# Monogenetic volcanism of the South Auckland and Auckland Volcanic Fields

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**Abstract** This three day pre-conference field trip will offer an overview of the eruption styles, eruption mechanisms and landform evolution of the Plio-Pleistocene South Auckland and the still active Auckland 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. The field trip will offer great opportunity to compare relatively young (e.g. Pleistocene) monogenetic volcanic landforms to similar volcanoes erupted just few thousands of years ago. This unique opportunity will enhance our understanding of the erosion, preservation potential, and volcanic hazard aspects of monogenetic volcanic fields. One of the most dangerous and largely not fully understood eruption style which the majority of the South-Auckland and Auckland volcanoes have experienced is the phreatomagmatic explosive eruptions. These played a significant role in the formation of nearly ¾ of the total number of the known eruption centers in Auckland, and probably half of the volcanoes had clear phreatomagmatic eruption history in the South Auckland Volcnaic Field. 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 SAVF and 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 SAVF and 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.

## 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 three day pre-conference field trip offers an overview of the eruption styles, eruption mechanisms and landform evolution of the South Auckland and Auckland Volcanic Fields on which New Zealand largest population, including its largest city, lives (Fig. 1). The AVF is in particular interest due to its still active nature. This still 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 South Auckland and 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, b). 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 (Kereszturi and Németh, 2012; Kervyn et al., 2012; Martin and Németh, 2006; Németh et al., 2011; Rodriguez-Gonzalez et al., 2011; Rodriguez-Gonzalez et al., 2012). 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 (Houghton et al., 1999; Lorenz, 1986; Németh, 2010; Valentine and Gregg, 2008; Vespermann and Schmincke, 2000). Tuff rings are generally low rimmed and wide cratered monogenetic volcanoes that form due to magma and surface and/or near surface aquifer interaction (Vespermann and Schmincke, 2000). 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 (Dellino et al., 2011; Lorenz, 2006; Valentine and Fisher, 2000; Valentine and Gregg, 2008).

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). 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, 2011) reflecting the intensified research at Auckland to develop an accurate method to be able to estimate future monogenetic eruptions' time and location. However, reliable age of volcanic events for the AVF is problematic due to the young age of the volcanism and the presence of unsuitable material for radiometric age datings for K-Ar and Ar-Ar method and/or the "border-line" age of the majority of volcanism for applying C14 dating techniques (Lindsay et al., 2011). To complicate the situation various techniques are commonly gave contradicting ages that difficult to interpret (Lindsay et al., 2011).

## SOUTH AUCKLAND VOLCANIC FIELD – GENERAL SETTING

There are six Late Miocene to Recent intraplate, alkalic basalt, monogenetic volcanic fields in northern North Island, New Zealand, situated in a continental tectonic setting on the Australian Plate, well behind the presently active convergent margin rifted arc of the Taupo Volcanic Zone (Fig. 1). These include two long-lived fields in Northland in the Kaikohe – Bay of Islands (9.3 – 0.06 Ma) and Puhipuhi – Whangarei (9.7 – 0.26 Ma) districts (Smith et al., 1993), and four relatively short-lived but discrete fields at Auckland [0.26 Ma – 500 years ago; 53 centres] (Lindsay et al., 2011; Needham et al., 2011), South Auckland [1.6 – 0.5 Ma; at least 82 centres] (Briggs et al., 1994b), Ngatutura [1.8 – 1.5 Ma; 16 centres] (Briggs et al., 1990) and Okete [2.7 – 1.8 Ma; 27 centres] (Briggs and Goles, 1984; Briggs et al., 1989).

The four volcanic fields in the Auckland Volcanic Province of Okete, Ngatutura, South Auckland and Auckland are spaced at 35 – 40 km intervals and progressively young to the north. The plate motion of the Australian Plate is to the north, which precludes movement of the plate over a stationary mantle plume source. Instead it implies a northward movement of the mantle source, and may be related to the development of the Hauraki Rift and fracturing of the lithosphere (Spörli and Eastwood, 1997). However, the volcanic fields in the Northland Volcanic Province show no younging trends and hence must have discrete sources from those of Auckland.

