby Fault, several unnamed basement faults
5 shallow focus tremors ML 3-3.9 1964 and 1988 (Gulliver and Matuscha)

Ormerod, 1989 (South Auckland)

Basement blocks NNW trend-Drury Fault
ENE trend-Waikato Fault
Max downthrow 2.5 km

E-W trending horst and graben

Waikato Fault high angle normal fault zone, downthrow of basement to north of about 2.5km at Port Waikato, 1,3 km further east. (scissor)

Puri fault ENE strike/downthrow south

Pokeno fault downthrow south of approximately 0.9km, increasing throw further west.

Drury fault-near vertical fault (actually 28W dip)
Normal fault, downthrow to west, 2.7km in S at Ramarama
0.5km in middle, west of Ardmore
0 north of Alfriston

St Stephens Fault, shallow dip, total downthrow 1.5 km(maybe passive boundary on sidestepping Drury Fault.

Map highlights: -sidestep downthrow dex from Drury Fault to S
- Reverse nature of Puri Fault
-Significant throw in basement across St Stephens and Whangarata Faults
-Lack of continuation of throw across Pokeno and Waikato Faults.

North Auckland

Mcmanus, 1981 (Albany to Paremoremo)

WAITEMATA GROUP
Small scale faults normal/ reverse dip slip approx 300mm sep, syn sedi
Med scale faults 10s m strata affected, norm/reverse, steep, beds match
Large scale faults- asymmetric valleys aligned to regional NE-SW to ENE and NNE-SSW structural trends.

Johnston(1999) Geophysics of the Albany Conglomerate

Faults in the area have NE trend.
Small scale reverse faults 150º/75ºS
Normal faults mainly N-NW/steep (65-85º)NE
Thrusts mainly E-W/42ºN
Albany conglom defined by geophys as tabular body with elongate central channel deep, narrow, parallel sided and probably fault controlled canyon, NNW-SSE trend.

Patterson (2002) Takapuna)
Normal and reverse present,
Reverse often associated with tight folds
Throw on normal faults often more than cliff height,
Steep – all more than 38°

Alldred (1980) Wenderholm-Orewa
Faulted contact Pakiri (strat lower, volc rich) with ECBF(stat lower, volc poor)

1) Normal strike E-W /N and S dipping. (2) folding)
3) Conjugate normal ENE-WSW-NNW

WAIWERA FAULT- cliffs show more than 2x cliff height throw-ie at least 50m
Boreholes show 50m to N drop of basement across EW stiking Waiwera fault
Hotspots and geochemical concentration maxima also along trace of fault.

470m drop to S of basement across Stingray Bay Fault from boreholes (N end of SRBay is fault controlled)

Blockfaults all have E-W trend, none have N-S trend
East west set have dips to N and S, (there are more S-dipping, and they have bigger throw) (also more of them as get closer to Waiwera fault)
Mutual offsets between E-W trends and N-S trends (Ns trends are as numerous as EW trends, but have smaller throws. (Looks orthorhombic but he doesn't analyse it as such)
All these faults post date slumping.
Waiwera – Cooks: "Orewa structure"-includes open anticline with reverse faults.
2 zones of NE striking thrusts, mean strike 065 gives compression NNW-SSE
Dip on Waiwera thrusts up to 80°.
The reverse faults are reactivated as normal faults,

Clockwise rotation of blocks occurs: individual shears/blocks are 126/30S, the shear zone causing rotation strikes 051°.

Conjugate normal faults strike 095°
Some near vertical normal faults strike 120-175º: dom dip slip, with minor strike slip

Reverse faults mean strike 072º,

Dip of beds increases from 12-25° to near vertical near Stingray bay Fault.
Normal faults also increase in number closer to Stingray Bay Fault. ENE trends.
Stingray Bay Fault initially NNW-SSE compression, later tension NNW-SSE (unclear where this comes from.)

Lipman 1993 (Albany Riverhead-Kumeu)
NE-SW trend possible
NW-SE trend possible
(poor exposure)

Christie (1986) Manley
E-dipping normal faults

Three zones present: 1) mostly E/steep and two Nstr/Edip
2)NW and SW trends
3)N-NNE trends
two major sets: NNE/shallow-mod E
East/shallow-mod S
Two smaller sets: N/shallow
WNW/shallow S

Daly (1988) Te Arai-leigh
Fault angle depression dipping N from greywacke outcrops at Te Arai Point for 10km
Max depth of greywacke is at Waipu,690m. (Mahurangi lst and other allochthon under Waitemata Group north of Te Arai Point (resistivity) but none under Waitemata Group south of Te Arai Point)

In west of area NNW/20-40ºW normal fault drops basement westwards from 200m to 500m bsl
In south of area, ENE trending fault norm fault drops basement 0to 200m bsl to S
In SE NE-ENE fault drops basement from 100asl to 100bsl towards E
Possibly some scissor in S fault if it continues into Whangateau Harbour.

Jugum (2000) Timber Bay (North Wait Basin equiv ecbf)
N Many Small faults NE/steep N
Large scale Faults NE-SW trends approx implied
Med scale faults Thrusts ENE/70º N
Horst and graben system(?)

Swain (1993) Leigh
Basement-late Cret ext blockfaulting NNW-ENE trends
Thrusts-NW-SE compression

Cape Rodney
NW-SE compression and thrusting
Normal faults-E, NNW, NNE

Pakiri-Major fault 168º strike

Gregory (1966) Whangaparaoa
Big ENE trend (c.f. strike of folds in slumps)
Lesser WNW trend
Less still NNW-N trend

Lots of small faults (most norm, signif reverse) few ft long few " sepn
Quite a lot a bit bigger-several 10's ft long, few " to few' sepn
45 dip
most norm no signif reverse
Major Faults-normal, steep beds unmatchable, NNW and ENE cf blockfaulting in Hunuas
Silverdale fault downthrow N in Waterhouse boreholes, Gregory has it reach the coast and upthrown S by at least 125 ft.

Major faults with little surface expression in some valleys.

Swhite (1989) Redvale Quarry-Allochthon (Mahurangi lst)
Low angle transcurrent simple shear (N-S sin or E-W dex
E-W ext faulting,1st w breccn then cct deposition
Thrusting from E

West Auckland

Pohlen (1934) Mid Waitemata County (west Auckland PiHA,Titirangi, Hobsonville, Muriwai
WAITEMATA GROUP

Swanson Stream, Henderson-Taupaki track , no of small strike-slip faults, NW in direction max throw of three feet. Small faults common-mostly intra formational, but one outcrop at Waitakere has two steep faults either side of a block of Waitemata Group and on the other side of the faults is Manukau sub group.

George (1993) South Waitakere ranges
Steep 60-80º normal faults dominant
Shallow 15-30º normal faults
Sometimes in fault zones
Thrust faults with soft sedi deformation at Cornwallis-several metres long.

Searle (1932) Geol of s Waitakeres

Thrust in Wait Gp 030º/NW Little Muddy Creek
Thrust at Shag Pt SW of Titirangi Beach, 060/30NW

In Henderson valley contact Manukau Breccia-Waitemata Group obscured by faulting (gen conformable)- also bedding tilted to NE/vert in breccia

Boundary of Waitakere Hills with Waitematas is steep and scarp-like.

Davidson, (1990) (upper Harbour)
Upper Waitemata ECBF, Faulting 1) E-W thrusting East/30-50º S
2) minor NW-SE
3) NNE/50-80°E biggest phase, mostly normal, some reverse
Generally planar fault planes, many with clay gouge.

Hayward (1975) Waitakers
WNW and NE trending faults, grid pattern, many blocks tilted, NW downthrows
Waitakeres NOT a raised horst, but due to hard cap of resistant Lone Kauri/Piha formation.
(Actually downthrown on a major fault on E flank that drops them down80-120m to west.)

Inland faults often inferred from strat lineaments- some concentric or radiating around volc centres, some formed during dep and eruption-active mid Miocene.

Muriwai-Te Waharoa –3 major NE faults, many sub parallel minor faults.
Blocks thrown progressively down to south, bedding dips low angle west
Canyons very steep sided and deep therefore tectonic origin (syn dep), but block faulting also post deposition
Waitak volcanic arc throws Manukau subgroup about 100m wrt Waitemata Gp. Andesite intrusives along this as well as volcanic neck/crater complexes and dykes

Central and eastern Auckland

Williams (2003) Gravity of Auckland area
Wairoa fault in Waipapa basement –gravity indicates could be up to 4.7km of vertical displacement (upthrown to east.) this is much greater than estimated Quaternary offsets (Wise has 120m min, left lateral-which may just represent more recent movement)
Large scale block faulting on a scale of several km proposed. Can be faulting with several km vertical throw late Cret-early Tertiary

Tejaksuma () Beachlands
Beachlands fault is active-vertical movement rate-0.827mm/1000yrs-minor
It offsets Waitemata Group by 3.7mand overlying tephra by 0.62m and is oriented 140/56W offset rate above is calculated using age of offset Quaternary Tephra(age range 0.69-1.34ma

Beachlands is small faulted block with uplift of 0.0168mm/year
Cf Port Waikato 0.0554mm/yr

Mostly normal and thrust faults
Seven thrusts trend NW-SE.
Normal faults trend NW or NE, one with at least 3.1m offset

Crush zones and shear zones with several fault planes are present.

Parvis Namjou (1996)(Hydrology of Mt Wellington/Peach Hill)
Regional rhombic fault system at Peach Hill mostly NNW and ENE block faults
Drury, Wairoa, Waikopua NNW,
Hunua, Waikato, Waiuku, Papakura Valley, Waikopu, Pokeno faults ENE

On site Hunua NNE
Drury NNW/65-90º, Normal, variable throw (0.4-2.7km (Nixon))
Greywacke-coal measures contact offset approx 70m on geological map

Simpson () East Coast engineering geol
Noted presence of simple and complex zones
Faults reverse pre normal (exc soft sed)

Normal, reverse and strike slip often present
Normal mostly NE-SW
    Less NW-SE, NNE-SW, E-W
Generally steep 55-75
        NNE shallower

Reverse faults mostly NNW-SSE, less NE-SW, dips generally 20-45º

<u>Morris, 1983 (Musick point)</u>
WAITEMATA GROUP
NE trending Faults crosscut and offset NNW trending folds
Conjugate thrust pairs NNW striking/dipping E and W
NNW striking normal faults prob assoc with ext in fold hinge
crosscut by four simultaneous normal fault sets: EW strike/steep N or S
NE strike/steep N or S
There are more of the EW striking set but S dipping, NE striking are best developed and have largest slips.
Maybe major doming with faulting.

<u>Codling (1970) . (mission bay -orakei)</u>
Three different types 1) Low angle reverse, west dipping
2) High angle normal, NW dipping planes, NE strike: Most
3) High angle reverse at least 30m displacement from Parnell grit in borehole east of fault.

<u>geelen, (1973) Wait Gp, N Manukau coastline</u>
Faulting in Wait Gp
Waikowai-Pukeha Ck-
Pukeha- Taylors Bay5-NNw or WSW trends, some reverse ESE upthrow up to8m
Taylors Bay-Wesley Bay-5-ENE most downthrow S, ESE thrusts, normal70SE with 20m S downthrow
Wesley Bay-Cape Horn-NNW and ENE: one fault 70Sedip, lg throw: NE/70NW throw 20m: Cape Horn, Waikowai Grit faulted contact with Waitemata Group: North/steep W more than 30m throw: thrusting from SE to NW on small thrusts
Cape Horn-Duck Creek-40m throw on faults, one reverse dips 70SE throw 5m:thrusting is S to N
Duck Creek-Flounder Bay-SW-NE thrusting
Flounder Bay-Green Bay-N trending faults downthrow W some normal some reverse, low angle thrusts with E to W thrusting
Green Bay-Oatoru Bay
Oatoru Bay-French Bay-NNW faults domin NE, ESE faults dom in SW
French Bay- Davies Bay-E-ENE trends
Davies Bay-Little muddy creek SSE/steep-vertical SW some reverse, most WSW
Little Muddy Creek- Big Muddy Creek-ENE dom, some NNW
Big Muddy creek-Mill Pt-NE fault
Mill Pt- Cornwallis Beach ENE one norm NNW/70W
Cornwallis beach-Kakamatua Stream-NNE strike on fault contact Grit and breccia
Kakamatua Stream-Kaitarakiki Point-2ENE faults
Kaitarkiki Point-Little Hunua ENE trends one NNW

Manukau Fault-major fault between upstanding Auckland Block and South Manukau Lowland Block
Strikes ENE
Local small scale faults are part of the fault zone, downthrown SE Fault zone is at least 1km wide Wait Gp at Clarkes Beach and Manukau Breccia at Weymouth- at least 100-800m throw.

Manning (1983) N Manukau Coast(Blockhouse Bay to Mt Roskill)
Mostly normal most NNE-NE trends with 50-70ºE or W dips, some up to 80º, separation mostly mm to 10s of metres.
Some high angle reverse –wide scatter, mostly N-NNE and NW directions dip sep mm to 10s cm
Minor low angle thrusts first phase in area assoc with slide horizons in complex structural domains NE-E/20-40º N or S
Parallel folds and faults (norm/high angle reverse could be related
Bed parallel faults throughout
Listric faults sometimes with multiple splays.

Gulf and islands

Milligan-GeophYsics of Rangitoto
Faults in the area west of Motutapu Fault have NE trend, East of Motutapu Fault strike NNW.
Generally faults are dominantly normal, N-NW or NE-E
Motutapu fault-strikes NNW, at least 90m throw. Down to west, affects greywacke but not Waitematas
Gravity indicates a major post Waitemata Group fault some distance west of Motutapu Fault "Islington Bay Fault " best fit model has vert, downthrow 120m to west, NNW strike (168-171/vertical) probably passes E of Musick Pt, may be ext. of Wairoa Nth Fault.

Pre Waitemata Group; 1) NW(140º)/65ºE normal
2)conjugate strike slip (dex 040-060º, sin 090-115º), compression E-W, NS ext.
3)NW-SE includes Motutapu Fault
4?) complex striations have low angle thrusting and compression parallel to fault(Striation on 080º/20º N or S)

In Waitemata Group 1)SW side, normal, (030-065º) extensional direction from conjugates 110-150º, min throw 9m, compression vertical
2)NW side, 120-150º (ie perp to 1)) extensional trends 030-150, compression vertical
3)Islington Bay Fault- no evidence on Motutapu so must follow trend of Islington Bay and pass East of Musick Pt therefore trend is 168-171º/vertical, 120m throw.

Rawson (1983) Hauraki Gulf-grav,seis and mag
NNW trends Primary, NE trends secondary
Normal NNW/40ºW eroded scarps some back to 20°

Tearney(1980) Hauraki Depression
Fault angle depression, median ridge, graben (going west to east)
Firth of Thames fault throws approx 100m, Eastern Boundary Fault angle depression, Kerepehi Fault, East is Hauraki Fault, step faulted, upper scarp is 35º+/-5°, lower scarp is 65º+/-5°

Fault trends NNW, NW in N, dissected by NE-NNE trending transverse faults (up to 7km offsets

Davidge-Geophysics of the South hauraki lowlands
Faulting in the region is NE-SW and NNW-SSE
NE-SW- late Plio-early Pleistocene, possibly since Cret, Waikato, Pokeno Faults, large but variably vert, maybe some dextral strike slip
NNW-late Tertiary onset

Both trends- Blockfaulting of Hunua and northern Hapuakohe Ranges
Marginal Faults of Hauraki Depression NS-NNW SSE trends-also seen in active faulting/lineaments in depression-i.e. this orientation controls.

Balance (1976) and Backshall have normal NNW faults
, dex strike slip has been observed and supports the first movement from Te Aroha (Backshall) No NE-SW trend in Hauraki Depression

Steep west dipping en echelon faults at least as far north as Te Aroha, Recent traces of dex strike slip of up to 4:1 horix:vert marker movement
Hauraki Rift currently under shear?
Average dip is less than 70°.

Bryner (1991) brown's island
Faults in tuff ring 160-200ºstrikes, mostly normal, a few reverse
Some conjugate normal NS extension (E-W extension) some conjugate normal EW strike (N-S extension)
Faulting maybe volcanic disruption/compaction/slumping of tuff ring rim, differential compaction on undulating surface or possibly tectonic
Largest offset 4m.

Folds

South Auckland

Tilsley, 1993. (Howick-Alfriston, Whitford)
ECBF fold axis plunge shallow N, cluster plunge towards NNE,
some N to NNW,
some ENE
Spread around primitive may indicate refolding.

Berry () ManukauLowlands
Park Estate-Drury- 330 trending anticline plunges NNW

Hingaia Bridge ENE-E trending folds, wavelength m to 10s m
NW-NNW trending folds, mostly north plunging, wavelength 10s m
N-NNE trending folds 10s to 100s m wavelength, mostly north plunging
Glassons CreekNNE trending and NW trending folds ESE trending folds present too
Karaka Point 240º trending, north plunging folds 10s m wavelength
Whatapaka NNW trending mod tight folds, n-plunge, 10s-100s m wavelength
Kahawai Point to Glenbrooke Beach fold axial traces bend eastwards from 010º to 110º may be associated with oblique slip faulting

Summary of Waitemata Group folding in the area
ENE-E folds, open to isoclinal, wavelength 10s metres, slump mechanism of formation
NW-NNW folds, open to tight north plunging folds, sometimes associated with normal faulting
NNE trending folds tight to open north plunging, constant strike over several km, slightly north plunging

<u>Wise (1999) Wairau North Fault</u>
-series of NNE trending folds parallel Wairau North fault

North Auckland

<u>Johnston (1999) Geophysics of the Albany Conglomerate</u>
Fold axis horizontal 105º

<u>Turner (1929) takapuna to silverdale</u>
WAITEMATA GROUP
Beds mostly very gentle dips or horizontal, very deformed strata Milford
Everywhere Parnell Grit is found intense folding faulting and shearing
Okura Estuary-gentle syncline, NW axis. Maori Bay, Whangaparaoa, undulating strata, but maintains strike of 250º (ie fold axes ENE).

<u>Mcmanus, 1981 (Albany to paremoremo)</u>
WAITEMATA GROUP
Spread NNE-SSW ??? ENE trending fold axis (Shallow plunge)
Small scale syn-sedimentary
Med scale some doming (elongate N-S)
large scale NE-SW and E-W

<u>Patterson(2002) Takapuna)</u>
SE plunging anticline at Narrowneck, other folds assoc with reverse faulting

<u>Alldred (1980) wenderholm-orewa</u>
Wenderholm-Waiwera E-W folding in Pakiri
Waiwera-Cooks gentle WSW plunging open anticline
Series of anticlines and thrusts 3 open antiforms
070º/horiz syncline S end of Robbers Bay,
refolding of horizontal folds

mean fold axis 260º/15º
fold axes plunge west

<u>Lipman 1993 (Albany conglom-wnw of albany)</u>
Poor exposure
Fold axis plunges NW W-limb dips 20-40ºE, E limb dips 70-90ºE
<u>Christie (1986) Manley</u>
Shallow N-plunging anticline, NNE and NNW limbs

<u>Jugum (2000) Timber Bay (North Wait Basinequiv ecbf)</u>
Possibly 2 phases of folding.
Axes plunge shallow-mod S or NW-N, a few shallow W
NW-SE gentle-mod plunge first
ENE-WSW horizontal second
Regional SW dip. Top allochthon-bottom Waitemata dips South
South vergence in early soft sedi folds.

<u>Swain (1993) Leigh</u>
Basement folding-first open-tight chevrons, upright, cylindrical, NNE-ENE sub horiz F.A.
second NNW-SSE striking upright open cylindrical folds

Waitemata Group, (Pakiri) NE-SW trending axes
tight recumbent w thrust fault, FA pl shallow SSW

<u>Gregory (1966) Whangaparaoa</u>
ENE fold axes in slumps

<u>Swhite (1989) Redvale Quarry-Allochthon (Mahurangi lst)</u>
N-S trending folds post date E plunging fold,

West Auckland

<u>Davidson, (1990) (upper Harbour)</u>
Upper Waitemata ECBF,

EW-shallow-horiz fold axes, 10s –100s m wavelength,
Upright, open anticlines and synclines
20 of them 0-28°plunge, one third plunge east, 12 plunge west, average of 10°

N-S folding predates E-W isoclinal folding
Folding only in Miocene, not Pleistocene

<u>George (1993) South Waitakere ranges</u>
Low angle plunge to fold axes, 2-5º in a variety of orientations

<u>Hayward (1975) Waitakers</u>
Very open N-S horiz anticline Otakamiro Bay,
broad ENE anticline ENE plunge at Maori Bay
series of small scale horizontal EW synclines and anticlines in the south of the area.

Central and eastern Auckland

Morris, 1983 (Musick point)

ECBF

NNW-SSE trending anticline about 1.5-2km

Refolded so axis plunges gentle N and gentle S, verges W

Bed strikes N-S, dips E and W

Wavelength 50m to several hundred metres

Very widespread soft sedi slumping/isoclinal folding gives downslope SSE movement

Kink folding

Codling (1970) . (mission bay -orakei)

ECBF Broad- low anticline, shallow SSW axis

E of Orakei Basin, NNE-S dips up to 80°

Geelen, (1973) Wait Gp, N Manukau coastline

Folding in Wait Gp

Waikowai-Pukeha Ck-NNW-SSE trending major regional anticline. Minor folds parallel or perpendicular to it, plunge NNW or SSE, vert AP, verge E. Onehunga SW-NE trend folds. Blockhouse Bay WSW-ENE, W-E at Opua as far as little Huia tend to verge NNW

Pukeha- Taylors Bay-SE plunging folds10-50°SE some NW. NNW folds then ENE folds

Taylors Bay-Wesley Bay-fold verges NW, trends WSW-ENE, NNW trend pre ENE

Wesley Bay-Cape Horn-NNW trend foldplSE some folds trend WNW others NW, pl 10S

Cape Horn-Duck Creek-WSW most folds, some NNW

Duck Creek-Flounder Bay

Flounder Bay-Green Bay--NE-Etrending folds

Green Bay-Oatoru Bay ESE trend, 20ºWNW pl

Oatoru Bay-French Bay- NNW folds pl 15ºS-!5N

French Bay- Davies Bay-NNW folds dom ESE less in NE and ESE_E folds dom in SW

Davies Bay-Little muddy creek NNW trending folds, but dom ENE trend

Little Muddy Creek- Big Muddy Creek-SSE trend 5-10Seplunge, but dom is WSW

Big Muddy creek-Mill Pt-WSW-ENE trends

Mill Pt- Cornwallis Beach-E trends

Cornwallis beach-Kakamatua Stream-

Kakamatua Stream-Kaitarakiki Point- NNW trends

Kaitarkiki Point-Little Hunua-ENE trends

Manning (1983) N Manukau Coast

Open gently NE-SW plunging symmetric upright folds. Subordinate open-NW fold

Tejaksuma () Beachlands

Axis trends NW-SE, plunging NW, assym syncline with west limb dipping at 5ºE and east limb dipping at 27ºW

Simpson () East Coast engineering geol
Noted presence of simple and complex zones
Complex, open-tight folding, gently plunging fold axes N,S, SW,SE and W
Takapuna, N-S fold post NE-SW fold, flex slip

Gulf and islands

Milligan-Geophysics of Rangitoto
Dom fold axis in greywacke is plunge shallow 350
Major syncline bounded by Motutapu and home Bay Faults. NNW trending faults and folds, anticlines flank both sides.

Joints, clastic dykes etc

South Auckland

Boedihardi (1990) Whitford-basement fractures

Fractures NW most dom, NE (filled with quartz-chlorite), and NNW (thick gouges assoc)

Berry () ManukauLowlands

Park-Estate to Drury- strong fracture set ESE, secondary set NNE, large fracture zone oriented NE, strong frac set in volcanogenic grit ESE
Hingaia Bridge-Bottletop Bay NE trending major fracture zone

Wylie,1989 (Redoubt Rd, SOuth Auckland)

Wide spread of Joints, mod-steep, most steep
Largest clusters NE strike, steep-vertical
EW strike/steep-vertical

Tilsley, 1993. (Howick-Alfriston, Whitford)

Most steep-vertical
Strongest trends parallel faults
Largest clusters NE strike, steep-vertical
N to NNW trending joints mutually offset/truncated by ENE trends.

North Auckland

Mcmanus, 1981 (Albany to paremoremo)
WAITEMATA GROUP
Most common structure in the area, NW-SE and SW-NE most common, often 2 steeply dipping sets.
Open, closed, limonite filled
Parallel to or oblique to structures
Stereonet shows most NNW/steep

Jugum (2000) Timber Bay (North Wait Basinequiv ecbf)

Notes clastic dykes- No readings

Swain (1993) Leigh

Joints in Waitemata Gp ENE trends (reactive. Waipapa trends)
NNW-SSE
NNE-SSW (strongly represented) The above three all parallel faults
NW-SE veins age progression NNE to ENE to NNW (consistent with NW to NE change in extension in Miocene) This in Cape Rodney
Pakiri has NW, ENE, NE

Ti Pt Basalt clastic dykes 150º/72ºW(Dyke), 114º/64ºW (clastic dyke)

West Auckland

Pohlen (1934) Mid Waitemata County (west Auckland PiHA,Titirangi, Hobsonville, Muriwai

WAITEMATA GROUP

New Lynn two joint sets, N-S and E-W

Hayward (1975) Waitakeres

14 dykes in Waitakere Group 040-010º/SE, one 170º/E

12 dykes 040-120º/10-48ºS

Rose plot of 153 dyes for whole of Waitakeres has 2 main clusters of strikes 1) NE-E 2) N-S, these parallel major fault trends

cf Tokatea- Black has 2 main directions in bosses dykes and sills: NNW/ENE (main struc trends of Northland.

George (1993) South Waitakere ranges

In Piha formation basaltic andesite dykes 5-50cm wide, 10m long, 5-40º dips no strikes mentioned

And sedi dykes 30-100mm wide 60-90ºdips (no strikes)

Joints steeply dipping (more than 70) Dom sets trend N, W and NNE

Central and eastern Auckland

Manning (1983) N Manukau Coast(Blockhouse Bay to Mt Roskill)

Calcite fill on fault planes NNE-NE faults

Sibson (1968) East tamaki

2 major joint sets are perpendicular to one another, two minor sets 60°

he claims minor 'settling' folds are the cause and parallels major joint sets. Orientation??

Tejaksuma () Beachlands

Joints common in ECBF rare in Quaternary

Systematic joints NW and NE trends, high dip-more than80

Rare joints in quaternary are NW and show same stresses on Wait Gp and Quat

No tectonic bedding parallel shear zones in the Waitemata Group at Beachlands

Parvis Namjou (1996)(Hydrology of Mt Wellington/Peach Hill)

Joint sets in Greywacke at Peach Hill mostly NE-ENE/mod SE or steep NW

Some NW-NNW/steep NE

Joint sets at Mt Wellington NW-WNW/steep-vert NE and SW

And N-NE/shallow (approx 10º) or steep (80-90º)SE and NW

Simpson () East Coast engineering geol

Noted presence of simple and complex zones

Joints Mostly very steep to vertical: strike N,S, NE, SE, joint-bed perpendicular

Simple domains-normally two orthogonal sets and two less well developed sets at 45° to others, complex domains, as for simple domains OR parallel fold axes OR highly faulted zones up to 9 sets, dominant set oblique to bedding at 20° angle

Most joints affect a single bed.

Veins, NW, NNE, weaker NNW and ENE, dips more than 70°
Veins commonly 2 orthogonal sets in sandstone

Morris, 1983 (Musick point)
Mean strike of joints 095º/vertical
Joints in sandstone 330º strike
Joints in Parnell grit 320º strike (wider and more persistent)

Bedding parallel clay seams due to flex slip folding.

Crosscutting relationships

South Auckland

Tilsley, 1993. (Howick-Alfriston, Whitford)
ECBF: NNW fault crosscut and offset by ENE trending faults
N to NNW trending joints mutually offset/truncated by ENE trends.
NS to NNW Topo lineaments crosscut and offset by ENE lineaments

wiegel (1978) port waikato
Huntly, Ngaruawahia Te akatea area
NE trending Fault truncates NNW-WNW strike
Folding in Waitematas pre NNW fold?

