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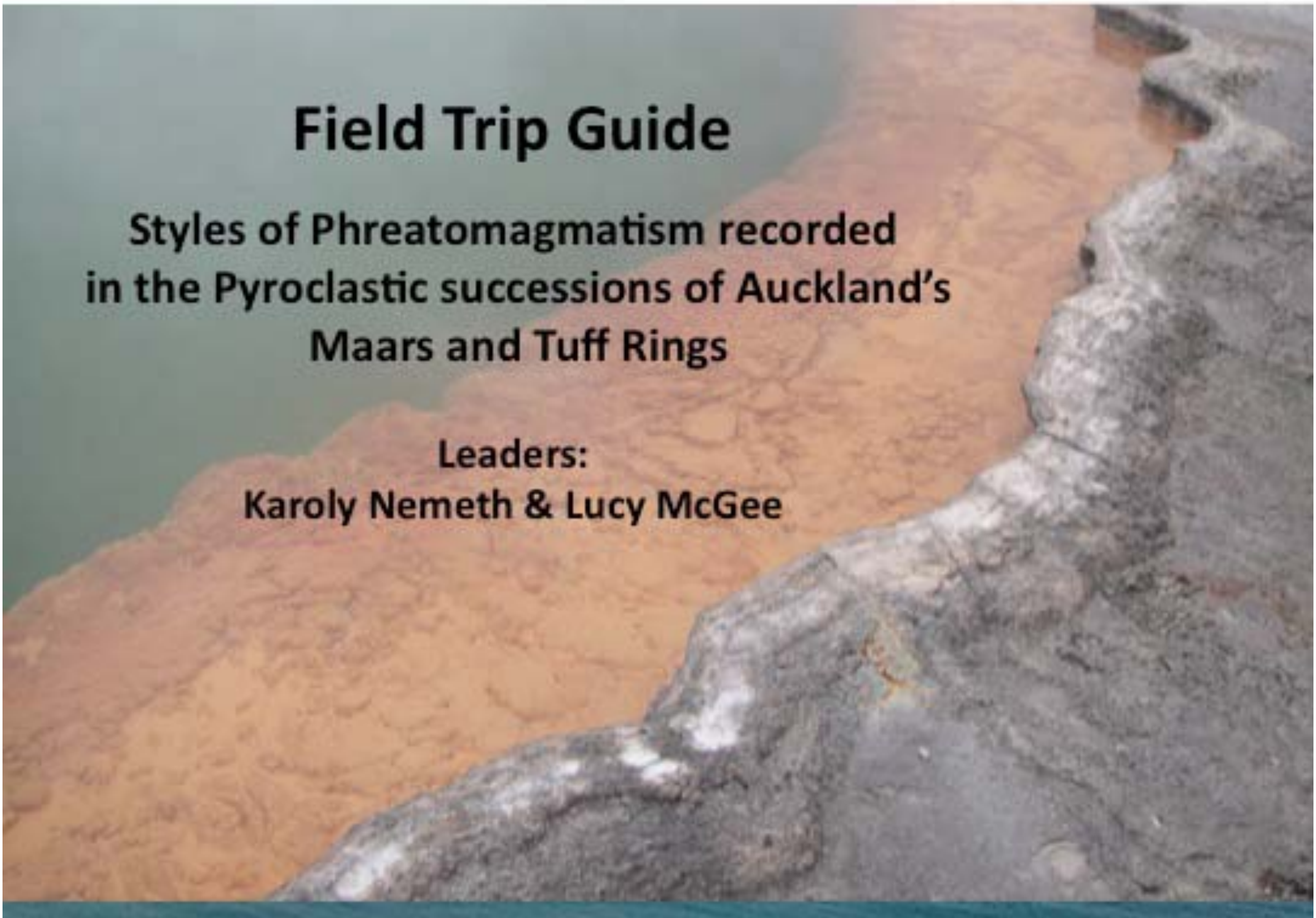

Field Trip Guide

Styles of Phreatomagmatism recorded in the Pyroclastic successions of Auckland's Maars and Tuff Rings

Leaders:
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STYLES OF PHREATOMAGMATISM RECORDED IN THE PYROCLASTIC SUCCESSIONS OF AUCKLAND'S MAARS AND TUFF RINGS: FIELD GUIDE

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Abstract This one day post-conference field trip will offer an overview of the eruption styles, eruption mechanisms and landform evolution of the active monogenetic volcanic field which New Zealand largest city is sitting on. The fact that the Auckland Volcanic Field (AVF) is still active makes volcanic research significant to develop a better understanding of the eruption mechanisms responsible for the formation of about 50 monogenetic volcanic centers over the nearly 250 ka years that the field has been active. Understanding the eruption mechanisms of past volcanic eruptions can help to develop better eruption scenarios that can be used to develop volcanic hazard management programs in case of future eruptions. One of the most dangerous and largely not fully understood eruption style which the majority of the Auckland volcanoes have experienced is the phreatomagmatic explosive eruptions; these played a significant role in the formation nearly ¾ of the total number of the known eruption centers. This field trip will concentrate on demonstrating the basic evidence to support the major role of phreatomagmatism in the formation of the majority of monogenetic volcanoes in the AVF such as tuff rings, shallow maars and tuff cones. The participants will be able to see, discuss and contribute to fundamental scientific problems associated with phreatomagmatic monogenetic volcanism in intraplate terrestrial settings. These include the role of water as a source to fuel phreatomagmatism, the relative role of substrate characteristics, the temporal evolution of eruption styles associated with monogenetic volcanoes, and the overall view of eruption styles and potential eruption scenarios expected in a volcanic field produced by very small volumes of magma in low-lying, near sea-level plains in the Auckland region. The field trip will also provide a unique opportunity to compare the AVF with other volcanic fields worldwide with an aim to draw a better picture of expected future eruptions in such settings.

Keywords: phreatomagmatic, maar, diatreme, tuff ring, tuff cone, base surge, accretionary lapilli, aquifer, sideromelane, volcanic glass, accidental lithics

1. Introduction

Monogenetic volcanic fields consist of individual, commonly mafic volcanoes, built in a single relatively short lived eruption cycle. Individual volcanoes in a field take the form of scoria cones, tuff rings, maars or tuff cones; scoria cones are the most common landform and show a great diversity in size, morphology and eruptive products (Valentine and Gregg, 2008). Individual volcanic edifices are characteristically small in volume (typically <0.1 km^3,Walker, 1993) in comparison with stratovolcanoes. Although referred to as monogenetic in some cases there is evidence for recurrence and multiple activity at single sites (Németh, 2010; Walker, 1993). This one day post-conference field trip offers an overview of the eruption styles, eruption mechanisms and landform evolution of the Auckland Volcanic Field on which New Zealand largest city is sited. In this active monogenetic volcanic field there is deemed to be a significant potential hazard from future eruptions because of the proximity of the city even though the scale of eruption is likely to be relatively small. The trip will provide an introduction to the variety of volcanic landforms associated with the Auckland Volcanic Field (AVF) and specifically those related to phreatomagmatic volcanism.

A common problem in studies of young volcanic fields is the lack of datable material. The use of morphometric parameters of scoria cones to establish their relative ages for instance has proven to be a powerful tool (Hooper and Sheridan, 1998; Wood, 1980a; Wood, 1980b). However, several lines of evidence have demonstrated that due to the complexity of scoria cones their structure needs to be established before morphology-based age estimates can be given (Martin and Németh, 2006). Scoria cones form due to magmatic gas-expansion driven moderate explosions in a vent and their typical products are scoriaceous ash and lapilli inter-bedded with bomb horizons (Porter, 1972; Valentine et al., 2005). They can also produce significant volumes of fine ash that can cover areas tens of km away from their source (Gregg and Williams, 1996; Houghton et al., 2006). Scoria cones represent a "dry" end member of small-volume volcanic eruptions typical in a volcanic field, while tuff rings and maars are considered to be the "wet" equivalents (Lorenz, 1986). Tuff rings are generally low rimmed and wide cratered monogenetic volcanoes that form due to magma and surface and/or near surface aquifer interaction (Lorenz, 1986). Their eruptions are considered to be more violent and to generate devastating pyroclastic density currents that may have a run-out distance of a few kilometres from their source (Lorenz, 2007).

Accurate age determinations of individual eruptive centres in a volcanic field such as the Auckland Volcanic Field are essential for probabilistic forecasting of eruptions (Cronin et al., 2001; Magill et al., 2005). Real-time eruption forecasting using the BET_EF (Bayesian Event Tree for Eruption Forecasting) method has recently been tested for the Auckland Volcanic Field (Lindsay et al., 2010). New spatio-temporal volcanic hazard estimation using a revised event-order model has also recently been developed for the Auckland Volcanic Field (Bebbington and Cronin, 2010) reflecting the intensified research at Auckland to develop an accurate method to be able to estimate future monogenetic eruptions' time and location.

2.The Auckland Volcanic Field

Auckland City is built on an active (~ 250ky to 750 y BP) monogenetic volcanic field containing some 50 volcanic vents (Edbrooke, 2001; Kermode, 1992b) (Figs 1 & 2). Eruptions have in general been small with volumes <0.05 km^3, but there is a trend of increasing volume and rate of eruption in the last 20 ky, with half of the total eruptive volume being produced in the last eruption, Rangitoto (Needham et al., 2010).

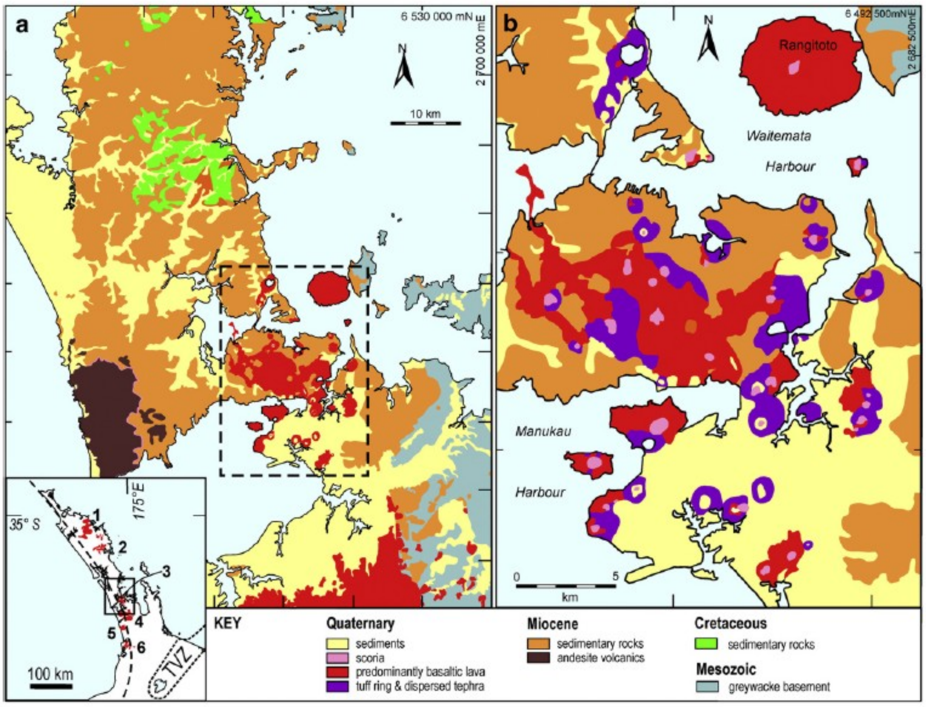

Fig. 1 *Simplified geological map of the Auckland region (a) and the Auckland Volcanic Field (b) from Cassidy and Locke (2010). Geological data based on Edbrooke, 2001; Kermode, 1992). Quaternary basaltic volcanic fields in northern New Zealand are: 1) Kaikohe-Bay of Islands; 2) Whangarei; 3) Auckland; 4) South Auckland; 5) Ngatatura; 6) Okete.*

Few monogenetic fields worldwide have the accessibility, temporal and spatial controls and exposure that can be seen in Auckland, making this a prime area for understanding the way that the magmatic system works and how magmas have interacted with the surface environment as they erupted.

Auckland's volcanoes have erupted a total of ~3.4 km^3 dense rock equivalent (DRE) of juvenile volcanic material (Allen and Smith, 1994) over the past 250,000 years, ~59% of which was erupted from Rangitoto ~600 years BP (Needham et al., 2010; Smith et al., 2008), by far the largest (and most recent) of all the centres.

The volcanoes are olivine basalt to basanite (Heming and Barnet, 1986) and have erupted through the Miocene Waitemata group composed mostly of interbedded sandstone and mudstone, and Pleistocene to Holocene marine sediments (Kermode, 1992a).

A wide range of eruption styles ranging from phreatomagmatic, to Strombolian and Hawaiian eruptions together with effusive volcanism are represented in the AVF (Affleck et al., 2001; Allen et al., 1996; Houghton et al., 1996; Houghton et al., 1999; Rogan et al., 1996; Smith, 1989). Phreatomagmatic eruptions produced tuff rings with wide craters surrounded by relatively thin crater rim deposits with gently dipping beds (Allen et al., 1996; Marra et al., 2006). Maar volcanoes are also present (Cassidy et al., 2007; Cassidy and Locke, 2006; Cassidy and Locke, 2010; Hayward et al., 2002; Molloy et al., 2009; Venuti and Verosub, 2010), although they are infrequent and cannot be readily/easily distinguished from broad tuff rings (Cronin et al., 2009; Németh et al., 2009) due to the flat and shallow volcanic edifices, similar to those in Eastern Oregon (Heiken, 1971) and the western Pannonian Basin (Martin and Németh, 2005; Németh et al., 2010).

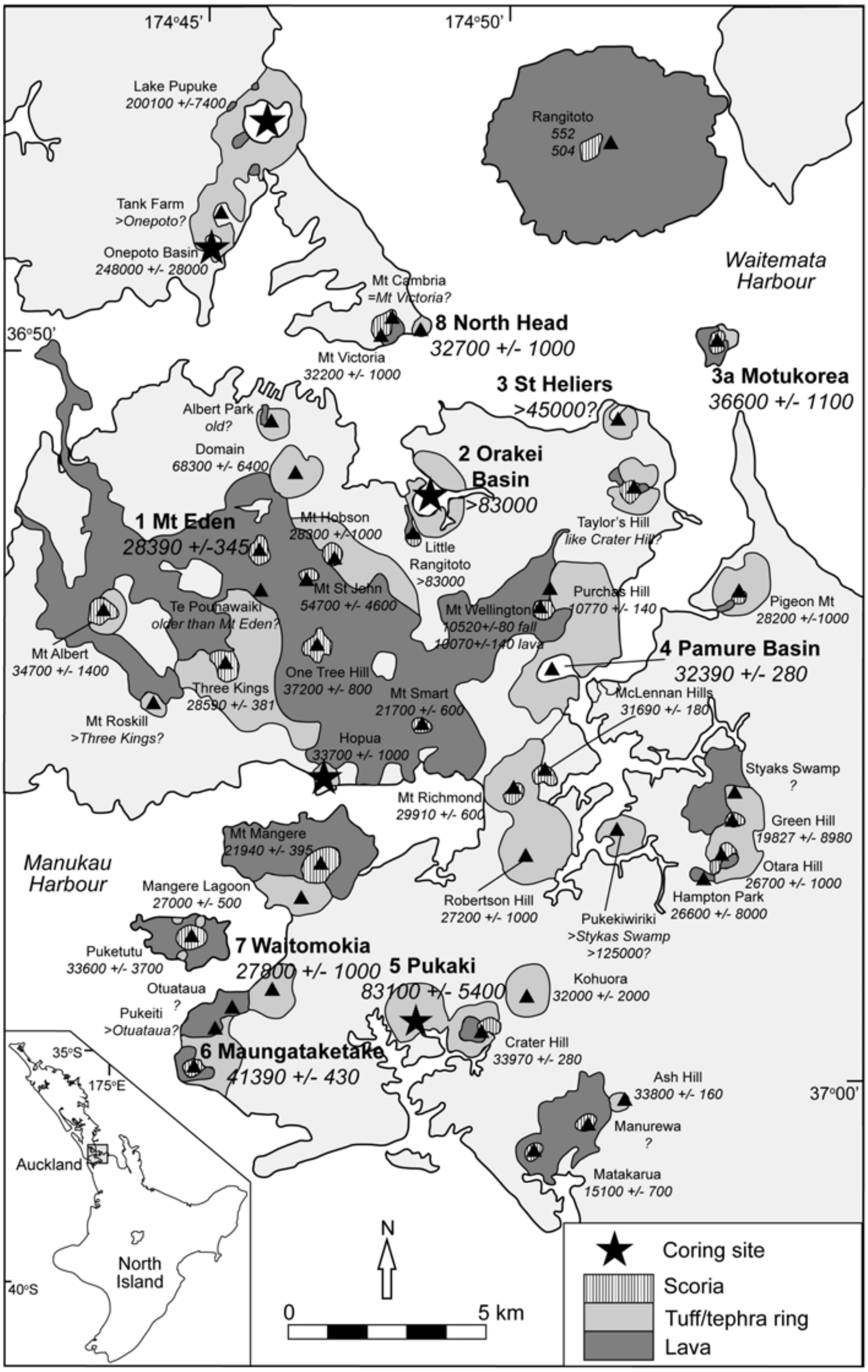

Fig. 2 *Eruptive centers and their ages (in years) after Bebbington and Cronin (2010) of the AVF. Phreatomagmatic explosive eruption products are marked as tuff/tephra ring on the map. Field trip stops are numbered and locations are written in bold.*

Tuff rings are commonly overlain by scoriaceous pyroclastic deposits (Fig. 3) resulting from Strombolian style eruptions as the water supply was exhausted in the course of the eruptions (Allen et al., 1996; Searle, 1959; Searle, 1962).