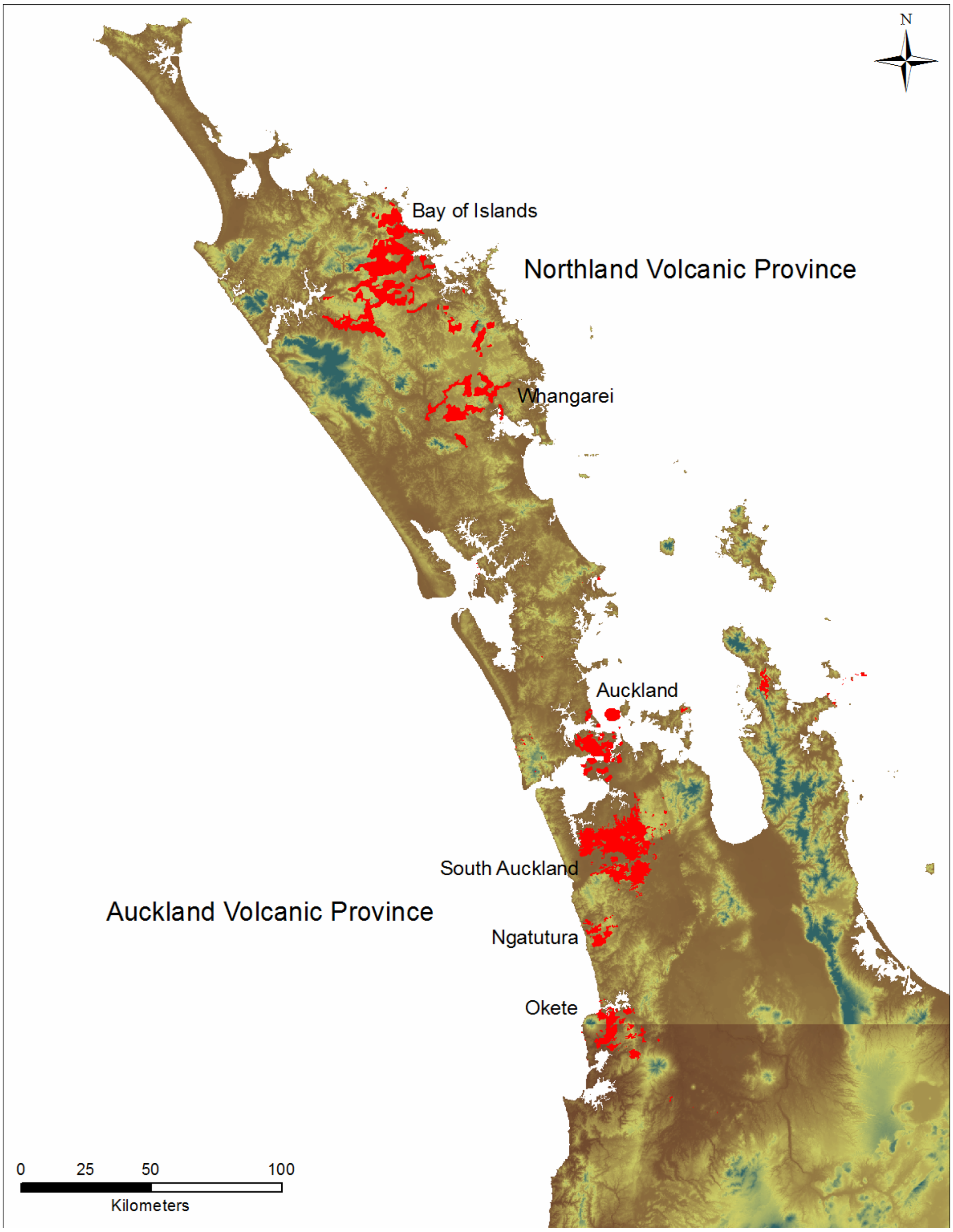


**Fig. 1** *Distribution of intraplate volcanic fields in northern North Island.*

The South Auckland Volcanic Field (SAVF) is located about 40 km south of Auckland City and covers an area of about 300 km2 centred around the Manukau Lowlands, and extending to the east to the Hunua Ranges, and to the south in the Waikato River valley and a basement block uplifted by the Waikato Fault (Fig. 2).