Boedihardi (1990) Whitford-basement fractures
1)qtz fibre striations, on normal, reverse and strike slip,
2)qtz cct prehnite,
3) Gouge and scratch striations
NW and NE trending faults post date E-W trends
NE-SW strike slip truncated by NW reverse

Berry () ManukauLowlands
Slump folding first ENE-E trends possibly with assoc 040 and 130-110 trnding small scale normal and reverse folds
Refolded along NNW folds
NNE trending folds last fold phase
NNW-NNE trending faults- steep normal
Then ENE normal faults crosscut folds,

wise (1999) Wairau North Fault
In Manukau block N faults offset E faults
In the Hunua block, East faults offset NNW faults,
But in Hunua block there is no evidence for Pleistocene movement on NE-E fault but evidence for movement on some NNW faults (eg Wairau North Fault).
However, most prominent set of topo lineaments are E_W and they cross Mesozoic-Pleisto boundary, and may have Quat movement.

North Auckland

Davidson, (1990) (upper Harbour)
Upper Waitemata ECBF,
n-s isoclinal folding predates open EW folding, EW more common
folding only in Miocene, not Pleistocene

then faulting 1)thrust EW/30-50ºS assoc w EW folding
2) NW/small displacement faults
3) NNE/50-80ºS normal and reverse, normal more common.

Alldred (1980) wenderholm-orewa

1) Slumping
2) EW strike/N +S dip and NS strike/ E +W dip normal faults
3) Folding
4) Conjugate normal ENE and NNW

Steep reverse reactivated as normal

Also has 1) thrust packages early
2) subsequently folded and thrusts reactivated as normal (Folding simple buckling with NS compression)
3)conjugate normal 4) Tilting 5-10°W

Christie (1986) Manley

Three phases of deformation:

13) Low angle east- west faults (normal)
14) E-W faults (reverse and folding some steep extensional faults
15) Low angle EW striking normal faults

Swain (1993) Leigh

BASEMENT

1) Broken Formation
2) Sub isoclinal fold
3) Chevron folding open NW folds
16) Prehnite veins
17) Pressure solution
18) Veining qtz albite-prehnite (Synchron w NW folds)
19) Chevron NW plunging folds
20) Black ultracataclasite layers.
21) Slide plane at Ray Rock
22) Late cret ext blockfaulting NNW-ENE trends
23) Late veining-prehnite, qtz-chl-cct
24) Striations
25) En echelon veins Dominant NW-SE compression, minor NE compression normal dip slip arrays.
26) Kink folds and thrusts NW-SE compression
27) Joints in Waipapa
28) Joints in Waitemata ENE trends- reactivation of Waipapa,

CAPE RODNEY

2) NE trending ridge-trough pair (unconf. Surface shape
3) NW-SE compr and thrusting
4) Crush zones dip shallow-mod NW cont from basement (prob part of NW compression
5) Deformed Ray feeding holes (NE elongation
6) Faults normal three sets EW, NNW, NNE all parallel joints
7) Joints as above plus NW veins

Pakiri

1) 168º strike on major fault (reactive. Basement, some mod S dipping thrusts
2) Joints and veins NW, ENE, NE

3) Folds NE-SW trending axis (NW-SE Miocene compression)
   Tight recumbent thrust with fold, fold axis shallow SSW

Swhite (1989) Redvale Quarry-Allochthon (Mahurangi lst)
1)Low angle transcurrent simple shear (NS sin or E_W dex
Synchron E plunging folds and clastic dykes (no orientation mentioned)
2) EW ext faulting,1st w breccn then cct dep
Synchron N-S trending folds and E tilting
3Thrusting from E

4) Penetrative transcurrent shear system
   Synchron compression from N to give large recumbent fold

Central and eastern Auckland

Geelen, (1973) Wait Gp, N Manukau coastline
crosscutting in Wait Gp
Waikowai-Pukeha Ck-
Pukeha- Taylors Bay-WSW faulting post SE plunging folds
Taylors Bay-Wesley Bay-NNW folds then ENE fold then ENE faults
Wesley Bay-Cape Horn-
Cape Horn-Duck Creek-
Duck Creek-Flounder Bay-soft sedi slumping from N then EW folds(related to slump?) then NE SW trends
Flounder Bay-Green Bay-
Green Bay-Oatoru Bay Oatoru Bay-French Bay-
French Bay- Davies Bay-
Davies Bay-Little muddy creek
Little Muddy Creek- Big Muddy Creek-
Big Muddy creek-Mill Pt
Mill Pt- Cornwallis Beach
Cornwallis beach-Kakamatua Stream
Kakamatua Stream-Kaitarakiki Point
Kaitarkiki Point-Little Hunua

Manning (1983) N Manukau Coast
NNW folds post NE makes dome and basin

1) slumps 2)NS thrusting low angle faults 3) folding (Syn-post thrusting)in disrupted domains 4) folding on NE axis assoc with faulting5)NNW axes folding 6)faulting NNW

Morris, 1983 (Musick point)
WAITEMATA GROUP

1) Slumping etc
2) NNW thrust-conjugate sets
3) Folds, kink, brittle, some cut by thrusts in diagram (though he says folds and thrusts related by orientation, but apparently thrusts first)
4) Faults EW trends and NE trends
5) Large scale doming
6) Joints 4)5)6) probably contemporaneous
7) Concretions
8) Calcite veins

9) Ptygmatic veins
10) Uplift and erosion

Stress/strain axes

South Auckland

Wylie,1989 (Redoubt Rd, SOuth Auckland)
Normal- ext NW, compression NE
Conjugate normal as above
Reverse gives compression WNW
Most common NW extension Joints give NW compression most common

Tilsley, 1993. (Howick-Alfriston, Whitford)
Conjugate normal σ1 shallow-mod SW
σ3 mod NNW

Boedihardi (1990) Whitford-basement fractures
ENE directed sub horizontal compression in greywacke

North Auckland

alldred (1980) wenderholm-orewa
Faults give 083º/04º I, T 353º/04º Wenderholm-Waiwera
185º/08º I, tension 095º/00º "

tension 002º shallow or 064º shallow Waiwera to Cooks

Tension348º or 062º shallow Stingray to Hadfields

Tension 326º or 040º Hadfields to Orewa

NOTE 2 SETS FAULTS MUTUALLY OFFSETTING
ORTHORHOMBIC AXES DIFFERENT FROM ABOVE

Has a whole lot of different axes without really spelling out where he got them from

Christie (1986) Manley
Tension axes from conjugate faults
N=28, contoured plots
Give maxima 020º/20º, 333º/15º, 295º/15º, 215º/07º

Daly (1988) te Arai-leigh
Mild deformation with NW-SE extension which persisted –Quaternary (Ti Pt Basalts)

Swain (1993) Leigh
BASEMENT
NW-SE compression dom
Minor NE compress

Cape Rodney
Ray holes elongate NE

NW to NE change in ext in Miocene

Swhite (1989) Redvale Quarry-Allochthon (Mahurangi lst)
conjugate faulting gives 10º/270º C, 45º/045º T, 15º/175º I
15º/180ºC, 30º/290º T, 45º/060º I
40º/165º C, 45º/290º, T, 35º/040º I

West Auckland

Davidson, (1990) (upper Harbour)
Has thrusting with E-W intermediate axis, N-S compression, vertical extension, assuming dip slip

Central and eastern Auckland

Morris, 1983 (Musick point)
Compression 095-275º (From mean strike of joints 095º/vertical)
Extension 005-185º
Vertical intermed

Folding and thrusting gives compression axis 5º/240º
Extension axis 85º/030º
Intermed 5º/170º

3d orthorhombic normal faults extension 337º/01º (or more likely 319º/01º)
compression 068/01º

Topographic Lineaments

South Auckland

Tilsley, 1993. (Howick-Alfriston, Whitford)

Straight streams and ridges, topographic depressions, straight steep scarps and cliffs show three orientation sets:

N-S to NNW-SSE
NNE-SSW to NE-SW
ENE-WNW to E-W

Reflects basement fracture and fault orientations

Boundaries of whole hill block s NNE in north , NNW in south so the whole block has a structural control.

ENE trends especially associated with the Polo Lane Fault, often offsetting N-NNW and SE trends

On the map, in Brookby, NNE trends are longer lineaments than E-W and ENE trends.

Ridges often follow antiforms and streams often synformal.

Geophysically detected basement faults form fractures and lineaments in overlying Waitematas.

Miller (1996)South auckland(mangere)

Possible NW-SE alignment if Crater Hill-Wiri-Puketutu
And Hampton Park- Otara Hill- Mclennan Hills)
Possibly NW-SE tension controlling lava.

Rout-Geophysics of Wiri and Papatoetoe volcano

The three Wiri Group volcanoes lie on a line bearing 050º (Wiri is youngest, don't know relative ages of McLaughlins and Ash Hill, but distinct ages.)

There is no geophysical evidence for major basement fault causing this alignment. (Although it is possible that they are on a small offset fault or a strike slip fault, which would have little difference in elevation of greywacke either side of it.)

Brown (1937) clevedon area

NE-SW and NNW-SSE (western boundary of Hauraki Graben is NNW)

wise (1999) Wairau North Fault

N-NNW bounding faults: Coromandel and Hunua are elevated horsts, Firth of Thames/ Hauraki Plains and Manukau Lowlands are grabens. Auckland city midway-higher than the lowlands, lower than Hunuas

Several faults transverse to or parallel to main trends, (ENE and NNW resp.) subdivides Hunua block, causing tilting to N, NE or E., and forming fault angle depression. Series of sub parallel folds trend ENE, Parallel to transverse faults

Wairau North Fault is prominent rangefront through Hunuas, downfaults greywackes and forms W. N. Fault angle depression (filled with Pleistocene to recent sediments.

There are also prominent East trending lineaments (faults/other defects) may offset rangefront.
Most prominent set of lineaments are East-west set, maybe suggesting quaternary movement (cross Mesozoic/Pleistocene boundary)
Also a prominent N-S set , parallel to Wairau North Fault

North Auckland

Mcmanus, 1981 (Albany to paremoremo)
WAITEMATA GROUP
Asymmetric valleys (possibly faults) aligned with regional NE and NW trends
Lineaments and faults have NE-ENE and NW trends.

Johnston(1999) Geophysics of the Albany Conglomerate
Air photolineaments predominantly N to NNW and NE-ENE with a few SE
(c.f. faults in the area are NE)

West Auckland

Davidson, (1990) (upper Harbour)

1) NNE-SSW to NE-SW trend- parallels late stage NNE-SSW faulting. Some creeks follow it.
2) E-W parallels bedding and folding but also E-W trending thrust faulting.

Hayward (1975) Waitakeres
Eruption along two NNW trending lines
Eastern belt 12km long, 2km wide, 330°strike of belt, coinc with major fault, downthrowing Manukau subgroup 100m with respect to Waitemata Gp, andesite intrusions, dykes and volcanic neck/craters along the line.
Western belt, along coast, 345° strike on line with 8 craters and volcanic neck complexes
Lineaments interpreted as faults, NE and ESE strong pattern

Central and eastern Auckland

Sibson (1968) East tamaki
NNE to N (014) alignment of vents Church cone-Otara Hill-Green Hill-Styak's Swamp
This parallels spurs on western flank of Maungamaungaroa Range and reckons there's a block fault origin for hills and therefore fault feeder for vents
He reckons minor alignment 105 for Pukewairiki- church cone and east trend in Otara vents and suggests a major-minor basement fracture intersection control on rising magma.

Affleck-Geophysics of lava flows in central Auckland Isthmus

Ridge in Waitemata Gp runs NNE-under Epsom (divide between ancient Rivers of Waitemata and Manukau

NNE Three Kings to Mt St John then splits in three, main ridge continues to Remuera, second to Mt Eden and the third runs south to Alexandra Park

The ridge between the Waitemata River and the Manukau River were previously modelled as NNE with a NW splay.

The gravity model shows the NW splay continues only 700m from the main ridge
On SW side, steep sided Waitemata Ridge, with two palaeovalleys divided by a spur under Alexandra Park.

(This is like palaeotopolineament?)

Tejaksuma () Beachlands
South of Beachlands the topography is controlled by fault angle depressions.
Beachlands is small, relatively low structural block

Thompson (1975) Sedi topics- Waitemata HArbour
Steep south facing, gentle north facing slopes on valleys with Lucas Creek and Hellyers Creek- possible structural control
Harbour is broad and shallow with main channel on north side. In interglacial times the Waitemata river went out to sea west of Great Barrier Island.
The Waitemata surface is very irregular with precipitous buried slopes like cliffs, and is locally overlain by 100' thick sediments.
"Waitemata River" falls steadily from 70m below harbour datum near Greenhithe to 90'below off Kauri Point to 102' below at Northcote and 115-129' below off North Head. At Te Atatu maybe 100' below and possibly an infilled valley, sloping shorewards.

France (2003) Domain volcano
Domain central crater is oval and elongate N-S
Redhill and Domain volcanoes on a line NE-SW (Redhill tuff ring also elongate NE-SW) but the two are distinct, different magma bodies.

Franklin-Orakei Basin
NE alignment of Mt St John, Mt Hobson, & Orakei Basin/Little Rangitoto
NNW alignment of Mt Eden and Te Pouhawaiki
But all are distinct , separate chemistry/events.

Searle (1961) Auckland volcanic field
Alignment of centres and vents in individual centres in a N direction (cf NNW?)
Shoal Bay- Pupuke 010º
Mt Eden system (at least 3 vents) Training college dyke + cinder pit, Grammar School shatter zone 010º
E Tamaki volcanoes 013º
Mt Wellington-Purchas Hill system 005º
Little Rangitoto- Orakei Basin 015º
Individual vents alignment prob more significant
Mangere Mt-Mangere Basin NNE
Ihumato-Otuataua-Pukeiti-NNE
Vents of Mt Gabriel NNE

Pleistocene marks palaeovalleys/tributaries of ancestral Waitemata River in Auckland block. South Auckland block rel downthrown and therefore has Plio and Pleistocene cover.

N part of Manukau Lowlands fault angle depression with downtilted cover of Whitford Block against Manukau Block (Pliocene?)

Palaeocurrent direction Indicators

North Auckland

Alldred (1980) wenderholm-orewa

Towards ESE in Pakiri Formation (SE-ESE)
Towards SE in ECBF

Lipman 1993 (Albany conglom-wnw of albany)

Imbrication in pebbles gives NW to SE or NNW to SSE

Sprott (1997) (Albany conglom-wnw of albany)

NNW to SSE in Albany Conglomerate

Gregory (1966) Whangaparaoa

Predom from NW (290-300º) in early stages (possibly swinging to 230º in later stages
Whangaparaoa grits emplaced by N or NE flowing submarine volcanic mud flows
Turb at Whang/Takapuna suggest almost horizontal deposition where currents had lost their ability to erode (axial basin) SE and SSE flowing currents.

Basin Shape
Coastline flanking basin to E, traceable through islands of gulf- Maraetai-Tiri Tiri Martangi-Kawau-Tokatau Point: rugged, varying conditions, limestones in some places, (Motuketekete, Motuihe), greywacke conglomerates elsewhere (Kawau, Tiri) Fosssiliferous sst elsewhere(eg Oneroa)
Rapid subsidence
West margin of basin- chain of partly submerged partly sub aerial volcanoes. Grits emplaced by N or NE flowing mud flow from volcano
Whangaparaoa- Takapuna very flat lying axial basin could be 4000ft deep basin
Deep origin, but fossil material shows proximity of land
Turbidites flow axially along the basin SE and SSE ie sedi provenance NW of here
W margin dom by volcanism, some grits seem to have come in from SW-much organics-provenance shallow sea.

Johnston(1999) Geophysics of the Albany Conglomerate

Flow towards SSE, (sim but not identical to ESE and SE of Waitemata group)

Central and eastern Auckland

Morris, 1983 (Musick point)

Palaeocurrent towards ESE
Isoclinal folding in slump beds have palaeo slope down towards SE 123º or 128°

Depth to basement

South Auckland

J Allen (1995) North Manukau Lowlands(geophys)
3Karaka oil bore 650m deep and did not strike greywacke (79000E,52000N)
Gravity shows general deepening to the south and the west
northern profile (running NE-SW) has 250m deep in E then to 1900m then rises to to 1200m in west
Southern profile (running NE-SW , almost through Karaka borehole) has 635m in East and 1835m in west
Eastern profile (running N-S) has a gradual decline to south- approximate 5° dip on greywacke surface, poss with increasing throw to west on Drury Fault
Borehole on Awhitu Peninsula hit GW at 349m BSL- ARC bore permit no274)- Waterhouse 1989

Boedihardi (1990) Whitford-basement fractures
Whitford area depth to greywacke ranges 25-95mbsl.(He shows cross section through Maltby (gw at 55bsl shallowing south to –40bsl)

Anderson (1977) NW Manukau city gravity
Wait Gp infills Deep basin in greywacke, steep sided, fault controlled ridge in centre
Depth to greywacke in deepest part of basement is a little over 300m bsl, and at the basement ridge it is about 200m bsl

Tilsley, 1993. (Howick-Alfriston, Whitford)
Basement at surface in Hills
Borehole data in E of inferred Drury Fault (R11849681) is 53m
In W of inferred Drury Fault (R11 820685) is 262m

Ormerod, 1989 South Auckland

Depth to basement increases to the west across the Pokeno Fault
List of borehole depths/locations provided Ranges +80 above sea level to 810m below sea level.
80,-343, -470,-125, -179, -81, -75, -728, -535, -475, -309, -810
Most boreholes North of Waikato fault not deep enough to encounter basement
East of southward extension of Drury fault, basement closer to surface, west of it thicker Te Kuiti and Waitematas.

North Auckland

Alldred (1980) wenderholm-orewa
7 boreholes through Waiwera 364-422 bsl(most 364-396)
ENE striking Waiwera fault at N end of Orewa village downthrows basement 50m to north.

One borehole in North Orewa has basement at 857m

Due to 470m downthrow to south on Stingray Bay fault (between Waiwera and Hadfields-north end of SRBay is fault)

Orewa borehole also encounters allochthon, including Mahurangi Limestone at 827-860mbsl.

………………………………………………….

Daly (1988) te Arai-leigh

Published data has greywacke increasing in depth E to W, possibly 4km deep on the west coast.
In this area GW outcrops at Te Arai Point and Leigh (Block Faulting) (Late Oligocene with Hauraki gulf formation)

Greywacke has irregular surface
Mostly less than 200m bsl.
NNW trending fault in west downthrows basement westwards to 500m bsl
ENE trending fault in South downthrows basement southwards to 200m bsl
NE -ENE trending postulated fault in Southeast downthrows basement southeastwards from 100m asl to100m bsl

Significant amount of basement is above sea level but has Waitemata Group cover.
Greywacke is sometimes more than 100m above sl
Where above sea level in S and E of area, it is fault controlled.
Greywacke surface slopes down to west at 3°, so Waitematas thicken westwards.
A further fault controlled thickening of up to 300m occurs in the west of the area on a fault that dips 20-40°W
Most of the greywacke has less than 50m of covering of Tertiary.
At Mangawhai max depth to basement is 700m.

Miller (1996)South auckland(mangere)

2km north of Mangere Mountain borehole has still Waitematas at 500mbsl

Central and eastern Auckland

Morris, 1983 (Musick point)
guessed at approximately 1000m (quoting Anderson 1977)

Williams (2003) Gravity of Auckland area
Depth to basement (Wairoa north fault 500m+/-100m (boreholes/gravity)
Thickness of basement is 4-6km (this change in velocity structure may be geophysical basement ie metamorphism leads to more uniform composition, eg Murihiku and Waipapa more similar at this depth)
Across Auckland, if there is a dip on the basement it may be towards the east- possibly due to faulting.

Very few deep boreholes in Auckland summary below

Borehole no	Location	Grid ref	Depth to basement (mbsl)	Greywacke terrane	source
1	Oratia	R11/558777	485	Not doc	W.Russell pers comm..2002
2	Grahams Beach	R12/564584	340	Murihiku	Waterhouse 1989
3	Mt Roskill	R11/644755	592-622	Not pen	Edbrooke et al 1998
4	Mt Eden	R11/675789	More than 590	Not pen	Isaac et al 1994
5	Orewa	R10/617127	Less than 876	Waipapa	Schofield 1989
6	Karaka-1	R12/789519	Less than 615	Murihiku	Isaac et al 1994
7	Ardmore	R11/883632	Less than317	Waipapa	Isaac et al 1994
8	Ardmore	R11/869622	Less than 322	Waipapa	Isaac et al 1994
9	Waiwera	R10/629163	424	Waipapa	Waterhouse 1968

Eccles (2003) Geophysics of jma

Depth to basement (Wairoa north fault 500m+/-100m (boreholes/gravity) Quotes same boreholes as Williams above.

Orewa 860m; Waiwera 389m; Waiwera 424; (all Waipapa), Oratia 485m (unidentified terrane); Mt Eden 610m min; Mt Roskill 590m min(intercepted Te Kuiti Gp therefore probably not far from basement); Grahams Beach (Awhitu Peninsula) 422m(Murihiku)

Gulf and islands

rawson(1983) Hauraki Gulf-grav,seis and mag

Ranges from 70m bsl on high portions

In western depression in north 100om depth and 1200m in south

In central depression 350m bsl in north to 1200m bsl in south

Fergusson (1974) Velocity struc. of seabed Leigh- Moko hinaus

Basement has depths greater than 2400m

Most of region Leigh-Moko Hinaus greywacke basement is approximately 100m below sea bed, locally 250m.

From Leigh, (greywacke outcrops on the shore) top surface of greywacke drops to 1.5km below seabed over 15km. Greywacke again outcrops on the north end of great Barrier Island.

A marked structural change occurs about15km from Leigh- probably a fault.

To the south the upper surface of the Greywacke is 1.5km below the seabed, 10km from Leigh. There is a marked change in vertical position of over 1.5km in a distance of about 5km-structural change

Increase in depth to basement 26-30 km from Leigh may represent a downthrown block.

Greywacke surface dips down to northeast of Leigh.
The greatest thickness of sediments on top of the greywacke is 1500m, of which700m are unconsolidated
Over most of the profile approximately 100m is unconsolidated.
Block faulting has led to a depression about 5km wide and several hundred metres deep.

JMA

<u>Ormerod, 1989 (south auckland)</u>

Dunite alters to serpentinite:
Involves a 25% density decrease
& 1500% magnetic increase

Smooth 26km wide 100 gamma high, NNW trend.
Can be up to 700 gamma elsewhere in NZ
Exact shape and axis cannot be determined because not known how close to surface body is and also how altered it is. Magnetic anomaly is produced as a combination of these factors.

<u>Woollaston, 1996 (auckland region)</u>

20km N of Auckland (and East of the peak JMA),discrete irregular lensoid bodies of Harzburgite and dunite. Serpentinite up to 24000cu metres. Two thirds of the bodies associated with faults. If they were emplaced by faults it was probably in the Miocene or later. No magnetic effects were observed over these outcrops.

Some consider these bodies to be part of the JMA (eg Sibson) pre late Eoc (Permian)
Some consider them Northland Allochthon Cret-Oligocene or younger

Quarrying shows they are rootless.
Could be fault bounded bodies emplaced from beneath.

JMA is pre Alpine Fault (end Olig)

2-5km wide JMA sidesteps sinistrally at Whangaparaoa.2-5km wide anomaly at bend, 055 strike.

Depth to JMA is 1580+/- 100m.
Modelled as a dyke shape gives a depth to base of up to 25km depth
Modelling shows some slivers of JMA causing repetition of the anomaly.
Could be due to splay <u>or</u> be displaced in association with the sinistral bend <u>or</u> complex dip slip.

The rocks of the JMA have rotated. (magnetic field shows this)
Whole rotation of 110-160° anticlockwise
Some of this (25°) explained by anticlockwise body rotation of NZ in late Cret-early Tertiary opening of Tasman
Therefore 55-135° anticlock rotn still unaccounted for.
Probably post emplacement but still possibly pre-syn emplacement.
Possibly rigid body rotation, or possibly rotation of SEGMENTS by simple shear.

Low gravity associated therefore some serpentinisation.

<u>Rodgers (1966)</u>

nodules in volcanics may be ultramafic Dunn Mt in basement.
Shoal Bay, Smales Quarry (Pupuke), Nth Head Mt Cambria, Stevenson's quarry Ramarama (Franklin Basalts), Roose's Quarry, (Bombay Basalts), Kirikiripu(Raglan),

Ngatutura Pt (9 miles S of Waikato Heads), Bridal Veil falls (Raglan) Todds Quarry Arapohue

J Allen (1995) North Manukau Lowlands(geophys)
JMA runs through East of the area

Rout-Geophysics of Wiri and Papatoetoe volcano
JMA runs NNW-SSE through the area, 25nTkm-1 on western flank, 65nTkm-1 on Eastern flank

Sibson (1968) East tamaki

Included blocks of basement in Pukewairiki tuff-semi schists with signs of cataclasis and high specific gravity 2.88- also highly zeolitised sst

Sibson claims similarity with Searle's inclusions at St Heliers as retrograde metamorphism of post Cret basic/ultrabasic intrusion (or Dunn Mnt/Matai) shearing maybe assoc with frac zone into which it's included.

Also some??Mahurangi limestone or Te Akatea siltstone

Williams (2003) Gravity of Auckland area

Decrease in gravity towards west over JMA. May not be a deepening of greywacke basement westwards but because Waipapa rocks east of JMA are denser than Murihiku rocks to the west of JMA

Actually, gravity increases both westwards and eastwards away from the JMA. From the west (where basement is Murihiku) to the JMA gravity drops 3mgu/km-1, (although the gradient steepens markedly very close to the JMA); the JMA then covers a distance of approximately 20km in the Auckland Isthmus. To the east of the JMA, the gravity is a step higher than in the west (where basement is Waipapa), but also climbs eastwards, away from the JMA, so the gravity is highest in the east. (Waipapa gravity in east is 70gu higher than Murihiku in west)

The regional gravity field strikes NW-SE which is similar to, but slightly oblique to the regional strike of the greywacke terranes.

Regional gravity field defined in Waipapa of Hunua block and Murihiku to the south of Auckland. This is the subtracted from the local field to give the local anomaly.

There is a blocky anomaly over Auckland central.(this also coincides with the JMA region. Three possibilities- due to variations in depth to basement boreholes don't agree)
-due to faulting (would require greater offset than 4.7km on the Wairoa Fault if it were the sole cause.
-due to the presence of a discrete body.

Using gravity to model a discrete body under the JMA:
-NW-SE strike (parallel to the regional strike of north Island structure, basement terranes and JMA
-steep eastern boundary coincides with peak JMA
-flat upper surface with 500m Waitemata Group on top
-eastern boundary is steep-vertical NE-SW strike
directly above where two vents erupted exotic fragments of ultra-mafic (unaltered) and sedimentary rocks comparable to

Dun Mountain and Maitai Terrane (sedimentary cover of Dun Mt) (the steepness of the boundary may be why xenoliths only occur here.) (maybe structural correlation of vents with Dun Mountain body)(also coincides with peak JMA)

It seems that the body has a shallow west dipping western contact (with Murihiku) and a steep east dipping/near vertical eastern contact (with Waipapa). Gravity shows the body finishes to the south (southern boundary dips south, more shallowly than eastern boundary)(anomaly decreases southwards to 0). Possibly serpentinised. Gravity anomaly and JMA also narrow to south,

Over the area of the gravity modelled body the JMA is wider and more complex than to the north or south

The modelled body is similar in size and shape to other pods of Dun Mountain Ophiolite Belt in the South Island

Not deemed connected with the Auckland Volcanic Field, even though coincident with it. Depths of 500m +/-100m not coincident with Mantle uprising (or eg Horsepool et al, or Sporli and Eastwood's ellipse)

In south island fault zone up to 4km wide between Dun Mt and other terranes and there is evidence for dex strike slip as well as dip slip movement. Dun Mt geochem suggest originally deep sea environment near extensional forearc setting. this then uplifted and accreted onto the inner wall of a west dipping subduction zone. (Waipapa is accretionary prism (formed in trench and trench-slope basins), Murihiku (Formed in arc-trench gap-frontal arc basin)relatively less deformed.)