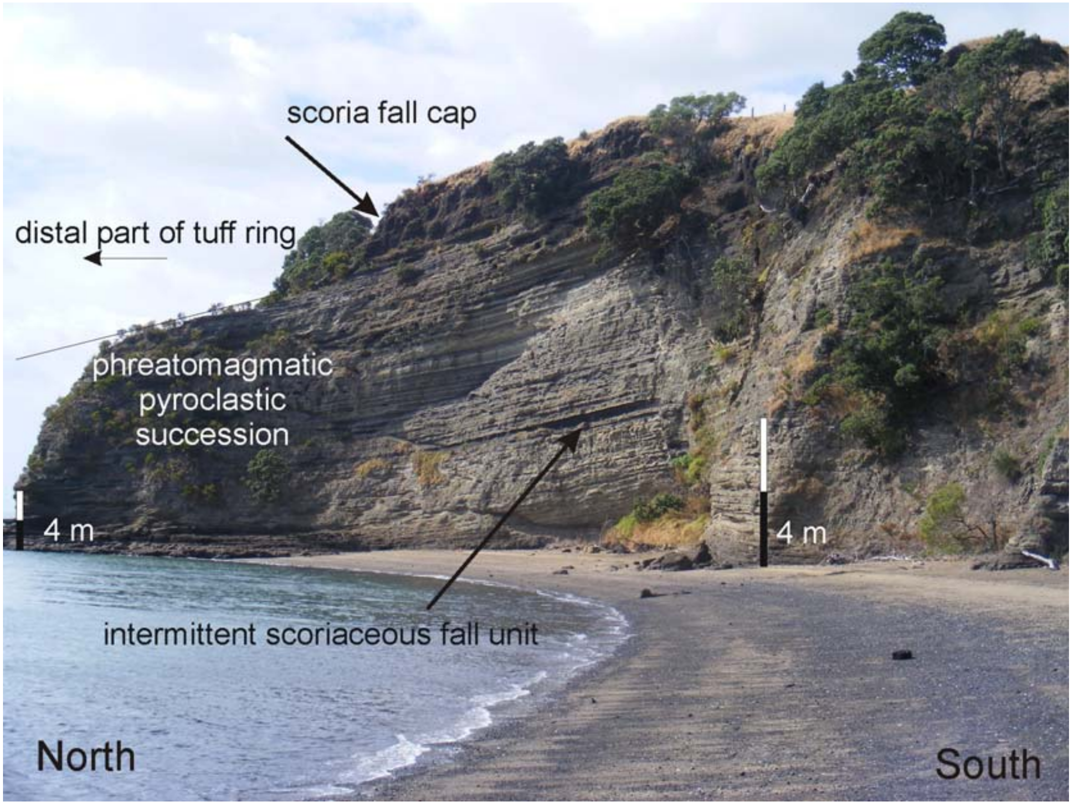

Fig. 3 *Scoriaceous lapilli and ash beds capping typical phreatomagmatic lapilli tuff and tuff (alternating base surge and fall) beds in the northern proximal section of Motukorea/Browns Island.*

Phreatomagmatism in the AVF produced pyroclastic density currents which deposited typically fine-grained cross- and dune-bedded ash interbedded with coarser grained tephra units from phreatomagmatic falls (Allen et al., 1996; Németh et al., 2010; Németh et al., 2009). The volume of accidental lithic fragments and/or crystal phases derived from country rocks in the accumulated pyroclastic deposits are typical for tuff rings and broad maars formed on a so-called soft substrate of sand and mud (Auer et al., 2007; Lorenz, 2003; Németh et al., 2007). Such bedrock is believed to enhance lateral eruptive quarrying of the vent site, forming broad craters and landforms of broad tuff rings and broad and shallow maars that are difficult to distinguish (Auer et al., 2007; Ross et al., 2010). The shallow-level pre-volcanic rock units at Auckland are dominated by mud, sand and silt beds of the Miocene Waitemata Group (Affleck et al., 2001; Cassidy et al., 2007; Kermode, 1992b). The state of water saturation and the presence of surface water together are inferred to be the main controlling parameters of the types of eruption in the AVF (e.g. magmatic effusive, explosive, and phreatomagmatic). The phreatomagmatic pyroclastic rock units have a matrix rich in sand and silt sourced from the substrate Waitemata Group and Pliocene sediments. Larger juvenile bombs and lapilli are commonly cauliflower formed, host thermally altered sand and silt, and are at times coated by mud. This demonstrates an occasional intimate interaction of intruding magma with a muddy impure coolant such as the Pliocene loose sediments and the unconsolidated part of the Waitemata Group.

Volcanic activity in the AVF probably began at least 250 000 yr BP although absolute and relative ages are poorly constrained and available reliable ages are few (Allen and Smith, 1994; Law, 1975; Marra et al., 2006; McDougall et al., 1969; Mochizuki et al., 2006; Mochizuki et al., 2004; Mochizuki et al., 2007; Newnham and Lowe, 1991; Smith, 1989). Past eruptions have generally been small with volumes less than 0.05 km^3, yet a trend of increasing volumes and number of eruptions in the last 20,000 years has been suggested (Allen and Smith, 1994) but so far not fully supported The most recent eruption (Rangitoto volcano) dated at around 700 years BP, had a volume of more than 2 km^3, Drilling into crater lake sediments has recently identified a significant volume of ash falls from local and distal eruption sites allowing establishment of preliminary eruption chronology of the AVF demonstrating an average of at least one eruption in every 2,500 years over the last 50,000 years (Lindsay and Leonard, 2007; Lindsay and Leonard, 2009; Lowe et al., 2000; Molloy et al., 2009; Sandiford et al., 2001; Sandiford et al., 2003).

3. Fieldtrip Stops

Stop 1: Mt Eden (Maungawhau) scoria cone lookout

Mt Eden is one of the larger eruptive centers in the central part of the AVF, with three overlapping scoria cone constructs forming a large cone with deep crater (Fig. 4). It is thought to be ~28 ka based on C^{14} dating (Lindsay and Leonard, 2009). The centre produced long voluminous lava flows in distinct spasms as seen in swamp silts between lava flow units (Searle, 1962). The old quarry face in the grounds of the Auckland Grammar School is composed of one of these units and is around 20 m high.

From this vantage point the extent of the Auckland Volcanic Field can easily be seen, from Rangitoto in the North down to Mangere and beyond in the South, Mt Albert in the West to Mt Wellington and beyond in the East (see Fig 1 and 2).

Fig. 4 *Mt Eden on Google Earth image represents a voluminous scoria cone with complex eruptive history involving eruptive phases and potential partial destruction of part of the growing edifice as evidenced from the irregular and scalloped outer edifice morphology. Along a nearly 800 m long NNE-SSW alignment at least three overlapping scoria cone formed.*

Stop 2: Orakei maar

Orakei Basin is thought to have a minimum age of 83 ka based on tephrochronology of sedimentary cores recovered from the maar lacustrine units (Lindsay and Leonard, 2009). It is a marine-breached, sub-circular shallow basin with gently dipping pyroclastic rock units typical for base surge and fall deposited phreatomagmatic eruptions cropping out around a partial rim structure (Fig. 5). The total thickness of the preserved tuff ring rim deposit ranges between 6 and 35 metres. The crater floor of the Orakei Basin is below the syn-eruptive surface and therefore Orakei can be interpreted as a shallow maar following definition of maar volcanoes (Lorenz, 1986). There is no evidence of preserved capping scoria fall units or lava flows that may indicate subsequent shift in eruption style in the course of the eruption of Orakei.

Fig. 5 *Orakei maar on Google Earth image. The areal distribution of the tuff ring around the maar is shown by a line. Little Rangitoto (green field) is a lava spatter cone remnant with a small volume of lava flow associated with it. The present day marine breached basin of the Orakei maar is inferred to be wider than its original maar basin (i.e. the present day inner basin wall is not the same as the structural boundary of the maar itself). Letters mark point of interest and correspond to the Figure 9 theoretical cross section. Bold letters mark field trip stops (other locations are tide and time permitted only).*

Orakei Basin is a perfect site at which to discuss the eruption mechanisms of a relatively simple phreatomagmatic volcano that formed a shallow maar. It is also a location where the role of soft-substrate-magma-water interaction can be discussed. Orakei maar represents a typical, relatively simple architecture of a monogenetic volcano of the AVF, where the external forces combined with a very low magma output rate produced a fairly large but simple phreatomagmatic landform (Fig. 6).

On the western rim, the immediate country rocks' sedimentary sequences crop out c. 5-10 m above sea level, indicating that the basin itself is a shallow maar and its floor located below the syn-eruptive surface with an estimated minimum crater floor subsidence of 20 metres (Fig. 6). However, the fact that 80 m thick sediment infill (23.5 m is estuarine mud and 56.5 m finely laminated maar lake deposit with tephra layers) have been recovered from the centre of the maar basin (Molloy et al., 2009) indicates that the crater floor subsidence can easily be in the range of nearly 100 m.

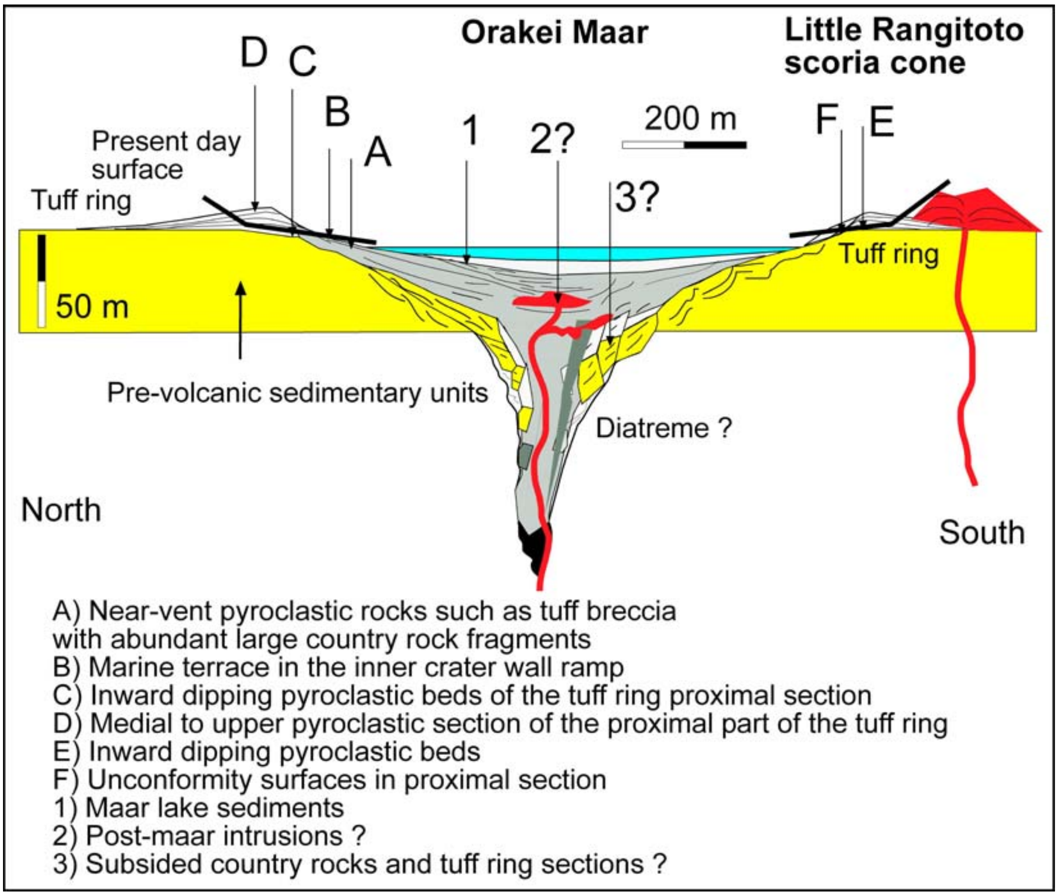

Fig. 6 *Theoretical cross section through the Orakei maar (not to scale) Letters correspond to points of interest shown on Fig.5 .*

The lowermost basal tuff breccia forms a 2-3 m thick unit that exhibits many textural features characteristic of the vent-opening stage of phreatomagmatic eruptions, overprinted by features reflecting the weak, easily pulverized near-surface sediment (Fig. 7). The best location to observe these pyroclastic rock units are in the near-sea level section of the western edge of Orakei maar, marked as "**A**" on Figure 8.

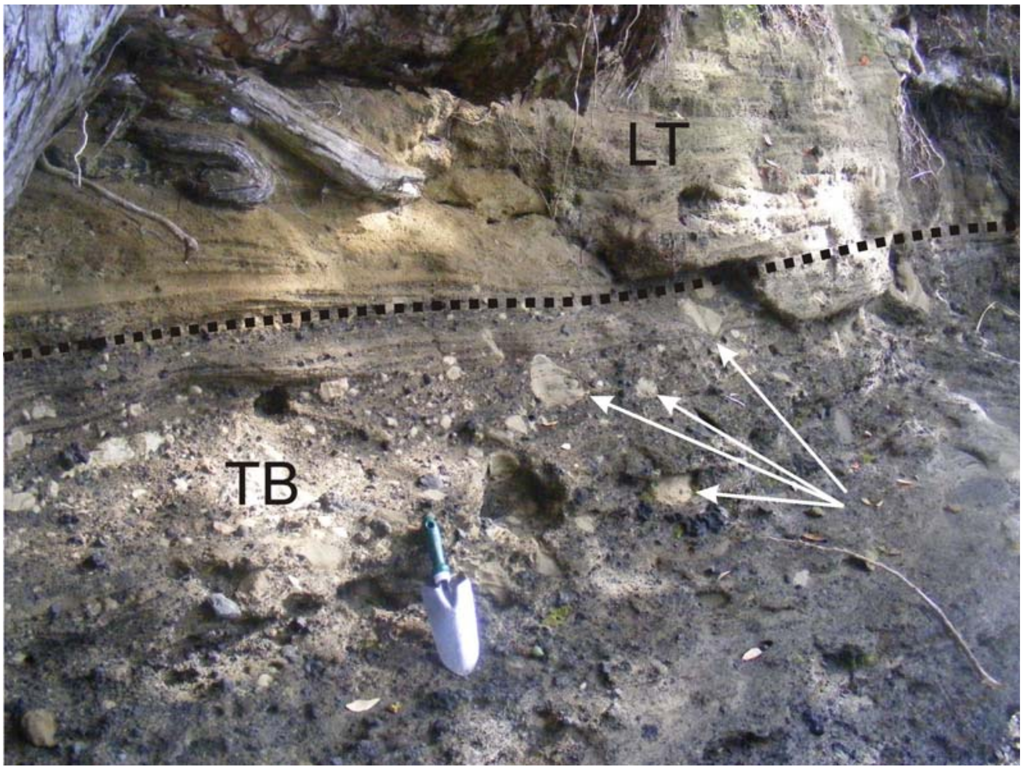

Fig. 7 *Basal pyroclastic breccia (TB) unit in location A (Fig. 5) is interpreted to be a pyroclastic succession representing the initial vent opening phase. Abundant country rock fragments (arrows) and lapilli size juvenile pyroclasts with common impact sags indicates energetic explosive eruptions opening up the syn-eruptive surface. The basal tuff breccia gradually transforms (dotted line) into a dune-bedded lapilli tuff succession deposited by proximal base surges (LT). Spade is about 20 cm long.*

The initial explosions disrupted large blocks of the weakly consolidated pre-volcanic sand and silt successions and propelled these out from the vent as intact fragments, showing evidence of milling during transportation. Juvenile bombs up to 0.4 m occur, with chilled margins resembling cauliflower shape (Fig. 8) and commonly riddled with baked inclusions of mud. These features imply that the phreatomagmatic interaction took place below the syn-volcanic surface in groundwater horizons and that the coolant for the explosions became rapidly impure, i.e, comprising muddy slurry.