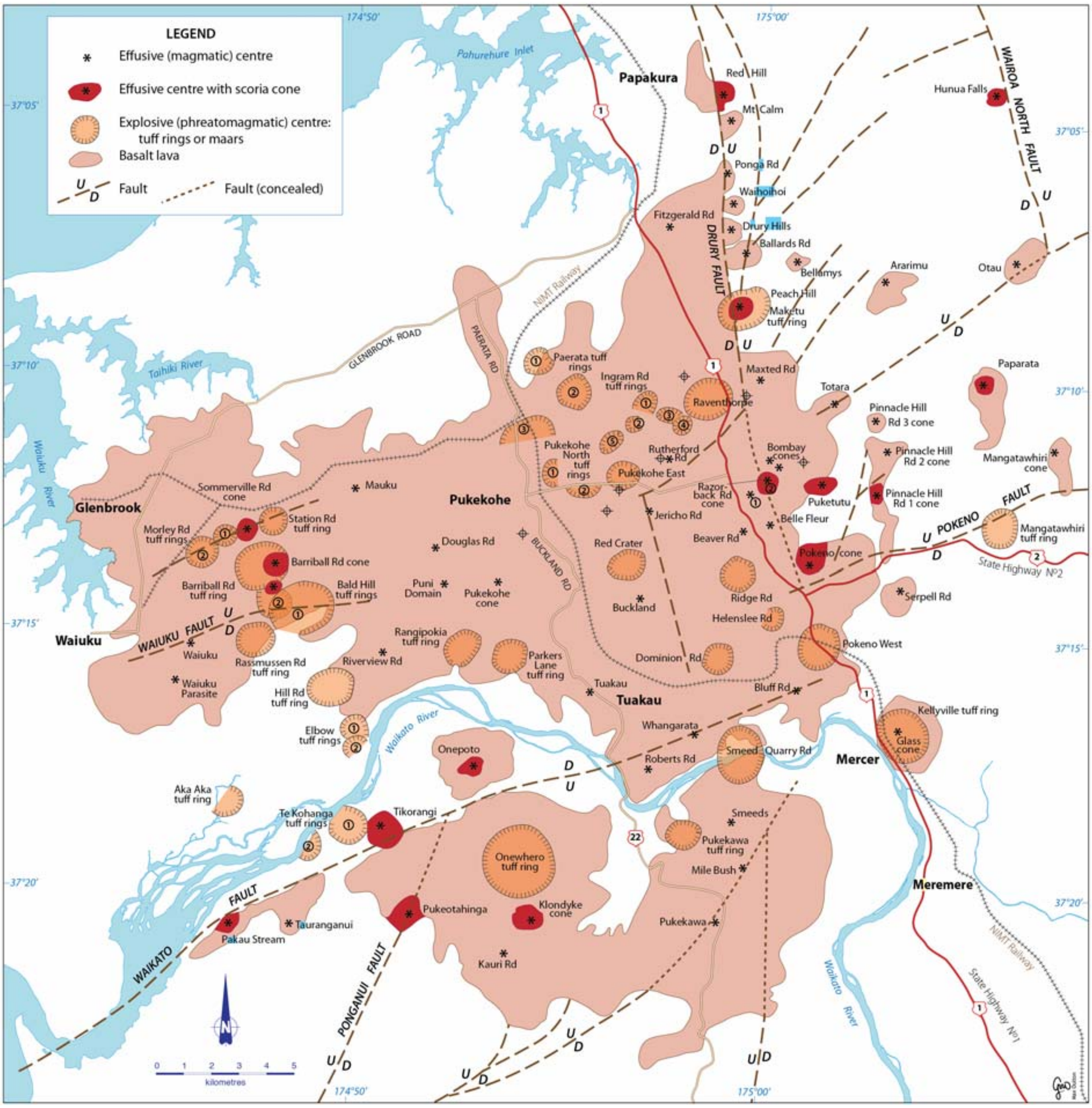


**Fig. 2** Map of the South Auckland Volcanic Field.

The subsurface geology of the SAVF is considered to play an important role in the nature and style of magmatic versus phreatomagmatic volcanism related to the availability of suitable aquifers and local hydrology, and a pronounced structural control by upper crustal faults which provided pathways for dike intrusion, and is summarised below.

Late Triassic to Early Cretaceous basement greywacke rocks outcrop in uplifted block-faulted parts of the South Auckland region. The Mesozoic basement rocks were originally formed on the eastern Gondwana margin, and consist of a western Murihiku terrane of volcanogenic sandstones and siltstones exposed south of the Waikato Fault, and a western Waipapa (composite) terrane of volcaniclastic sandstones, manganiferous cherts and local spilitic basalts metamorphosed to prehnite-pumpellyite and pumpellyite-actinolite grades, exposed in the Hunua Ranges east of the Drury Fault (Black et al., 1993; Edbrooke, 2001b). These terranes are separated by the ultramafic and mafic rocks of the Dun Mountain-Maitai Terrane west of the Drury Fault, which are not exposed but are inferred at depth from a strong linear positive magnetic anomaly named the Junction Magnetic Anomaly (Cassidy and Locke, 2010; Edbrooke, 2001b).