In Auckland don't know nature of Murihiku-Waipapa contact or Murihiku- Dun Mountain-Maitai-Waipapa contact

<u>Eccles (2003) Magnetic study of JMA in Auckland.</u>

Gravity-magnetism sporadic along JMA

JMA offset in only a few places.

South of Whangaparaoa a 6km offset was interpreted as fault offset by Sibson and Hatherton: 460km offset on Cenozoic Alpine Fault: JMA has gentle 'Z' curve through NZ consistent with continental scale deformation.

Dun Mt ophiolite –serpentinised melange with large unserpentinised massifs. (ie gravity and magnetism varies)- part of deep sea extensional forearc basin (Maitai- full ophiolite sequence unconformable on Permian ocean floor)

Nixon (1978), Oremrod(1989), Jukic (1995) all observed +ve gravity anomaly connected with JMA

Allen (1995) no measureable anom on JMA

Milligan (1977) had –ve gravity to magnetic anomaly coincidence,

General History

Accretionary complex with main structural trends NNW-SSE, accretion of terranes and Rangitata Orogeny

East of Hamilton Waipapa-Murihiku contact exposed: no Dunn Mt present

Adjacent to Waipa Fault at Pio Pio, Dun Mt Serpentinite present (intrusion of ultramafics into overlying seds)

N-NNW and E-ENE faulting late Cret-Palaeocene extension (Rifting of NZ from Gondwana

Convergence in Miocene reactivated structures as reverse.
Kaikoura orogeny caused cessation of volc/sedi in Waitematas15ma
Then Auckland in extension in back arc situation due to TVZ led to blockfaulting 7-2ma, youngest faults in Auckland N-S and E-W extension.

Lava flows from Mt Albert, Mt Roskill, Three Kings and Mt Eden all coincidentally run parallel with JMA

Xenoliths from St Helliers- amphibolite metamorphic facies, ultramafic parent, varying degree of schistosity, veining, folding, faulting-cataclasite, Permian age on fossils (same fossils found in Maitai terrane.)
Source is fracture zone in basement , and explosive eruption occurred at depth (an occur at up to 1km depth)
Only a few volcanoes have such xenoliths (St Heliers, Taylors Hill, Little Rangitoto) consistent with basement frac zone which could be a path for water and/ or magma.

JMA offset at Whangaparaoa Not offset as previously thought, new resolution shows it as a series of sub-parallel bodies, converging north and south of the area
Peripheral bodies are thinner, depth to top of magnetic source shallows to east
Bodies can be a)shallow (less than or equal to 400m with limited depth extent (less than 2km)).
b) deeper (more than 1km and significant depth extent (more than 12km)
bodies can dip east of west
main gradients in gravity-indicates density contrasts Waipapa and Murihiku and increasing sediment thickness to the west

Modelling of the body shows similarities with DMOB in southern syncline and with Coast Range ophiolite complex in California at junction of Great Valley Group and Fransiscan Complex

Various models for why slivers-up to 10 slivers over 40km distance

2) Could be variation in magnetisation of Murihiku/ Waipapa terrane
3) Slivers of DMOB/Maitai tectonically incorporated into surrounding terranr
4) Maitai terrane anom wide (unlikely-elsewhere 20km max also boreholes don't agree. Could be Maitai at depth)

DMOB likely locus of reactivation –serpentinite mechanically weak (only needs 10% serpentine to behave as weak)
DMOB equivalent to or coincident with major fault system, eg Livingston-Mcpherson fault system, Wairau Fault in south Island and Waipa Fault, possibly Taranaki Fault Zone. Leads to repetition with faulting. These faults active in Tertiary

Suggested mechanisms include:

Faulting sub parallel to JMA displaces magnetic material along strike of JMA, structurally thickening the Matai terrane in the centre of the study region

strike slip duplex formation of a serpentinised fault zone and melange along bounding and internal faults

anomalous block of peridotite, serpentinised margins and fault planes give the observed lineaments or block acts as an asperity during shear sub parallel to JMA

thrust repetition during accretion

Positive Bouguer anom in centre of study area may mean dense Maitai terrane within Akl basement (Williams) likely to be unserpentinised peridotite or gabbro
Lack of gravity anomaly to north may indicate DMOB is a tectonic melange

If DMOB active during Tertiary like some coincident faults along the belt, may contribute to complexity of Waitemata Group Structure. (In addition to Piggyback on Allochthon)

Hauraki Rift Formation

Possibly upper Miocene initiation (Hochstein and Nixon)
Others think Pliocene (Balance, Tearney, Davidge)
Others Pliocene-Quaternary (Brothers, Delaloye)

Daly, 1988 (Pakiri-Leigh)

Cape Rodney possibly edge: topography high on greywacke, which depth increases sharply.
Only active faults in the area are offshore in. Hauraki Gulf
Postulates late Olig fmn

Rawson(1983) Hauraki Gulf-grav,seis and mag

Hauraki gulf stretches from Matamata in south to Whangarei in north.
Structurally rift is a series of basement depressions, up to 1500m deep. Horsts reach up to 70m below sea level.
Fault scarps defining the changes in basement elevation are extremely eroded and trend NNW-SSE with zigzag development.
Basins are infilled with Quaternary sediments.

Firth of Thames-evidence of recent subsidence,
No new evidence for age of onset of rifting.

(There's a large basin NE of Hauraki Gulf: maybe part of a series of basins going up east coast of Coromandel from Tauranga to the Poor Knights.)

Possibly some ENE trending transverse faults.
Basement dips westwards

Pacific plate dips under Tauranga at NE/50ºNW at a depth of 200km, so the Hauraki Rift is outside the main seismic zone.
It still records seismic activity.

Structures have a NNW strike.(at 70° to Pacific plate) or NE trends (cf Pokeno/Waikato/Silverdale,(South Whangaparaoa) /Manukau and Waiwera faults.

In rift strucs have NNW trend(dom) and minor NNE trend.
NNW trends onshore and offshore often have throws up to 1500m.Normal NNW/40ºW (eroded scarps) at least four active :Hauraki Fault (E Boundary fault), Waitoa Fault, Firth Fault, Okauia Fault. These mostly in the south

NE trends offset major faults- possibly incipient transforms
In the south Davidge showed en echelon faulting during rifting.

Hauraki Gulf is extension of active Hauraki Depression.

Cross section structure of Gulf is as follows: In west is a fault angle depression, then a median horst and then an eastern graben.

Rift also continues to the south of Te Aroha, but becomes more complex (4 depressions)
There are 20 known geothermal springs on the Hauraki Depression.

Anom hot upper mantle beneath the region
Slightly higher heat flow in region and geothermal gradient, EXCEPT on flanks, where markedly higher (Whitianga, Tryphena, Waiwera, Huntly)

Normal faulting from sporadic seismicity (seismicity is shallow-typical of active rifts, due to anom hot rocks beneath crust)

Basement highs 70m bsl, basement lows unknown depth.
Firth of Thames has only visible fault scarps-he postulates maybe this represents only recent activity.
Gravity shows that in the northern part of the region the western depression is approx 1000m deep. (Fergusson has 1500m deep due to inferred velocity of body)
South of the area, 1200m depth to greywacke (Tearney).
Possibly the basin deepens southward

The central depression steepens southwards 350m deep in north to 1200m in south
Fault scarps in bathymetric record show the Hauraki Gulf is still subsiding in the central, offshore portion.

Depression is filled with recent unconsolidated sediments: no evidence of terriay sediments found.

East side of Gulf and faults on the northern part have volcanic intrusions.

Magnetic anomaly south of Kawau- magnetically very quiet, with high amplitude anomaly on eastern boundary fault.

Age of rifting:

Hochstein and Nixon (1979)	upper Miocene age
Skinner (1976)	late Mesozoic init, but main subsidence late Tertiary
Balance (1976)	Pliocene
Schofield (1967)	upper Pliocene
Davidge (1982)	3-2 million years ago
Tearney (1980)	less than 2 million years ago.
Brothers and Delaloye (1982)	Pliocene-Quaternary (2my or less) after late Cenozoic warping above upper mantle swell and rift collapse in late Pliocene

Backshall A Microearthquake study of the Hauraki Depression

Hauraki Depression major tect feature- 20-40km wide, at least 270km long
Hochstein and Nixon call it a Rift structure
SHALLOW SEISMICITY active rift

Greywackes (Hunuas and Hapuakohe Range on western boundary
Tertiary volcanics (N), Tert-Quat (Kaimais (S) (with gravity showing greywacke within a few 100m of surface) on East side of depression
Greywacke at sea level at Thames/Moehau
Some extrusive upper Tertiary Kiwitahi volc on W boundary of the Depression.

South of Te Aroha, active fault on Eastern Boundary. No known surface fault on western boundary.

But some faults in centre of rift.

Therefore complex tectonic structure.

EQ 5.1M-Te Aroha Jan 1972 (only substantial earthquake in the region are at a depth of 200km beneath S Hauraki Depression in subducted slab)

Microeathquakes M less than 3 need specialised seismographs- not picked up by normal network.

This is 23 day study.

In northland most eq in south Coromandel and Hauraki Plains (Hauraki rift)

Eq swarms nr Grt Barrier Island June 1953 (Eiby 1955) and nr Moko Hinaus (June 1957) (Eiby 1964)

Short term variation in activity in period 1964-1979, 76% of microeq were in 1970 and 1972

Eq swarm Coromandel August- September 1970.

12 Sept M3,7 20km N of Thames

next 42 days more than 50 shocks of M less than or equal to M3

largest shock M4.6 on 26 August

All largest eq within 20km of each other 15km east of Hauraki Fault,

shallow-all in Gulf less than 10km deep.

Apparent stress release with swarm

65% of energy released over 2x2 day periods- typical of earthquake swarm of tectonic origin

8 Jan 1972 Mainshock M5.1, 4km S of Te Aroha. Normal faulting NNW modal planes, one 336/60W, one 332/30 E over 33 days there were 213 aftershocks largest M4.1, (3minutes after mainshock)

<u>Tearney(1980) Hauraki Depression</u>

Fault angle depression, median ridge, graben (going west to east)

Firth of Thames fault throws approx 100m, Eastern Boundary Fault angle depression, Kerepehi Fault, East is Hauraki Fault, step faulted, upper scarp is 35º+/-5°, lower scarp is 65º+/-5°

Fault trends NNW, NW in N, dissected by NE-NNE trending transverse faults (up to 7km offsets

Depression may increase in age to N, No direct evidence suggesting subsidence in Nth

Relatively unconsolidated seds infill the depression prob less than 2ma old.

SEISMIC REFLECTION: Thames foreshore- at least 340m unconsolid muds, (Tauranga Gp) (from boreholes) 350m at Ngatea (Hochstein and Nixon) much greater thickness in middle of depression from gravity.

Numerous hot springs in vicinity of East and west boundaries: chemistry shows anomalously hot mantle

No deep seated magnetic anomaly

Fault throws in Gulf up to 200m in some cases

Sedi velocities compatible with Plio-Pleistocene seds (although weathers greywacke not considered)

North of Thames 90% seds are unconsolidated and therefore prob Pleisto or younger(1.8ma).
Underlying seds probably younger than upper Plio
Therefore this part of gulf is probably 2ma or younger.

The eastern graben is absent in northern offshore zone and the thin sedimentary cover may suggest younger here, or less active overall than in south.
There is no evidence for offshore active subsidence.

Rest of Northland is aseismic, but anomalously high no of earthquakes under southern part and near outer flanks of Hauraki Graben.

NNW trending zone of crustal earthquake epicentres extends from east of Coromandel Peninsula north to Moko Hinaus- activity tends to occur in swarms of magnitude 4 or less. Foci all less than 25km deep. Eiby (1971) suggests this is independent of Main Seismic region and Northland Seismic Region. He suggests close connection between location of the swarms and mapped Quaternary Volcanism.

South Hauraki Graben is 200km above Benioff zone (NE/50NW). Depression is at 75° to the strike of the Benioff zone

Active, high angle rift structure, EW section is fault-angle depression, median horst, and graben- similar in north. 20-30km wide, extending at least 220km- maybe offset by small transverse faults. Approximately 650m of unconsolidated seds in inferred fault angle depression off Cape Rodney (Fergusson)

Age of rifting,	Hochstein and Nixon (1970)-assuming connection with Kiwitahi Volcanics-Upper Miocene inception -Schofield-similar -Skinner (1975) late Mesozoic palaeograben, but structural depression late Tertiary and continuing to at least late Pleistocene Balance(1976) initial development of depression in Pliocene, in response to subduction along Indo-Pacific boundary -Upper Pliocene to Pleistocene from Schofield 1967- coarse ignimbrite boulders within conglomerate of Upper Pliocene age 12km SW of Miranda-maybe transported across depression from Coromandel Range prior to onset of Rifting/subsidence (Battey (1949) -displacement of Mid Plio Waiteariki Ignimbrite of Coromandel Range , east of Matamata by about 400m into Hauraki Depression indicates Mid Pliocene subsidence

<u>Grieg(1982) Hauraki Gulf-sediments</u>
Bathymetry of Colville channel (Gr Barrier Isl- Coromandel) .50-70m deep flat
Hauraki Gulf 40-45m, 50m in extreme north
Shallows to 25m bsl in west and south.
Drops steeply to 25m bsl in north and east.
Depths of approx 75m adjacent to Colville channel.
Most of central Gulf 35-50m- very flat (1:2000) gradient

Gulf is approximately 50km wide, Firth of Thames approx 20km wide
35m to swampy mudflats, 1:1500 gradient
Low relief except conspicuous axial high with two distinct depressions.

Hauraki Plains, alluvial pumicious sands (Hinuera Fmn)-seds derived from erosion of Mamuka Plateau, with minor contributions from Taupo and Kaimai

During last glaciation seafloor 100m below present: Gulf was a plain.
Strong gravel-coarse sand belt. Poor Knights, south to Hauraki Gulf
Finer seds either side
Rivers flowed draining lowlands to south. (Waikato River)

Sample grabs, short cores, echograms, sonar done.
Similar assemblage found in Gulf seds to present Waikato River.

Onland Hauraki Lowlands Hinuera Formation formed in Waikato River 23,900bp-19,400bp (then it abandoned its course)
Mamukau plateau TVZ rhyolites

Phosphatic deposits from lower sea level times (14000-7250bp?)

Hauraki Rift from geophysics 270km long and 20-40km wide.
Hochstein and Nixon say since Miocene activity
Cuthbertson infers S Hauraki Lowlands much younger (840,000-750,000bp)
(Cuthbertson1981: The Hinuera Formation in the South Hauraki Lowlands, Central North Island, NZ. Unpublished MSc Thesis , Waikato University)

Hauraki Depression- max depth at south Firth of Thames foreshore 1,100m, but varies 250-750m through the firth and the Gulf.
Tearney implies 90% seds are Pleistocene or younger (less than 1.8ma)
Deepest part of the depression compressive waves velocities similar to surface Miocene.

Peats in cores- Whangaparaoa Bay, 35m water depth, 45,000bp
Miranda, 30,000 bp

From 6500-fine terigenous seds, Northwards porpogation from chores and echograms.
Firth and inner Hauraki Gulf max t+2m, north Firth, approx 0.5m, some airfall

Davidge-Geophysics of the South Hauraki Lowlands
Basement structure- parallel en echelon basins, up to 1500m deep, bounded by east-lying normal faults. Basins extend from North Hauraki depression through study area to underneath the Mamaku Plateau.
1000m unconsolidated Pleistocene sediments, and mid-late Pleistocene ignimbrites (5oom thick in south)
then late Pleistocene seds (possibly 300m ignimbrites under this as far north as Waharoa)
Depression widens south of Matamata (active continental Rift)
Probably initiated 3 million years ago or less.
Horizontal crack prorogation from south

Faulting in the region is NE-SW and NNW-SSE
NE-SW- late Plio-early Pleistocene, possibly since Cret, Waikato, Pokeno Faults, large but variably vert, maybe some dextral strike slip
NNW-late Tertiary onset

Both trends- Blockfaulting of Hunua and northern Hapuakohe Ranges
Marginal Faults of Hauraki Depression NS-NNW SSE trends-also seen in active faulting/lineaments in depression-i.e. this orientation controls.

Balance (1976) and Backshall have normal NNW faults,
dex strike slip has been observed and supports the first movement from Te Aroha (Backshall) No NE-SW trend in Hauraki Depression

Gravity shows that the Hauraki Depressionin the basement is controlled by steep west dipping faults
In west , fault angle depression bounded by small east- dipping fault in the east.
Abutting a median basement ridge and east-lying graben shaped depression.
Bounded in the east by the Hauraki Fault.
Themes structure continues to Coromandel Harbour
Then to north diverges into 2 weakly developed fault-controlled basins.

O'Leary shows the presence of a line of depressions occur under the east of the Coromandel Peninsula, probably filled with rhyolite/ignimbrite
Rift goes as far south as Tokaroa

Seismicity: Frequent seismicity beneath Hauraki Depression- occurs along active faults: normal with a small dextral strike slip component.
Earthquakes are shallow (Hochstein and Nixon infer upper mantle swell beneath the graben)
Hot Springs within the depression with the active faulting70°+/-30° per km below 5km depth-anom high heat flow

Miranda hotsprings controlled by steep basement fault East-west/downthrow north probably extension as a result of regional trends.

North of profile show west fault angle depression and eastern graben structure

South of this area shows development of additional N-S trending basins, bounded on west side by east dipping normal faults
No definite eastern margin-depression widens

9widening of rifts at margins is typical (Illies,1969)
Tearney and Hochstein and Nixon also noted widening but put it down to movement on transverse faults.
No such faults inferred here under S Hauraki Lowlands,-en echelon basins rather than offset by active faults.
This may also be true in the Hauraki Gulf

Steep west dipping en echelon faults at least as far north as Te Aroha, Recent traces of dex strike slip of up to 4:1 horix:vert marker movement
Hauraki Rift currently under shear?

Average dip is less than 70°.

Resistivity of sedi fill 2.07x103 kg/m3 , implying it may be lower Pleistocene

Hauraki Rift is currently subsiding leading to numerous fault traces and microseismicity
Ngawha may indicate that the depression is moving northwards.

Extension in Hauraki Depression may be as a result of extension vectors due to spreading in Taupo Graben (7mm/year at the NE end). One would expect extension with a strong component of dex strike slip

Brown (1937) clevedon area
western boundary of Hauraki Graben is NNW
suggests Hauraki Graben is early Pliocene-Kaikoura Orogeny.

Hookaway (2000) Geochem of Rangitoto
No conclusive evidence for rift signature in Rangitoto basalts (alkali basalts)
More rift signature in rest of basalt of AVF (alkali basalts)
Although Hauraki Rift could play a role in Magma ascent
Change in pressure in the upper mantle and melting of second source could be due to extensional forces at depths of 80-140km.

E-W tension in Hauraki Rift could be related to changes of decompression &/or changes in oxygen fugacity.

Berry (1986) S Manukau lowlands
A strong Coromandel derived influence in sediments is taken to indicate absence of the Hauraki Rift at the time of deposition (Hautawan)

Fergusson (1974) Velocity struc. of seabed Leigh- Moko hinaus
Basement has depths greater than 2400m
Most of region Leigh-Moko Hinaus greywacke basement is approximately 100m below sea bed, locally 250m.
From Leigh, (greywacke outcrops on the shore) top surface of greywacke drops to 1.5km below seabed over 15km. Greywake again outcrops on the north end of great Barrier Island.
A marked structural change occurs about15km from Leigh- probably a fault.
To the south the upper surface of the Greywacke is 1.5km below the seabed, 10km from Leigh. There is a marked change in vertical position of over 1.5km in a distance of about 5km-structural change
Increase in depth to basement 26-30 km from Leigh may represent a downthrown block.
Greywacke surface dips down to northeast of Leigh.
The greatest thickness of sediments on top of the greywacke is 1500m, of which700m are unconsolidated
Over most of the profile approximately 100m is unconsolidated.
Blockfaulting has led to a depression about 5km wide and several hundred metres deep.

Williams (2003)
Hauraki Rift has over 700m of Tauranga Group

Structure of Volcanoes

Miller (1996)South Auckland (mangere)
Mangere Mountain and Puketutu: gravity shows large dense bodies underlying Mangere Mnt
N of Mang Mnt, conical bodies (tapering)-gravity

Magnetics- significant basalt bodies underlie centres characterised by scoria cones and explosion craters (Mang MT, Otara Hill, Hampton Park, Puketutu)

Hampton Park and Otara Hill have chemistry consistent with same magma batch

Crater infills after phreatomag- heavy dense bodies extending 100-200m bsl

No evidence for basement faults in geophysics

Puketutu similar timing to Crater Hill-Wiri, different batches, Possible NW-SE alignment
Also possible NW-SE alignment Hampton Park/Otara Hill-McLennan Hill centres
Similar to NNW late Quaternary structural trend immediately east of the area.
Could indicate SW-NE tension.

Marija Jukic(1995) Subsurface of South Akl Volcanic field
Volcanic material avge thickness 35m, max 61m nr Pukeowhare
NE of area, Raventhorpe avge thickness 45m max thickness 92m Puni, (1-2km W of Pukekohe Hill) max thickness 182m.

Pukekohe Hill- basalt plug (gravity) or secondary vent- rel symmetrical form, broken by a basalt ridge and 2 small dome-like structures on SW flank

Onewhero crater approx symm with –ve anomaly (lo density) seds from past crater lake 40-60m thick probably formed by explosion

Magnetics show volcanics rel thin but strong anom assoc with volcanic centres

Pukekohe Hill- shield volcano central cone max thickness 210m (cf Rangitoto)
Thick lava flows-160m thick North half, basaltic plug 80m thick with basalt beneath it
2 other plugs-100m thick: one 1kn SE of summit, one 2,5 km NW
Youngest in field-predom dense lava flows

France (2003) Domain volcano
Domain more than one vent , central crater is oval and elongate N-S, surrounded by a tuff ring

Novak (1995) Rangitoto
Lava flows follow palaeotopo

Nunns-Geophysics of explosion craters
Gravity and magnetics of Onepoto, Orakei and Pupuke
Large volume of basalt in water and mud in crater

Top surface basalt approx flat
Bottom tapers to thin pipe

Phreatomag formed crater, flow of lava partially filled it

Tank farm- probably no sheet of basalt
Pupuke- very disturbed magnetic field due to surface basalt

Roberts-Geophysics of mt wellington

Pre Mt Smart (20,000yr) broad valley flanked by Waitemata seds
Eruption dammed valley forming a swamp,
Then Mt Wellington (9000yr)filled the dammed valley and overtopped it and ran into the Manukau Harbour

Volcano has 1) surface weathered layer 1.5-6.0m
2) Dry basalt- varies widely
3) Water saturated basalt 10-15m thick
4) Weathered Waitemata clay-silt

Rout-Geophysics of Wiri and Papatoetoe volcano

Pukaki Crater-negative gravity anom-low density mud/colluvium
No magnetic anom no subsurface plug beneath the crater-cone with a top surface 650m diameter, depth of 25m
Crater Hill-positive gravity anomaly -solid lava body infilling a crater and
Strong mag anom -pipe down to 110m, cylindrical upper 65m, conical lower 45m, 100m asl to 110m bsl diam 100m
Wiri Mt positive gravity anom with a broader gravity low
No sharp magnetic anom, broad, weakly negative anom, assoc with vent - probably eruption into alluvium filled river channel, filled by later lava flows. Geology shows more than 15 phreatomag explosions then srombolian Hawaiian forming 90m high scoria cone and lava flows, small plug 7m asl to 25m depth 50m diam tapers within this valley.
McLaughlins Mountain-classical dipolar magnetic anomaly, gravity subdued and variable-scoria cones and surface lavas-no significant subsurface structure

Ash Hill-magnetic anomaly shows a body of magnetised rock beneath it.100m diameter at sea level to 50m diameter at 40mbsl not a clear model, this only one possibility.

Wiri and Crater Hill dated as 25000-30000 yrs-geomagnetic excursion recorded.
Geochemically similar- sourced from the same magma batch?
Geochem suggests mantle source of 100-150km depth .
There are differentiation trends in Crater Hill but not Wiri.
Probably simultaneous, even though they are at different localities.

Hookaway (2000) Geochem of Rangitoto

No conclusive evidence for rift signature in Rangitoto basalts (alkali basalts)
More rift signature in rest of basalt of AVF (alkali basalts)
Although Hauraki Rift could play a role in Magma ascent
Change in pressure in the upper mantle and melting of second source could be due to extensional forces at depths of 80-140km.

E-W tension in Hauraki Rift could be related to changes of decompression &/or changes in oxygen fugacity.

Multiple magma sources for alkali basalts/tholeiites.

Affleck-Geophysics of lava flows in central Auckland Isthmus

Ridge in Waitemata Gp runs NNE-under Epsom (divide between ancient Rivers of Waitemata and Manukau

NNE Three Kings to Mt St John then splits in three, main ridge continues to Remuera, second to Mt Eden and the third runs south to Alexandra Park

He uses isopach models of tuff to work out palaeotopography- photocopies of isopach maps and palaeotopo included.

Mt Eden and Three Kings both erupted on top of Ridges latter began with phreatomag activity, former lava only, but shows spasms of lava flow and periods of no activity (a well at the foot of Mt Eden passed through seven lava flows over 65m, each separated by thick scoria beds (these 7 may not all belong to Mt Eden if the channel was deep) At 55m, between bottom two layers was a 2m thick layer of plant material beneath which lava dipped southwards (upper lava flows dipped northwards) the last flow may have come from the domain volcano)(Les Kermode, pers comm, Firth 1874, Searle 1981(Firth 1874 Deep sinking in the lava beds of Mount Eden. Trans NZ Institute vol7 (Article 75)460-464, and Searle 1981 City of Volcanoes: a geology of Auckland (2nd ed) Longman and Paul)

The ridge between the Waitemata River and the Manukau River were previously modelled as NNE with a NW splay.

The gravity model shows the NW splay continues only 700m from the main ridge

On SW side, steep sided Waitemata Ridge, with two palaeovalleys divided by a spur under Alexandra Park.

<u>Disturbed zone-simple zone</u>

<u>Morris-Musick Point</u>
<u>Swain (1993) Leigh</u>
<u>Patterson(2002) Takapuna)</u>
<u>Manning (1983) N Manukau Coast(Blockhouse Bay to Mt Roskill)</u>
Suggests complex zones are structural transitions (struc transition is made up of break (contact) and complex zone))i.e. kind of movement zones between two simple struc domains.
<u>Berry () ManukauLowlands</u>
<u>Simpson () East Coast engineering geol</u>
Noted presence of simple and complex zones
Complex, open-tight folding, gently plunging fold axes, N, S, SW, SE and W
Joints Mostly very steep to vertical: strike N,S, NE, SE, joint-bed perpendicular
Simple domains-normally two orthogonal sets and two less well developed sets at 45° to others, complex domains, as for simple domains OR parallel fold axes OR highly faulted zones up to 9 sets, dominant set oblique to bedding at 20° angle

<u>Turner (1929) takapuna to silverdale</u>
WAITEMATA GROUP
Beds mostly very gentle dips or horizontal, very deformed zones present Milford Beach to Red Bluff and East Coast of Whangaparaoa

<u>Pohlen (1934) Mid Waitemata County (west Auckland PiHA,Titirangi, Hobsonville, Muriwai</u>
WAITEMATA GROUP
Beds mostly very gentle dips or horizontal, very deformed zones present SE of New Lynn. Most strata in the Waitematas of the area are horizontal, with local very complicated zones.

<u>Miscellaneous</u>

<u>Milligan (Rangitoto)</u>
In general Volcanism initiated in the valleys of Waitemata Group

<u>Sharon Allen(1991) Auckland Volcanic Field.</u>
Of about 50 volcanoes in the field ,
25 erupted through a country rock of Waitemata Group +/- alluvium
1 (Rangitoto) erupted through Waitemata Group and mudstone
3 erupted through Waitemata Group + Kaawa Formation
18 erupted through Kaawa formation
ONLY ONE (Motukorea) erupted through country rock of Greywacke + Waitemata Group

None erupted into just greywacke.