Fig. 8 *Cauliflower bomb in the basal tuff breccia unit of Orakei maar.*

Fig. 9 *Pathway at locality C cut into the thin preserved proximal tuff ring sequence just a few metres above the basal pyroclastic breccia in locality A. Note the undulating coarse – fine beds with occasional impact sags. Spade is about 20 cm long.*

Just a few metres above the basal tuff breccia unit (e.g. location C), the pyroclastic succession gradually becomes an alternating massive, chaotic lapilli tuff and cross-bedded tuff section (Fig. 9) that is inferred to reflect repeated transitions between development of a stable vent site, and periodic inward collapse and vent choking.

The basal beds grade upward into a more regularly bedded rhythmic succession of fine tuff and lapilli tuff with rare larger sedimentary rock fragments. Locality D, which represents a medial section of the proximal part of the tuff ring, is an especially good site to demonstrate this trend. The majority of the exposed pyroclastic succession around the basin is a relatively uniform sequence with increasing regularity in its bedding upward (Fig. 10). The beds are generally finely and/or cross laminated and dominated by accidental lithic fragments from pre-volcanic units. Juvenile clasts are commonly palagonitized (Figs 11, 12 and 13) and/or rimmed by a film of mud producing cored ash and lapilli textures (Fig. 14). Rim-type accretionary lapilli and mud aggregates are common. The tuff beds are also commonly vesicular (e.g. vesicular tuff). The more regular pattern of tuff and lapilli tuff beds up-section is inferred to reflect stabilization of the vent, where magma-water interaction generated a pulsating style of eruptions. Phreatomagmatic eruptions at all times, however, seemed to occur within a mud-rich vent.

Fig. 10 *Medial pyroclastic succession in the proximal part of the tuff ring of Orakei maar exhibits a rhythmic sequence of coarse, juvenile ash and lapilli rich beds (usually fall) and accidental lithic fragment-rich, cross laminated tuff beds (base surge origin). Spade is about 20 cm long.*

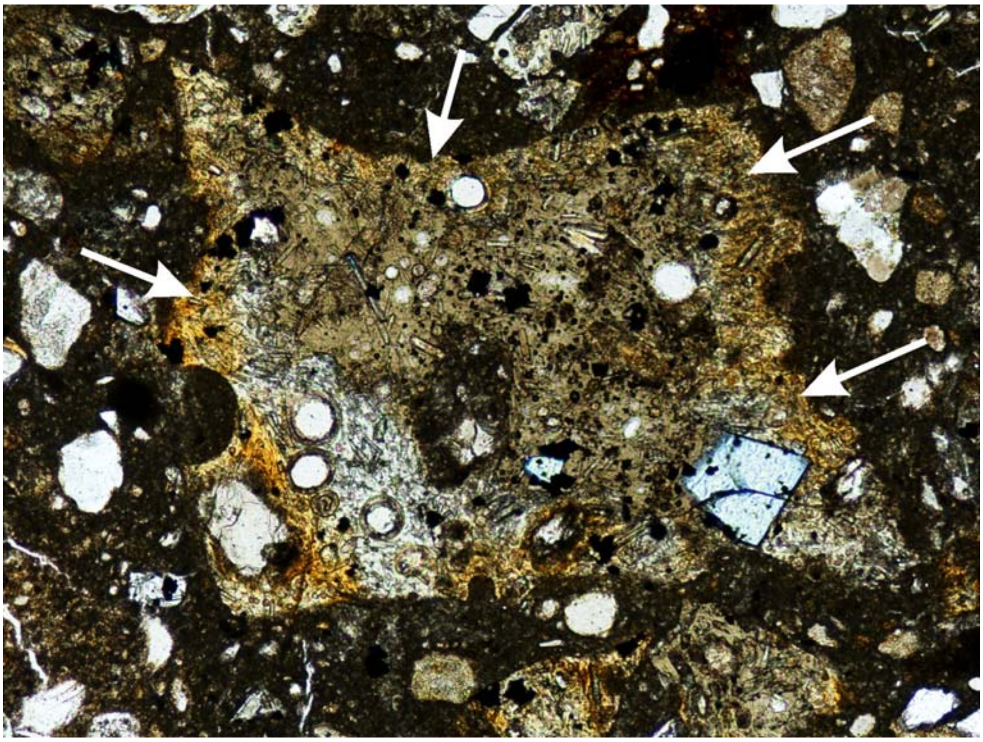

Fig. 11 *Photomicrograph of a coarse ash particle from a coarser grained, juvenile particle-rich lapilli tuff bed from the upper section of the tuff ring succession at locality D. Note the advanced palagonitization (white arrows) of the sideromelane glass shard and its moderate vesicularity, but high microlite content. The long side of the view is about 1.2 mm.*

Fig. 12 *Photomicrograph of a strongly palagonitized ash particle from the same locality as the sample from Fig. 11. The long side of the view is about 1.2 mm.*

Fig. 13 *Photomicrograph of a fine grained tuff bed showing great variety of shapes of interactive juvenile sideromelane glass shards (white arrows) in a muddy matrix. The long side of the view is about 500 micron.*

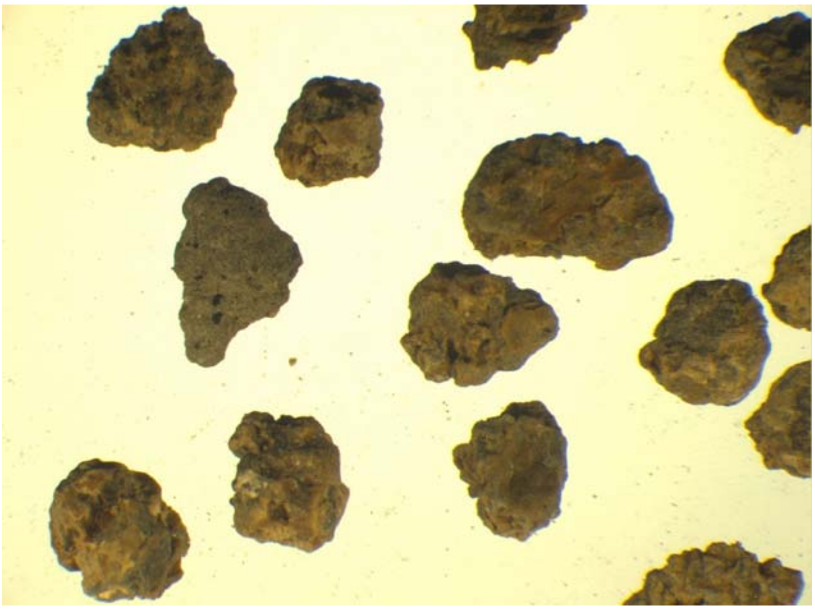

Fig. 14 *Light microscopy image of juvenile coarse ash particles with palagonite and mud-coated rims. The long side of the view is about 9 mm.*

Sporadic coarser grained lapilli tuff beds occur throughout the sequence with a higher proportion of more vesicular juvenile lapilli, indicating brief periods where the magma had less interaction with water. However, there appears to be little evidence for any progressive drying out of the explosion locus indicating that it was remaining in a water-saturated soft substrate during the entire course of the eruption. Some magma pulses, however, were able to partially escape the mud pool covered vent to produce the irregularly occurring tuff beds containing higher proportions (up to 10%) of vesicular scoriaceous lapilli higher in the sequence.

In contrast, even in the stratigraphically high section of the tuff ring, accidental lihtic rich commonly fine grained tuff beds are common (Fig. 15). These beds exhibit over 90 vol % accidental lithic particle content (Fig. 16).

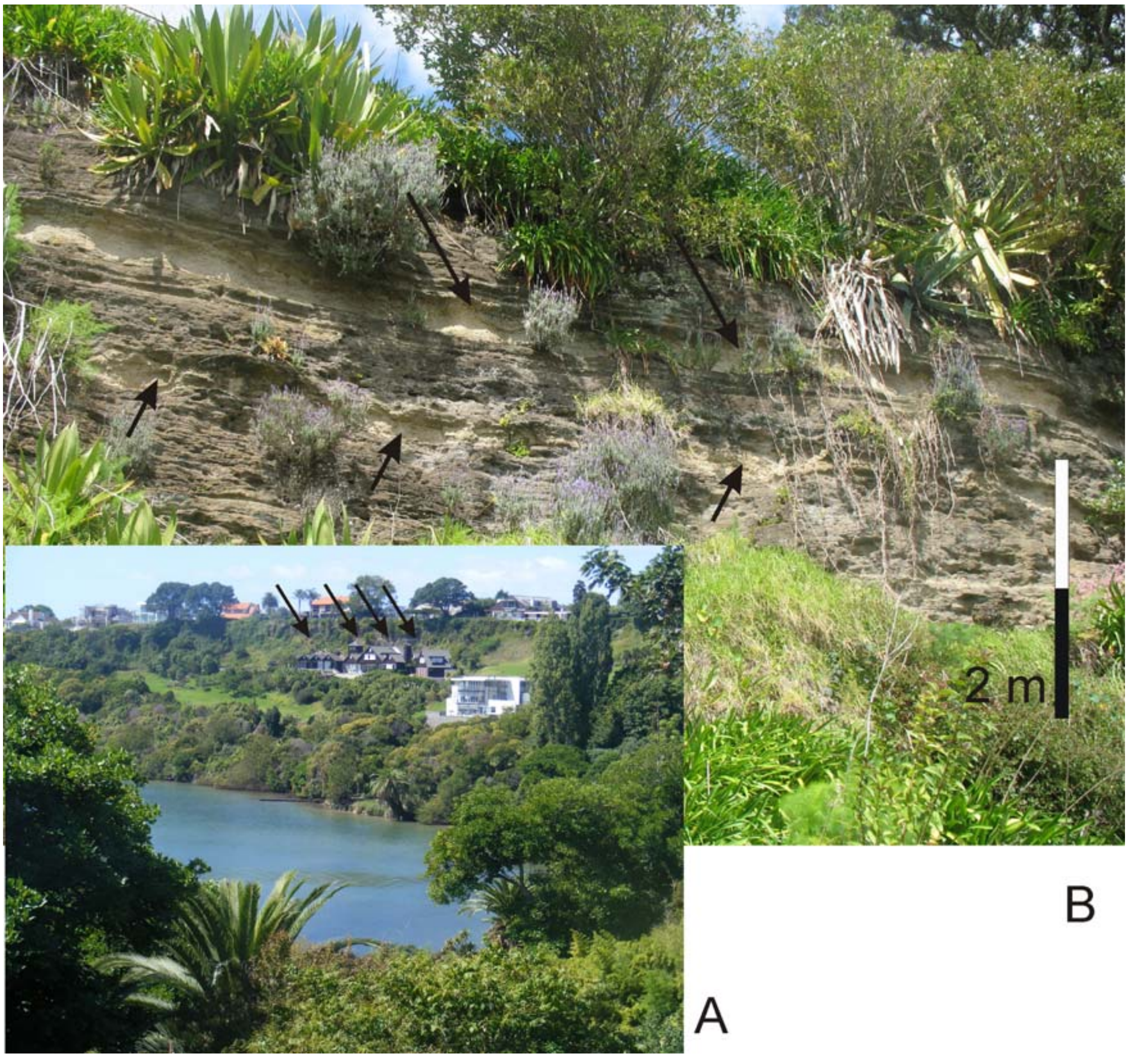

Fig. 15 *Accidental lithic fragment rich marker bed (arrows) in the upper section of the tuff ring sequence in the eastern sector of the volcanic edifice (A). Note the white colour of two beds (arrows on B) and its laterally persistent nature.*

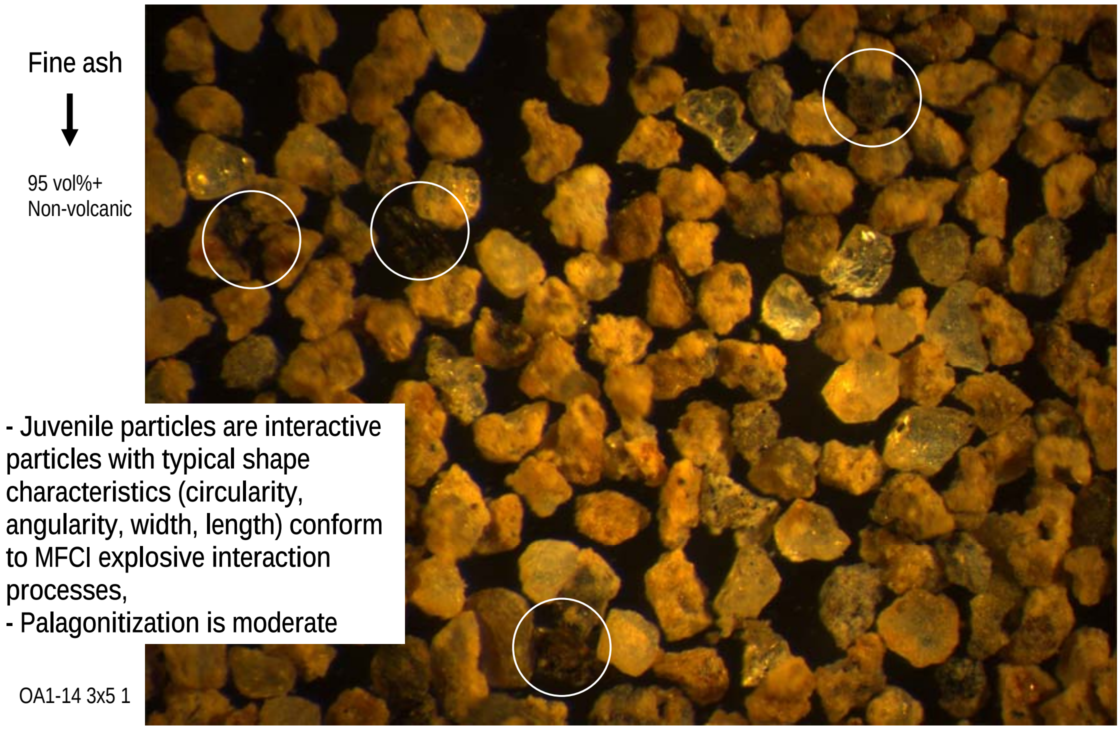

Fig. 16 *Light microscopy image of fine tuff bed from the upper section of the tuff ring sequence. The tuff is composed of over 95 vol % of accidental lithic fragments (siliciclastic fragments from country rock units). Juvenile particles are sideromelane (circle). The long side of the view is about 3 mm.*

The eruption at Orakei maar never reached the typical magmatic stage seen in other phreatomagmatic volcanoes in the AVF; this is thought to be due to the very limited volume of magma involved in the eruption. A combination of limited magma output with a potentially stable water recharge through porous media aquifers into the vent/conduit zone was likely enough to sustain phreatomagmatic explosions throughout the eruption.