The Mesozoic basement rocks are separated by a regional unconformity from Late Eocene to Oligocene Te Kuiti Group rocks of coal measures, calcareous siltstones, sandstones and limestones. Te Kuiti Group rocks only outcrop south of the Waikato Fault and in a small inlier east of the Drury Fault. A minor episode of block faulting, uplift and erosion followed, and these rocks were unconformably overlain by the Miocene Waitemata Group sandstones and siltstones.

The structurally down-faulted block of the Manukau Lowlands, north of Waikato Fault and west of Drury Fault, underwent a period of shallow marine and estuarine sedimentation during the Early Pliocene, resulting in the unconformable deposition of the Kaawa Formation on the post-Waitemata Group surface. The Kaawa Formation is a highly porous and permeable, slightly indurated thick sandstone (up to 250 m thick around Pukekohe and Tuakau) and forms an important aquifer system in South Auckland (Greig, 1989; Hadfield, 1988; Hollis, 1986). The Kaawa Formation contains two distinct shell horizons which are highly fossiliferous, generally located at about 100 and 150 m depths (Hollis, 1986). The Kaawa Formation is overlain by the Pliocene to Holocene fluvial and lacustrine gravels, sands, silts and muds of the Tauranga Group, which are intercalated with distal ignimbrites and tephras derived from southern Coromandel and early Taupo volcanic zones.

There are at least 82 volcanic centres in the SAVF which have been counted as a single volcanic centre if they occur either as an isolated volcano, or as groups of overlapping volcanoes, e.g. a scoria cone nested inside a tuff ring or maar. 43 of the volcanic centres have been dated by K-Ar methods on basaltic crystalline groundmass and ages range from 1.59 to 0.51 Ma (Briggs et al., 1994a). The SAVF is now considered to be extinct. There were two peaks of activity at 1.3 and 0.6 Ma although volcanic activity was intermittent over the 1 Ma age span of the field.

Phreatomagmatic activity in the SAVF has formed 38 maars or tuff rings which vary from 0.5 to 2.7 km in diameter measured from topographic rim to rim, and average 1.3 km in diameter. By comparison the 26 maars and tuff rings in the Auckland Volcanic Field (AVF) average 0.7 km in diameter with a maximum of 1.4 km at Pupuke (Cassidy and Locke, 2010). Magmatic activity has produced 17 scoria cones and 40 lava shields or cones. In the central part of the field extensive basaltic lava flows from multiple centres overlap and intercalate with Quaternary sedimentary rocks and have produced broad shields, whereas on the periphery of the field the volcanic centres are isolated and generally smaller in volume, and it is interesting to contemplate whether the AVF will develop along similar patterns in the future.

Furthermore, it is most likely that there are many older volcanic centres which are not exposed and have been buried by younger centres, particularly in the central part of the field, so that the number of volcanic centres in the SAVF is considered to be much greater than 82 as reported here.

## AUCKLAND VOLCANIC FIELD – GENERAL SETTING

Auckland City is built on an active (~ 250ky to 750 y BP) monogenetic volcanic field containing some 50 volcanic vents (Edbrooke, 2001a; Hayward et al., 2011b; Kermode, 1992b) (Figs 1, 2 & 3). The number of volcanic vents however is in change due to some recent discovery of new tuff rings in the southern part of the field (Hayward et al., 2011a; Hayward et al., 2011b) Eruptions have in general been small with volumes <0.05 km$^3$ (Allen and Smith, 1994a; Allen and Smith, 1994b; Kereszturi et al., 2012) 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 (Kereszturi et al., 2012; Needham et al., 2011).

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, 1994b) 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).