There is a large concentration of volcanoes in the past 20,000 years.
……………………………………………………………………………………
Height above sea level at time of eruption
One tree Hill, Mt Eden and Three Kings all 115-135m asl

5 dated volcanoes 60-85m asl,
6 dated volcanoes 40-55m asl,
2 (Motukorea and Rangitoto below sealevel (-5 and –14 respectively)

Bryner (1991) Brown's Island
Magma rose up through a ridge in the Waitemata Group (Musick Point northwards)

Sibson (1968) East Tamaki

Included blocks of basement in Pukewairiki tuff-semi schists with signs of cataclasis andhigh specific gravity 2.88- also highly zeolitised sst

Sibson claims similarity with Searle's inclusions at St Heliersas retro-metamorphism of post Cret basic/ultrabasic intrusion (or Dunn Mnt) shearing maybe assoc with frac zone into which it's included.

Also some ??Mahurangi limestone or Te Akatea siltstone

Simpson () East Coast engineering geol
Noted presence of simple and complex zones
Complex, open-tight folding, gently plunging fold axes, N, S, SW,SE and W
Joints Mostly very steep to vertical: strike N,S, NE, SE, joint-bed perpendicular
Simple domains-normally two orthogonal sets and two less well developed sets at 45° to others, complex domains, as for simple domains OR parallel fold axes OR highly faulted zones up to 9 sets, dominant set oblique to bedding at 20° angle

Thompson (1975) Sedi topics- Waitemata HArbour
Steep south facing, gentle north facing slopes on valleys with Lucas Creek and Hellyers Creek- possible structural control
Harbour is broad and shallow with main channel on north side. In interglacial times the Waitemata river went out to sea west of Great Barrier Island.
The Waitemata surface is very irregular with precipitous buried slopes like cliffs, and is locally overlain by 100' thick sediments.
"Waitemata River" falls steadily from 70m below harbour datum near Greenhithe to 90'below off Kauri Point to 102' below at Northcote and 115-129' below off North Head. At Te Atatu maybe 100' below and possibly an infilled valley, sloping shorewards.

wise (1999) Wairau North Fault
-Basalt only on downthrown side (1,3ma) possibly means most movement predates this.
Basalt in contact with greywacke on the upthrown side.

Turner (1929) Takapuna to Silverdale
WAITEMATA GROUP
Where Parnell Grit is present there is always intense folding, faulting and shearing (photos show soft sedi slumping)

Moore (1989) Auckland area

Auckland is tectonically stable, but extensive late Quaternary raised terraces, up to 180m above sea level may indicate slow, long term tectonic uplift averaging 0.3mm/year over the last 0.4Ma (Chappell(1975)- paper from Bay of Plenty).

APPENDIX 2. NOTES FROM PUBLISHED REFERENCES.

Affleck, DK, Cassidy J and Locke, CA, (2001) Te Pouhawaiki volcano and pre-volcanic topography in central Auckland: volcanological and hydrogeological implications, NZJGG44: 313-321

Gravity defines palaeotopographical divide between ancestral Waitemata and Manukau River systems-complex ridge system.

Buried ridges peak at c.10-20m depth (60-70m asl) with a saddle in the eastern limb of the ridge which may have allowed lava to flow north of the divide. Volcanoes erupted into deeply dissected landscape- predominantly Waitemata Group, underlain by greywacke at about 0.5km. (Edbrooke et al 1998)

The ancient system is used to define present groundwater flow.

Te Pouhawaiki predates Mt Eden but post dates Three Kings.

The divide comprises a steep-sided ridge of Waitemata sedimentary rock, which runs northeast from the southern limit of the study area towards Mt St John, southwest of which the ridge splits into three. One limb extends to the east (where it outcrops outside the study area) another follows around the Te Pouhawaiki crater, extending north and then turning west to the south of Mt Eden volcano, and the third limb forms a steep-sided narrow ridge extending to the south. These ridges stand generally at 60-70m a.s.l. (i.e. 10-20m depth). However, there is a saddle (c. 50m a.s.l.) in the eastern limb's ridge, south of Mt St John, and the lava flows that straddle it may come from one tree hill.

Te Pouhawaiki sits on ridge in Waitematas, as does Three Kings but nonetheless phreatomagmatic activity occurred.

Allen, S.R. (2004) The Parnell Grits revisited: are they all the product of sector collapse of western subaerial volcanoes of the Northland Volcanic arc?

Volcanism in eastern arc (23-11Ma) and western arc (25-15.5Ma) in response to southwest directed subduction. First Parnell Grit beds (early Miocene-i.e. early-mid Otaian) have no recognised in situ volcanic source and are the first indication of volcanism. Four large offshore to the west centres recognised geophysically.

Kaipara and Manukau stratovolcanoes most active.

Eastwards advance in volcanism and associated uplift saw bathyal sedimentation in west of Waitemata Basin replaced by shelf and terrestrial accumulation.

Palaeocurrents in Warkworth Group predom ESE-SE.

Volcanic rich facies (Pakiri) in north,

Volcanic poor in centre (East Coast Bays Formation)

Volcanic rich-volcanic poor in west and south of basin (Blockhouse Bay Formation)

Pakiri Formation has upslope, proximal source for the sedis. Ballance concludes that volcanic poor assemblage (ECBF) was younger. Alldred had faulted contact, but Pakiri younger

Blockhouse Bay formation grades stat upwards (i.e. westwards) from volcanic poor flysch and is overlain by basaltic and andesitic Waitakere Group. Palaeocurrent indicators suggest that it was deposited on or near the slope separating the western volcanic belt from the central Flysch basin, receiving seds from both north and west.

Major structural trends – numerous late extensional faults in Warkworth Subgroup-also zones of complex structure.

Major folds have NE and NW trends, approximately perpendicular to the inferred palaeoslope. Deformed intervals commonly include a Parnell Grit Bed. Considered to be slump structures. Gregory suggests that deformation associated with the Parnell Grits has occurred after their emplacement.

Ashcroft, J., (1983) The Kerikeri Volcanics: A basalt-Pantellerite Association in Northland. Roy Soc N Z 23:48-63

Auckland undersaturated basalt. Transitional and tholeiitic basalts only in younger lavas of Auckland (e.g. Rangitoto)

c.f. Northland, transition undersaturated to tholeiitic.

Differences probably due to setting: basement apparently thicker and more complex in Northland than Auckland. Isotopic evidence for differences in mantle source.

Ballance, P.F. (1964) The sedimentology of the Waitemata Group in the Takapuna Section, Auckland, New Zealand. NZJGG 19:897-932.

Bearings of fold crests in convoluted laminae in one bed range S-SSW giving an average SSE palaeocurrent direction.

In another bed range is SSW-WNW giving an average palaeocurrent direction of SE.

In another bed flute and flow casts indicate a NNE flow indicating that some turbidity currents might have flowed across the general SE track. Ripple-drift bedding and transverse ripples on upper surface of bed indicate SE and SSE palaeoflow.

Slumped movement deduced from folds, which align NE-SW indicating flow either NW or SE- SE most likely since this is compatible with other indicators.

Basal beds are exposed in a NNW-SSE belt in east of basin, including some parts of eastern coastline plus islands of the Hauraki Gulf. Turbidite facies occupies the eastern part of Northland Peninsula, running roughly NW-SSE. Westwards the turbidites pass laterally into massive volcanic and tuffaceous sandstones of the Manukau breccia, many of which are marine and trend NNW-SSE along flanks of Waitakere Hills.

Turbidites cover an area at least 15x50miles

Ballance, 1974. An inter arc flysch Basin in North New Zealand. J of Geology 82:439-471

Waitemata Group formed following a major Mid-Upper Oligocene block faulting in Northern New Zealand. Central flysch basin 130x60km bounded to the north and south by basement horst on which shelf facies accumulated, to the west by an active basaltic/andesitic ridge, and to the east by high basement ridge/active andesitic arc. Lithic sediment from the north mingled with contemporaneous volcanic debris to give poor-volcanic, rich volcanic and mixed volcanic flysch facies. Turbidity currents entered the basin from a western shelf, travelled an average of 30km and built a SE dipping palaeoslope oblique to the basin axis. The flysch is relatively proximal, overstepping eastwards across a steep and uneven basement surface with a thin shallow-water facies, Conglomerates and lahars, slumping all present. Western volcanic arc built up a thick, largely shallow-marine fragmental pile, overstepping eastwards across the flysch basin. Basin was 2000m deep or more-requires substantial vertical movement.

Late Oligocene area north of Waikato Fault subsided markedly by at least 1km and maybe 5km to form the west Northland Graben. On the eastern half of the country, and south of the Waikato Fault, they did not subside: and on the eastern basement ridge they raised considerably.

There is everywhere a thin and highly variable “basal facies”

Overall the structure of the flysch is simple, with gently dipping, undeformed flysch, but interrupted by intervals of severe deformation. Penecontemporaneous slumping. Palaeocurrent directions in the flysch are mostly towards the ESE to SE, whereas the long axis of the flysch basin is NNW-SSE. Figure 17 shows Non-turbidity current flow as NNW-SSE in western part of the basin and SW off the eastern margin (sub-perpendicular to the margin) whilst turbidity current flow is ESE-SE, diagonally crossing the basin at about 45° to the axis. Volcaniclastic lahars and movement of conglomerate facies parallels turbidity currents in the north and south and parallels turbidity or longitudinal non-turbidity flows (i.e. SE or SSE) in central part.

The initial subsidence of the basin was rapid-zero to 2,00m during deposition of 38m of conglomerate and slumped sediment, then accumulation of 222m of thin-bedded distal flysch, followed by 38m of Parnell Grit, then elevation to sea level plus for conformable deposition of terrestrial volcanics of the eastern arc. Drastic events on a narrow timescale, but feasible in active double arc situation.

Ballance, P.F. (1976) Stratigraphy and Bibliography of the Waitemata Group of Auckland, New Zealand. NZJGG 19:897-932.

Waitemata Group interdigitates with proximal-volcanic Waitakere Group. Waitakere Group oversteps eastwards across Waitemata Group. These two are lateral equivalents, and there is a general eastwards migration of volcanism with time. (Junction of two is conformable Blockhouse Bay Formation (Waitemata Group) with overlying Cornwallis Formation (Waitakere Group)

Palaeogeographic considerations suggest that Pakiri formation is generally younger than East Coast Bays Formation. Contact between the two at Hadfields and at the east end of Whangaparaoa is a rapid, apparently lateral transition.

Ballance P.F., 1976, Evolution of the upper Cenozoic magmatic arc and plate boundary in northern New Zealand. EPSL 28:356-370

He adopts a date of c. 18Ma for inception of eastern arc. Eruption sub-aerial through horst of basement that had been subsiding during deposition in the Waitemata basin.

Between 18-15Ma both Waitakere and Northland arcs active,

Important Block faulting in northern New Zealand at approx 15Ma coincided with extinction of the Waitakere Arc. Alpine fault 20Ma –total of approx 230km dex movement.

Ballance PF 1995: Neogene sandstone provenance, North Island and its tectonic significance Geol soc NZ misc publ 81A: 74

Early and mid Miocene seds had two sources, one locally derived, one with northern provenance. Northern provenance was in part a reflection of the obduction of the Northland and East Coast Allochthons, and of the establishment of volcanic arcs in Northland. From 20Ma a marked Dichotomy in provenance occurred, reaching a maximum in the Pliocene with strong volcanic arc derivation.

Ballance P.F., Pettinga J. R. and Webb C., 1982. A model for the Cenozoic evolution of New Zealand and adjacent areas of the SW Pacific Tecton 87:37-48

The onset of subduction as recorded in accretionary prism at 25Ma(early Miocene) coincides exactly with the emplacement of the Northland Allochthon and the beginnings of arc volcanism in Northland. Cause of great uplift to the North of the North Island that seems to be necessary to evert the basin and allow gravity slide of its contents is not known. From the fact that the uplift immediately preceded the Miocene Arc volcanism in Northland, a connection with the inception of subduction may be inferred, perhaps the initial development of a fore-trench flexural bulge.

Early Miocene to mid Pliocene two more or less parallel arcs above west-dipping subduction zones. They began activity at about 25Ma in the west and 22Ma in the east. They were twin arcs for at least 7Ma.

Ballance, P.F. and Spörli, K.B. (1979), Northland Allochthon J Roy Soc NZ 9:259-275

Allochthon is unconformably overlain by the Waitemata Group and was itself emplaced by gravity sliding during the Waitakian. Allochthon now extends from Waikato fault northwards, probably to North Cape, a distance of more than 350km, and westwards beneath the present continental shelf, a width approaching 100km. It was emplaced from the present day north, from an everted marine basin with oceanic volcanic basement. There is abundant evidence that the Onerahi chaos breccia overlies the Waitemata Group. But also observations suggest that the Onerahi Chaos Breccia is interbedded with near-basal Waitemata Group. Allochthon is unconformably overlain by Waitemata Rocks around southern Kaipara Harbour, Silverdale and Dairy Flat.

There is a significant late or post-emplacement deformation of the allochthon. In most places the two fold sets form interference patterns, but in other places, the Northwest tending folds appear to be rotated by the east-trending folds. Major trends of post-emplacement faults are NW and NE. NE trending faults form prominent jogs in the eastern boundary of the allochthon at Kawakawa.

The NW trending faults are parallel to the 80-60ma spreading centre in the Tasman Sea and the NE trending faults are subparallel to the transforms associated with the spreading system. The post allochthon faults are therefore inherited from pre-existing basement patterns.

Black, P.M. Briggs, R.M., Itaya, T., Dewes, E.R., Dunbar, H.M., Wawasaki, K., Kuschel, E., Smith I.E.M., (1992) K-Ar ages of the Kiwitahi Volcanics, western Hauraki Rift, North Island, New Zealand. NZJGG, 35:403-413.

Kiwitahi volcanics (west of Hauraki Rift, but equivalent to Coromandel. Present at Stoney Batter on Waiheke.

Blake,S., Wilson C.J.N., Smith I.E.M., Leonard G.S., (2006) Lead times and precursors in Auckland Volcanic Field, New Zealand: Indications from historical analogues and theoretical modelling. GNS Science Consultancy report 2006/34 Nov 2006

Eruptions in AVF fed from upper mantle by dykes with no evidence of stalling at intermediate depths. Eleven comparable fields show they have less than 2 weeks of felt seismicity prior to eruption. Epicentres not always directly above the eventual vent sites.

Other precursors e.g. thermal/chemical changes were absent or occurred after the seismicity.

Modelling: important thermal effects can lead to focussing of upwards flow of magma –may cause magma to rise in complex branching patterns that can focus magma to a single point or very short dyke section at the surface.

AVF magmas suite of alkali basalts and a single tholeiite basalt (Rangitoto), low degrees of partial melting at depths of 80-100km. Crater Hill demonstrates virtually continuous pathway from source to surface, with no stopping off.

Flow rate is the main determinant of whether deeply sourced basalt breeches surface as a vent or a fissure. Low flow rates lead to rapid cooling and branching and point eruption. Faster flow rates allow magma to reach large distances on a broad front.

It seems as though the AVF has 1km max length of sub-surface feeder during eruption.

Seems that transit times from Moho range 1.5 hours to 2 days.

Briggs, R.M., Okada,T., Itaya,T., Shibuya, H., Smith, I.E.M., 1994.K-Ar ages, palaeomagnetism and geochemistry of the south Auckland Volcanic Field. NZJGG 37:143-153

Age data from four volcanic fields (Okete, Ngatutura, South Auckland, Auckland) show that they have developed within a time span 0.3-1.1MA. After activity ceased in a field, a new field developed 33-38 km to the north. Possibly indicates a mantle source migration of 5cm/yr. No correlation of rock comp with time, not consistent with rising diaper model.

Intraplate volcanic association, well behind the active convergent plate margin.

Fig 2 has map of South Auckland Volcanic Field showing distribution of effusive and explosive centres, K-Ar ages and structural patterns.

South Auckland Region is characterised by block faulting consisting of uplifted blocks of Mesozoic greywacke, argillite and conglomerate, overlain by late Eocene coal measures and Olig-early Miocene zst, sst , lst (Te Kuiti Gp and Waitemata Gp). Downfaulted blocks infilled by Pliocene Kaawa formation and Quaternary fluviatile/estuarine deposits.

Many of the south Auckland volcanoes lie directly over fault lines, which appear to have provided easy upper crustal pathways for ascending magma. Particularly shown by ENE alignment of vents along Pokeno and Waiuku Faults, and in the uplifted Hunua Block where faults such as the Drury Fault (NNW) have been important in structurally controlling the localisation of centres. In other parts of the field (e.g. at Pukekohe) thick layers of basalt and Tertiary strata obscure any structural control.

South Auckland is in an oblique extensional tectonic environment characterised by rhombic pattern of NNW and ENE striking block faults. Throws up to 2.7km on Waikato Fault, downthrown to the north, decreasing eastwards to about 0.7km near Tuakau.

No systematic younging in any direction within the field.

Apparently older ages in NE of the field.

Younger volcanoes apparently occur in the centre of the field, in region of Pukekohe, Pukekohe east and Puni. Older volcanoes more peripheral and isolated distribution (but may just be covered by younger ones.) could be that older vents more widely distributed, becoming more centrally focussed with time.

Northland magma/mantle sources have remained stationary w.r.t. one another-10ma- consistent with palaeomag that shows Northland has not rotated during late Cenozoic.

In contrast eastern part of north Island have undergone a pronounced rotation in Pliocene-recent (Walcott 1989). Auckland province lies between rel. stable Northland Peninsula and mobile eastern belt. Volcanism in Auckland temporally overlaps inception of Arc-type volcanism in TVZ, logical to seek a tectonic link between contrasting volcanic associations. Auckland region clearly mantle related volcanism, no evidence for subduction related magma. Relationship of individual fields to one another suggests mantle source migrating north at c.5cm/yr.

Geochem is not consistent with rising diaper model.

If source stationary then Auckland has moved south at 5cm/yr rel. to Northland. No evidence to support this. So source must have moved north.

During last 5Ma arc volcanism has changed from NW Northland- Coromandel-Mio-Pliocene Arc to present NE orientation of Kermadec-TVZ. Kermadec has “captured TVZ by southwards propagation in last 2Ma. Northwards migration in Auckland may be in response to inception of subduction at southern end of propagating convergent plate margin to the southeast of Auckland.

Magma sources for the fields seem to be distinct-further work needed.

Unclear why such regular spacing and why such abrupt end in one field and start in the next.

Briggs R.M., Utting A.J. and Gibson I.L. 1990. The origin of alkaline magmas in an intraplate setting near a subduction zone: the Ngatatura basalts North Island, New Zealand. Jour Volcanology and geothermal research 40:55-70

Ngatutura Basalt.16 small volume monogenetic volcanic centres occupying an oblique extensional tectonic environment characterised by NE-striking block faulting. (Actually rhombic pattern). In some cases these vents have controlled the localization of the volcanic vents.

There are no spatial or compositional variations with time in the field. However the age of FIELDS youngs northwards to Auckland.

Ngatutura basalts are perched on a Mesozoic basement high in the horst and graben system of the western North Island. It is unlikely that they have anything to do with the NNW-striking Hauraki Rift, since it is 60km to the east, or the Challenger Rift System to the SW and offshore N. Isl.

Eruption centres seem to overlie basement faults with regional NE striking block fault pattern. At Ngatutura Point basalts intrude dikes along both NE and N striking faults.

Ngatutura Basalts were generated within the low velocity zone, estimated to lie 75-120km deep according to geophysical evidence, and significantly above the subducted slab.

Brothers RN 1954, Relationship of the Waitemata Formation and Manukau Breccia, Auckland, New Zealand. Trans Roy Soc NZ v81:521-538

Manukau Breccias are composed of fragmental andesitic debris with interbedded lava flows produced from a number of small centres. They were coeval with Waitemata Group, the two groups either intergrading through transitional sediments or overlying one another. Parnell Grits of the Waitemata Group are very similar to Manukau Breccia (mudflow-type deposits) and share a common origin.

Roughly same age, interdigitate and Parnell Grits derived from slumping of same igneous activity as Manukau Breccia. They are the same thing. Whereas 'ordinary' Waitematas have northern source.

Bedding along the west coast mostly strikes NW-NNW and dips shallowly west, occasionally east. Travelling westwards up the Anawhata stream, strikes mostly NW, dips alternate, 45NE, 20SW, 24NE, 20SW before strike swings west-east. I.e. series of horizontal NW-striking folds.

Severe folding of the Manukau Breccia on a minor scale is not infrequent. Very varied structural axes. The structural picture is similar to the Waitemata Formation on the east coast where Turner and Bartrum, 1929, described them as "a tangled skein of facts" where corrugations and faults "constantly succeed one another and trend with directions so diverse that their maze almost obliterates evidence of structural control in their creation." Widespread slumping in Manukau Breccias brought on by gravity slides of varying magnitude and intensity. In areas where severe folds are absent, the general structure is simple, with strikes trending E-W or NW-SE.

Stereonet shows that between Orewa and Milford, Waitemata beds are horizontal where the Parnell Grit is absent, and form a girdle with a horizontal N-NNW to S-SSE trending fold axis where Parnell Grits are present. I.e. structurally more simple when grits not present. The suggested fold axis may be perpendicular to transport direction by slumping associated with the grits.

Waitemata Group and Manukau Breccia are conformable at Manukau North Head.

Waitemata Gp has northerly source. In southwest interdigitation and continuous sedimentation into area from two sources, one to the north and one to the southwest, and closer. Waitakere Gp now lower lying due to greater erosion. Waitemata Gp is present at 480ft a.s.l. on flat ridge between Bethell's Beach and Waitakere, and were probably part of a more extensive sheet.

Brothers R.N. and Delaloye, M.(1982). Obducted Ophiolites of North Island, New Zealand: origin, age, emplacement and tectonic implications for Tertiary and Quaternary volcanicity. NZJGG 25:257-274.

Obduction was from northeast to southwest by gravity sliding of seamounts upon autochthonous strata of Permo-Jurassic greywackes and cretaceous to Oligocene seds. Obduction marked beginning of mid-Tertiary volcanics in North Island.

Important young lineaments with northwest-southeast trends are the East Coromandel Rift (follows the line of the Whitianga-Whangamata graben) and the parallel Hauraki Rift. At its northern end the Hauraki Rift becomes wider, western boundary fault can be traced northwest-south east line of earlier major thrust faults (Palaeocene to Oligocene age) and post-obduction tensional faults (early Miocene age). Along its length the Hauraki Rift shows no clear evidence for strike-slip movement, but transverse NE-SW faults had normal and transcurrent movement components. Main patterns for dislocations for North Auckland and South Auckland are dominantly NW-SE or NE-SW orientations of rectilinear faults, which were active Miocene- Quaternary. They reflect the character of the Hauraki Rift, which may have been the core for the late Cenozoic regional warping above a linear upper mantle swell culminating in the collapse in the late Pliocene or Quaternary.

These northwest or northeast oriented dislocations appear to be parallel to deep-seated structural trends, which were established in the metagreywacke basement as early as late Mesozoic and were reactivated as fault zones.

Some of Miocene volcanics in Whangarei area have rift characteristics.

Miocene volcanic arcs, as defined by chronology, are oriented northeast-southwest and become younger towards the southeast, but they consist of isolated eruptive centres for which the loci were mainly northwest-southeast faults.

Carter, L., (1970) Stratigraphy and sedimentology of the Waitemata Group, Puketotara Peninsula, Northland.

Simple structure, dipping at a low but variable angle to the southwest.

Numerous faults present. Two large faults strike NNW. On the western side of the peninsula fault strike changes to NE. Two NE striking normal faults have vertical displacements of 56m and 39m.

Intraformational faults, steep-vertical with vertical displacements of 5cm-1m common in Pakaurangi and Timber Bay formations. Majority strike NE.

Jointing in tuffs well developed- often two perpendicular sets, with NE trend being better developed. Joint fill is laminated calcareous mudstone.

Broad, gently undulating folds with limbs rarely steeper than 10º, but Timber Bay Formation also has highly contorted tight folds with undisturbed strata above and below (syn sedimentary slumping.)

Cassidy, J., Geomagnetic excursion captured by multiple volcanoes in a monogenetic field, Geophys Research Letters 33:L21310

Monogenetic fields most likely result from low magma supply rate and regional extensional stress.

The Auckland field has no obvious structural control –different from other fields in the world.

Average recurrence in Auckland is 1 volcano per 1-5kyr.

Three volcanoes at SW perimeter have similar anomalous magnetism (Crater Hill, Wiri and Puketutu). This study shows that Mt Richmond and Taylors Hill also share the same palaeomag excursion.

Result shows a recurrence interval of 10-20years for the five volcanoes-possibly some were simultaneous. In other fields this occurs where there is a structural link, such as sharing a fissure. In Auckland they do not appear to be structurally related.

Given likely rapid ascent of magma, implies that magma overpressure was concurrent throughout the reservoir. Possibly lack of connectivity of sources, because otherwise one vent opening up might cause a reduction in pressure throughout. Alternatively a transient increase in regional extension rate might have initiated relatively rapid decompressional melting across the source region and also fractured the overlying lithosphere.

Multiple eruptions very rare in monogenetic fields.

Cassidy, J. (2002) Geophysical Data from the Auckland Volcanic Field: structural and temporal Implications.

High res aeromag shows subsurface structure of volcanoes in the field can vary significantly, even where similar at surface. Some have large basalt bodies infilling maar crater, others have sediments. No diatremes recognised in AVF. Some volcanoes show magnetisation within a very short-lived geomagnetic excursion.

Cassidy, J., France, S.A., Locke, C.A., (2007) Gravity and magnetic investigation of maar volcanoes, Auckland Volcanic Field, New Zealand. Journ. volc. and geothermal Research 159:153-163

Detailed gravity and aeromag reveals contrasting anomalies, even where surface geology is similar. Pukaki and Pukekiwiriki are sediment filled craters and tuff rings. The domain and Waitomokai maars have similar tuff rings but with a central scoria cone has gravity and magnetic anomalies revealing dense magmatic bodies –solidified magma that ponded in early crater.

No geophysical evidence for diatreme or shallow/extensive feeder dykes associated with the maar. Therefore no evidence on local structural control. Dykes may exist at depth, but shallow feeders appear to be confined to central part of maar.

Very few reported alignments elsewhere in the field (contrast with e.g. Eiffel)

The two centres of the Domain modelled here line up with (E-W trend?)

Cassidy, J. and Locke, C.A., (2004) Temporally liked volcanic centres in the Auckland Volcanic field. NZJGG 47:287-290

Aeromag shows five separate volcanoes in the AVF occurred during a geomagnetic excursion, which is short lived and implies a strong temporal link of the volcanoes. The volcanoes are Taylor Hill, Mt St John, Puketutu, Wiri, Crater Hill

Total time period for Puketutu, Wiri and Crater Hill may be only 100years, and for all five volcanoes possibly less than 1000yrs. Gives average recurrence of 200yrs during this period. Much less than overall estimates for the field. The volcanoes are spread throughout Auckland and there is no simple structural link.

Cole, J.W., (1986). Distribution and tectonic setting of Late Cenozoic Volcanism in New Zealand. Bull Roy Soc N Z 23:7-20

Auckland Volcanic Province –intra plate back-arc setting to TVZ. Includes alkali-basalt and sub-alkaline/tholeiite.

Ti Point basalt late Miocene could be similar, back-arc to Miocene arc setting.

Shows rotation of Eastern North Island and movement along transform from NE NZ to current position over period35-0Ma.

Cook, C., Briggs, R.M., Smith, I.E.M., and Maas, R., (2005) Petrology and Geochemistry of Intraplate Basalts in the South Auckland Volcanic Field, New Zealand: Evidence for Two Coeval Magma suites from Distinct Sources. Jour. Petrology. 46 (3): 473-503

South Auckland Volcanic Field 0.51-1.59Ma, approx 100 volcanic centres, two distinct magma sources but no pattern of occurrence in space or time. (apparently random occurrence)

Monogenetic nature of events in field and distinct geochem of Gp A and Gp B lavas precludes presence of long-lived shallow magma reservoir.

South Auckland Field is in an extensional tectonic environment, about 160km behind active TVZ front.