The overall high volumetric proportion of accidental lithic fragments and the high content of milled sand and mud (derived from the substrate sediment) making up the tuff ring, also shows that only a very limited volume of magma was involved in this eruption and the eruption products were accidental lithic fragments disrupted from the country rock substrate. The geometry and sedimentology of the deposits, however, indicates that although the locus of the explosions was probably below mean sea level in the soft-substrate country rocks, the eruption site and surroundings were likely on the near-sea level coastal plains.

The well-bedded to dune-bedded pyroclastic successions of the majority of the pyroclastic rim facies together with interbedded coarser grained lapilli tuff indicates that the succession was deposited from pyroclastic density currents relatively distal to the vent(s). The presence of accretionary lapilli-rich beds and vesicular tuffs also indicates that the transporting base surges must have been cooled below the boiling point of water, allowing aggregation of fine ash. This usually takes place about 500 – 700 m from a phreatomagmatic vent. These observations suggest that the present day broad Orakei basin very likely expanded due to inward-collapse (as reflected by the vertical inner walls in places), marine incursion and erosion, and possibly post-volcanic subsidence of the basin after the original volcanic crater was formed.

During eruption, lateral excavation of the country rock and vent migration is shown by at least one unconformity during the eruption sequence (Fig. 17). Development of a sink-hole like subsidence feature, containing a boiling "mud pool" in the active vent would have destabilized the surrounding shallow subsurface rocks, leading to both lateral collapse and possibly down-sag of the soft substrate (Fig. 17). Deposits mantling the internal surface of the down-sagging crater may have been readily redistributed by mass flows into the centre of the crater-lake, enlarging and clearing off large portions of the near vent area.

The morphology of the Orakei basin, along with drilling evidence from its centre and presence of intact shell beds, implies that it was formed prior to the last interglacial high-sea level stand in this area (>100 ka).

The importance of this structure in the context of the Auckland Volcanic Field is that it is the best exposed of one of the few centres that remained phreatomagmatic throughout its entire course of eruption. Most other sites show transitions to more magmatic styles of eruption in later stages, with mantling scoria, spatter and lava sequences common; in the case of Orakei maar, the absence of this transition implies the rise of extremely low magma volumes to generate the eruption. This has strong hazard implications for the Auckland field (last eruption, c. 650 yrs ago), because such small intrusions – which may be difficult to detect seismically – may trigger an eruption capable of forming a nearly 1 km across maar and destroy immediately (in the matter of hours) a semi-circular area similar to 5 to 10 km^2.

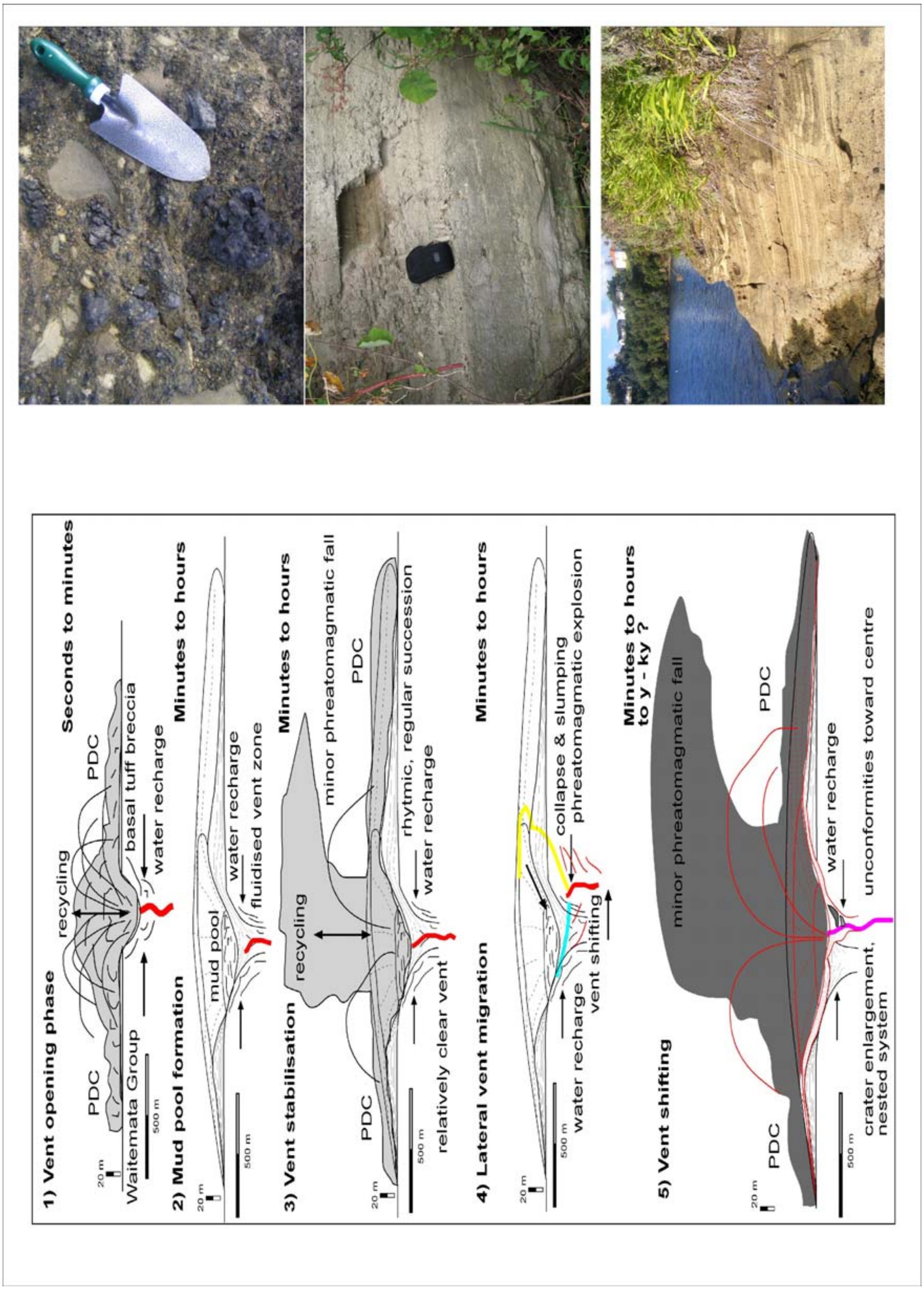

Fig. 17 *Evolutionary model for the Orakei maar eruption. Field photos next to the evolutionary steps represent typical eruptive products and associated features*

Stop 3: St Heliers tuff ring lookout (Te Pane O Horoiwi) and Brown's Island (Motukorea) nested tuff ring

St Heliers has an estimated minimum age of 45 ka based on tephrochronology (Lindsay and Leonard, 2009). In spite of the relatively young age of the volcano the shape of the explosion crater and its steep walls of the surrounding tuff ring are poorly preserved as the grassy Glover Park.

In the beach front of St Heliers however, a large number of bedded, dune-bedded and scour-fill bedded lapilli tuff blocks can be found as a sign that the original tuff ring (or parts of) still exist and sourced some debris into the recent wave-cut platform on the beach. The majority of the lapilli tuffs are yellowish-brown moderately indurated and rich in accidental lithic fragments, mostly as matrix material of the lapilli tuff. Juvenile pyroclasts are moderately vesicular, angular, and glassy. The coarse, juvenile pyroclast-rich cm-thick beds likely resulted from phreatomagmatic fall events, while the fine tuffs are typical of base surge dominated events. Higher in the section (about 40 m above sea level), a cliff exposes a near-vent pyroclastic succession of a surrounding tuff ring of the St Heliers phreatomagmatic volcano. The in-situ pyroclastic rocks are rich in accidental lithic fragments in a broad size range. The larger bombs and blocks commonly deform the underlying pyroclastic beds, indicating significant ballistic events during their emplacement. The large amount of accidental lithic fragments in the exposed section as well as debris from the beach indicate significant excavation, and therefore a potential maar-forming event as a main eruptive event responsible to the formation of St Heliers. The preserved crater is also a distinguished feature, having a c. 30 m deep depression, which is likely to be filled with crater-filling deposits. The significance of the St Heliers phreatomagmatic volcano is that it is located well above the present day sea level (which marks a high-stand in the past 250 ka history of the region), and suggests that the triggering mechanism of magma-water explosive interaction was ground water and/or water saturated country rocks in the region, and not the surface (e.g. sea) water.

From St Heliers a perfect view shows Browns Island/Motukorea (Fig. 18) about 2 km from the shoreline. Motukorea is estimated as being 7-9 ka from early Holocene high stand terraces over lava flows on the island (Bryner et al., 1991). Recent event-order study however places it significantly older at 36.6 +/-1.1 ka (Bebbington and Cronin, 2010). The island is the type locality of the mineral called motukoreaite which is a mineral assemblage formed by reaction of basaltic volcaniclastics with seawater (Bryner et al., 1991). Motukorea is one of the most intact, complex but small-volume mafic volcanoes in the AVF and its good coastal exposures allow observation of both lateral and vertical pyroclastic facies changes. The small volume of the volcano and its thick basal phreatomagmatic pyroclastic succession indicates that a small volume of magma together with external water was involved in initial explosive eruptions. The small magma volume involvement with an estimated relatively low mass-ejection rate makes Motukorea an ideal site for investigating the relative role of external environmental versus internal (magmatic) factors on the eruption manifestation.

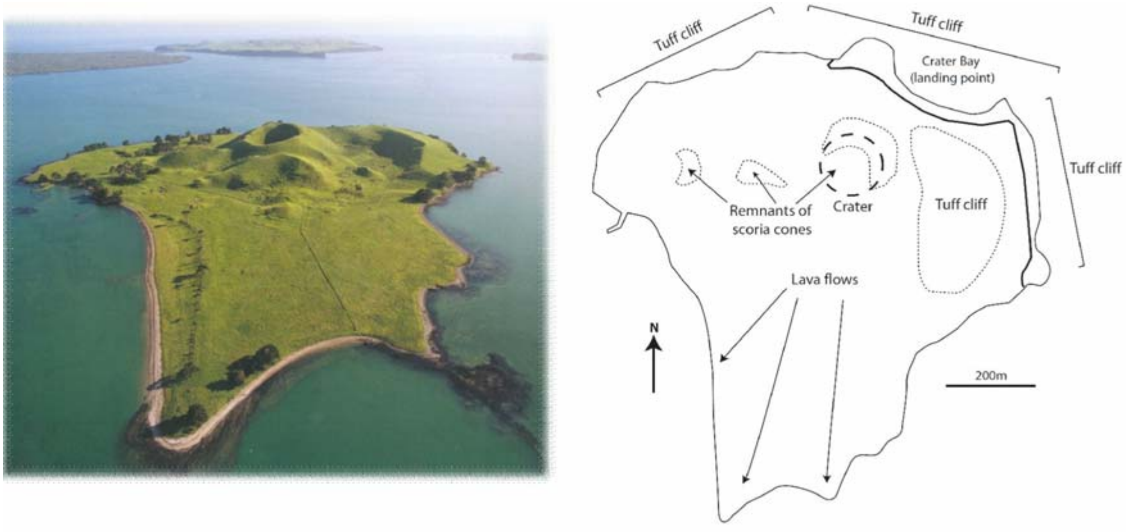

Fig. 18 *Aerial photo (left) and sketch map (right) of Motukorea (Brown's Island). Sketch shows extent, orientation and direction of the tuff ring, scoria cones, crater and lava flows associated with Motukorea. Photo credit: Lloyd Homer*

The base of the pyroclastic succession is composed of an 8 m-thick tuff and lapilli tuff unit (Fig. 19). Its pyroclastic rocks are rich in accidental lithic fragments, mainly derived from the underlying siliciclastic Pliocene terrestrial and Miocene marine sediments, indicating the probable shallow (0-100 m) locus of the explosive magma fragmentation. Accidental lithic fragments are commonly plastically deformed with minor heating effects and block-sized fragments causing impact sags (Fig. 20). Highly fragmented fine ash, cauliflower bombs, accretionary lapilli, low-angle cross-bedding, mega-ripple bedforms, as well as abundant glassy pyroclasts in this succession are evidence of its phreatomagmatic origin. The low vesicularity index of pyroclasts, showing thick vesicle walls and palagonitization are indicative of phreatomagmatic fragmentation. During the initial stages of eruption the vent area was broad allowing some lateral migration of the active vent site across the crater. As the eruption progressed, however, lower degrees of interaction occurred between rising magma and external water and water-saturated sediment. This culminated in a phase of magmatic-gas driven fragmentation, producing a distinctive scoriaceous ash and lapilli fall unit with a NE-trending dispersal axis (Fig. 21). The uppermost part of the pyroclastic sequence exposed is a 15 m-thick succession of very fine, cm-to-dm thick accidental-lithic rich ash beds, alternating with coarse-scoriaceous ash and lapilli fall beds (Fig. 22). This suggests either a regular alternation between wet and dry vent conditions, or that more than one locus of eruption was concurrently active. The gradual "drying" of this eruption may reflect the developing stability of a vent location and conduit. The tuff cone succession is capped by scoria and spatter beds and cones derived from several points within the tuff ring. Some of these vents produced a lava flow that forms a platform in the southern margin of the island. The resulting volcanic landform demonstrates the sensitivity of eruption style in such volcanoes to slight changes in the style of magma-water interaction.

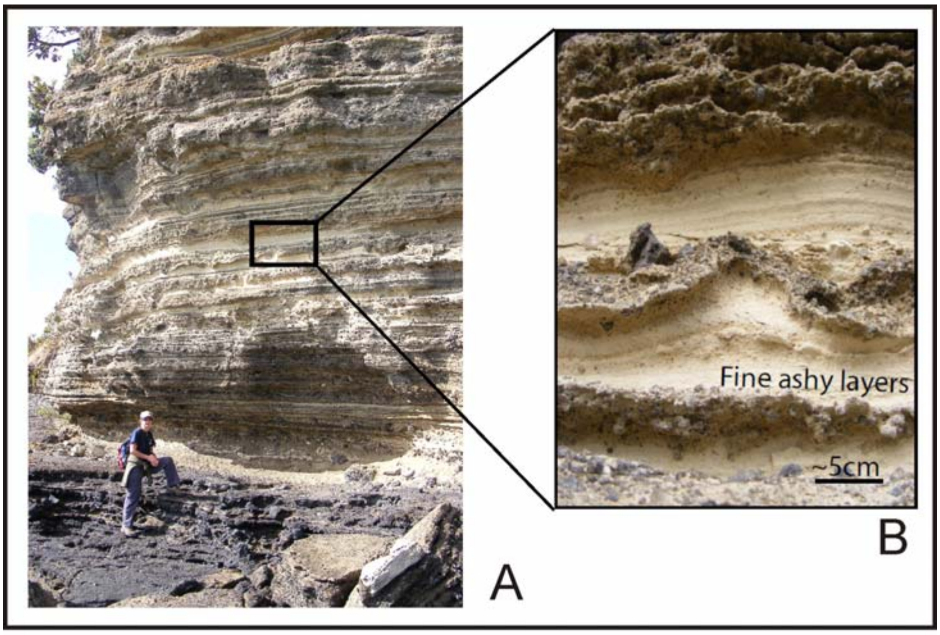

Fig. 19 The *basal pyroclastic succession of Motukorea tuff ring is a bedded, dune-bedded accidental lithic-rich lapilli tuff and tuff unit (A) that is interbedded with bomb horizons (B) representing changing vent/conduit geometry and/or magma pulse that are clearing the instable volcanic conduit.*