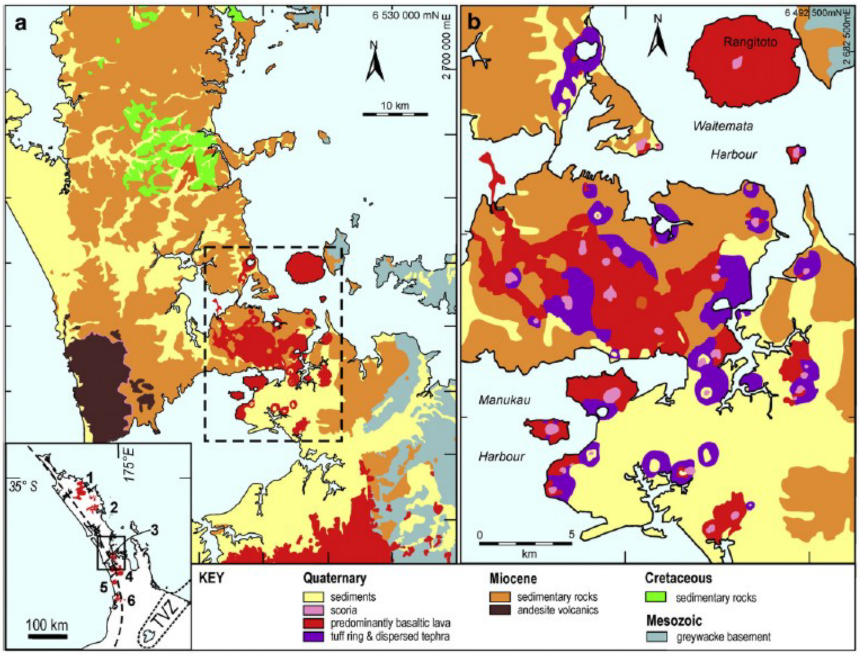


**Fig. 3** *Simplified geological map of the Auckland region (a) and the Auckland Volcanic Field (b) from Cassidy and Locke (2010). Geological data based on Edbrooke, 2001; Kermode, 1992). Quaternary basaltic volcanic fields in northern New Zealand are: 1) Kaikohe-Bay of Islands; 2) Whangarei; 3) Auckland;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

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; Cassidy et al., 2007; Cassidy and Locke, 2004, 2010; Houghton et al., 1996; Houghton et al., 1999; Rogan et al., 1996; Smith, 1989; von Veh and Németh, 2009).