No seismic evidence for subducting slab beneath the field.

Many of the volcanic centres are located along or adjacent to faults or inferred extensions of faults. Spörli and Eastwood argued that tensional stresses inherited from Mesozoic tectonic events could control the location of individual intraplate fields within the Auckland Volcanic Province, as well as facilitate localised decompressional melting and thus the onset of volcanism.

Despite the relative proximity of the South Auckland Volcanic Field to the Coromandel and Taupo Volcanic zones, the geochemical characteristics show no evidence of an arc component in their source associated with the subduction of the Pacific Plate during the late Cenozoic.

Model has intraplate tensional forces occurring 160km NW of the active TVZ arc causing partial melting of lithospheric fragments. Partial melting must have taken place in the sub-continental Lithospheric mantle west of the present subducted slab.

Davy, B. (200?)Marine Seismic Surveying of the Auckland Volcanic Field. GNS Science. Auckland Marine seismic proposal.

Within the Waitemata Harbour (c. Kauri Point to Rangitoto Channel) there are enough successful seismic sections to get well-imaged sedimentary cross-sections to basement, image basement structure and clearly image faulting down to basement.

Includes Waitemata Group down to 340m b.s.l., Te Kuiti Group down to 600m in east and 780m in west (greywacke surface slopes westwards). Some faults cut through to basement and appear to be steep to vertical. Others just affect Waitemata Group and/or Te Kuiti Group.

West to east section just south of Whangaparaoa. Waitemata Group (?) up to c. 300m b.s.l. in east of section and 280m in west of section. Large upfaulted block of?? Te Kuiti Gp, underlain by Waikato Coal measures a between 2 major faults in centre of section. The major faults are difficult to correlate with existing line density. These faults are likely major controlling factors on volcano locations. Greywacke basement slopes westwards. In west Waitemata Gp underlain by thick sequence of Te Kuiti Gp and coal measures. In east Waitemata Gp? directly on basement.

Dogleg N-S section in Rangitoto Channel from off North Head to Takapuna. Deformation evident. Undulating surfaces on top of basement, and Te Kuiti Gp(?) Rapid thickening of Waitemata Gp in north of section from 150-300m b.s.l.

Chanelling and unconformities well defined in some places; faulting well defined including seafloor surface displacement in some places; in some places recognisable gas/fluid escape with faulting.

Davy, B. (2008) Marine seismic reflection profiles from the Waitemata-Whangaparaoa Region, Auckland. NZJGG51: 161-173.

Seismic reflection profiling: greywacke dips west 250-800m b.s.l. overlain by 400m Te Kuiti Group which is overlain by ca. 350m Waitemata Gp. Strong, probably igneous reflector (V1) (although magnetics do not confirm) at Waitemata- Te Kuiti Boundary beneath the Waitemata Channel. V1 has 500m wide, 200m high opposing shoulders, which are fault bounded and ca. 2km apart. Faulting, some of which involves displacement of the modern seafloor, extends from near surface to V1 and sometimes into greywacke. Up to 10m displacement. One of these displacing modern seafloor extends NNE from Wynyard Wharf, where there is a 2m scarp, into middle of Harbour Channel. Upthrown to west, seafloor displacement. Normal, poss. some dextral strike slip. An opposing parallel normal fault proposed 600m further east, eastern margin of Victoria Park. He sees NNE faults as a strong influence on volcano location, and suggests recently active faults NNE faults, such as the one on Wynyard Wharf, are paths of weakness along which volcanism has erupted.

Regional fault trends ENE or NNE.

Te Kuiti Gp is basal Waikato coal Measures with overlying by marginal marine to outer shelf calcareous mudstone, calcareous sandstone and limestone.

Very intense syn-depositional deformation in Waitemata Gp near downtown Auckland Harbour Bridge, along Beachlands and Musick Pt and in a few 1km wide zones towards Whangaparaoa Peninsula.

Very few faults of any significant lateral extent mapped within a 20km radius of Auckland city centre. Uncertainty regarding basement distribution and fault pattern, but also very little published on subsurface distribution of volcanism assoc. w. AVF. Generally assumed that point sources of magma. Seismic reflection difficult due to dense urban development, Shallow water (<30m) means that seismic sections extending>50m below seafloor historically dominated by multiple energy symbols masking primary reflection information.

Edbrooke et al. (1998) –Te Kuiti Gp tends to be more heavily eroded in the east with much less, if any erosion in the west. Max estimated thickness is 500m. In Mt Roskill 61m above Coal Measures, in these profiles Te Kuiti Gp thins from ca. 440m near Auckland Harbour Bridge to ca. 150m south of North head volcano. Interface of Waitemata Gp-Te Kuiti Gp is 280-350m here (c.f. 431-475m at Mt Roskill). Model has WSW tilting post Te Kuiti then subsidence of the Waitemata Basin. Boundary between the two is easily discernable (upper laminated unit-lower featureless unit. The TK Gp is ca. 200-400m thick and possibly includes some coal measures south of Whangaparaoa.

Northland Allochthon not apparently present.

Basement dips west, 500m below sea floor at south Rangitoto Channel to ca. 800m below seafloor at Wynyard wharf. Minor faulting with ca. 50m total vertical throw offsets basement immed. E of Harbour Bridge.

East of Auckland's North Shore, in the vicinity of Rangitoto Channel, large scale folding (anticline on a scale of 2km horizontally and 150m vertically) affects Basement, Te Kuiti Gp and Waitemata Gp-possibly associated with late-early Miocene uplift of the Waitemata Basin.

Possibly a buried post TK Gp, Pre Waitemata Gp volcano. The favoured model is that it could also be an AVF intrusion, but its shape is affected by strike slip faulting prior to its intrusion (shoulders formed first.) (Strike-slip faults previously unrecognised but may bound the North shore Peninsula). V1 may be up to 90m thick in places, but elsewhere <5m thick. If so volume and extent of magma is much greater than previous estimates. This igneous feature extends over 6km

Davey FJ 1974 Magnetic Anomalies off the west coast of northland, New Zealand. J Roy Soc NZ 4:203-216

Magnetic anomalies over Northland and offshore to the west: several isolated positive magnetic anomalies lie off the coast of northland, parallel to JMA. Brothers, (1954) –Manukau Breccias sourced from not far offshore to the west.

The southern three anomalies are probably caused by andesitic volcanoes; lower Miocene, equivalent to the Manukau Breccias.

Edbrooke, S.W., Crouch, E.M., Morgans, H.E.G., Sykes,R., 1988. Late Eocene-Oligocene Te Kuiti Group at Mt Roskill, Auckland, New Zealand. NZJGG 41:85-93.

592m deep water bore drilled at Mt Roskill (Roma Rd, NZMS 260, R11/644755) intersected:

Products of AVF 0-12m
Pumiceous seds of Tauranga Group 12-23m
Interbedded sst/mudst Waitemata Gp 23-475m
Te Kuiti Gp sediments 475-592m

First record of Te Kuiti Gp in Auckland comprises erosionally truncated Glen Massey Formation, complete Mangakotuku formation, and incomplete Waikato Coal Measures-drilling probably stopped within 30m of Palaeozoic/Mesozoic Basement. (complete sequence through coal measures at Pokeno and Onewhero are 55-85m thick).
Coal measures show transition from predom. Terrestrial late Eocene to predom. shallow marine early Oligocene.

Previously furthest north Te Kuiti in drillhole at Ardmore (d8427 in National Coal Database) where thin late Eocene coal measures underlie early Miocene Waitematas.
Thin remnants of Te Kuiti locally east of Drury Fault on western flanks of Hunuas between Ardmore and Pokeno. Thick Te Kuiti Gp in Lower Waikato Basin.

Waikato Coal measures probably accumulated in coastal plain setting, subject to periodic marine incursion.

Edbrooke et al. (1994) has late Eocene development of N-NW flowing, anastamosed and meandering fluvial drainage systems, and accumulation of Waikato Coal Measures (including thick peats) on an extensive alluvial plain, confined to the west by the hills of the Murihiku terrane basement and to the east by the hills of the Waipapa Group basement but close to the sea. Earliest Oligocene transgression from the north brought a change to estuarine and shallow marine sediments across the region (Mangakotuku Fm). Progressively more open marine conditions early-mid Olig (Glen Massey) Delta fed by NW flowing river in time of coal measures.

Southernmost exposure of Northland Allochthon is at Coatesville, 18km NW of

Auckland. These are probably at its southern limit. Ballance and Sporli (1979) suggested Allochthon may extend as far south as the Waikato Fault under the Waitemata Group, but the only drillhole reported to have possibly encountered allochthon is the Karaka 1 well on the Manukau Lowlands, but this has, among other problems, known contamination of drill cuttings, rendering its results very unreliable.
It is therefore believed that northland Allochthon is not present under Auckland city.

Edbrooke S.W., Mazengarb, C. and Stephenson, W. (2003) Geology and geological hazards of the Auckland Urban area, New Zealand. Quaternary International (2003)3-21.

Waipapa Group basement surface dip west.

At depth Waipapa inferred to be in faulted contact with Murihiku and an intervening slice of Dun Mt-Maitai terrane.

Only 2 recorded earthquakes have occurred in Auckland region over last 150yr with M greater than 5. 1891 Waikato Heads Eq M=5.5-6.0, Te Aroha EQ M=5.1 in 1972.

Several active faults known NNW trending Wairoa and Kerepehi Faults. Evidence of late Quaternary movement on Drury Fault

Edbrooke, S.W., Sykes, R. and Poknall, D.T. (1994). Geology of the Waikato Coal Measures, Waikato Coal Region, New Zealand. IGNS Monograph 6.

Pre coal measure structure and topography influenced structure of coal measures. Also some syn depositional faulting. Coal measures deposited in a structurally controlled, pre coal- measures, rel. narrow, N-NNW trending basin (best developed in the north). Cret-late Eocene, intervals of faulting and prolonged periods of weathering. A phase of late Cret- early Palaeogene strike-slip faulting preceded normal block faulting, which was major control on coal measures depositional valley. (Strike slip on Waipa Fault- NNW-NE along contact between Murihiku and Waipapa, although JMA undisturbed and interpreted as a sub horizontal shear plane below which strike slip not happened. Above dislocation Murihiku rotated through 50º dextral. This before TK Gp.)

Many late Neogene faults may have begun in early Palaeogene extensional faulting, pre TK, predom normal N-NNW and parallel struc grain.

Topo low, NNW trends in broad inland valleys and ridges, most formed pre coal measures. There had been a prolonged period of tectonic stability and erosion in a temperate to sub-tropical climate resulting in thick regolith up to 20m preserved below coal measures. Soils were source of esp. early sediments. Through Eocene slow regional subsidence. Some (rel. rare and mostly in south) deformation with syn-depositional faulting. Most internal deformation due to differential compaction over basement topography, with increasing sediment loading, including some slumping? Faulting/ bedding parallel shears.

Regional subsidence occurred through Te Kuiti deposition. Terrestrial sedimentation, alluvial plain and coastal plain, then marginal and shallow marine. Thick peat mires when subs. slowed. (up to 240,000yrs continuous peat). Major influence on extent of coal measures was basement topo. Faulting during coal measures only in Rotowaro coalfield. Waipuna Fault zone stopped prior to coal measures, but still had a youthful 60º scarp up to 100m high. Mangakotuku fault zone active prior to and during Eocene coal measures deposition. Eastern downthrow produced downwarping on western side of the valley, deposition largely kept pace with subsidence. Up to 200m coal measures in the fault angle depression. Later coal overtopped fault after it had stopped. SW dip on basement surface towards Mangakotuku Fault reflects late

Eocene downwarping towards it.

Some syn-depositional deformation resulted from compaction of peat beds and gravity sliding on listric normal faults, towards areas of thicker, older sediments. Bedding plane shears and listric normal faults are common in W. Coal Measures. Overpressures/ undercompacted conditions reduce angle for gravity slide to <3º.

Increased tectonism during Miocene-regional tilting and normal block faulting, uplift and erosion of earlier seds. 3º W on Te Kuiti Gp prior to Waitemata Gp- reflected by observed regional dip differences between two Groups, but also coal rank variation, which is higher in the west.

Structural features in coal measures include bedding-parallel shears (most commonly associated with coal seams and shale beds) and related faults, calcite-cemented crush zones and feather veins. Shears within coal seams can be up to 1m thick, composed of shattered and powdered coal, and some also produce small, flat, polished, striated lozenges of coal. Multiple movement phases from more than one lineation set. Faults of moderate dip (35-60º), without associated gouge commonly terminate at bedding-parallel shear zones (some in both directions). Tend to be less than 5m and have no gouge. These features all during burial. Flex slip during compaction especially over basement highs.

Feather veins rare-feathery aragonite-masses up to 1m in diameter, approx circular, flat disc, Tension gash formation in vertical shear zones, followed by horizontal extension.

Regional uplift in earliest Miocene stopped sedimentation and caused substantial erosion of the TK Gp. West-SW tilting 3-4º. Differential uplift due to tilting. No evidence for major faulting at this time. Early Miocene rapid regional subsidence again. (Unconformity-TK-Wait. Gps). Thick Waitemata Group accumulated then uplift again-not known exactly when, due to pre Tauranga Gp erosion. Late Miocene. Regional tilting of up to 15º- most dips 10-15º. Mid-late Miocene dom def normal block faulting- N-NNW and NE-ENE strikes on faults. Crustal stress fields have horiz. axes oriented N-S and E-W- still the same today. N-NNW dominate-less but longer and larger displacements than E-ENE sets. Most probably reactivated from late Cret-early Paleogene pre-coal measures. Many have displacements of 500m. Many have no surface expression due to overlying Tauranga Group and volcanics. ENE faults-some reactivated from pre coal measures, but most formed during mid-late Miocene and terminate against N-NNW faults. Displacements vary inconsistently along the lengths, up to 250m and tend to downthrow SE.

Fault planes in Huntly West have main fault plane dipping 60-70º and a number of diverging subsidiary planes dipping 45º. Fault planes have gouge or sheared mudstone and zone of powdered or shattered coal.

Late Neogene Tectonism produced extensive jointing in coals (cleat), Huntly coalfield two well-defined cleats, perp. to seam and each other, dominant set follows regional strike of 070ºwith 90% of cleats falling 040º-100º. This is aligned with least principal horiz. stress. Many joints have thin coating of Kaolinite or pyrite-no calcite and therefore interpreted as post Olig/early Miocene deep burial.

Eiby, G.A., 1955. The seismicity of Auckland city and Northland NZJSciTech B36: 488-494

Very few felt earthquakes reported in Auckland area. Only one really convincing. (earthquake in 1891 with magnitude MM 8 with epicentre just offshore off the Waikato River Mouth,). None since seismographs operated in the region. (i.e. up to 1954).

A line of seismic activity does extend through the Coromandel Peninsula to Great Barrier Island, and the western boundary of the stable area runs through the Firth of Thames, following NE trend of Auckland coast. Auckland city could still be susceptible to significant earthquakes.

Eiby,G.A., (1964) The Northland earthquakes of 1963 November-December and the seismicity of Northland. NZJGG 7: 745-765.

Earthquake at Mangonui (near Doubtless Bay) on 16 November, magnitude 3.2, less than or equal to 12km focal depth (probably a little under 10km). 22 Dec 1963 2 further earthquakes, 10km south at Peria. Difficult to separate data from the two to determine magnitude. Cumulative magnitude recorded was 5.3 probably about 10km deep.

Contains a table of 25 earthquakes identified in Northland 1956-1963, 8 of which occurred March 14-16 1954 in pretty much the same location, with one on Jan 30 and one on April 7 not far away. Offshore off Whitianga. And 6 in Jun-2-9 1957 off Moko Hinaus. Three in Doubtless Bay area in 1963 mentioned above. 1919 MM4.5-5 Nov 223-24 in Paihia and Russell.

Fergusson, S.R., Hochstein, M.P. and Kibblethwaite, A.C. (1980) Seismic Refraction studies in the northern Hauraki Gulf, New Zealand. NZJGG 23:17-25.

Cape Rodney to Moko Hinau profile.

Jurassic greywacke rocks occur at shallow depths of 100-200m beneath most of central profile. They are downfaulted to the west in the southwestern part of the profile by about 2km to the southwest. 13km wide fault angle depression between fault and major fault is infilled by unconsolidated sediments, underlain by more than 650m of consolidated sediments.

The high standing basement rocks in the central part are dissected by a graben 5km wide and 250m deep, infilled with unconsolidated sediments (assumed to be Quaternary). The fault angle depression and the graben belong to the northern extension of the Hauraki Rift.

Unconsolidated sediments in the graben reach thicknesses of c. 250m

Basement dips at rather shallow depths towards the east.

About 12-13km north east of Cape Rodney there is a thick wedge-shaped sequence of sediments (i.e. basement deepens for some distance)-this interpreted as a fault-angle depression. Eastern boundary of depression interpreted as a major normal fault with throw of 1.5-2km. (Magnetics confirm greywacke rather than igneous basement).

The major fault has been active in the Quaternary- sediments (which are up to 650m thick) increase in thickness towards the fault.

Assuming the fault angle depression and central graben are continuous with those in the southern part of the Hauraki Rift, then a NNW strikes indicated for both features.

Gregory,M.R.(1968) Sedimentary Features and Slumping in the Penecontemporaneous slumping in the Waitemata Group, Whangaparaoa Peninsula, North Auckland, New Zealand. NZJGG 12:248-282.

Waitemata sediments accumulated towards the axial parts of a marine basin within a continental borderland. Current flow was predominantly SE. Soft sediment slumping occurred in response to tilting of the seafloor. Injection of sedimentary dykes often associated with last stages of slumping. Evidence suggests that one such slump extends over a distance of c. 10miles from near Red Beach in the West to Whangaparaoa Head and possibly Tiritiri Matangi in the east.

Sub-horizontal and gently dipping alternating sandstone and siltstone of Otaian age. Intercalated are thick volcaniclastic grits (Parnell Grits) –lensoid deposits and frequently associated with deformed strata associated with penecontemporaneous slumping.

Palaeocurrents:-flute casts, microcross-laminated sets of planar and trough types all indicate flow towards the southeast- the same direction as Balance (1964) reported at Takapuna.

The style of deformation in 'slumped horizons' is disordered and highly irregular- in fact chaotic. Seems to be an abrupt switch from tensional to compressional regimes over a very short distance. Deformation does not affect beds above or below.

Slump horizons may be quite thick. Tarihunga, there is a slump sheet with minimum thickness 30-45 feet. At Stanmore Bay there is one c. 40ft thick, West of Red Beach, another one 40 ft thick. Army Bay to Whangaparaoa Head progressively more complex deformation where at W. Head, a minimum of 300ft of steeply dipping and locally overturned strata exposed in cliff-face and platform. Probably total amount of strata involved in the slumping probably >400ft.

Slumping can occur on slopes of less than 1º. Grant Mackie and Lowry (1964) suggest slumping on a broad shelf in response to regional tilting accompanying tectonic movement leading to temporary oversteepening of the seafloor. It is probable that an environment where turbidites were accumulating that depositional gradients would be minimal and the possibility of slumping due to gravity alone would be slight. Movement may have occurred on a major fault now obscured by the Whangaparaoa Passage. Possibly tectonic spasms heralding the onset of the Kaikoura Orogeny.

Clastic Dykes are occasionally present and are attributed to momentary and spontaneous liquefaction of a water-saturated sediment in response to some shock mechanism, probably associated with seismic activity.

Hatherton and Sibson (1970) Junction Magnetic anomaly North of the Waikato River. NZJGG 13: 655-662.

JMA believed to be due to a serpentinite, probably part of ultramafic belt. If serpentinite pods in Northland allochthon are part of it, then emplacement is from west. (Later papers decide the pods are not Dunn Mountain, but Tangihuas –i.e. part of the allochthon)

Varying amount of serpentisation used to explain varying manifestation of the anomaly, and associated gravity anomalies. Serpentinite outcrops on the anomaly at Piopio.

They note a possible lateral offset of the JMA and suggests a sinistral strike-slip displacement on a fault south of and parallel to Whangaparaoa Peninsula.

Hayward, B.W. (1984) Lithostratigraphy of the basal Waitemata Group, Kawau Subgroup (new), Auckland, New Zealand. NZJGG 27:101-123

Basal Waitemata Group-10-45m thick heterogeneous accumulation of shallow marine sediments. Covers a very narrow zone north, east and south of Auckland.

Locally Northland Allochthon is overlain unconformably by Waitemata Group. Balance and Spörli (1979) suggest that rapid subsidence of proto- Waitemata Basin was associated with gravity sliding of the Northland Allochthon. Breccia of Northland Allochthon clasts, occasionally with cross bedding sometimes overlies the allochthon-Waitemata Group unconformity and locally there is evidence for considerable erosion prior to deposition of Waitemata Group Flysch. Hayward (1982) thinks it is possible that shallow-water Kawau subgroup sediments underlie Northland Allochthon at depth under Northland.

Kawau Subgroup rocks usually structurally very simple. Beds have gentle dips, mostly 10º or less, occasionally up to 20º. Post depositional preferential compaction over basement greywacke highs causes dip. Sometimes crops out as small basinal structures, or small, open synclines.

The occurrence of the subgroup at progressively deeper present-day levels westwards suggests a regional dip to the west. Exceptions occur in Northern Coromandel where there is a consistent NE dip, and in the northern Hunuas where consistently NW dipping Kawau subgroup sits on top of an upfaulted greywacke block.

Kawau subgroup apparently not subjected to compressive tectonics. Soft sedi slumps generally absent.

Post depositional faulting has occurred.

Hayward BW, 1993, the tempestuous 10 million year life of a double arc and intra-arc basin –New Zealand's Northland Basin in the Early Miocene. In: South Pacific sedimentary basins. Sedimentary basins of the world 2 (ed. Ballance PF): 113-142

End Oligocene, Indian-Pacific plate boundary propagated through New Zealand, producing 8-10 million years of regionally variable, compressional tectonism (thrusting and major vertical and lateral displacements). And voluminous calk alkaline volcanism. Resultant early Miocene sedimentary record in the Northland Basin (area north of Waikato Fault) consists of five parts:

1. A thin, basal transgressive sequence of coarse, lithic, shallow marine sediments that passes rapidly up into deep bathyal flysch. This records subsidence in the eastern parts of the Northland Basin that Accompanied oblique compression along the new plate margin. The subsidence began in the north in the earliest Miocene and migrated southwards through the basin during the succeeding 2-3Ma.

2. A series of Nappes (Northland Allochthon) incorporating approximately 40,000km3 -60,000km3 of deep-water Cretaceous and Palaeogene sedimentary and oceanic igneous rocks that were obducted onto Northland continental crust from the Northeast. In the earliest Miocene, the nappes moved south westwards into the northern part of the subsiding Northland Basin, with subsequent southeastwards mobilisation into southern Northland. The allochthon is more than 3km thick in the north, and on average 2km. It extends 15km off the west coast.
3. A submarine fan facies accumulated in a bathyal flysch basin (Waitemata Basin) around the southern toe of the advancing Northland Allochthon. Two fans with separate source areas are recognisable within this 1-2km thick sequence of flysch and associated canyon and canyon-filling conglomerates. Complex deformation within the lower Waitemata Basin fill records a major sub seafloor failure. This slid into the basin from the Northwestern slopes, where several hundred metres of flysch had buried the less stable toe of the allochthon.
4. Bathyal and shelf sandstone and deltaic conglomerate that accumulated in actively deforming "piggyback" depressions (Otaua and Parengarenga Basins) on top of the still mobile Northland Allochthon.
5. Terrestrial and Marine volcaniclastic facies of the ten large (30-60km diameter) basaltic and andesitic volcanoes and dozens of smaller cones and domes that were active within and on the margins of the Northland Basin throughout the early Miocene. The substantial increase in the rate of sedimentation within the Northland Basin in the early Miocene is directly attributable to plate boundary events. Most sediment was derived by rapid erosion of newly uplifted land areas of relatively soft obducted rocks (Northland Allochthon and from ash showers and erosion of the subduction-related volcanoes.

Southwest plunging subduction began 30-35MA, 5-10million years before volcanism. Emplacement of Northland Allochthon –vast nappes- suggests that subduction choked and frozen near the surface about the end of the Oligocene. The continued compression appears to have been translated into significant uplift in the northeastern area followed by obduction of nappes of formerly passive margin and oceanic seafloor rocks into Northland.

Allochthon was emplaced as separate thrust slices into passive basinal setting. Base of allochthon is a decollment surface, with little deformation underneath it. Internal folding within the nappes indicates that subhorizontal compressive strain occurred locally during emplacement, partly as a result of nappes impinging on and overriding earlier nappes. Subsidence occurred prior to nappe emplacement and the main mechanism may be gravity slide. Sediments shed off front and then overridden. Orientation of major thrust faults and folds shows main emplacement direction was to the southwest. Main emplacement direction in Kaipara and Silverdale was south and southeastwards. Presence of Serpentinite pods to west of JMA may indicate westwards or northwestwards emplacement. Southwestwards emplacement began in the latest Oligocene. Southwestwards emplacement began in the north n the late Olig-early Miocene and advanced southwards over a period of several million years. The southern front reached the central Kaipara –Wellsford area by early Otaian and a large, detatched mass reached Silverdale in mid-late Otaian. Piggyback Basins formed. Allochthon stopped in the North by mid Otaian and in the south by end Otaian.

Deformation in Waitemata Group unusually intense: strat low dips in most places, but elsewhere zones of intensive folding over several km. (Spörli 1989)
Eastern ECBF predominance of east-verging folds and west-over east thrusts.
Elsewhere in ECBF, Pakiri and Blockhouse Bay Formation predominance of N and S verging folds and NW over SE folds. NE and NW trending open folds refold predominant bedding-parallel deformation (Spörli and Browne, 1981). Disrupted blocks of allochthon, with NW over SE thrusts, amongst NW ECBF and W Pakiri- e.g. Silverdale Dome (which has ECBF folded around it. N of Silverdale, dips in Pakiri Fmn mostly NW for 20km, probably due to series of imbricate, NW-dipping thrust sheets with occasional slivers of allochthon. NE Pakiri gently folded about NW and NE axes. Kaipara area mostly N over S and NE over SW thrusts and E-NE verging folds. Upper Timber Bay and Cornwallis rel. little deformation, with NE- and NNW trending open folds.
Whole Miocene is cut by a number of large-scale, relatively steep normal faults. Major NE trending extensional faults appear to predate NW trending ones.

There has been regional westwards tilting since early Miocene, several km subsidence west of Northland, and several km of uplift east of Auckland. Thus most of the early Miocene is preserved in the west and have eroded off the east of Northland and Coromandel Peninsula (along with some basement rocks).

Deformation as follows:

5. an early syn-basinal phase of thrusting and folding with east vergence (as in east ECBF)
6. a later syn-basinal phase of thrusting with S and SE vergence (refolding earlier folds, but not affecting eastern ECBF), more complicated near Kaipara
7. a post basinal phase of gentle regional tilting of western areas towards the west and open folding on NE and NW axes.
8. later phase of normal faulting NE first then NW.

1. early def in southern half of the basin-ECBF and Blockhouse Bay
2. only part of the basin Blockhouse Bay, NW and NE ECBF, Pakiri) predates Cornwallis). Compatible with a model of fairly rapid S and SSE movement of allochthon and its piggyback Pakiri and ECBF in NW part of central Waitemata Basin. (Spörli 1989). Appears to've involved major gravity slide failure on NW slopes, possibly associated with some deep-seated compressional thrusting in the north. Silverdale Dome formed with blocks of allochthon stacking up and imbricate thrusts in behind, to the NW and ECBF folding around its toe to the south. Associated S-verging compression penetrated to the base of the Waitematas in the North (Pakiri and northern Kawau) but only deformed upper part of the sequence in the south (Blockhouse Bay Formation) Phase 2 in the Kaipara area was associated with regional uplift and growth of the NNW antiform ridge over the JMA with NE over SW thrusts splaying off to the W and associated folding of the lower Timber Bay Facies. Possibly related to stresses associated with deep dextral displacement along the JMA in the Silverdale area, which could have caused the kink in the JMA and may also have caused the major thrusting and sliding on Waitemata's northwestern slopes.
3. and 4. deformation post-dates the early Miocene history of the basin.