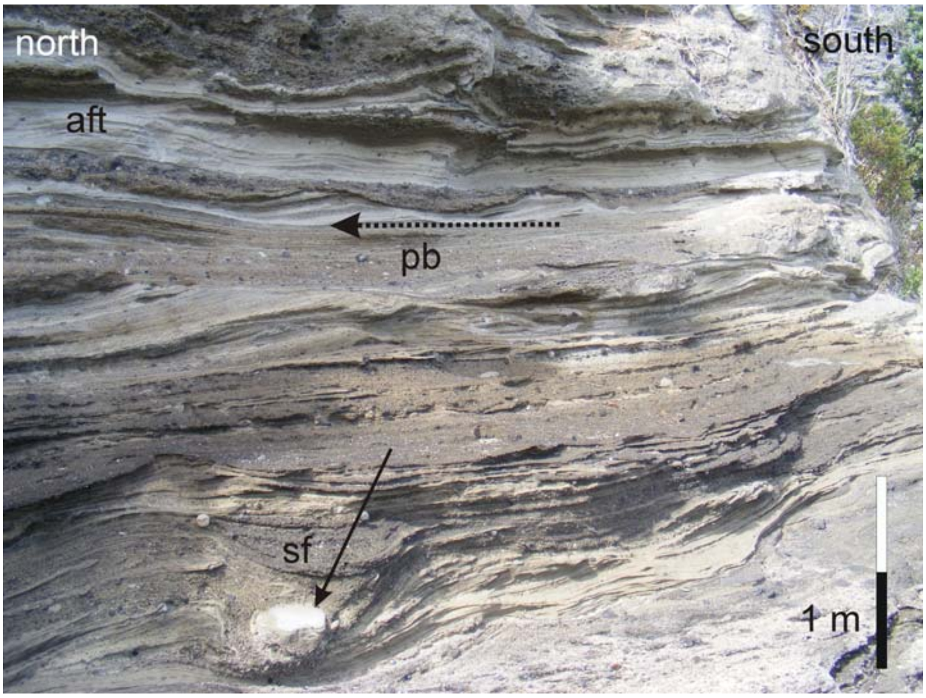

Fig. 20 *Basal pyroclastic succession of Motukorea tuff ring with ballistic bombs and impact sags (arrow), scour filling (sf), parallel bedded tuff (pt) and accidental lithic rich fine tuff all characteristic for a typical subaerial tuff ring forming eruption. Dotted arrow represents base surge current movement inferred from dune geometry.*

Fig. 21 The *distal basal phreatomagmatic (PH) pyroclastic unit is overlain by a thick, scoriaceous, bedded Strombolian-style fall unit (MS) indicating abrupt eruption style change in the final stage of the eruption of Motukorea tuff ring.*

Fig. 22 *Dark juvenile ash and lapilli rich beds intercalate with fine ash dominated accidental lithic rich, cross and/or dune-bedded tuff beds in the upper phreatomagmatic unit of the Motukorea tuff ring proximal section.*

Stop 4: Panmure maar (Wai Mokoia) [lunch stop]

Panmure Basin is an oval (100 x 600 m) depression connected to the sea through a narrow channel in its SW side (Fig. 23). The depression is almost completely surrounded by a tuff ring, with its highest point ~50 m above the sea level in the SW (Fig. 23). NW of the basin the terrain is low and flat (Fig. 24). The tephra ring comprises tuffs and lapilli tuff beds that gently dip out from the centre of the depression and extend ~1.5 km from the shoreline of the lagoon (Fig. 24). The Basin is a volcanic depression, currently filled with intertidal muds and a shallow lagoon. It is located along the Tamaki River forming part of a chain of phreatomagmatic volcanoes aligned NW-SE (Fig. 1). Panmure Basin drew attention recently, when in February 2008, a scientific drilling project recovered 44 m of crater-fill sediments, and identified pyroclastic successions distinct from the basal crater-forming pyroclastic units that suggested rejuvenation of volcanism at the same “monogenetic” centre. In addition the drilling recovered a 2.6 m ash-layer inferred to be sourced from the nearby 9200 yr B.P. Mt. Wellington scoria cone (Bebbington and Cronin, 2010). On the basis of the tephra record preserved in the recovered crater infill deposits, the age of the Panmure Basin is inferred to be 28 ka, while the identified younger pyroclastic unit could be as young as 10 ka (Lindsay and Leonard, 2009). A new event order study places Panmure as 32 390 +/- 280 years old (Bebbington and Cronin, 2010). Panmure Basin is a nested and complex phreatomagmatic volcano with magmatic infill different from Orakei, St Heliers and Motukorea phreatomagmatic volcanoes. Panmure volcano has a characteristic magmatic infill that operated in its late stage of eruption primarily as a Hawaiian lava fountain dominated chain of vents in the broad tuff ring crater, but this eruption never reached the stage to be able to build a well-distinguished scoria cones such as in those formed at Motukorea. Panmure Basin is regarded as a transitional landform between Orakei Basin/St Heliers maars/tuff rings and the Motukorea tuff ring complex.

Fig. 23 *Panmure Basin on Google Earth image. Thick arrows mark dip direction of lava spatter and spindle bomb rich scoriaceous units filling the interior of the basin. Scoria beds inferred to be from Mt Wellington form a gentle hump in the basin margin (MtW and light arrow). Field trip stop "A" represents proximal and basal phreatomagmatic lapilli tuff and tuff units while stop "B" exposes a half section of the tuff ring crest.*

Fig. 24 *Panmure Basin from the top of Mt Wellington. Note the flat tuff ring surrounding the basin forming an asymmetric tuff ring crest in the SE (left side of picture) side of the volcano.*

Tuff units can be traced in a slightly ellipsoid distribution elongated toward the south. The tuff shows only subtle facies changes from proximal to distal zones. A general increase of finer grained tephra beds, better developed bedding features, and a decrease in large accidental lithic fragments are the main characteristic changes. However, around the crater lake margin, lateral facies variations are more pronounced. At the present day outflow area (SE) the tuff ring edge exposes pyroclastic units of both the inward- and outward- dipping beds of tuff and lapilli tuff rich in accidental components (Fig. 24). A cliff exposes a 20 m section of coarsely bedded, dune-containing and massive weakly consolidated phreatomagmatic pyroclastic deposits (Fig. 25). They are composed of coarse-grained lapilli tuff and subordinate tuff breccias, rich in lapilli size clasts from pre-volcanic rock fragments of Parnell Grit (volcaniclastic conglomerate), muddy sandstone from the Tertiary Waitemata Group (siliciclastic) and subordinate silicic tuff clasts (Fig. 25). These deposits are commonly internally faulted and disrupted, reflecting near-vent syn-depositional collapse occurring throughout their emplacement.

Fig. 24 *The outflow of the Panmure Basin exposes the tuff ring crest, marked by inward and outward dipping proximal pyroclastic beds (dotted white arrows). The location of the crater is marked by a black arrow.*

Along the present day shoreline the bed dip directions show variations from inward to outward dipping, and many complex fracturing structures indicating the proximity of a crater crest. These pyroclastic rock units have a matrix rich in sand and silt sourced from the substrate Waitemata Group sediments. The juvenile clasts are fine-medium ash sized volcanic glass shards and angular juvenile lapilli with common chilled margins indicating sudden chilling of the melt prior to fragmentation. Larger juvenile bombs and lapilli are commonly cauliflower formed, host thermally altered sand and silt, and at times coated by mud. This shows at times that there was intimate interaction of intruding magma with a muddy impure coolant formed from milling of the Waitemata Group sediments. Up-section tuff beds show internal bedding, stratification, cross-bedding, and contain occasional accretionary lapilli, features that are indicative of transportation by base surges. The abundance of accretionary lapilli in such units increases in distal areas. The coarser ash and fine lapilli beds are juvenile clast-rich. These juvenile clasts are angular, with irregularly shaped vesicles. This texture indicates magma-water interaction through an open vent. In distal areas, the tephra ring beds are dominated by accidental lithic rich tuff beds with undulating bed thickness, mega-ripple structures, and an abundance of accretionary and cored lapilli.

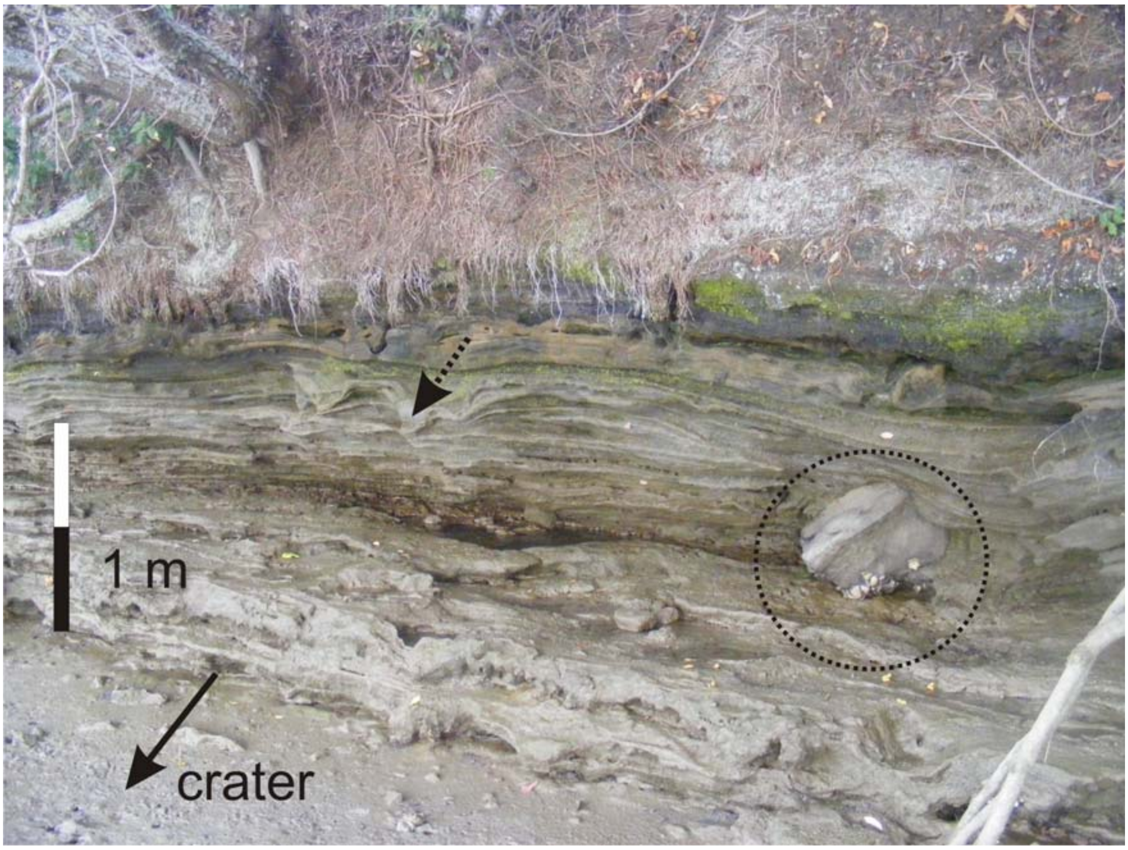

Fig. 25 *Proximal basal phreatomagmatic pyroclastic unit in the southern margin of the Panmure Basin. Note the large accidental lithic bombs (circle) and bomb horizons causing impact sags on underlying tuff beds.*

The near-shore pyroclastic units on the northern side of the basin are distinguished by inward dipping tuff beds of few cm thicknesses. These contain common, large fluidal-shape (spindle) basalt bombs preserved in their impact craters (Fig. 26). Toward the NW, the pyroclastic units grade into thicker beds of 0.1-1 m thicknesses, containing high concentrations of juvenile bombs. Bomb-bearing tuff horizons are sandwiched between scoria beds of 2-5 cm thickness. Bed dip directions define sub-circular patterns pointing toward the basin, delineating sub-vents inside the wide structure. This infilling is inferred to be the result of localized and sporadic lava fountaining and Strombolian style eruptions forming cone(s) inside the volcanic depression.

At the northernmost shore of the depression a mantle bedded, 2.5 m thick coarse scoria lapilli succession is exposed, gently inwardly dipping. Commonly vesicular and spatter-forming bombs occur, demonstrating their deposition within a few 100 m of their vent site.

Fig. 26 *Fluidal shape lava bomb in the inward dipping scoriaceous unit mantling the inner crater wall of Panmure Basin.*

Exposures along the eastern inner margin of the basin show thick sequences of chaotic and weakly bedded lapilli, lapilli tuff and block/bomb rich lapilli tuff. Many beds are disrupted and distorted by syn-depositional and post depositional crater-inward slumping processes. The beds are rich in juvenile clasts, which are moderately to poorly vesicular in most beds, but range to high-vesicularity scoria end members in isolated units which also contain vesiculated and scoriaceous bombs.

800 m further east, distal sequences show a transition from fine matrix-rich, finely bedded tuff and rare lapilli tuff, up to an interval of coarser, scoria-lapilli dominated units (0.1-0.2 m beds) and scoria-rich tuff units, that is, in-turn, capped by further fine-grained, poorly sorted and finely bedded (1-5 cm thick) tuffs.

The tuff ring surrounding the Panmure basin is highly variable, much more so than other similar phreatomagmatic volcanoes in the AVF. This shows that either vent conditions rapidly changed during the eruption, or that there were 2-3 vents operating under different conditions in different parts of the basin. This eruption probably occurred above sea-level at the time, although much of it was focused within saturated and weakly consolidated muddy sandstone sediments of the Waitemata group. Development of the vent areas led to common near-vent faulting and disruption of beds, probably due to collapse of the soft substrate materials. No soil breaks or other clear evidence in outcrops show significant time gaps between any of the contrasting deposits of this sequence; this suggests that they were probably formed by a complex set of variable vent conditions in 2-3 sites throughout this eruption.

Panmure Basin is a strongly modified volcanic landform. Its present day depression is thought to have been enlarged by erosion and modified by sedimentary infill. There is no evidence preserved to demonstrate the contact between the tuff ring and pre-volcanic country rock to support crater floor subsidence needed to establish its maar origin. However, the thick sedimentary infill (44 m plus) in the basin suggests a significant flat floored depression closely resembling a maar.

Stop 5: Pukaki maar lookout

Pukaki is a typical example of tuff cone/explosion crater, with explosive, phreatomagmatic, basaltic fall and surge deposits forming a tuff ring (Searle, 1959) that is poorly exposed. In the eastern side of the crater typical accidental lithic rich brown-yellowish lapilli tuff crops out in a subhorizontal fashion that is inferred to have phreatomagmatic origin. In the same location pre-volcanic country rocks are inferred to be located above the present day crater floor, suggesting the depression maar crater origin. The maar crater was once filled with a shallow lake that has been drained in recent times to make way for allotments and farmland. Pukaki was recently drilled and is now the subject of tephrochronology work as the swamp-like environment in the crater provides the perfect setting for ash-based studies (Sandiford et al., 2003; Venuti and Verosub, 2010). From such studies it has been estimated as having a minimum age of 52 ka (Lindsay and Leonard, 2009) or 83.1 +/- 5.4 ka (Bebbington and Cronin, 2010).

Stop 6: Maungataketake (Ihumatao) tuff ring

Maungataketake is a scoria cone (Figs 27 & 28) crowning a field of tuff erupted from several explosion craters (Searle, 1962); cone building and lava effusion are inferred to have been later events (Searle, 1959). The age of this centre is not well known due to conflicting dating results but placed in the 41 390 +/- 430 years using recently combined tephrochronology and event-ordering (Bebbington and Cronin, 2010).