Where the upper surface of the nappes of Nland Allochthon formed land, it began eroding. Elsewhere, where it was completely below sea level, marine sediments began burying its upper surface, especially where there were significant depressions. “piggyback basins” e.g. Parengarenga and Otaua Basins. Complex structure.

Hayward, B.W. (2004) foraminifera-based estimates of palaeobathymetry using modern Analogue Technique, and the subsidence history of the early Miocene Waitemata Basin. NZJGG 47:749-767

Early Miocene Waitemata Basin was relatively short-lived (c.22-17Ma) marine depression that accumulated 500-1000m thickness of turbiditic sand and interbedded mud prior to its eversion in the latter part of the early Miocene. Subsequent uplift, regional westward tilting and erosion have resulted in extensive exposures of Waitemata Group rocks throughout the Auckland region. Greater uplift has exposed the oldest Waitemata Basin sediments (Kawau sub groups-includes Cape Rodney Formation) in the east and south of the region.

In the early Miocene, northern New Zealand lay to the west of Aust-Pac boundary, above southwest plunging subduction zone. Two belts of calc-alkaline, arc-related volcanoes erupted along either side of the Northland Peninsula during the early Miocene. During the period of subsidence and later turbiditic accumulation in the Waitemata basin, two large andesitic stratovolcanoes were active to the west and northwest of the basin, but volcanism did not start in the east until after the basin’s eversion. The regional subsidence and later eversion was presumably related to oblique compression across the plate boundary. It lagged 2-3Ma behind a similar cycle of subsidence and eversion in northern Northland, during which giant nappes of Cretaceous to Palaeogene rocks (northland Allochthon) were emplaced from the northeast, burying older, in situ Miocene sedimentary rocks.

Hayward BW and Smale, D, 1992, Heavy minerals and the provenance history of the Waitemata Basin Sediments NZJGG 35:223-242

Basal Waitemata heavy minerals entirely from basement greywackes. Following rapid subsidence, two discrete sediment sources contributed to the older parts of the mid-bathyal turbidite basin. Northland Allochthon and volcanic source in North Kaipara or located beneath the basement nappes of the Whangarei area. Younger parts of the central basin (Blockhouse Bay and Cornwallis, Timber Bay and upper Pakiri) had a single Kaipara source with a mixture of Northland Allochthon igneous and sedimentary rocks and contemporaneous andesitic volcanism. Another large andesitic volcano, located west of Auckland, provided increasing amounts of sediment, first as sporadic debris flow (Parnell Grit) and later as a broad volcaniclastic apron around its lower slopes.

Early Otaian (c. 22Ma):- Kawau facies shallow marine seds on coast in east. Subsidence to mid bathyal depths, provenance Northland Allochthon-volcanic poor (ECBF). As subsiding in the east nappes of Cret-Paleogene were thrust or slid into northern and northwestern part of basin from the north. First nappes stopped at bathyal depths but later nappes seem to’ve formed land in the Kaipara area. Some early Waitematas where overwhelmed by the emplacement of the Allochthon, which also ripped up and incorporated some of Miocene.

Mid Otaian (c.21Ma):- Pakiri Fmn, proximal, volcanic rich in north, submarine fan further south, fed by erosion of Nland Allochthon from west central Kaipara area (also

Tangihuas). Proximal parts of the fan buried the frontal allochthonous nappes. Albany conglomerate sourced from Tangihuas in northern part of basin.

Pakiri and ECBF interfinger.

Late Otaian (c.20Ma) :- Thrusting in Whangarei area- basement thrust blocks, too. Further south, a pulse of increased tectonism and deformation occurred mid-late Otaian, allochthonous nappes thrust southwards over Waitemata Group in Kaipara area, uplift in northern part of basin, same time earlier frontal nappes and piggyback basins slid south-mass of folded and jumbled rock “Silverdale Dome)

And additional nappes of Pakiri Formation thrust in behind the major Silverdale lobe.

Turbidite facies reflect increased Kaipara and Manukau volcanism and the additional, uplifted area of allochthon.

Early and mid Altonian (c.18.5Ma)

All the northern and central Kaipara area uplifted to form land and shallow sea by early Altonian. Several small volcanoes erupted in east central Kaipara-major sediment source, also continued erosion of the Northland Allochthon. In the south, Waitemata Basin mid-Bathyal until mid Altonian. These are youngest Waitematas known- any younger have eroded away. Manukau volcano grew at this time, too.

Heming R.F. and Barnet, P.R. (1983). The Petrology and Petrochemistry of the Auckland Volcanic Field. Roy Soc N Z 23:64-75

Partial melting of low velocity zone 75-125km under Auckland.

Diapiric rise of mantle.

Convective overturn in mantle behind active subduction zone.

Pupuke and Onepoto 36000-42000years bp. Pupuke markedly less undersaturated than other early period basalts. Possible that early explosion and later high volumes of lava erupted, which would make it the only volcano in the field where there is a reoccurrence of activity after along interval.

South Auckland and Whangarei Fields both terminated with production of tholeiitic lavas.

Herzer RH 1995 Seismic stratigraphy of a buried volcanic arc, Northland, New Zealand and the implications for Neogene subduction. Marine and Petroleum Geology 12: 511-531

Approximately 50 volcanic edifices, from major massifs to small cones identified on marine seismic profiles of western belt, which is largely buried. Volcanoes are important sources for sediments. They were active only in the early Miocene, -most were active by 22Ma and extinct by 16Ma, with many extinct by 19Ma.

No pattern in their inception or their extinction.

NW-SE trend of volcanoes. Eastern arc largely eroded away, whilst the western arc is largely buried.

Rifting before Tasman opened in late Cret, formed depression west of northland Peninsula, which became the locus of the Northland Basin in which western belt later developed and was buried. Little faulting affected the basin after the Cret. Late Oligocene, South Fiji Basin opened and whole Northland area subsided to bathyal depths.25-22Ma ocean crust and sediments to the NE were obducted across Northland. Obduction closely followed by inception of calc-alkaline volcanism. (subduction probably began earlier mid-late Oligocene, whilst S.Fiji Basin still actively opening. In Northland only the highest part of the allochthon were exposed in early lower Miocene and sedimentation was significant mainly close to its periphery and in piggyback basins. Important exception was the Waitemata Basin that developed at the southern end of the allochthon. There much allochthon and volcano-fed sedimentation occurred. Significant westwards infilling did not take place until late early Miocene in response to regional tilting and uplift of the Northland Peninsula. Sedimentation of local volcanic derivation was insignificant in the later Miocene.

Hochstein and Ballance 1993, Hauraki Rift: A young active intra-continental rift in a Back-Arc Setting. In: Ballance PF(ed) South Pacific Sedimentary Basins. Sedimentary Basins of the world 2. Elsevier New York, pp295-305
Hauraki Rift is an active, NNW trending rift, which extends more than 250km from a concealed junction with the active Taupo Volcanic Zone to the northern Hauraki Gulf. It ranges from 25 to >40km wide and has a simple structure if 1,2 or 3 half-grabens adjacent to the W-dipping master faults. Older quasi-consolidated sediments are thicker in the south; upper, unconsolidated unit thickens to the north suggesting dominantly longitudinal sediment supply from the south. Max sedi thickness is >/= 2.5km in the central part of the rift.
Age of the Rift is not known directly. Precursory uplift may have begun c. 10Ma, Rift probably receiving sediment by 5-7Ma. Periods of accumulation seem to've alternated with non-deposition, allowing pyroclastic flows and sediments to cross the rift from east to west.
Initially the Rift developed in a back arc region from 10-2Ma, and was parallel to the now extinct Coromandel Arc. At present it lies at a high angle to the back-arc region of the active TVZ (<2Ma) arc. It is the largest and most coherent structure in a regional field of extensional NW and NE-trending block faults. The inferred tensile palaeostress field has rotated clockwise about 40° during the last 13Ma and is now almost parallel to the master faults. The rift is presently amagmatic but it contains at least two extinct andesitic volcanoes of uncertain age: the rift is associated spatially with both andesitic and basaltic back-arc volcanism located to the west.

Series of concealed, elongate basins, all trending NNW, infilled with younger sediments. Thickest seds are in the eastern fault angle depression, under the Firth of Thames.
Rift is associated with a distinct pattern of late Cenozoic block faults bounded by NW and NE trending block faults.

Asymmetric basin structure with west dipping interface usually steeper than east-dipping- former are interpreted as eroded fault scarps of W-dipping faults that extend to at least o.5km depth. Some NNW trending fault zones are also associated with recent shear movement, as shown by the attitude of a few exposed, active faults in the central part of the Hauraki Depression. Dip steep W and reflect dominant dextral strike-slip movement with horizontal to vertical movement approx. 4.5:1. Offsets of median basement ridge apparently en echelon rather than offset as no evidence for ENE trending cross faults found. Hauraki Lowlands shown to be displaced downwards at a rate of 0.13mm/yr over last 11,000 years. In far south the 0.14Ma Mamuka Fault not displaced by Hauraki Fault (master fault). Vertical movement also affects rift shoulders; uplift rates of between 0 and 0.3 mm/yr have been inferred from observations of Pleistocene marine sediments.
Calculates that rift floor has subsided by at least 2.5km in central segment, where rift is only 18km wide, and by about 1km in Hauraki Gulf, where it is c. 40km wide.

If rift has been active during last 5Ma, and most of the vertical movement occurred on master faults in the central part of the graben, then average long-term extension rate is 0.3-0.8mm/yr for this part, if the faults are 35-60° dips.
Rift is very similar to other described rifts. Simple structure-one, two or three half graben structures all dominated by W-dipping normal faults. According to the development proposed by Scott and Rosendahl (1989) the Hauraki Rift would be somewhere between a juvenile and a mature rift.
Published data seem to indicate that between 7-5Ma, mainly sediment bypass over Rift (or pre rifting); 5-2.5Ma, sediment accumulation in rift: 2.5-1Ma, mainly sediment bypass: 1-0Ma mainly accumulation. (This from deltaic sediments from a major river, and flow-banded rhyolites have passed over rift from Coromandel range almost as far as Port Waikato during times when rift in sediment bypass stage.) This only for central parts of the rift, not north or south.

When Hauraki Rift was first classified as a continental rift (Hochstein 1978) it was thought to be caused by crustal arching in response to some updoming of the asthenosphere (upper mantle swell). This is usual for intra-plate rifting. The specific location of the Hauraki Rift near an active subduction zone was not considered. In 1980 it was postulated that the rift was a “high angle rift” driven by a stress field associated with the present day volcanic arc of the TVZ. When results of in situ stress measurements over the western Rift shoulder became available, a regional tensile stress field was proposed (0.25km depth, present day principal horizontal tensile stress is 335°) to explain present day rifting. (Hochstein et al, 1986). If crustal arching occurred prior to rifting both phenomena can be linked to arc volcanism. It could be that 1.Hauraki Rift developed in response to tensile palaeostress field associated with interaction of plate boundaries (general subduction related process) or 2. it developed as a back arc rift (linked with Coromandel arc). 335° almost parallels the master faults-hence modern day dominance of dextral strike slip on them. At 13Ma the direction of tension was c. 295°, at an angle of 30-40° to faults. Throughout the time period 13-0Ma the Rift has been in an area under tension. It explains why it’s still active, but not why it is where it is. There are no known analogues of a continental back arc rift that is so narrow and has such clearly defined master faults. (only in oceanic setting. Hauraki Rift, then, not taken to be back arc rift.

Arcing of crust on NW axis is evidenced by uplift Jurassic now present on shoulders of the rift. Same in Northland, along extrapolated axis of rift. Lithosphere is still anomalously hot. Widespread Miocene to recent basaltic volcanism can be found over the arched crust of Northland and the outer rift shoulders. (South Auckland, Auckland.) . Can be explained if subduction processes of the Northland/Coromandel arc caused some updoming of got asthenosphere material that may have been sufficient to cause arching in the crust. Probably affected northern part of the rift when volcanism began-15Ma. When volcanism ceased in Coromandel arc, c. 2Ma, a large volume of anomalously hot rocks had migrated into the lithosphere beneath the back-arc region. If some rocks had reached temperatures close to the pressure-melting point, minor upward movement would be enough to produce magmas, even after subduction had migrated to the Hikurangi trench.

Can’t go further than that until rotation of eastern NZ is better understood.

So Hauraki Rift is believed to be formed as a response to some arching of the crust behind the Coromandel arc: incipient rifting may have started 7 or even 10Ma, in the Hauraki Gulf. Arching of crust induced prior to rifting by upwards moving asthenosphere rocks that heated the whole lithosphere beneath the rift. These rocks are still at elevated temperatures. Probably insufficient time to develop a full plume, but rifting continued and was driven by tensile palaeostress field in the whole Northland plate segment. The superposition of an axially symmetric stress field associated with the arching and a regional palaeostress field probably produced a non-symmetrical stress field (w.r.t. rift axis), which could explain the asymmetry of the basement structure in the rift.

Area of rift has maintained a tensile stress environment, in spite of a 60° clockwise rotation of arc segments. It will probably continue rifting as long as the tensile stress regime is maintained by plate tectonic processes.

Hochstein,M.P. and Nixon, I.M. (1979) Geophysical study of the Hauraki Depression, North Island, New Zealand. NZJGG 22: 1-15.

Geophysics shows that the southern part of the Hauraki Depression is a rift structure. In W-E section it is made up of a fault- angle depression, a median horst, and a graben. A maximum thickness of c. 3km of Quaternary and Tertiary fill the two depressions. Fault angle depression and graben are bounded on eastern side by major normal faults dipping 70+/-10 W. (Kerepehi fault in centre and Hauraki Fault, forms eastern boundary of the depression. Minor hinge fault (Firth of Thames Fault) prob. Runs along western boundary.

Transverse faults crosscut and offset normal faults by up to 3m. Recent rifting in south-active faults and shallow seismicity-less than 12km focal depth. Hotspring chemistry indicates anomalously high temperatures (250-250ºC) at less than 5km depth. (Disappearance of earthquake focus at depths of more than 12km also suggests anom. High heat flow and geothermal gradient of >30ºC/km.

Overall parallel sides of depression suggest some fault control.

Complex tectonic structure in south- segmented active fault traces in central part of depression and as indicated by location of hotspring activity along the median part of depression. Gravity high in centre of depression with hotsprings on it at Kerepehi. Magnetics show non-igneous nature of high gravity rocks.

Hauraki Rift is active, and its tectonic setting is over an active subduction zone. Subduction surface is about 200km beneath the southernmost part of the Hauraki depression. The rift is at a high angle to the subduction zone (about 70º difference in strike).

H.R. is not a marginal basin to subduction zone-otherwise it would parallel it. Not a “failed arm of a three-armed rift system (includes Taupo zone)-no large-scale doming.

Could be some mantle upwelling

Could be formed by tensional stress field associated with horizontal crack propagation.

Both mantle plume and crack propagation models include uplift of margins, as is observed in flanks of Hauraki rift by absence of Tertiary sediments

No direct evidence for current subsidence in Hauraki Rift, but the fact that a significant part of the depression is at sea level and the thick sequence of unconsolidated sediments can be taken as indirect evidence for present day subsidence.

If Kiwitahi volcanics directly related to rifting then age could be 15Ma. It is possible that the rift is significantly younger than 10Ma. Battey (1940) has boulders of banded rhyolite in an early Quaternary deposit to the west of Miranda that may have been transported from Coromandel before the rift opened.

They prefer an upper mantle swell causing the rift.

Hochstein M.P. and Nunns A.G. (1976). Gravity measurements across the North Waikato Fault, North Island, New Zealand. NZJGG 19:347-358

Gravity surveys across perpendicular to fault used to investigate profile and vertical offset.

Waikato Fault runs ENE/75+/-15N. Normal fault, with Murihiku basement displaced vertically down at least 2.7km to the north in the west near Port Waikato with the offset decreasing eastwards to 0.7km near Tuakau. Possibly continues eastwards, merging with the Pokeno fault, which downthrows southwards-scissor-type fault.

Basement rocks form 200-300m high plateau south of Port Waikato; eastern part of the plateau is downfaulted to about sea level and is covered in Tertiary seds, also overlain with Quaternary seds and basalts. North of the fault are South Manukau Lowlands with Quaternary seds and basalts at surface.

Borehole at Karaka penetrated 600m of probable downthrown sediments without striking greywacke.

A smaller subsidiary fault lies about 0,5km south of the main fault.

Near Tuakau the fault appears to be offset by 2km to the north. This northern fault trace is aligned with the Pokeno Fault. Displacement could be offset on a transverse fault or ‘flexure ‘ of fault or en echelon. Waikato-Pokeno fault may be pivotal fault Later crosscut by Drury Fault. There is some evidence in this geophysical data for downfaulting of the western part of the greywacke block at the Drury Fault, corresponding to a throw of about 500m.

It is also possible that the Waikato Fault extends to the western edge of the continental shelf.

Movement on the fault probably caused by a regional west-southwest tilt of the large block of greywacke, at least 60km wide, pivoting in the region of the western foothills of the Hunua block

Hodder, A.P.W., 1994. Late Cenozoic Rift development and intraplate volcanism in northern New Zealand, inferred from geochemical discrimination diagrams. Tectonophysics 101:293 –318

Rocks of the Northland area are shown (major and trace element discrimination diagrams) to have rift affinities, whereas Auckland and South Auckland appear to have evolved in an intraplate environment. He proposes the common link is the Hauraki Rift. The Northland Basalts are directly connected with the rift, whereas the Auckland and South Auckland Basalts developed on the flanks of the rift or their origin is linked to the membrane stresses during the opening of this rift, but the chemistry is complicated by the influence of the developing Taupo Volcanic Zone, which adds a shoshonitic character to the rocks.

Heming (1980a) reviewed three models for the origin of Cenozoic basalts of northern New Zealand: 1. back-arc to present TVZ, 2. a convection model with diapiric uprise from the mantle behind the arc, and 3. hot spot volcanism. (doesn’t consider back arc to earlier arcs or association with continental rifts like Hauraki Rift) Heming rejects hot spot volcanism no linear trend of volcanoes and coeval volcanism Northland to Auckland.

(actually aging of fields would be north to south according to plate vectors worked out elsewhere) Heming favours mantle convection with a number of convection cells resulting in geographical spacing of the fields.
Geochemical discrimination Diagrams do not suggest all have same tectonic setting.
Northland basalts associated with rifting
Waikato andesites and basalts back-arc
Auckland and South Auckland intraplate volcanic activity. These possibly associated with propagation of continental-type rifts.
Diagrams can be used to calculate the approximate spreading rates of various rifts. Ti Point and Kiwitahi volcanics (8-0Ma) similar ages they may be associated with the same rift, Calculates spreading rates that seem high (27km/Ma) compares to observed rifting.
Kiwitahi and Whangarei basalts have rift association. Kaikohe basalts rift association with some intraplate affinities
and Tearney (1981) considered Hauraki Rift to be no older than Pleistocene, which would limit the volcanic association to the Kaikohe and Whangarei basalts in the north, and possibly the Maungaturi in the south. H. Rift considered to be more akin to a continental rift, resulting from a fracture propagation mechanism rather than a fast-spreading oceanic ridge.

Auckland and South Auckland Basalts akin to other rocks in intraplate tectonic setting. Geochemical trends show only minor fractionation of the magma.

The Hauraki Rift may be on top of a mantle swell that initiates the volcanism. Alignment of the fields and the direction of rifting. He takes rifting to be perpendicular to axis of rift, then he calculates an angle of 34º to the line running through Auckland, South Auckland and Ngatutura and Okete basalts, and compares it to Turcotte and Oxburgh's criterion for membrane-stress tectonics.
"If the force causing the propagating failure of the oceanic lithosphere lies perpendicular to the direction of seafloor spreading, then the island chain should lie at an angle of 34º16' with respect to the direction of seafloor spreading." The similarity of angle and aging to the south suggests that membrane stress origin could be operating.
Okete Volcanics are older and more alkaline than South Auckland field and have intraplate association-possibly flank eruptions.
Alexandra volcanics started out with intraplate association but may have developed increasing shoshanitic characteristics as TVZ developed.

Hoernle,K., White, J.D.L, van den Bogaard, P., Hauff,F., Coombs, D.S., Werner,R., Timm, C., Garbe-Schon berg, D., Reay, A. and Cooper, A.F. (2006), Cenozoic intraplate volcanism on New Zealand: Upwelling induced by lithospheric removal. EPSL 248:350-367

Major continental rifting associated with the separation of New Zealand from west Antarctica ceased in the mid cretaceous, but Weaver and Smith (1989) proposed that intraplate volcanism was at least in part related to shallow upwellings related to local rifting events. (Weaver, S.D. and Smith, I.E.M. (1989) New Zealand intraplate volcanism. IN: Johnson, R.W., Knutson, J., and Taylor, S.R. (eds), Intraplate Volcanism in Eastern Australia and New Zealand, chapter 4, Cambridge University Press, 1989, pp157-188.

Horsepool N.A., Savage ,M.K. and Bannister S., 2006. Implications for intraplate volcanism and Back-Arc deformation in northwestern New Zealand, from joint inversion of receiver functions and surface waves. Geophys. J. Int. 166,1466-1483

LVZ under Auckland, in upper mantle, is interpreted as body of partial melt and source for basalts—i.e. shallow upper mantle source rather than deep seated mantle plume. Moho 26+/- 1km. Upper crustal velocity 3.4-3.6 kms-1, lower crustal velocity 3.6-4.0 kms-1.

Akl field straddles transition from back arc extension to a 'normal' back arc setting on cont landmass of New Zealand.

The positions of intraplate basalt fields have remained static during subduction zone migration, ruling out any ongoing relationship between subduction zone and intraplate volcanism.

U-Th isotopes suggest a shallow mantle source-probably 80-140km rather than deeper (Huang et al 1997). Auckland volcanoes are classic 'one-shot' plumbing sourced from mantle and not a magma chamber (Smith et al 1993, Hemming 1980)

Station in Hunuas, where greywacke outcrops shows a shallow Moho 27-29km upper mantle velocities

Station in Waitemata Basin shows jump from crust to upper mantle velocities at 26-29km depth

There appears to be a LVZ at 70-90km depth below AVF-this extends approximately 10km north of current extent of volcanism-i.e. future volcanism could migrate northwards. (4.0 kms-1)

Houghton, B.F., Wilson, C.J.N., Rosenberg, M.D., Smith, I.E.M., and Parker, R.J., (1996) Mixed deposits of complex magmatic and phreatomagmatic volcanism: an example from Crater Hill, Auckland, New Zealand. Bulletin of Volcanology 58:59-66

Series of wet and dry pyroclastic deposits form the tuff ring at Crater Hill. Six of seven units are conventional magmatic or phreatomagmatic. One unit can only be interpreted as the products of simultaneous wet and dry explosions at different portions of a multiple vent system-i.e. more than one vent active simultaneously. Apparently associated with an elongate source of highly variable and fluctuating magma: water ratios and magma discharge rates.

Houghton B.F., Wilson C.J.N., Smith I.E.M., 1999. Shallow-seated controls on styles of explosive basaltic volcanism: a case study from New Zealand. Jour Volcanology and geothermal research 91:97-120

Eruptions have a variety of eruptive styles. Dry magmatic vs. wet phreatomagmatic. Transitions controlled by variations in degassing patterns, magma ascent rates and degree of interaction with external water.

Crater Hill eruption took place from at least 4 vents spaced along a NE trending 600m long fissure that is contained entirely within the tuff ring that was generated during the earliest eruption phases.

Magma: water interaction is heterogeneous in space and time and shows a lack of thermal equilibrium between magma and water/wall-rock phases.

At Crater Hill, in order of decreasing age there is an outer tuff ring and maar, scoria cone 1, the lava shield, and scoria cone 2.
Rests on poorly consolidated Miocene Marine sediments. Dominance of these wall rocks in ejecta and the presence of shelly fragments in the volcanic deposits imply that most of the crater excavation took place at very shallow levels.
Smooth and progressive change in the erupted magmas suggest a simple and uninterrupted ascent history with only limited opportunities for mixing between portions of magma batch.

The majority of the phreatomagmatic deposits appear to be products of interaction between rising magma and groundwater, within soft, water-saturated sedimentary strata, There is no evidence to suggest that the vent was flooded or occupied by mobile slurry as typifies Surtseyan volcanism.

Intrusion to shallow levels took place as a c. 600m long dike.

Situations for causing contrasting eruptive styles at the same vent could include:

1. Small contrasts in the architecture of the fissure (for example, elevation differences or construction of protective spatter ramparts, which may have excluded water from some parts but not others,
2. Development of local ponds of partially degassed magma that could interact with external water in some parts of the vent system, whilst water was precluded from other more vigorously erupting vents. At shallow levels in the conduit, non-uniform widths of the conduit walls can produce significant local variations in magma ascent rate along a fissure. In a situation like Crater Hill, where degassing and fragmentation appear to be telescoped into a very narrow depth interval, these processes in the vent and in the very shallow conduit could merge and combine to produce wide contrasts in eruptive styles at adjacent short-lived vents.

At Crater Hill the occurrence of simultaneous activity of contrasting styles from closely adjacent vents imply a dominance of very shallow-seated controls on degassing and fragmentation. Te authors infer that vesiculation and fragmentation occurred mostly<80m from the pre-eruption ground surface. This supports models that consider transitions between Hawaiian versus Strombolian activity reflect degassing patterns controlled by magma rise rates in the conduit rather than the geometry of the holding reservoir.
Crater Hill shows the extent to which clasts ejected from adjacent vents mix during transport and deposition.

Houghton, B.F., Wilson, C.J.N., and Smith, I.E.M., (1999) Shallow seated controls on styles of explosive basaltic magmatism: a case study from New Zealand. Journal of Volcanology and Geothermal Research 91: 97-120

At Crater Hill at least four vents in a linear chain trending NNE along a 600m long fissure that is entirely within the tuff ring generated by earliest eruption phases.

Crater Hill has the largest residual gravity and total field magnetic anomalies within the Auckland Field, reflecting a thickness of up to 120m of dense basalt. Almost certainly includes the subsided deeper portion of the lava shield.

Mixture of clasts in one unit (wet/dry eruption products) suggests that at any instant, portions of the ejected magma were being fragmented at many different points on their ‘vesiculation path’. It does not appear to be the product of simultaneous ‘wet’ and ‘dry’ volcanism from two discrete vents as there are systematic vertical and lateral variations in clast populations. An alternative way of producing a diverse assemblage of juvenile clasts, which remains relatively constant with time, is multiple point sources along a short fissure. Discharge rates and water: magma interaction could vary along the fissure leading to diverse products.

The linear arrangement if inferred vents suggests that magma intruded into shallow levels along a 600m long dyke. Different styles of eruption and therefore different products arise from varying wet and dry conditions at very shallow levels in the conduit. Rout et al (1993) suggest vesiculation and fragmentation occurred mostly less than 80m from the ground surface.

Crater Hill unique in showing full range of explosive basaltic volcanism both simultaneously and sequentially from vents only 600m long.

Hunt, T (1978) Stokes Magnetic Anomaly system. NZJGG 21:595-606

JMA caused mostly by Dunn Mountain Ophiolite Belt. (some parts are caused by mafic intrusives. (Rotoroa Igneous complex.))

Isaac, M.J., Herzer, R.H. and Brooke, F.J. (1994). Cretaceous and Cenozoic Basins of Northland, New Zealand. IGNS Monograph 8.

Te Kuiti Gp in Waikato and King Country has Late Eocene coal measures and overlying predominantly calcareous facies, the youngest being the earliest Miocene (Waitakian, Aquitanian) Otorahanga Limestone. Erosional contact with terriginous Akarana Supergroup (incl Waitemata Gp).

No Te Kuiti Gp strat known between Brynderwyn Hills and South Auckland. Northernmost known Waikato Coal Measures are in Clevedon Fault-Angle Depression, 28km south of Auckland. Apparently thin eastwards, but this may be post Eocene erosion. Palaeogeographic reconstruction suggests that coal measures may have been present below Manukau Lowlands but may have eroded subsequently.