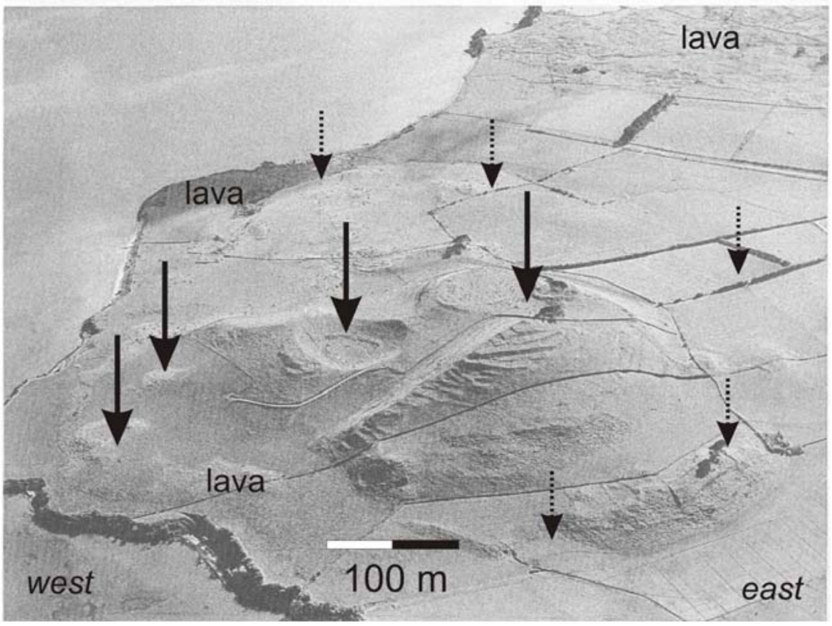

Fig. 27 *Maungataketake in 1958 before quarrying. Note several craters of scoria and spatter cones (thick, black arrows) and tuff ring crest remnant (dotted arrows). Photo from Whites Aviation, National Archive Library, Wellington*

Fig. 28 *Maungataketake today on Google Earth image. Arrow points to the location where a fossil forest is preserved beneath phreatomagmatic pyroclastic rocks.*

Age determination (C^{14}) was performed in the late 50s on the outer margin of a standing position of tree trunk destroyed by pyroclastic density currents derived from Maungataketake and this provided an age of 29 000 +/- 1500 years (Fergusson and Rafter, 1959). Repeated C^{14} measurements from similar tree remnants however subsequently provided conflicting age data ranging from 31 000 +/- 1000 to 43 600 +/- 1400 years (Grant-Taylor and Rafter, 1963; Pollach et al., 1969). Recent C^{14} dating on an in-situ A. australis stump and a small podocarp tree provided an age of > 55 000 years BP which questions the validity of the previous measurements (Marra et al., 2006). Recent OSL-dating yielded ages of 140.3 +/- 14.2 and 177.1 +/- 23.4 ka, that is significantly older than any previous C^{14} dates, however correspond with the inconclusive age of > 55 000 years. This older age is similar to those reported sporadically from the AVF as an onset of the eruptions around 200 ka (Hall and York, 1984) using Ar/Ar radiometric dating methods. An older age of 189.7 +/- 13.8 ka hass been determined by Ar/Ar radiometric method recently on a juvenile cauliflower bomb from the phreatomagmatic succession (Wijbrans and Nemeth, 2010 unpublished data), that is similar in range than those older dates determined earlier. However, recent work (Bebbington and Cronin, 2010) on spatio-temporal hazard estimation of the AVF re-ordered all the available reliable (mostly C^{14}–based) age data and estimated Maungataketake to be 41 390 +/- 430 years. The correct age of the volcano however is still under debate and this location highlights the problem of dating volcanism in the AVF.

Maungataketake is a complex small-volume mafic volcano. It is composed of a simple basal tuff ring with a broad crater (about 800 m across) partially filled with post-tuff ring scoria and spatter cones as well as thick ponded lava (lava lake), that is quarried today. The scoria cones that fill the tuff ring crater are aligned in a NE-SW direction and composed of typical proximal welded scoriaceous rock units and capping lava flows many of them clastogenic in origin. Scoria is well-stratified and large lava lumps are common as a result of occasional lava fountaining during the course of the eruption (Fig. 29). The tuff ring crater filling lavas are ponded, and in the western side have slightly breached the tuff ring rim forming a short (tens of metres) lava outpour over the phreatomagmatic pyroclastic succession confining the ponded lava.

The basal tuff ring succession forms a near perfect circular crest confining the subsequent magmatic explosive and eruptive products. The base of the tuff ring sits on a black, highly carbonaceous mud with trees and stumps in growth position. Broken logs are underlain by creamy to brown inorganic mud (Marra et al., 2006). The tuff ring sequence exposed on the beach is about 4 m thick and comprises of alternating accidental lithic-rich lapilli tuff and tuff (Fig. 30). Fine tuffs are mm-to-cm thick, planar to dune-bedded with low angle cross bedding and density grading all suggesting their base surge origin (Fig. 31). A plastering effect over larger lapilli or bombs indicates a transportation direction from the centre of the Maungataketake vent (Fig. 31). Accretionary lapilli beds are thin (mm-to-cm thick) fine tuffs (Fig. 31) that are inferred to represent fall beds accompanied by successive base surges.

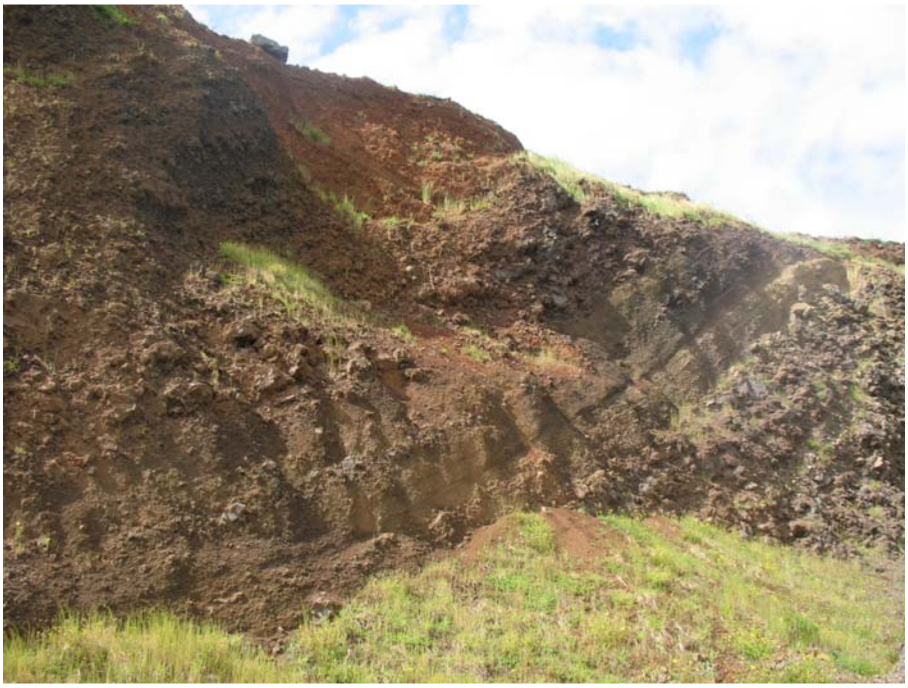

Fig. 29 *Magmatic infill of the tuff ring crater of Maungataketake volcano.*

Fig. 30 *An approximately 4 m thick phreatomagmatic pyroclastic (PH) succession forms the tuff ring deposit (and the tuff ring edifice outer slope) in a medial location, about 500 metres from the vent of Maungataketake volcano. White arrows mark the contact between the tuff ring forming sequence and the overlying scoriaceous unit inferred to have been derived from a nearby scoria cone source (Marra et al 2006), while yellow arrows point to the underlying carbonaceous mud horizon with tree stumps.*

Fig. 31 The *basal phreatomagmatic succession of Maungataketake volcano is dominated by base surge deposits and phreatomagmatic fall beds. Tree stumps are in living position (dotted rectangle) and fallen tree logs in the basal deposits (dotted circle) are common in the base of the deposit. Higher up non characteristic ballistic bomb horizons can be recognized.*

Random ballistically transported bomb horizons can be recognized through the entire section suggesting relatively steady conditions in the volcanic conduit/vent site without major vent clearing events. Ballistic bombs are dominantly accidental lithic fragments in the base of the section, while above this impact sags are dominantly caused by cauliflower shaped juvenile lapilli suggesting pulse-like magma discharge through a loose and water-saturated slurry-rich vent/conduit zone.

In the distal areas, (about 1000 m away from the vent site) the phreatomagmatic pyroclastic succession – totalling about 4 m thickness 500 metres from the source – decreases to about 0.5 m thick (Fig. 32). Alongside the dramatic thickness reduction, the beds became very fine grained, dune bedded, with thin strings of angular and glassy lapilli beds. In spite of the distance from the source and the thin nature of the deposits, large (few metres long) logs can be seen as fallen trees beneath the deposit (Fig. 33) indicating that their removal might have been facilitated by shock waves accompanied with the phreatomagmatic explosive eruptions.

Fig. 32 *Distal phreatomagmatic pyroclastic succession about 1000 metres from its source. Note the loading structure (arrow) and the plastering effect (dotted circle) of the fine grained deposit inferred to have been accumulated from base surges and minor phreatomagmatic fall events.*

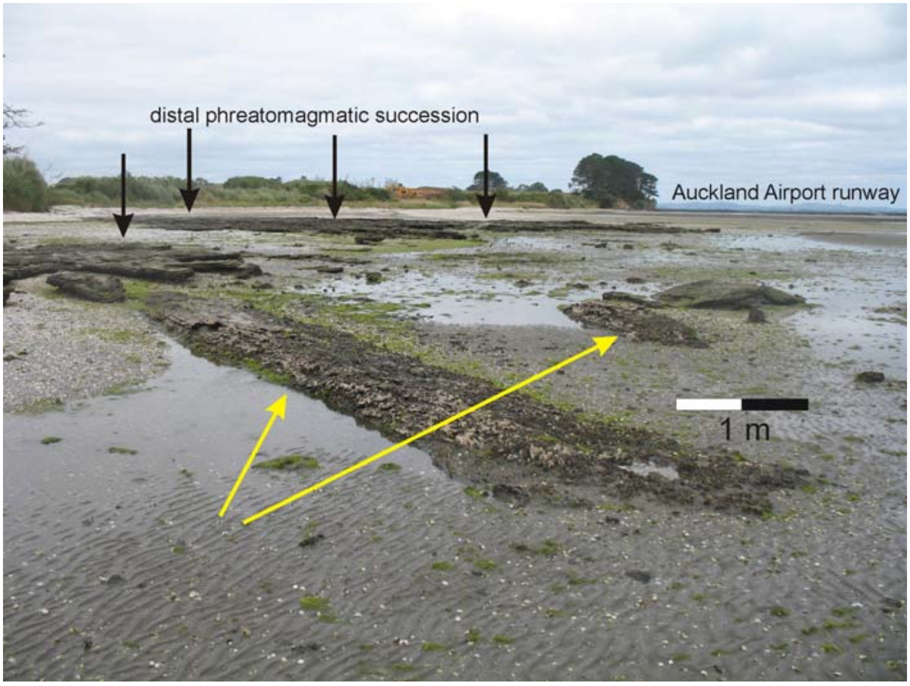

Fig. 33 *Even in the distal units large (few metres scale) fallen logs (marked by yellow arrows) can be identified beneath the thin (dm-scale) veneer of the distal, base surge dominated phreatomagmatic succession about 1200 metres from their source.*

Stop 7: Waitomokia tuff ring

This is an alternative stop during the field trip depending on time. The significant outcrop is on the road leading to the Villa Maria Vineyard which occupies the tuff ring crater (Fig. 34); this exposure shows the tuff ring rim perfectly.

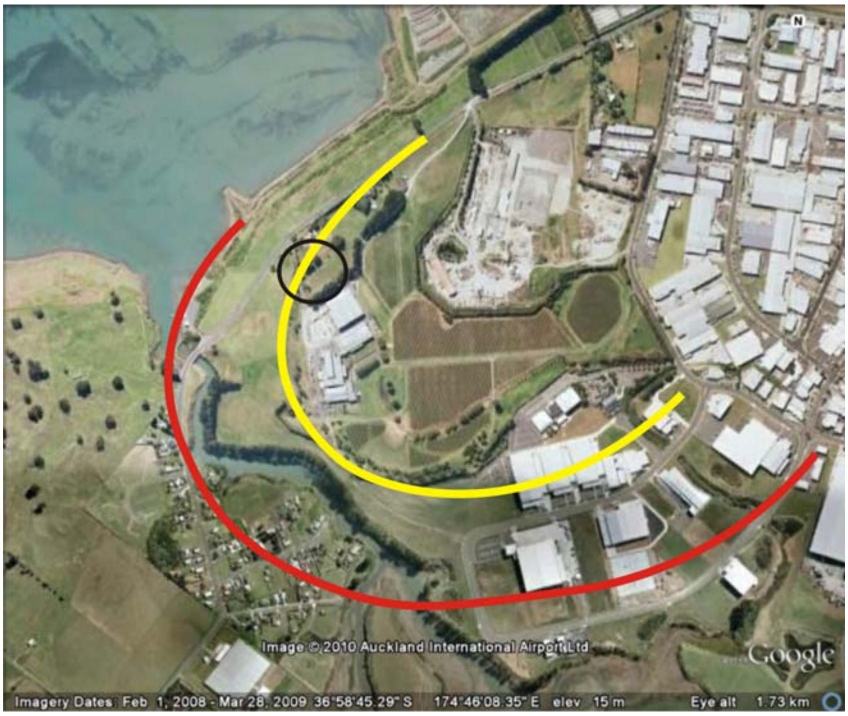

Fig. 34 *Waitomokia tuff ring on a Google Earth image. The preserved crater floor is flat and surrounded by a crescent shaped tuff ring. The tuff ring crest is marked by a yellow line, while the lateral extent of the tuff ring is shown by a thick red line. Note the present day crater floor seems to be slightly higher than the tuff ring base in the foot of the volcano indicating that this volcano is a tuff ring or shallow maar that has been completely filled (overfilled) by crater lake deposits. Black circle marks the sections shown on Figs 35 & 36)*

The tuff ring crest along a road cut exposes an unconformity involving the proximal pyroclastic succession (Fig. 35). The unconformity is sharp and consists of a sub-horizontal part representing the proximal section of an earlier accumulated phreatomagmatic succession of the tuff ring rim (Fig. 35A). On a steep depositional surface a younger phreatomagmatic pyroclastic succession formed a few metres thick sucession of bedded lapilli tuff and tuff unit that is similar in texture, components and grain size population to those forming the sub-horizontal pyroclastic units. The steeply inclined beds gradually transform to a subhorizontal succession that is connected to an extensive sheet like pile of pyroclastic rocks forming the crater-ward foot of the tuff ring rim (Fig. 36). The pyroclastic succession is rich in accidental lithic fragments (sand/silt and mudstone); large accidental lithic fragments are common in coarse grained beds, that are composed of moderately vesicular juvenile fine lapilli and cauliflower bombs (Fig. 35B). The grain-supported nature of this bed indicates their fall origin, however the unsorted texture is more consistent with some sort of combination of debris jet and fall process being responsible for their formation. The rounded nature of sand and silt fragments indicates some recycling and milling process prior the exit of these fragments from a volcanic vent. Accretionary lapilli and vesicular tuff are common among the fine grained tuff beds.