Initial rifting probably 95-110Ma. Rifting and subsidence at a passive (divergent) margin occurred mid Cretaceous-Oligocene: Opening of Tasman 80Ma, then thermal contraction and subsidence of rift troughs and ridges with continued drift. West of NZ landmass mid Cret-earliest Miocene strata in rifted and subsiding basin. Axis of basin and major depocentres were west of present west coast. With continued marine transgression, Eocene to earliest Miocene carbonate-dominated strata were deposited over much of landmass.

Major boundary Fault may be present offshore close to and parallel to present west coast of Northland Peninsula. At Latitude 37º 05’ S a drillhole near South Manukau Head intersected basement at 340m b.s.l., yet 40km offshore depth to seismic basement is at least 4200m.

Mid-late Cret palaeogeography has high standing block where present day Northland Peninsula. Orientation of inferred and observed normal faults has extension almost orthogonal to Northland Peninsula.

On western side apparently no faulting during Eocene deposition. Last of fault-block highs offshore were buried during Eocene with no sign of differential uplift or downwarp.

South of Auckland the Waikato Coal Measures were deposited in a north-flowing drainage system confined to the west by hills of the Murihiku Terrane and to the east by hills of the Waipapa Terrane basement. Te Kuiti Gp. Isopachs and facies patterns indicate that the valley system in which the Waikato Coal Measures accumulated drained north, across what is now the Manukau Lowlands. The major river is inferred to have flowed northwest to feed the Eocene delta represented by the depocentre west of the Kaipara Harbour, The Paleocene depocentre slightly south may have resulted from an even earlier, similarly oriented but high-gradient drainage system, which left no onshore sedimentary record. A dissected landmass of Waipapa Terrane still extended east from eastern Northland; the position of the northern shoreline is unknown. The planar truncation at the eastern pinch-out of the Eocene sequence suggests a marine regression on late Eocene- early Oligocene time. Locally the truncation surface is also cut into the underlying Paleocene.

Most of present western offshore region appears to have subsided to 1km or deeper by end Oligocene. Te Kuiti facies south of Waipapa Horst indicates that shelf conditions prevailed and that rather rapid subsidence of this area must have happened in the late Oligocene. An area up to 50km beyond the present western shore subsided, but there was little if any subsidence further west. This subsidence interpreted to be the first indication of the evolving convergent plate margin, and is attributed to crust being dragged down by the subducting slab.

Kamp PJ 1986 Challenger Rift (mid Cenozoic) GSA Bull 97.255-281
Mid Eocene to early Miocene continental Rift system 1,200km long and 100-200km wide in western New Zealand. 2-4km deep troughs and half grabens bounded by normal faults NNW-NW. Some of these are still offshore, some are now onshore. The probable continuity of the rift system in its early development precludes pre- Miocene transcurrent displacement on the Alpine Fault-inception of Alpine Fault must be c.23Ma with compression that originated at the Australia-Pacific Boundary. The Australia and Pacific Plates were not discrete entities until the Early Miocene. Occurrence and tectonic subsidence of the Challenger Rift System contributed in a major way to the nearly complete mid Cenozoic submergence of NZ.

Kear, D., (2004) Reassessment of Neogene Tectonism and volcanism in North Island, New Zealand. NZJGG 47: 361-374

‘Waitemata tectonic event’ (26-25Ma) established subduction beneath greater Northland, creating Northland Allochthon and two volcanic belts lasting (23-16Ma).

‘Kiwitahi Volcanic event’ (15-14Ma) volcanism migrated southwards and 200-300km transcurrent movement on Alpine Fault in North Island. 25°dextral curvature imposed on North Island

‘Kaimai Tectonic Event’ (5-2.5Ma) halted volcanic migration, Further 40° of curvature. Caused rotational rifting of Central volcanic Region, initially tearing away along Alpine fault trace, creating volcanic zones further and further inland (SW).

He has claims the basaltic volcanism migrated southwards only, from Kerikeri volcanics in Whangarei area c. 10ma. ‘volcanic fronts ‘ migrated southwards, southernmost extent of volcanism, but volcanism can occur anywhere behind the front (i.e. further north.). So he says the apparent northward migration of the four fields in the Auckland area (Raglan to Auckland) isn’t real/significant.

Rotational rifting has been the most important movement in the North Island since 2.5Ma with no evidence of movement on the abandoned Alpine Fault in that time.

CVR has elongate, triangular shape, open to the NNE with near straight long margins.

Broad northeast aligned expansion (southeast surface extension of 1.8m) and sinking (2m) observed in Edgecombe earthquake, 1987, and rifting in Tarawera eruption in 1886-compatibility with simultaneous dextral rotation, which imposed 30°+ curvatures into southern North Island. He estimates southeastwards extension of Whakatane Graben (and TVZ, CVR) as 1.8cm/yr. CVR straight western limit is weakened major fault line from which rotational rifting took place, hinge point moving progressively southwards (SSW)

His fig 1 also shows Hauraki Rift as wedge shaped, opening northwards, and fig 3 shows beginning of opening at 2Ma (2° rotation by then), at 1Ma 5°, and in the period 0.9-0Ma, opening a further 5°

Kear, D. and Schofield, P. (1959). Te Kuiti Group. NZJGG 2: 689-717

Te Kuiti Gp unconformable on basement. Top Te Kuiti Gp is an unconformity. Lowest Te Kuiti Gp is coal Measures. Prior to this landscape cut by deep valleys, which probably became inlets during marine transgression. Shorelines paralleled isopach trends, and migrated south and west, so successively younger formations onlapped basement or coal measures. Maximum transgression in Waitakian (unless subsequent erosion). In north Te Kuiti Gp thins eastwards, probably due to onlap with transgression.

Pre Tertiary landmass in south Auckland was not a peneplain. Coal measures in low-lying areas in north-south trending depression. Thickest coal measures within land-locked depressions of northern part of Waikato Coal Region. Initially with transgression anaerobic conditions continued, becoming more aerobic with continued transgression as depression became less land-locked. Eventually open-sea, aerobic conditions. Halts in transgression meant that deposition reached wave- base so that sands were deposited further offshore than usual, and became interbedded with mudstones. Eventually limestone.

Transgression mainly by regional subsidence and eustatic sea level causing onlap and migrating shoreline. Deposition stopped when tectonic activity caused 1) angular unconformity between Te Kuiti and Waitemata, and 2) uplift of source province from which subsequent clastic sediments were derived.

Kear, D. and Schofield, P. (1978). Geology of the Ngaruawahia Subdivision. NZGS Bull 88.

Basement rocks (Hokonui) –broad, open folds with dips averaging 45º, Te Kuiti and Waitemata Groups essentially block-faulted with low-angle dips averaging 10º and Tauranga Rocks essentially horizontal: dips of around 3º may be due to differential compaction.

Te Kuiti and Waitemata dips 5-15º though locally higher, even vertical dips e.g. close to large faults. Region of block faulting with blocks tilted north or northwest. Local variations usually due to uneven pre-Tertiary topography, differential compaction or the proximity of major faults. e.g. In the Maramarua Coalfield structural contours indicate a regional northwest dip but near Kopuku opencast, near the angle between the Maungaroa and Foote Faults, the strike swings round steadily to the northwest.

Reliable structural data present in coalfields. Dominant strike of faults in N is NNW and south is N. Lesser sets strike NE-NNE. (050-031º). Two major north-trending faults (Mangakotuku in E and Paerangi to the west) converge, meet and form a northern limit to the graben-like structure of the Glen Massey Coalfield to the south.

Block faulting in both Te Kuiti and Waitemata Groups and is therefore predominantly post- Waitemata. Mostly pre Pliocene Kaawa Formation and is taken to be phase of Kaikoura Orogeny. Some tectonic movements may have been associated with breaks within the Waitemata and Te Kuiti sequence. Three factors point to syn-coal measures movement. 1) Lower coal measures were deposited in a fault-angle depression, which parallels major fault strike in the north, and must have been young at time of deposition. Deposition may have been initiated by relative tectonic movements.2) Basal conglomerates are rare in the coal measures, so their presence and the local angularity of their pebbles within 100yards of the Karaka Fault, SW of Glen Massey, implies a locally steep topography at the time of their formation e.g. fault scarp. 3) Common tendency for coal seams to become thinner and dirtier towards the major north-south faults, which implies at least topographic irregularity roughly coincident with Kaikoura faults, Kaikoura were at least in part reactivation of earlier faults.

Geophysics shows Waikato Fault striking ENE through Port Waikato and downthrowing to the north, and a fault runs along eastern Hauraki Plains, through Paeroa, and downthrown west.

Pre Pliocene rocks of the Tertiary were tilted and faulted rather than folded in the Kaikoura Orogeny. Major faults are NNW-N and may in part be reactivation of Eocene faults, or earlier. Minor normal faults swing away from major ones, towards the northeast, and are all normal.

Minor movements, especially following Rangitata trends, heralded coal measure deposition in the Eocene and occurred at intervals in the Te Kuiti and Waitemata deposition. Major Kaikoura Orogeny faulting is post Waitemata. Main effect block faulting with possible reactivation of Rangitata orientations. Swing in minor faults to NE suggests stress direction had by that time swung anticlockwise to the Northeast.

Jill Kenny (2008) Northland Allochthon-related slope failures within the Waitemata Group. Geocene #3 p5-7

Lack of published faults in Auckland.

Block faulting inferred from offset on “late Miocene” eroded surface of the Waitemata Group

ENE-NE trending faults and arcuate faults may be sub-horizontal and associated with emplacement of thrust slices of allochthonous Waitemata rocks.

A series of arc-shaped ridges, with steep south facing and gentle north facing slopes, dominating Auckland area are interpreted as arc shaped sub horizontal faults, fanning out from just north of Albany.

South of Auckland Isthmus, ENE trending faults as eastern extension of splay faults from offshore west coast

NNW faults truncate both these trends

Some areas of Waitemata seds simple, others very complex and interpreted as syn-sedi or pene-contemporaneous slumping in actively subsiding basin

Hayward's (1982,1993) proposed catastrophic seafloor failure may reach further than Albany- these imbricate slices may reach Henderson and Howick

Mid-late Otaian seafloor failures in Waitematas, deposition cont through early Miocene then uplift causing late Miocene or Pliocene eroded surface.

South of study area then cut by post early Miocene block faults forming east trending horst and graben features

Imbricate slope failures and block faults have been truncated by N to NNW trending normal faults, (mostly downthrown W) probably related to NNW trending regional faults with NE-SW extension (e.g. Drury, Wairoa, Waikopua Faults-mid to late Miocene?) and NNW trending Hauraki Rift zone.

Jill Kenny (2008)b Just Another Fault for Auckland. GSNZ newsletter145 (2008)p3-11

Lack of published faults in Auckland itself.

Recognised and inferred block faulting in Hunuas, Maraetae in East, Waitakeres to west, Franklin to south, South Manukau Lowlands and Awhitu Peninsula. Offshore to the west ENE trending fault splays recognised seismically. To the north, in the Albany area, faults have been inferred to be associated with thrusting and sliding southwards.

Late Miocene peneplain no longer constant heights above sea level. Series of near horizontal ridges across Auckland.

Some lineaments on aerial photographs offset topography and may represent faults separating regions of different height.

Preliminary results show block faulting/ horst & grabens similar to that in S. Man. Lowlands. Some splays may be onshore extension of splays offshore. Others parallel to NNW trends of Hunuas and Hauraki Rift.

Drury and Wairoa Faults could extend into Auckland.

Most NNW trending faults are downthrown to the west. Sediments in the east are older, lower in the sequence and unaffected by allochthon-related deformation that affects the western Waitematas

Manukau Fault reinstated East trend, downthrown south (peneplain tens of m above sea level to north and many metres below sea level to the south)

Fault under Harbour Bridge drawn trending NW. East coast Bays fault may trend SSE, possibly liking up with the Drury fault. Lucas Creek Fault taken to be E-NE trending thrust, downthrown to the south.

Imbricate slices of Wait Gp fanned out more than 30km from toe of Nland Allochthon in Albany towards the west to SSE quadrant. This mid-late Otaian.

Western faults merge with those mapped in the Waitakeres.

South of Howick Waitemata Gp down dropped along E trending faults and covered by younger seds of the South Manukau Lowlands.

East trending faults in Awhitu and Clevedon inferred to be onshore extension of faults to west (post early Miocene) rather than part of the imbricate, allochthon related group.

NNW faults inferred to be mid-late Miocene extensions of Drury and Wairoa/

Waikopua faults. Period of uplift and erosion to form Late Miocene eroded surface is crucial before these faults become active. Therefore timing must be modified. Works if as Ballance (1968) suggested uplift and block faulting continued into Pliocene.

Uplift may still be occurring. Displacements, tilting and buckling have affected seds of Plio and Pleisto, seismic activity is still recorded.

Locke, C.A., Cassidy, J., Sporli, K.B., Eccles, J.D. and Williams, H.A., 2007. Auckland Volcanic Field, New Zealand: geophysical characteristics and regional structure. IAVCEI- International association of Volcanology and Chemistry. IUGG XXIV General Assembly July 2-13, 2007, Perugia, Italy. Poster presentation 6694.

AVF lies at tip of northward propagating lithospheric fracture along which volcanism has migrated for last 2Ma (Briggs et al. 1994). AVF coincident with Dun Mountain Ophiolite belt, now buried but rep by JMA, running NW-SE. JMA subdivided into multiple parallel linear magnetic anomalies across AVF interpreted as serpentinite shear zones in DMOB. AVF also marks abrupt narrowing and subtle change in strike of JMA. Gravity shows AVF also located on 50km wide gravity anom- probably non-sheared ultramafics of Maitai terrane. This large competent crustal body may have temporarily arrested the northward propagation of the fracture, resulting in complex crack-tip stress field that allows formation of joint arrays extending into and decompressing lithospheric mantle regions- allowing magma mobilisation. No clear alignments, but some equivocal alignments of vents along regional Quaternary structural trends. Some vents apparently simultaneous, but no other clear connection.

Magill C.R., McAneney, K.J. and Smith, I.E.M., 2005. Probabilistic Assessment of Vent Locations for the next Auckland Volcanic Field event. Mathematical Geology 37, 227-237

69% of events involved at least one eruption centred either on land or within 1km of the coast.

Several eruption points within the field occur along lineaments.

Distribution of eruption points probably has a deep-seated structural control, although orientation of visible vent lineaments is likely to be controlled by shallow faults.

Changes in chemistry of Rangitoto suggest a shallowing source, also consistent with greater volume. Smith and Wood (1997) concluded that Styaks swamp; Green Hill, Otara Hill and Hampton Park represent the same magma. Batch. Crater Hill and Wiri Mt also share a magma Batch (Rout et al) Wiri Mt, Crater Hill and Puketutu all same excursion and therefore similar timing, Otara Hill, Hampton Park and McLennan Hills may also relate to same geomag excursion (Shibuya et al 1992)

Some volcanoes have more than one vent. Rangitoto has 3 overlapping vents over 0.5km aligned NW-SE

Onepoto-Tank farm-Lake Pupuke

Mt Victoria-Mt Cambria-North Head

Little Rangitoto-Orakei volcano

Eruptions occur preferentially closer to the last eruption

Groups and alignments in the field in lines running NE to NNE (about 10 lots, 6of which have 3 or more vents) or NW (5lots but all only have 2 vents)

(with 3 vents, 2clusters NNE, 2 clusters NE, with 2 vents: 3NNE, 3NE, 2ENE, 3NNW)

Most recent five groups of eruptions have occurred progressively northwards (but remember that earliest eruptions were in the north!)

Malpas J, Spörli KB, Black PM, and Smith IEM, 1992, Northland ophiolite, New Zealand and the implications for plate tectonic evolution of the SW Pacific. Geology 20:149-152

The ophiolite was probably emplaced as a single sheet and separated into individual massifs during subsequent movement of the allochthon, N-MORB also some seamounts. Two alternative models, one involving a subduction flip, the other involving continuous westwards subduction to account for the obduction of the upper part of the Northland Ophiolite. The oceanic crust from which the ophiolite originated was formed simultaneous with Tasman seafloor spreading.

Significant change in the plate tectonic configuration of SW Pacific at 25Ma led to the emplacement of ophiolitic massifs onto N NZ. Tangihuas occur as structurally discrete bodies ranging in outcrop from 0,2 to 90km2. Part of allochthon which was emplaced in a very short period of time, as indicated by the age of the youngest allochthon rocks versus the age of the onlapping early Miocene sediments. Emplaced from the NE. (Convergence after prolonged period of extensional tectonics and quiescence.
Allochthonous sedi strata are folded, fractured, sheared and sometimes tectonically transposed to give complex age reversals. Total statigraphic thickness is c.7000m. Geophysical data indicate a maximum depth of 4-5kmto greywacke. The massifs are faulted against the surrounding sedimentary rocks and shown geophysically to be rootless. Vein material shows that major faults juxtapose igneous rocks that have undergone zeolite facies against those that have greenschist. Usually fault contacts, but where there is a conformable contact, alkali basalts are consistently younger than. Tholeiites. On the eastern side of Northland pillow layering and sedimentary bedding fluctuate about the horizontal. In the western massifs there is a constant westwards and southwestwards overall dip, apart from areas of local deformation. Most dyke trends are northwest to north. Maybe that Tangihua massifs are part of one formerly continuous sheet of ocean floor.

Nelson, C.S. (1978). Stratigraphy and palaeontology of the Oligocene Te Kuiti Group, Waitomo County, South Auckland, New Zealand. NZJGG 21: 553-594.

Te Kuiti Group –all seds between Mesozoic greywacke basement and Miocene Waitemata Group- represent major margins transgression in Oligocene –calcareous mudstones, calcareous sandstones and sandy and pure skeletal limestones with subordinate, but locally abundant coal measures and conglomerates.

Eocene and Oligocene seds mark the slow encroachment of shallow seas across generally subdued topography cut in Mesozoic and older rocks. Apart from freshwater mudstones, sandstones and coals preserved by inundation of swamplands marginal to the advancing seas, the sedimentary rocks are mainly neritic and form extensive rel. thin units, up to a few 100m thick, of highly calcareous and commonly fossiliferous and glauconitic sandstones and mudstones, and also skeletal limestones.

Te Kuiti Group is generally flat-lying and there is a gross lithologic simplicity, with lateral facies changes present and so different formations correlate in time (foraminifera). Isopach lines are elongate N-S and are comparable for whole group, Lower Te Kuiti Group and Aotea Sandstone (uppermost lower TK Gp.)

Orderly stacking of units is interrupted by lateral variations in lithology, locally rapid changes in thickness, reflecting palaeorelief, differential tectonic movements in source and depositional areas, the position of source areas and dispersal paths of terrigenous sand and mud, and distance from shore. Formations are mutually exclusive locally. On a regional scale pars of different formations are lateral equivalents. Formations commonly bounded by unconformities, mainly disconformities.

Nelson, C.S. and Hume, T.M. (1987). Palaeoenvironmental controls on mineral assemblages in a shelf sequence: Te Kuiti Group, South Auckland, New Zealand. NZJGG 30: 343-362.

Late Eocene-Olig seds of Te Kuiti Gp are classical transgressive sequence from basal non-marine coal measures to overlying shallow marine mudstones, sandstones and limestones. Mineralogy affected by climate, soil provenance, depositional environment and digenesis more than by tectonics and source-rock provenance.

TK Gp several laterally extensive, essentially flat-lying and partly time-equivalent formations, with total thickness 800m, but typically only 200-300m. Sedimentary sequence records shallow marine inundation of large, partly land-locked embayments formed in Triass-Jurass mudstones and sandstones. Basal non-marine coal measures pass upwards into siliceous mudstones, then marine highly calcareous fossiliferous mudstones and sandstones, then skeletal limestones. Late Oligocene transgressive peak had deposition of shallow marine limestones.

The sediments were deposited in a tectonically quiescent time. Mineralogy not very influenced by rock mineralogy. Conditions had been quiescent for a long time, so a thick soil regolith (up to 10s m) had been weathered, in a warm climate, low relief, and some fossil regoliths remain in modern landscape. The chemically weathered mineralogy was the dominant influence on subsequent sediments. Coal measures completely dominated by quartz and kaolin, with very little feldspar. Acid conditions/leaching. This contrasts with overlying marine beds, which are dominated by low-Mg calcite. Of non-carbonate minerals, detrital quartz is common but accompanied by more feldspar than in coal measures. Partly because now supplied from lower, less weathered regolith but also due to cooler climate and so less chemical weathering. Alkaline marine conditions preserved feldspar better.

Rait, G.J., (2000) thrust transport directions in the Northland Allochthon, New Zealand. NZJGG 43, 271-288

Information from sites all over Northland indicates overall transport direction towards 220+/-10°. Consistent with location and all structural levels-throughout thrusting history. (Broadly older –on –younger, distal-on-proximal, (piggy back) initial activity on thrusts on top of the pile would have been earlier than those on lower down.) All seem consistent, even where out of sequence movement (e.g. sub ophiolite thrust) early and late fabrics (ductills/brittle) are compatible.

Mean transport is approximately perpendicular to the thrust front, to folds affecting the allochthon and its basement, to belts of Miocene andesite volcanism and the Vening Meinesz Fracture Zone. (Also sub perpendicular to JMA). Strongly suggests allochthon driven by Miocene subduction beneath Northland, being obducted as a ‘flake’ peeled from the down going slab. It suggests that the Silverdale serpentinites are part of the Tangihua Complex (allochthon) rather than from the Dunn Mountain Ophiolite Belt. (Otherwise they would need east or northeastwards transport-no evidence.) Supported by ubiquitous association with Northland Allochthon Rocks)

Rait G, Chanier F and Waters DW 1991, Landward and seaward directed thrusting accompanying onset of subduction beneath NZ. Geology 19:230-233
A short (roughly 5My) episode of deformation accompanied the onset of the present phase of subduction beneath northern and eastern New Zealand into the early Miocene. Structures dominated by subhorizontal thrusts sheets with 10s km of movement. Thrusting was directed both landwards and seawards. The structures show that delamination of the down going plate occurred at some places and suggests a high degree of coupling between the upper and lower plates occurred at others.
The onset of deformation (fold and thrust) on the northeastern margin of New Zealand at the beginning of the Miocene has been correlated with the onset of subduction there (c.22Main North Cape and by 21 Ma, well established arc along the peninsula almost as far as Central V.Z.). Early Miocene deformation was short lived, it produced a variety of styles of structure and they are different from structures at active trench slopes.
Northland has undergone little post early Miocene deformation, a consequence of the arc having migrated to the south.
In Northland, a>3km stack of allochthonous sheets of Early Cretaceous –early Miocene deep water rocks has been thrusted southwestwards. Associated "ophiolites" are only 0.5-1km thick and are composed almost exclusively of intercalated basaltic lava flows and mudstone or limestone, with minor mafic dykes, suggesting that only the upper levels of the oceanic crust are present. Ultramafic rocks only present at North Cape, and no high temperature metamorphic sole is present anywhere. Oceanic lithosphere must have been descending during obduction of the ophiolites in order to reach sufficient depths for magma production. Upper levels only, plus other ocean floor subducted suggests the "ophiolites were peeled off the subducting slab and driven up the continental slope and onto the shelf. "ophiolites are now 150km from the northeastern edge of the continent. Deformation was dominated by subhorizontal thrust sheets with tens of km of displacement. Such structures are not typical of active trench slopes and accretionary prisms, which are dominated by seaward-directed thrusts and associated folds.

Raza, A., Brown, R.W., Ballance, P.F., Hill, K.C. and Kamp, P.J.J., (1999) Thermal history of the early Miocene Waitemata Basin and adjacent Waipapa Group, North Island, New Zealand. NZJGG 42: 168-188.

Apatite fission Track and vitrinite reflectance techniques used to investigate burial depths/temperatures and sources for sediments of Waitemata Basin. Total sediment thickness in the basin shown to be less than or equal to 1km max., burial temperature never exceeded 60°C. Four dominant sources of sediment: contemporaneous volcanism, metagreywacke of Waipapa, Northland Allochthon and an unidentified source south of the basin. The basin has not been buried deeply before exposure at present day surface.

History

Tectonic activity from Palaeozoic to present.

Subduction on Pacific edge of Gondwana

Mid Cret (c.105Ma) subduction ceased (due to collision of Pacific-Phoenix ridge and subd on east of Gondwana)

Then convergence switched to extension. Seafloor spreading circa 80Ma, sep from Australia.

Then thermal subsidence.

Late Eocene-mid Olig, more extension along western margin of NZ.

Olig-Miocene boundary subduction resumed. Initially in Northland. Also formation of Alpine Fault.

Along with it, obduction of nappes of Northland Allochthon (former passive margin) between 24-22Ma, plus Tangihua/Matakaoa ophiolites and development of inter-arc basin (Waitemata Basin)

At 15Ma, arc to west of Wait. Basin extinct, basin fill was uplifted above sea level. As subduction system propagated southwards, so did the volcanism. Mid Miocene back-arc rift with rhyolitic volcanism established on the Coromandel Peninsula.

Late Plio-present migration of the arc to present position in the TVZ.

Response to renewed subduction was sedimentation in Waitemata Basin c. 25Ma between two coeval parallel NW trending calc alkaline arcs.

In east basin onlaps autochthonous Waipapa Group. Northwest and in centre of basin, unconf overlie strongly deformed and displaced deep-marine Northland Allochthon.

In north and south flanked by uplifted basement blocks, (Te Kuiti and Waipapa/Murihiku)- only thin Waitematas here.

Main part of the basin deposited at bathyal depths during Otaian (c.23-19Ma). Most of supply from NW.

There is a general regional tilt and younging towards the west. Strata commonly flat lying but zones of intense folding and faulting occur. (syn- and post-depositional deformation)

Youngest preserved seds are c. 17Ma, in far west. Any record of more recent geological history is missing from most of the basin. In southernmost part of the basin Wait seds are unconformably overlain by Kaawa Formation, meaning earliest denudation pre late-Pliocene.

Biostat age and K-Ar ages show volcanism took place between 27-16Ma, contemp. With subsidence in the Waitemata basin.

Ricketts BD Balance PF, Hayward BW and Mayer W,1989 Basal Waitemata Group facies, rapid subsidence in early Miocene interarc basin, NZ Sedimentology 36:559-580

Abrupt transition from coastal and shallow shelf sediments (Kawau subgroup), formed in a rocky, craggy coastline, to bathyal sediments provides a record of rapid subsidence and deepening of the early Waitemata Basin. Response to continued rapid subsidence and transgression in the Waitemata basin was a decrease in the supply of coarse clastic sediments. Beach gravels progressively displaced down slope. Bathyal turbidites on top, first using up local seds then getting into classic turbidity current background mud and transported sand sequence.

Subsidence from zero to bathyal depths may have taken one million years- or even significantly less time. Average subsidence rate of 1-2mm/year suggested-means 1-2km could be achieved in much less than 1million years.

Robertson,1986. A palaeomagnetic study of Rangitoto Island, Auckland, New Zealand. NZJGG 29: 405-411

Palaeomag measuring natural remnant magnetisation. Palaeomag declinations measured and compared to historical recorded declinations, and found to give dates in good agreement with 14Cmethods: Rangitoto active AD 850-AD1800, wuth maximum of activity AD1200-AD1500. Some sites with especially high magnetisation, consistent with rapid crystallisation of small magnetite grains, likely by quenching, are found in samples collected from current intertidal zones, confirming ses level has remaines roughly the same since eruption.

Rout D.J., Cassidy, J. and Locke, C.A., Smith I.E.M. (1993) Geophysical evidence for temporal and structural relationships within the monogenetic basalt volcanoes of the Auckland volcanic field. Journal of volcanology and geothermal research. 57 71-83

Geomagnetic excursion shows similar timing of Crater Hill and Wiri but not Wiri and neighbouring McLaughlins Mountain.

Crater Hill and Wiri appear to have tapped the same magma batch (Crater Hill is about 4km NNW of Wiri.

Saturation of sedimentary host important in defining eruption style.

Samsonov,S.V. and Tiampo (2008) Deformation occurring at the city of Auckland, New Zealand as mapped by SAR interferometry. In press(Geophys Res Letters)

Results of three different techniques show good agreement.