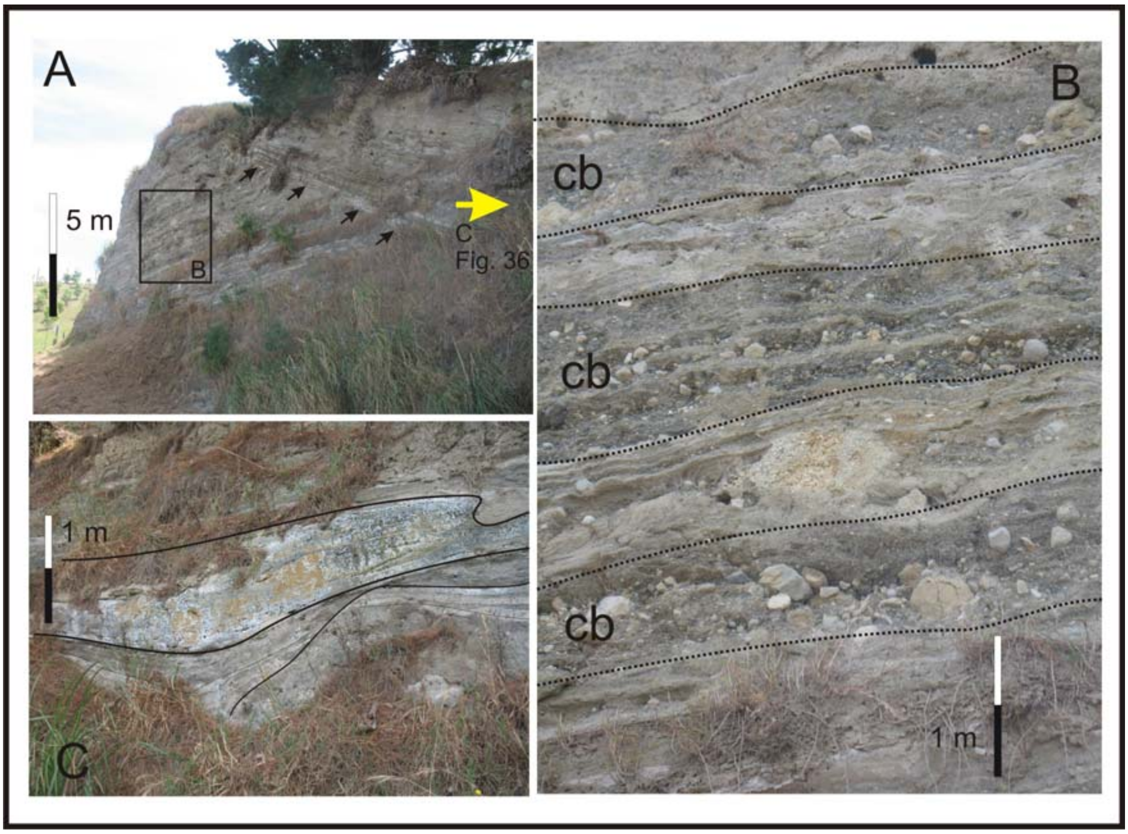

Fig. 35 *Unconformity surface (arrows) in the tuff ring crest cross section at the Waitomokia tuff ring (A). The view is looking from the crater location. Rectangular field marks the view in "B". Yellow arrow points to the location from where the "C" view and about 20 m further away the Fig. 36 view was taken. A close up section shows the bedded characteristics of the proximal phreatomagmatic succession consists of a coarse pyroclastic breccia (cb) alternating with well-bedded, cross and/or dune-bedded tuff. Close to the unconformity surface common soft sediment deformation features can be observed alongside syn-eruptive faulting and folding (C).*

Slightly away from the unconformity surface, the pyroclastic succession becomes sub-horizontal, slightly inward dipping (Fig. 36), but in all other respects they remain the same as the main part of the pyroclastic rim. Transportation indicators consistently suggest an origin from the present day depression of Waitomokia tuff ring.

The unconformity surface can be interpreted as a result of syn-eruptive sliding and collapsing of freshly deposited tephra in the crater rim that was overrun by subsequent base surges and related phreatomagmatic fall of pyroclasts preserving scar surfaces along the crater rim. Such a situation can also be explained by the slight migration of the active vent site along the broad crater. The common presence of large accidental lithic fragments in a fall dominated juvenile rich pyroclast matrix indicates that rising magma actively played a role in vent clearing event, in that a new magma impulse may have triggered conduit wall collapse and erosion, gradually excavating the broad crater left behind.

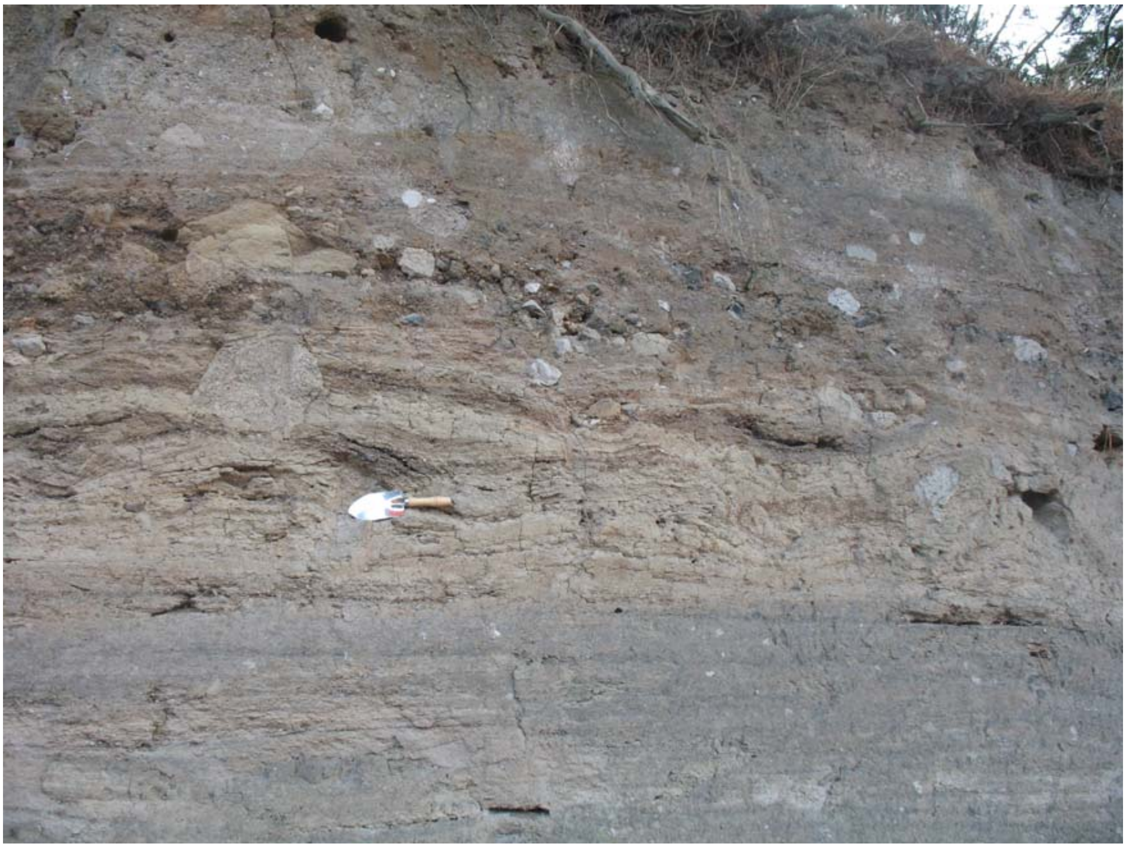

Fig. 36 *Waitomokia tuff ring crater-ward dipping phreatomagmatic succession exposed in a road cut. The pyroclastic succession can be subdivided into at least three major units representing vertical bedding and grain size variations.*

Stop 8: North Head tuff cone

North Head volcano is very different from the previously visited phreatomagmatic volcanoes an in spite that this location is not visited it is included here because its features complete the range of pyroclastic eruption styles shown by the AVF. North Head has a well-distinguished positive landform (Fig. 37) that closely resembles a scoria cone (i.e. similar geometry parameters as other scoria cones in the AVF). The volcano is well-preserved with a recognisable crater and outward and inward dipping pyroclastic beds. The base of the tuff cone is composed of juvenile pyroclast-rich, bedded lapilli tuff. The top of the volcanic edifice is capped by a lava spatter rich moderately agglutinated pyroclastic breccia. The pyroclastic rocks in the base sequence are rich in glassy pyroclasts that are coarse ash to fine lapilli in size. They are angular in shape and moderately vesicular. Commonly lava mantled siliciclastic sediments in sand to gravel size can be recognized (Fig. 38). The bedding dip angle and orientation quickly changes in accordance to the observed position in regard to the tuff cone rim crest. The bedding surfaces are sharp and laterally persistent; in the medial section however, the pyroclastic succession became an alternating sequence of coarse lapilli rich and matrix rich lapilli tuff pile (Fig. 39). In the medial section large fluidal shaped juvenile lapilli as well as various siliciclastic country rocks are more prominent (Fig. 40). Soft sediment deformation (e.g. mud chunks) of mud and silt fragments is common as well as gradual disaggregation of such clasts provident matrix material to the matrix-rich lapilli tuff beds (Fig. 40). Overall the basal sequence exhibits textural features characteristic of magma-water interaction driven explosive eruptions that took place in open vent conditions. During the course of the eruption, conduit wall instability is inferred to be responsible for the increased excavation of siliciclastic country rocks. The eruption sequence in its upper level became gradually more typical for a lava fountain fed eruption where the external water role in the explosions became gradually minimised. As a result the capping sequence is a typical lava spatter deposit. North Head is a volcano where the magma-water interaction was driven by pure external water at shallow depth. Subsequently the growing edifice feeding conduit suffered some collapses and allowed excavation of a moderate amount of country rock from the immediately underlying siliciclastic successions. In the final stage of the eruption the volcanic conduits became more stable, and sealed from the external water, allowing magma to reach the surface without significant interaction, and transforming the eruption to a lava fountain-fed lava spatter cone building stage.

Fig. 37 *View of the North Head tuff cone landform from the south.*

Fig. 38 *Lava mantled siliciclastic sediments (sand/stone) in the basal pyroclastic succession of North Head suggests some pre-mixing (coarse mixing) of magma and water-saturated siliciclastic sediments before the fragmentation and explosion energy erupted these particles through the vent. Clast is about 2 cm across.*

Fig. 39 *Medial phreatomagmatic pyroclastic succession of the North Head tuff cone. Note the accidental lithic fragment-rich light coloured tuff (alt) that is accretionary lapilli bearing. The fine tuff exhibits soft sediment deformation as a result of its sticky, water saturated nature upon deposition. Note the large intact sand- and siltstone fragments (black arrow) and cauliflower bomb (white arrow) that cause impact sags. Lens cap in circle is about 6 cm across.*

Fig. 40 *Capping lava spatter deposits of the North Head tuff cone mark the eruption style change and the potential stabilisation and sealing off of the conduit/vent from external water. Outcrop face is about 4 m tall.*

4. Discussion

Phreatomagmatic explosive eruptions played an important role in the evolution of Auckland's monogenetic volcanoes. The majority of the AVF volcanoes went through – at least in their initial stage – some degree of magma-water explosive interaction driven eruptions. This has significance for the volcanic hazard aspects of the AVF regarding future eruptions, and certainly needs to be understood better. The style of initial explosive events especially is crucial for any future planning and volcanic hazard management. It seems that the resulting eruption style of Auckland's volcanoes reflects the constant interaction between internal (magmatic) and external (environment) forces. Their relative role is the decisive parameter in which direction the eruptions evolve, and that which decides which style of eruption we can expect in the future.

The recent research on the physical volcanology of monogenetic volcanic fields has highlighted the need to formulate our research efforts along 4 major lines of questioning (Fig. 41) to help to characterise the potential volcanic hazard a monogenetic volcanic field such as Auckland may pose in the future. These main lines of research questions can be summarized as:

1) Understanding how monogenetic are monogenetic volcanoes,
2) The relative role of the external and internal forces and how they may control the formation of individual volcanoes,
3) The long term (over tens of thousands to millions of years) environmental changes may effect the overall manifestation of volcanism over the life span of the volcanic field, and
4) How the syn-eruptive landscape and the volcanic landform looked like, and how these can be connected with the preserved pyroclastic rock units.

On this field trip we have concentrated on the second point with regard to the role of external forces such as water saturation level of substrate, hydrologeological characteristics of the substrate and availability of surface and ground-water in the formation of Auckland's volcanoes.

For the initial phreatomagmatic events the external conditions of the substrate and the potential magma flux are the key controlling parameters. With low magma flux the small volume of magma can interact with porous media aquifers of the shallow Pliocene to Recent siliciclastic units and produce energetic explosions. In addition the existence of inter-beds commonly confined within aquitard layers in the Miocene marine sediments (Waitemata Group) are inferred to add an extra variable to the potential explosive energy release such an eruption can produce. Simplistically, the existence of confined deeper water sources can produce a more dramatic pressure release and conversely higher explosivity if the magma encounters such zones. Also, deeper level of fragmentation can add extra hazard by the disruption of intact hard rock fragments from the consolidated, commonly non permeable rock units causing discharge of large (lapilli to bomb or block) lithic fragments that can travel as individual ballistic blocks.

Higher magma discharge situations on the other hand are able to "overrun" the potential controlling force of the substrate and can reach a nearly steady stage of the eruption quicker, and turn the eruption more lava fountain driven eruptions as demonstrated in the Crater Hill pyroclastic succession (Houghton et al., 1999).

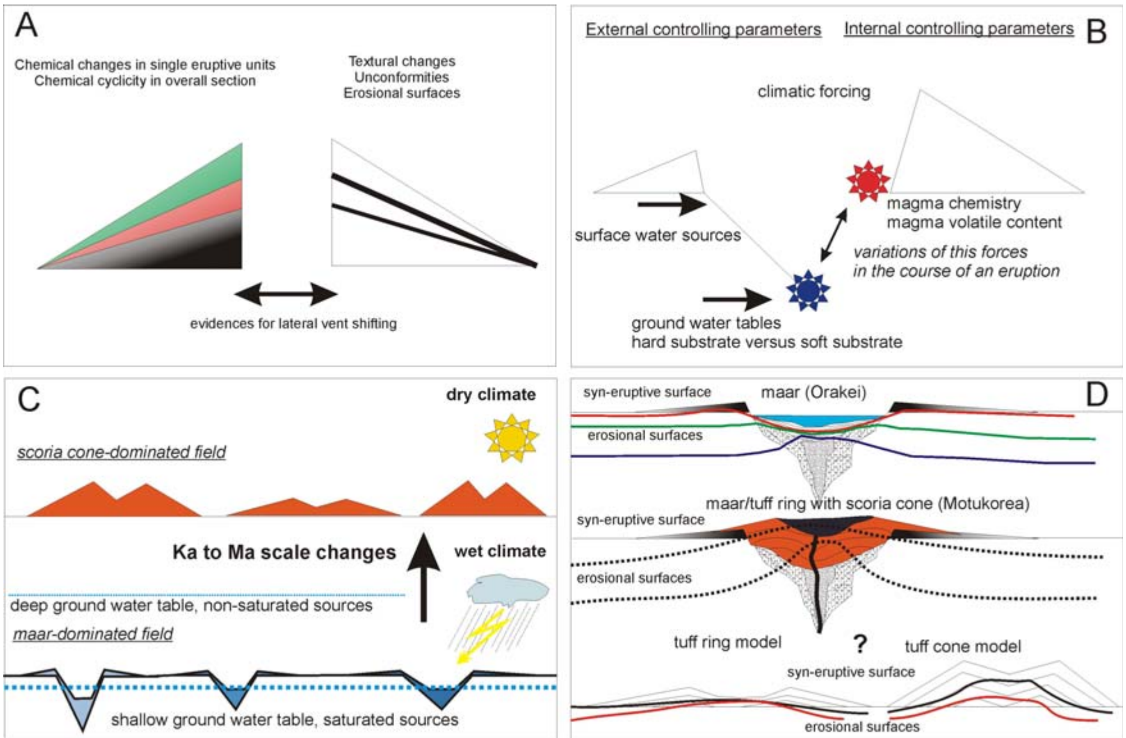

Fig. 41 *Basic research questions to understand monogenetic volcanic fields (modified after Németh 2010). A) Monogenetic versus complex monogenetic volcanism, B) Role of internal versus external controlling parameters, C) Long term environmental changes recorded in volcanic field history, D) landscape evolution questions. In the case of the AVF A-C points are relevant, whilst D is an important link between young and older monogenetic volcanic fields.*

5. Conclusion

The volcanoes visited on this trip have demonstrated a full spectrum of eruption styles influenced strongly by phreatomagmatism.

Orakei Basin is clearly a well preserved, old maar. Its eruption never switched from the stage of water-exhaustion to purely lava fountaining and/or a scoria cone building stage.

St Heliers is a good example to demonstrate that phreatomagmatism has no direct connection with the present day location of sea covered areas, and the main control on magma and water explosive interaction were various and potentially complex ground water sources.

Motukorea tuff ring – complex in spite of its small edifice and volume – shows a gradual change in eruption style from pure phreatomagmatic to pure magmatic fragmentation driven explosive eruptions accompanied with lava effusion. The eruption style changes correspond well with the gradual vent localisation to a well-defined area, that lead to the building of a late scoria cone in the interior of the tuff ring.

Pukaki maar is the most similar to Orakei maar, however, a late magmatic episode likely took place in its northern margin. The size of Pukaki maar and the estimated crater floor subsidence is in the same range to those estimated for Orakei maar.

Maungataketake is a tuff ring complex with a relatively simple tuff ring resulting from energetic blast-like (shown by the ability to demolish a mature hard wood forest) base surge dominated eruptions, that was followed by multiple lava spatter and the building of scoria cones in the tuff ring crater. Confined and ponded lava accumulated in the floor of the tuff ring crater as a result of a complete seal off of the vent/crater/upper conduit from external water allowing the degassed magma to outpour and form a lava lake.

Waitomokia is a tuff ring that demonstrates active conduit processes leading to repeated choking and clearing events in the upper conduit upon each magma pulse reaching the near surface regions.

North Head is a tuff cone that was governed by magma and water interaction in a relatively open conduit/vent leading to form glassy juvenile pyroclast-rich basal units. Subsequently some conduit wall instability is inferred to lead to recycling and excavating of shallow level country rocks.

Evidence of pre-mixing of water-saturated siliciclastic sediments (as prerequisite for a fully developed molten fuel–coolant explosive interaction) has been identified in many cases in the form of irregularly shaped sedimentary clasts encapsulated in lava skin (i.e. peperitic domain). Juvenile glass shards in the majority of deposits are non-to moderately vesicular and angular, however, the variety of vesicularity and shape is generally large suggesting a complex (potentially fast changing) fragmentation style finely balanced between internal (magmatic) and external (environment) parameters.

The AVF is a very similar (and potentially a typical example of) volcanic field to those fields which have erupted a small volume of magma in an alluvial plain where water saturated siliciclastic deposits and semi-consolidated rocks form combined (but soft-substrate dominated) aquifers. Due to the small magma output per individual volcano, the style of eruptions are strongly influenced by the laterally (and temporally) quickly changing external conditions.

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7. References

Affleck, D.K., Cassidy, J. and Locke, C.A., 2001. Te Pouhawaiki Volcano and pre-volcanic topography in central Auckland: volcanological and hydrogeological implications. New Zealand Journal of Geology and Geophysics, 44(2): 313-321.

Allen, S.R., Bryner, V.F., Smith, I.E.M. and Ballance, P.F., 1996. Facies analysis of pyroclastic deposits within basaltic tuff-rings of the Auckland volcanic field, New Zealand. New Zealand Journal of Geology and Geophysics, 39: 309-327.

Allen, S.R. and Smith, I.E., 1994. Eruption styles and volcanic hazard in the Auckland Volcanic Field, New Zealand. Geoscience Reports of Shizuoka University, 20: 5-14.

Auer, A., Martin, U. and Németh, K., 2007. The Fekete-hegy (Balaton Highland Hungary) "soft-substrate" and "hard-substrate" maar volcanoes in an aligned volcanic complex - Implications for vent geometry, subsurface stratigraphy and the palaeoenvironmental setting. Journal of Volcanology and Geothermal Research, 159(1-3): 225-245.

Bebbington, M.S. and Cronin, S.J., 2010. Spatio-temporal hazard estimation in the Auckland Volcanic Field, New Zealand, with a new event-order model. Bulletin of Volcanology, DOI 10.1007/s00445-010-0403-6.

Bryner, V., Rodgers, K.A., Courtney, S.F. and Postl, W., 1991. Motukoreaite from Brown Island, New Zealand, and Stradner kogel, Austria - a Scanning Electron-Microscopic study. Neues Jahrbuch fur Mineralogie-Abhandlungen, 163(2-3): 291-304.

Cassidy, J., France, S.J. and Locke, C.A., 2007. Gravity and magnetic investigation of maar volcanoes, Auckland volcanic field, New Zealand. Journal of Volcanology and Geothermal Research, 159(1-3): 153-163.

Cassidy, J. and Locke, C.A., 2004. Temporally linked volcanic centres in the Auckland Volcanic Field. New Zealand Journal of Geology and Geophysics, 47(2): 287-290.

Cassidy, J. and Locke, C.A., 2006. Gravity and magnetic investigation of maar volcanoes, Auckland Volcanic Field, New Zealand. Journal of Volcanology and Geothermal Research.

Cassidy, J. and Locke, C.A., 2010. The Auckland volcanic field, New Zealand: Geophysical evidence for structural and spatio-temporal relationships. Journal of Volcanology and Geothermal Research, 195(2-4): 127-137.

Cronin, S.J., Bebbington, M. and Lai, C.D., 2001. A probabilistic assessment of eruption recurrence on Taveuni volcano, Fiji. Bulletin of Volcanology, 63(4): 274-288.

Cronin, S.J., Németh, K., Smith, I.E.M., Leonard, G. and Shane, P., 2009. Possible rejuvenation of volcanism at the “monogenetic” phreatomagmatic/magmatic volcanic complex of Panmure Basin, Auckland Volcanic Field, New Zealand. In: M.J. Haller and G.I. Massaferro (Editors), Abstract Volume of the IAVCEI-IAS 3rd International Maar Conference. Geological Society of Argentina, Buenos Aires, pp. 23-24.

Edbrooke, S.W., 2001. Geology of the Auckland area. Geology Map 3 - 1:250 000, Institute of Geological and Nuclear Sciences, Lower Hutt, New Zealand.

Fergusson, G.J. and Rafter, T.A., 1959. New Zealand C14 age measurements, 4. New Zealan Journal of Geology and Geophysics, 2: 208-241.

Grant-Taylor, T.L. and Rafter, T.A., 1963. New Zealand radiocarbon age measurements 1 - 5. Radiocarbon, 5: 118-162.

Gregg, T.K.P. and Williams, S.N., 1996. Explosive mafic volcanoes on Mars and Earth: Deep magma sources and rapid rise rate. Icarus, 122(2): 397-405.

Hall, C.M. and York, D., 1984. The applicability of Ar40/Ar39 dating to young volcanics. In: W.C. Mahaney (Editor), Quaternary dating methods. Elsevier, Amsterdam, pp. 67-74.

Hayward, B.W. et al., 2002. Foraminiferal and molluscan evidence for the Holocene marine history of two breached maar lakes, Auckland, New Zealand. New Zealand Journal of Geology and Geophysics, 45(4): 467-479.

Heiken, G.H., 1971. Tuff rings: examples from the Fort Rock-Christmas Lake Valley Basin, South-Central Oregon. Journal of Geophysical Research, 76(23): 5615-5626.

Heming, R.F. and Barnet, P.R., 1986. The petrology and petrochemistry of the Auckland volcanic field. In: I.E. Smith (Editor), Late Cenozoic Volcanism in New Zealand. The Royal Society of New Zealand, pp. 64-75.

Hooper, D.M. and Sheridan, M.F., 1998. Computer-simulation models of scoria cone degradation. Journal of Volcanology and Geothermal Research, 83: 241-267.

Houghton, B.F. et al., 2006. Proximal tephra hazards: Recent eruption studies applied to volcanic risk in the Auckland volcanic field, New Zealand. Journal of Volcanology and Geothermal Research, 155(1-2): 138-149.

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(1): 59-66.

Houghton, B.F., Wilson, C.J.N. and Smith, I.E.M., 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.

Kermode, K., 1992a. Geology of the Auckland urban area. Institute of Geological and Nuclear Sciences Ltd, Lower Hutt, New Zealand, 63 pp.

Kermode, L.O., 1992b. Geology of the Auckland urban area [with map in scale 1: 50 000]. Institute of Geological & Nuclear Sciences geological map 2. 1 sheet + Explanatory Book 63 p., Lower Hutt, New Zealand. Institute of Geological & Nuclear Sciences.

Law, R.G., 1975. Radiocarbon dates for Rangitoto and Motutapu, a consideration of dating accuracy. New Zealand Journal of Science, 18: 441-451.

Lindsay, J. and Leonard, G., 2007. Volcanic hazard assessment for the Auckland Volcanic Field: State of the play. Geological Society of New Zealand Miscellaneous Publication, 123A: 88.

Lindsay, J. and Leonard, G., 2009. Age of the Auckland Volcanic Field. Institute of Earth Sciences and Engeneering Report 1-2009.02, The University of Auckland, New Zealand: 1-38.

Lindsay, J. et al., 2010. Towards real-time eruption forecasting in the Auckland Volcanic Field: application of BET_EF during the New Zealand National Disaster Exercise 'Ruaumoko'. Bulletin of Volcanology, 72(2): 185-204.
Lorenz, V., 1986. On the growth of maars and diatremes and its relevance to the formation of tuff rings. Bulletin of Volcanology, 48: 265-274.
Lorenz, V., 2003. Maar-diatreme volcanoes, their formation, and their setting in hard-rock or soft-rock environments. Geolines - Journal of the Geological Institute of AS Czech Republic, 15: 72-83.
Lorenz, V., 2007. Syn- and posteruptive hazards of maar-diatreme volcanoes. Journal of Volcanology and Geothermal Research, 159(1-3): 285-312.
Lowe, D.J., Newnham, R.M., McFadgen, B.G. and Higham, T.F.G., 2000. Tephras and New Zealand archaeology. Journal of Archaeological Science, 27(10): 859-870.
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(3): 227-242.
Marra, M.J., Alloway, B.V. and Newnham, R.M., 2006. Paleoenvironmental reconstruction of a well-preserved Stage 7 forest sequence catastrophically buried by basaltic eruptive deposits, northern New Zealand. Quaternary Science Reviews, 25(17-18): 2143-2161.
Martin, U. and Németh, K., 2005. Eruptive and depositional history of a Pliocene tuff ring that developed in a fluvio-lacustrine basin: Kissomlyó volcano (western Hungary). Journal of Volcanology and Geothermal Research, 147(3-4): 342-356.
Martin, U. and Németh, K., 2006. How Strombolian is a "Strombolian" scoria cone? Some irregularities in scoria cone architecture from the Transmexican Volcanic Belt, near Volcan Ceboruco, (Mexico) and Al Haruj (Libya). Journal of Volcanology and Geothermal Research, 155(1-2): 104-118.
McDougall, I., Polach, H.A. and Stipp, J.J., 1969. Excess radiogenic argon in young sub-aerial basalts from the Auckland volcanic field, New Zealand. Geochimica et Cosmochimica Acta, 33: 1485-1520.
Mochizuki, N., Tsunakawa, H., Shibuya, H., Cassidy, J. and Smith, I.E.M., 2006. Palaeointensities of the Auckland geomagnetic excursions by the LTD-DHT Shaw method. Physics Of The Earth And Planetary Interiors, 154(2): 168-179.
Mochizuki, N. et al., 2004. K-Ar ages of the Auckland geomagnetic excursions. Earth Planets and Space, 56(2): 283-288.
Mochizuki, N. et al., 2007. Further K-Ar dating and paleomagnetic study of the Auckland geomagnetic excursions. Earth Planets and Space, 59(7): 755-761.
Molloy, C., Shane, P. and Augustinus, P., 2009. Eruption recurrence rates in a basaltic volcanic field based on tephra layers in maar sediments: Implications for hazards in the Auckland volcanic field. Geological Society of America Bulletin, 121(11-12): 1666-1677.
Needham, A.J., Lindsay, J.M., Smith, I.E.M., Augustinus, P. and Shane, P.A., 2010. Sequential eruption of alkaline and sub-alkaline magmas from a small monogenetic volcano in the Auckland Volcanic Field, New Zealand Journal of Volcanology and Geothermal Research, doi:10.1016/j.jvolgeores.2010.07.017
Németh, K., 2010. Monogenetic volcanic fields: Origin, sedimentary record, and relationship with polygenetic volcanism In: E. Cañón-Tapia and A. Szakács

(Editors), What Is a Volcano? Geological Society of America Special Papers 470: (Boulder, Colorado), pp. 43-67.
Németh, K., Cronin, S.J., Haller, M.J., Brenna, M. and Csillag, G., 2010. Modern analogues for Miocene to Pleistocene alkali basaltic phreatomagmatic fields in the Pannonian Basin: "soft-substrate" to "combined" aquifer controlled phreatomagmatism in intraplate volcanic fields. Central European Journal of Geosciences, 2(3): 339-361. [10.2478/v10085-010-0013-8].
Németh, K., Cronin, S.J., Smith, I.E.M. and Stewart, R.B., 2009. Mechanisms of a maar-forming eruption through soft fine-grained sedimentary substrate: Orakei Basin, Auckland, New Zealand. In: M.J. Haller and G.I. Massaferro (Editors), Abstract Volume of the IAVCEI-IAS 3rd International Maar Conference. Geological Society of Argentina, Buenos Aires, pp. 83-84.
Németh, K., Martin, U. and Csillag, G., 2007. Pitfalls in erosion level calculation based on remnants of maar and diatreme volcanoes. Geomorphologie-Relief Processus Environnement, 2007(3): 225-235.
Newnham, R.M. and Lowe, D.J., 1991. Holocene vegetation and volcanic activity, Auckland Isthmus, New Zealand. Journal of Quaternary Science 6: 177-193.
Pollach, H.A., Chappell, J. and Lovering, J.F., 1969. Australian National University radiocarbon date list. Radiocarbon, 11: 245-262.
Porter, S.C., 1972. Distribution, morphology, and size frequency of cinder cones on Mauna Kea Volcano, Hawaii. Geol.Soc.Am.Bull., 83: 3613-3626.
Rogan, W., Blake, S. and Smith, I., 1996. In situ chemical fractionation in thin basaltic lava flows: Examples from the Auckland volcanic field, New Zealand, and a general physical model. Journal of Volcanology and Geothermal Research, 74(1-2): 89-99.
Ross, P.-S., Delpit, S., Haller, M.J., Németh, K. and Corbella, H., 2010. Influence of the substrate on maar–diatreme volcanoes — An example of a mixed setting from the Pali Aike volcanic field, Argentina Journal of Volcanology and Geothermal Research, doi:10.1016/j.jvolgeores.2010.07.018.
Sandiford, A., Alloway, B. and Shane, P., 2001. A 28 000-6600 cal yr record of local and distal volcanism preserved in a paleolake, Auckland, New Zealand. New Zealand Journal of Geology and Geophysics, 44(2): 323-336.
Sandiford, A., Newnham, R., Alloway, B. and Ogden, J., 2003. A 28 000-7600 cal yr BP pollen record of vegetation and climate change from Pukaki Crater, northern New Zealand. Palaeogeography Palaeoclimatology Palaeoecology, 201(3-4): 235-247.
Searle, E.J., 1959. The volcanoes of Ihumatao and Mangere, Auckland. New Zealand Journal of Geology and Geophysics, 2(5): 870-888.
Searle, E.J., 1962. The volcanoes of Auckland City. New Zealand Journal of Geology and Geophysics, 5(2): 193-227.
Smith, I.E.M., 1989. North Island. In: K.J. Johnson RW, Taylor SR (Editor), Intraplate volcanism in eastern Australia and New Zealand. Cambridge University Press, Cambridge, UK, pp. 157-162
Smith, I.E.M., Blake, S., Wilson, C.J.N. and Houghton, B.F., 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(4): 511-527.

Valentine, G.A. and Gregg, T.K.P., 2008. Continental basaltic volcanoes - Processes and problems. Journal of Volcanology and Geothermal Research, 177(4): 857-873.
Valentine, G.A., Krier, D., Perry, F.V. and Heiken, G., 2005. Scoria cone construction mechanisms, Lathrop Wells volcano, southern Nevada, USA. Geology, 33(8): 629-632.
Venuti, A. and Verosub, K.L., 2010. Paleomagnetic record of basaltic volcanism from Pukaki and Onepoto maar lake cores, Auckland Volcanic Field, New Zealand. New Zealand Journal of Geology and Geophysics, 53(1): 71-79.
Walker, G.P.L., 1993. Basaltic-volcano systems. In: H.M. Prichard, Alabaster, T., Harris, N.B.W. & Nearly, C.R. (Editor), Magmatic Processes and Plate Tectonics. Geological Society Special Publication. Geological Society, London, Special Publications, pp. 3-38.
Wood, C.A., 1980a. Morphometric analysis of cinder-cone degradation. Journal of Volcanology and Geothermal Research, 8(2-4): 137-160.
Wood, C.A., 1980b. Morphometric evolution of cinder cones. Journal of Volcanology and Geothermal Research, 7: 387-413.