-Three areas of subsidence identified, each with deformation rates of about.-0.4cm/year. The two smallest (S36.89 E174.63 and S36.94 E174.84) are about 1km in diameter and possibly due to groundwater extraction. The third, east of the southern Manukau Harbour (S37.03 E174.93), is approximately 5km in diameter and its cause is unknown.

- Three areas of uplift are also identified, (S36.98 E174.88, S36.94 E174.66 and S36.91 E174.69), with deformation rate approx. 0.35-0.4cm/yr. The first is the largest (4x8km) and has a well-defined SW-NE trend, uplift at a maximum in NW corner. A small earthquake was recorded here on 15 March 1995(M less than 2). The second area of uplift is 3km in diameter and the third is about 1km in diameter.

Searle, E.J. (1959) Petrochemistry of the Auckland Basalts. NZJGG 3:23-40.

North Auckland region-the block north of the Manukau Fault – has been seismically stable during Pleistocene times (Eiby, 1955) and probably so since well back in Pliocene times (Brothers 1954). Manukau Lowlands exited as basin from Pliocene. Movement on the fault began post Altonian and pre Opoitian.

Sherburn, S., Scott, J.S., Olsen, J., Miller, C., (2006) Monitoring Seismic Precursors to an eruption from the Auckland Volcanic Field, New Zealand.

1995-2005, 24 earthquakes located in Auckland region. All less than 15km deep. Only one in AVF. (six in Hunuas, 11 offshore in Hauraki Gulf, one north of AVF, the rest probably within AVF. Only one definitely in AVF) ML1.6-3.3.No deep low-frequency earthquakes detected. (Deep, long period earthquakes occur in other fields at c. 30km depth as magma rises. May be first sign of an impending eruption.)(Need to know epicentres of shallow earthquakes, 5km or less to detect eruption site). Precursory EQ could be as little as 2 weeks before an eruption, could be M4.5-5.5. Nodules suggest 10-100days total eruption time.) Geodetic monitoring may be as useful for eruption site identification. Tephra is biggest risk.

NE-SW and NW-SE faults in Hunuas, where clusters of vents alignments sometimes NE-SW-possibly reflecting basement structure.

1960-1983 81 earthquakes with M greater than or equal to 4 and depth less than 40km within 100km of Auckland. Most in Hunuas, or Coromandel, only one close to AVF (M5.5-6.0, 60km south of Auckland.)

Brittle-ductile transition is at 15-20km beneath Auckland. Seismic precursors 3-30days before an eruption.

Knowledge of crustal structure is severely limited and could significantly handicap the interpretation of precursory earthquakes.

NE-SW lineation in some of the volcanic vents, that is parallel to faults in the basement, may suggest an influence by basement structures of vent location. Once magma is within a few km of the surface, knowledge of the location of faults may help in estimating the eruption sites. Thermal structure of the crust also needs more research.

<u>Skinner, D.N.B., (1986) Neogene Volcanism of the Hauraki Volcanic Region. Bull Roy Soc N Z 23:21-47</u>

Includes Kiwitahi volcanic zone in west (southwest), Coromandel volcanic zone in east and Hauraki Rift separating them.

NNW trend of the zone is not in itself a volcanic arc, but is inherited by episodic Neogene arc volcanism through a horst-graben structure in Mesozoic basement.

Age constraints poor, but andesitic-dacitic volcanism began in the north c. 22-23Ma lower Miocene. Spread south with time. Minimum age of 2.5Ma.

Rhyolitic volcanism began in north 7-8ma and spread south. Some basalt associated with rhyolite 6-8Ma

Regional basement trends are NNW and NE-inherited in Neogene from basement.

NNW trend of Great Barrier-Coromandel not in itself an arc, but inherited from horst structure in basement.

NNW trends, half throw down west, half east.

NE-ENE trends mostly downthrow south.

Possible active faults in the basement and volcanic of the Coromandel Volcanic Zone.

Smith I.E.M., Blake, S, Wilson CJN, and Houghton BF (2007) Deep-seated fractionation during the rise of small-volume basalt magma batch: Crater Hill, Auckland Contrib Mineral Petrol

General chemical characteristics of Crater Hill are consistent with derivation from a magmatic system that was originally generated by a process of partial melting in upper mantle. Magmas did not at any stage accumulate in a magma chamber.

Rising magma cools to chilled margin at depth. High pressure cpx preferentially crystallises and therefore the initial melt is depleted in cpx. Once chilled margin is established, blanketing occurs and magma no longer so depleted. In bigger systems initial cpx depletion may be obscured by larger volumes of unfractionated magma.

Spörli KB 1978 Mesozoic tectonics, North Island, New Zealand. Geol Soc Am Bull 89:415-425

Waipapa Terrane east of JMA, three deformational phases recognised.

4. Formation of melange and imbrication of strata with fold axes trending across the now-dominant basement grain and fold vergence predominantly towards the south. Several hundreds or even thousands of metres thick sequence.
5. 2. Strongly asymmetric folding and imbrication and further melange formation on horizontal axes parallel to the present structural grain; folds verge east and beds in the axial ranges have rotated to overturned and vertical attitudes. Fold axes often trend NW
6. Open folding on steeply plunging axes. Dextral and sinistral present.

Phases 1 and 2 are part of early Cretaceous Rangitata Orogeny or predate it. Age phase 3 unknown..

JMA ultramafic belt between Murihiku and Waipapa.

Spörli, KB, 1982, review of Palaeostrain/stress directions in Northland, NZ and of structure of the Northland Allochthon. Tectonophysics, 87:24-36

Folding, shearing and fracturing in the Northland Allochthon occurred prior to deposition of the upper Oligocene-Miocene Akarana Supergroup. Fold vergences shows allochthon moved from NNW to SSE. Pre Miocene def in basement includes thrusting and strike slip faulting with compression trending NE-SW across Northland. NW-SE thrusting followed by NW-SE extension affected Miocene rocks and persisted into the Quaternary.

-In basement can often recognise three phases of folding-youngest (sinistral bending on steep axes.) probably postdates the Rangitata Orogeny.

-Basement: qtz-chl striations on basement faults post early Cret meta, pre Waitemata.

-Source basin of allochthon everted by unknown mechanism. Transport probably dominated by gravity slide. Waitemata Gp deposited on basement and allochthon. Initial transgression followed by rapid subsidence.

-Reactivation of Allochthon produced Onerahi Chaos Breccia-overlies/ interbedded with Waitemata Gp. Serpentinite in O.C.Breccia could be from JMA, possible W-E transport.

-Emplacement of allochthon coincident with inception of the Alpine Fault.

-Allochthon: can't separate pre- and post emplacement structures. (Except dikes and pre-dike folding.)Dike trends vary N-S to NW-SE.

-Allochthon-Bedding dips low angles, cross-folded into NE and NW trends, although E-W and N-S trends more important in south. NE trends folded by E-W axis, in one place NE structures older than NW.

-Allochthon: Closely spaced normal faults parallel fold axes with dom downthrow in same direction as fold vergence. I.e. shortening switch to extension parallel to movement direction. Low angle thrusting switches to normal faulting at Flat Top Hill.

-Allochthon-clastic dyke cut the fabric of the Allochthon and are mostly related to sedi of overlying Wait. Gp. NE and NW orientations. In places NE trends in clastic dykes apparently closely related to Miocene igneous dykes.
-Unconformity between allochthon and Waitemata Group oriented WNW/20ºNNE.
-Most shearing ad shattering predates Waitemata Group. WNW trend of tilted unconformity surface may mean similar trends in allochthon are pre Waitemata.
-Waitemata Gp: Mesozoic thrust faults predate normal faults with various trends. Compression direction from thrust couples are NW-SE. Possibly due to mass flow down palaeoslope. At Mathesons Bay, thrusts with NW-SE compression also affect basement therefore more deep seated tectonic processes involved.
-Waitemata Group: extension axes from conj. normal faults three directions NW-SE most common, NE- SW, NNW-SSE least common. No clear age relationship. Regime of overall extension in horizontal plane developed after thrusting. (Or also norm faults due to extension across hinges of fold axes running NE, NW and ENE.)
-Miocene arc dike trends indicate predominance of NW-SE extension. In one place a switch from NE to NW extension is recorded (in North).
-NW-SE extension has persisted into the Quaternary.
-Dike trends and vent alignments in southern part of Northland Peninsula have a bimodal distribution of alignments, with northerly trends becoming important. (possibly because of swing in tectonic grain from NW in Northland to NE in central North Island.

Spörli and Anderson HJ 1980 Palaeostress axes from mineral striations in faulted Mesozoic basement NZJGG 23(2): 155-166
Conjugate systems of quartz-chlorite fibre striations in Mesozoic greywackes south Auckland indicate a palaeostress regime with ENE-directed, sub-horizontal compression, accompanied by dilatent movement within the rockmass. Some time between lower Cretaceous and lower Miocene. Whitford mostly strike-slip and Haliwells reverse dip slip predominates-more complex. Other areas have striations indicating ENE or ESE compression.

At Whitford, NNW-trending east-dipping thrust plane. Gives statistical intersection line of planes plunging moderately ENE.

Compressional regime recorded by striations similar to that in large-scale faults: NE trending faults have dextral displacements, NW trends are sinistral and N-S are reverse.

Elsewhere (e.g. Motutapu) striations indicate N-S compression. Strike slip and reverse both present. E-W and N-S orientation of principal stress axes and these were interchangeably occupied by compressions, extensions and intermediate axes. This well known at shallow levels of the crust where vertical principal stress small enough to occasionally be counterbalanced by other stresses.

The Waitemata Group (from near Harbour Bridge, Musick Point, Howick and Motutapu) has post consolidation Faults with extensions trending NE and NW and N-S. Same three sets of normal faults found in the underlying basement – so these trends extend down to the basement. These are different from those seen at Whitford and Halliwells and may indicate a switch from horizontal compression to horizontal extension

Sporli, K.B., 1989. Exceptional structural complexity in turbidite deposits of the piggyback Waitemata Basin, Miocene, Auckland/Northland, New Zealand. In: Sporli K.B. and Kear D. (eds), Geology of Northland: accretion, allochthons and arcs on the edge of the New Zealand Micro-continent. Bull. Roy. Soc. NZ. 26:183-

194.

Basin between two arcs with palaeo currents mainly NW to SE, unconf. on Northland Allochthon, except in the east where unconf. on greywacke basement. Zones of complex structure alternate with zones of simple structure, and all sections cut by late extensional faults. Def is soft sedi to mod brittle. Sequence: early thrusts, some rooted in basement: glide sheets with extensional headwall strucs incl listric faults with roll-overs; major thrusts with dominant NE-SW movement, (down palaeocurrent) and W to E. NE trending strucs most common, and involve parts of the Northland Allochthon. Late folds, often kinks, form dome-and-basin strucs. Normal faulting last stage indicates a change from NW-SE extension to NE-SW extension. Combination of soft sedi and Allochthon-driven tectonic deformation.

Total thickness of Wait Gp impossible to know because of late faulting. Balance (1974) considers it to be 1000m or less.

Zones horizontal/ complex. Along western boundary of basement onlap and along northern Manukau harbour deformation zones are more closely spaced and larger.
Northern Manukau Harbour has NW and NE trending folds interfering, refolding bed-parallel deformation zones. Auckland has a predominance of west-over-east thrusts and of open, kink- like folding.

Major structural trends are NE and NW. A zone of N-S trends near Musick Point. North of this Waitemata Group sediments dip S for 10-15km.
In Waitakere ranges ENE verging folds interfere with SE-verging folds.

-Compactional folding over basement topo.
-Syn-sedi slides, up to 6m thick, gravity and tectonic driven (at least earthquake)
-Intraformational def. some beds contorted but have non-erosional contacts with overlying undeformed beds and therefore deformed during early burial
-circular structures funnel-shaped clastic intrusion
-Thrusts mesoscopic dom NW-SE shortening, thin clay seam, early, larger scale have throw of 10s to 100s metre complex zones of disruption, many m thick. Large NE trending N-over-S thrusts most common but at Musick Point N-S trending W-over-E thrusts.
-Onerahi Chaos Breccia –sheets of reactivated of Northland Allochthon. Don't know whether large syn-sedi slides or due to thrust repetition of Allochthon/ Waitemata Boundary.
-Boudinage, Broken Formation. Locally important only
-Listric extensional Faults and roll-overs. Some may form headscarps for major slides with thrusts at other end.
-Open folds-concentric to kink-band. NE and NW trends of fold axes. Dome and basin
-Late Faults –numerous large scale faults-some into basement. NE-SW extension generally postdates NW-SE extension. Strike-slip faults very rare in the Waitemata basin and unknown where in sequence. Dextral strike-slip faults are recorded at Waiwera and Algies Bay, but there are also E-W striking dextral faults.

Correlation between areas is difficult
e.g.1 north shore Manukau Harbour, 1) soft sedi 2) NW-SE thrusting along bedding 3) open folding an NE-trending axes, 4) open folding an NW-trending axes 5) Sinistral shear

e.g.2 Musick Point 1w-over E thrusting 2) NE trending normal faults with SE tension axis and down-to-SE

e.g.3 15km west, 1) intraformational sliding 2) larger scale bedding-parallel slide, recumbent folding 3) normal separation faults 4) open folding NNE axes

e.g.4 Whangaparaoa 1) N-over S sliding, thrust sheets and strong south verging folds. 2) Extension on listric faults 3) Faulting on steep faults.

Unconformable onlap of Pliocene seds at Weymouth show LL DEFORMATION PRE Pliocene, except a few persistent normal faults (e.g. N-S fault at Beachlands cuts Waitemata Gp and Pliocene.

In allochthon significant NE trending, SE-verging folds w. pressure solution on limest. Cut by unconf between alloch-Wait. Gp but folding in same orientation resumed in Wait. Gp.

Late ext. faulting led to current topo, but must remember inherited from Cret-olig rifting and may have influenced basin throughout.

Spörli and Browne, GH (1982) Structure in a Miocene interarc Basin, Waitemata Group at White Bluff, Auckland, New Zealand. Journal of the Royal Society of New Zealand v11: 87-92

900m long exposure on Manukau Harbour coastline. Blockhouse Bay Formation. (mid bathyal). Structure, in probable order of occurrence is:

1. Soft sediment disruption of individual beds;
2. Thrusting NW-SE along bedding (E-NE trending faults which intersect bedding at angles of between 20 and 40°.):
3. Folding along NE trending axes- main folds are upright and symmetrical. Overall gentle SW plunge;
4. Folding along NW -NNW trending axes combined with dextral shear found all through the area, but mostly in the north. Refolding pattern suggests that NW folds were produced in a strike-slip regime; and
5. Sinistral shear, dominantly along NE and N-S trending faults.

Major structural feature is an open, NE-trending, upright anticline in southwest and another in NE.

Liquefaction of some beds may be related to seismic activity.
Slide horizons sub-parallel to bedding postdate thrusting and sometimes form boundary between deformed and undeformed layers.
Many NE trending normal faults sub parallel fold hinges and indicate extension across them.
The major folds are part of a northeast to E-W trending system exposed along much of the northern shore of the Manukau Harbour. Approx normal to palaeoslope. But thrusts definitely predate folding (so not nec. slumping) and thrusts are part of a regional system of such faults which at one locality north of Auckland passes down into basement greywacke-so must be at least in part deep origin.

Spörli, K.B. and Eastwood V.R. (1997) Elliptical Boundary of an Intraplate volcanic field, Auckland, New Zealand. JVGR79(1997)169-179

Outer vents in Auckland field lie within 19 to 559m of a best-fit ellipse (mean 224.75m) with major axis trending approx N-S and 28.9km long, minor axis 16.5km long. Centre is near town centre of Ellerslie

Boundary is an expression of elliptical feature in lithosperic mantle – maybe a depth contour on a small upper mantle dome or lens intruding into the neck of an elliptical structure, or possibly a boundary of a flat elliptical area where tensional stresses allow decompressional melting. Such tension may result from a releasing bend during strike slip faulting along a fundamental lith. Structure inherited from Mesozoic tectonics, associated with the NNW trending Dunn Mountain ophiolite belt, or may represent the tip of a fracture along which the Auckland Volcanic province is propagating northwards,

Little obvious relation of ellipse to surface geology, which is dominated by NNW and ENE trends. N-S trending faults (mostly e-directed thrusts) occur in the Ellipse in Waitemata group.

JMA NNW but swings sinistrally south of Whangaparaoa- modelling of steep-sided source body in crust below the magnetic high.

Ellipse is centred on the JMA, lying at southern end of the bend. Long axis is oblique to the main trend.

Because of rapid ascent of magma it is postulated that well defined ellipse at depth should be matched by similar at depth. Unlikely that smooth ellipse be defined in brittle part of the lithosphere-most likely is in lith. Mantle.

Can’t be fracture propagation of 5cm/yr as there has been no surface migration of source over the last 10ma. The source is within the lithosphere as it is moving along with the field at 5cm/yr by plate movement.

Decompressional Melting would occur in higher parts and the zone of melting would be defined by a depth contour on an upwelling elliptical dome.

Alternatively there may be no physical updoming, just an elliptical zone of different properties- e.g. elevated tensile stress and /or higher volatile content.

Control of elliptical pattern throughout life of field (e.g. Rangitoto, Pupuke).

Possibly deep-seated mechanically resistant body encased in serpentinised sheared rock-maybe allowed extensional strain at boundary between them.

Generating structure could be a passive fold-like intrusion into a boudin neck with EW extension-also compatible with Hauraki Rift and with non-doming scenario where extension sets up tensional stress in upper mantle causing localised decompressional melting. East west tension also compatible with dex strike slip faulting along the JMA and ellipse could be part of en echelon pattern.

N-S elongate ellipse is parallel to implied northwards migration of mantle source-possibly lithosphere crack tip affecting AKL Volcanic Field.

Possibly en echelon and crack tip acting together,

Expect future volcanic activity to occur within the ellipse.

Sporli, K.B. and Rowland, J.V. (2007). Superposed deformation in turbidites and syn-sedimentary slides of the tectonically active Miocene Waitemata Basin. Basin Research 19:199-216.

Wait. Basin deposited on moving base provided by Northland Allochthon, (emplaced late Olig with new plate boundary). Basin experienced complex interaction between tectonic and gravity driven shallow deformation. This study on eastern Whangaparaoa.

D1 syn-sedi slumping and grit emplacement; D2 large scale, deeper seated sliding extensional and low-angle shearing associated with generation of boudinage and broken formation; D3 thrusting and folding with transport mostly to the SE-S: D4 thrusting and folding to the N-NE; D5 further folding, including a) N-S trending folds, b) E-W trending folds and c) sinistral shear; D6 steep faults, initially Strike slip and then normal.

Intermittent or continuous SE-wards transport of units with increasing sedi and structural burial. By D3 low levels of consolidation.

Basal Wait. seds indicate very shallow water with a sudden drop to bathyal depths, possibly due to down-dragging of the hanging –wall plate in the subduction zone. (commonly assoc. with forced subduction as a new convergent plate boundary is formed. 27-23Ma plate boundary migrated into northern New Zealand.

Beds in Wait. Gp commonly low dip except for zones of complex deformation up to 100m or so thick, which occur throughout the basin. These grade laterally and in some cases vertically separated by packets of less- deformed rocks. Isolated thrust faults, folds and bedding parallel shears and steep normal faults can also be present in less deformed areas. NO cleavage therefore interpreted as slumping but here interpreted as influenced by tectonic forces.

Northland Allochthon sheets interleave with Wait. Gp., sedi reworking of allochthon, bedding-confined slumps all indicate still-moving allochthon at deposition of Wait. Gp.

Assym, folds usually trend NE-SW to E-W and usually verge S (assoc w. allochthon movement) but in south of basin N-S trending, E-verging folds are present. Occasional folds with opposite vergence.

Some thrusts also cut deeply into Mesozoic basement so deeper seated tectonics involved.

Maybe diff. movement between central basin (turbidites on allochthon) and peripheral areas (turbidites on basement and transport less intensive). Latest phase is widespread normal faulting with NW-SE extension followed by NE-SW extension.

A major N-S trending fault between Whangaparaoa and Tiritiri Matangi upthrows basement and basal Waitematas to 80m a.s.l. to the east.

Overlap in time of formation of structures.

I) W Army Bay- bedding N-s changes E-W: shallow syncline, coinc. W. listric oblique-slip dex norm fault. Ext shear zones predate southward thrusting.

II) E Army Bay- rel. simple structure ENE-trending vertical fault with kink fold at tip causing 90º strike change. Boundary faults either side of section, S fault has carbonate veining, N fault trends ENE and dex str slip component.

III) N shore, W Part- Large slump-slide (Northshore Slide), with grit horizons (one includes basic lava and crystalline limestone (Te Kuiti Gp?)) extension followed by bed-parallel thrusts and folding with curved axes swinging NW in W to NE in E. Last NE trending extensional folding.

IV) N shore, E Part- Prom top to SE thrust cut by NE trending ext fault then top to east bed parallel shear.

V) Huaroa Pt- NW trending structures. Some folds verge to N

VI) East coast, N part- mushroom fold N-S trending recumbent and upright faults on E-W trending antiforms and synforms

VII) Whangaparaoa Head- Large S-verging/ sinistral fold refolds smaller ME trending, SE-verging folds.

VIII) East coat, s-part- Dome and Basin structures NE trending, doubly plunging folds, some verge SE

IX) Headland E-Te Haruhi Bay- south verging folds, thin bedded sequence capped by rel. simple thick sst.

X) Okoramai Bay- E-W trending, gently W-plunging open folds. Two segments have both N and S-verging structures. Prom low-angle shear has top-to south in both extensional and thrust mode

Wait. Basin small enough to be a single mega-slump, but multiphase events shown by incompatibility of the southwards thrusting with eastwards thrusting in the south. Widespread northwards thrusting also easiest to explain with separate event.

Although early and rel. soft rock deformation, also facilitated by allochthon emplacement and reactivation of the basement (Structural interlayering of allochthon plus debris slides from the allochthon.) Infolding of allochthon into basement on similar structural trends shows involvement of basement in movement.

Stern, T., Smith, E.G.C., Davey, F.J. and Muirhead, K.J. (1987). Crustal and Upper Mantle structure of the northwestern North Island, New Zealand, from seismic refraction data. Geophys. J. R. astr. Soc. 91: 913-936.

Seismic refraction used to derive crustal thickness over a 575km long line from Lake Taupo to Cape Reinga. Crust is interpreted as 25+/-2km thick, and is underlain by upper mantle seismic velocity of 7.6+/-0.1km/s that increases to 7.9 km/s at a depth of about 45km. Average crustal seismic velocity is 6.04km/s. Similar to Basin and range of USA with low upper mantle seismic velocity, thin crust w.r.t. elevation and high heat flow (70-100mW/m2), and type of volcanism. -due to situation behind active arc for last 20 Ma.

NW North Island including Northland, Waikato-Taranaki, characterised by tensional block faulting, and many volcanic intrusions of varying age interspersed among greywacke. Heat flow is an order of magnitude lower than for TVZ but still rel. high (70-80 mW/m2 rather than the average continental heat flow of 60 mW/m2

The model has lateral variation in velocities but not in crustal thickness.
Could be a step up in velocity 1.6-7.9km/s at 45 km depth, or there could be steady increase in velocity in upper mantle to reach 7.9km/s at 45km depth. (Vertical velocity

gradient of 0.013kms-1km-1).
Moho under Auckland at 25+/-2km depth under Auckland first-order estimate assuming no significant hidden high or low velocity layers.

Gravity has zero isostatic anomaly running across N Island from MT Egmont to Mt Ruapehu and then doglegs north out to Bay of Plenty. Anomaly N of this line +ve, south it is –ve. Also N of this line crust is thinner and upper mantle velocity lower than to south of the line (from this seismic survey)

Heat flow may indicate a partial melt in upper mantle (possibly causing seismic attenuation.) Possibly partial melting as shallow as 25km.

Supermarine NZ is part of largely submerged continent including Lord Howe Rise-Norfolk Ridge and possibly owes its upift to boundary of Pacific and Indian Plates, and its higher heat flow. (with lithosperic thinning behind subduction zone. NW elongation of Northland Peninsula is probably parallel and adjacent to Miocene plate boundary. (Consistent with Walcott (1984)*) and Cole and Lewis (1981)**
*Paleogeogr. Paleoclim. Paleoecl., 46:217-231; ** Tectonophys,72:1-21

Strachan, L.J., 2008. Flow transformations in slumps: a case study from the Waitemata Basin, New Zealand. Sedimentology 55: 1311-1332.

Little Manley Slump, Whangaparaoa, as an example of a slump transforming to other flow type (turbidite). Slump motion was unsteady, non-uniform, arrested rapidly.

Slump='laterally displaced sediment masses bounded by a basal shear plane and with evident contortion and rotation of contained strata.' Debris flow='as above except very poorly sorted with few signs of internal structures and the absence of original bedding'. Modern seafloor e.g. s show transformation from slump to debris flow and turbidity current.

East Coast Bays Formation lowest strat unit was in central part of the basin with estimated water depth 1000-2000m. Previous Palaeocurrent shows sediment sources to the NW and W. (only emergent landmasses to W and NW.). This study shows from cross bedding in turbidites at Little Manley has palaeocurrents to the NE and SW (additional hinterland emergent in SW and NE). Average current direction was to SW. Northland Allochthon and Waipapa basement important sediment sources.

Little Manley slump is complex, but single event.

Folds recumbent-upright, similar or parallel, decimetre to sub-centimetre. Three phases with progressive slumping: 1) flat-lying, long wavelength (up to 5m) isoclinal folds, usually in coarse sandstone and often only limbs are preserved. 2) south verging. 3) upright. Fold vergence to SW (dominant) and to E (locally, at SE end exposure). Facing consistently SW. Fold hinges NW-SE/ subhoriz. Axial plane fans about the trend. Axial planes that strike NE-SW have greater hinge pitch angle and gentler dip than those with axial plane striking NW-SE. NE-SW folds have smaller inter-limb angles than NW-SE. Fold hinges that pitch >40º on axial planes have small interlimb angle (<35º)
SE and S –striking axial planes tend to have greatest dip angle and greatest interlimb angles.

Faults range 5-0.05m Faults >2m long always compressional: those <2m long normal or reverse. Faults 90.1-2m long usually in sandstone lithology, often within fold hinge. >2m long thrusts crosscut all other deformation and are characterised by curved, ramping geometry. Poles to faults trend round SE-NW girdle, secondary NW-SE girdle.

Principal deformation style is folding, therefore low shear strain rate applied. Three fold phases and varying fold style indicates progressive deformation with slumping (stress nature and orientation changed with progressive def.)
Asymmetric folds typically SW vergence –major shear direction in the slump. Southern end of outcrop atypical, upside down and opposite vergence. More complex deformation there.
Average movement direction 230º in the slump.

Similar direction in overlying turbidites, implying a NE source area.
Initiation includes earthquake, related to volcanics and high sedimentation rates.

Multiple fold phases suggest slump was pulsed, with accelerations and decelerations.
Late stage thrusts, intense zones of shear strain, were due to high applied strain rates due to rapid slump arrest.

Slump was therefore unsteady, non-uniform and arrested rapidly.

Thrasher, G.P. (1986). Basement structure and Sediment thickness beneath the continental shelf of the Hauraki Rift and offshore Coromandel region, New Zealand.

Basement is composed of igneous and non-igneous- rocks in the vicinity of the Coromandel Peninsula and Great Barrier Island; further north almost entirely non igneous. Basement has undergone extension and is faulted into a series of fault-angle depressions and grabens. Within Hauraki Gulf, poor seismic reflection data precludes analysis of the sedimentary section.

South of Bream Head a major northwest trending fault with normal displacement down to the west forms the western edge of the platform. Between this and the Auckland coast is a fault angle depression up to 1km deep.

The faults immediately north of Coromandel indicate a northwest trend cutting diagonally across the N-S trend of the Firth of Thames.

North of Great Barrier Island the basement is mostly composed of non-igneous rocks and is faulted into steep-sided grabens and northeast-facing fault angle depressions.

Hauraki Rift is an area of low tectonic activity.

Faulting must be Miocene or younger.

Unconformity between the basement and the overlying sediments is faulted and may have been regionally tilted to the east.