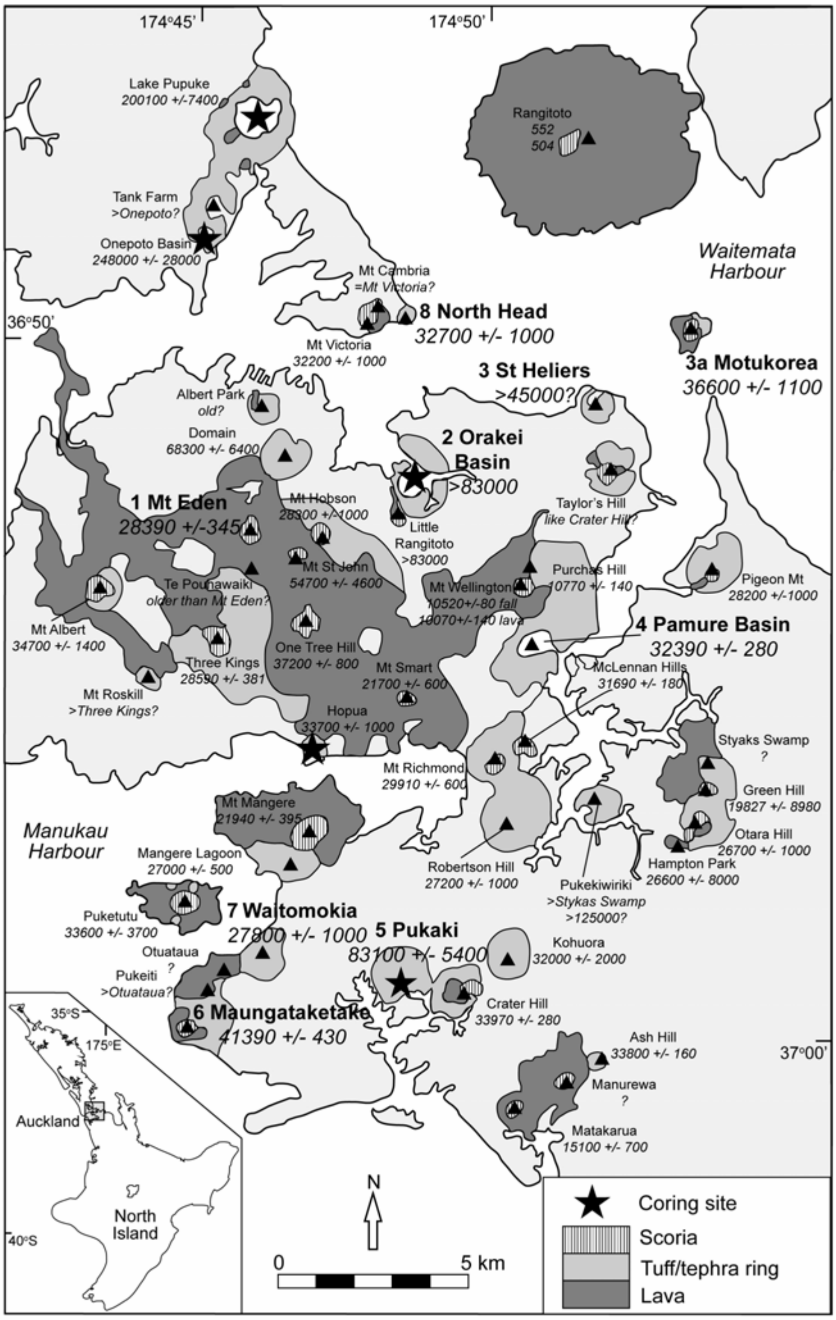


**Fig. 4** *Eruptive centers and their ages (in years) after Bebbington and Cronin (2010) of the AVF. Phreatomagmatic explosive eruption products are marked as tuff/tephra ring on the map.*

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, 2010; Hayward et al., 2002; Molloy et al., 2009; Venuti and Verosub, 2010), although they cannot be readily/easily distinguished from broad tuff rings (Cronin et al., 2009b; Németh et al., 2009b) 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., 2010b). Tuff rings are commonly overlain by scoriaceous pyroclastic deposits (Figs 4 & 5) resulting from Strombolian style eruptions as the water supply was exhausted in the course of the eruptions (Agustin-Flores et al., 2012; Allen et al., 1996; Searle, 1959, 1962) similarly to many observed scenarios when monogenetic volcanoes erupted in a low-lying, alluvial plain or coastal plain (Martin and Németh, 2005; Németh et al., 2010a; Sohn et al., 2008). 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 (Agustin-Flores et al., 2012; Allen et al., 1996; Németh et al., 2010b; Németh et al., 2009b). 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 (Agustin-Flores et al., 2012; Németh and Cronin, 2009; Németh et al., 2009a) similar to other phreatomagmatic volcanism-dominated fields elsewhere (Auer et al., 2007; Kereszturi and Németh, 2011; 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 (Cronin et al., 2009a) as documented elsewhere (Auer et al., 2007; Kereszturi and Németh, 2011; Ross et al., 2010) that are difficult to distinguish.

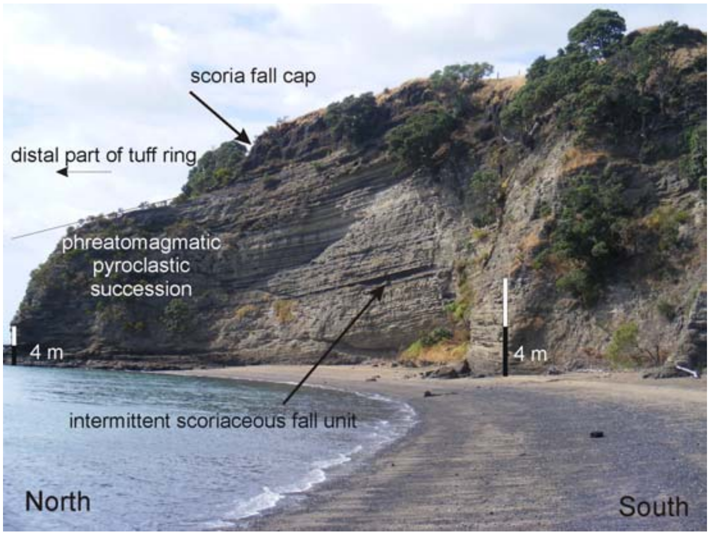


**Fig. 5** *Scoriaceous lapilli and ash beds capping typical phreatomagmatic lapilli tuff and tuff (alternating base surge and fall) beds in the northern proximal section of Motukorea/Browns Island*

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) intercalated with some volcanic rock which origin is under debate (Shane et al., 2010). 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 siliciclastic-dominated substrate of Waitemata Group and younger fluvio-lacustrine to shallow marine 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, 1994a; Hayward et al., 2011b; Law, 1975; Lindsay et al., 2011; 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, 1994a; Allen and Smith, 1994b; Kereszturi et al., 2012) 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$^3$ (Allen and Smith, 1994b)but this number has been revised and halved to about 1 $km^3$ in recent calculations (Kereszturi et al., 2012).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, 2009; Lowe et al., 2000; Molloy et al., 2009; Sandiford et al., 2001; Sandiford et al., 2003).

# FIELD GUIDE

## DAY 1 – SOUTH AUCKLAND VOLCANIC FIELD

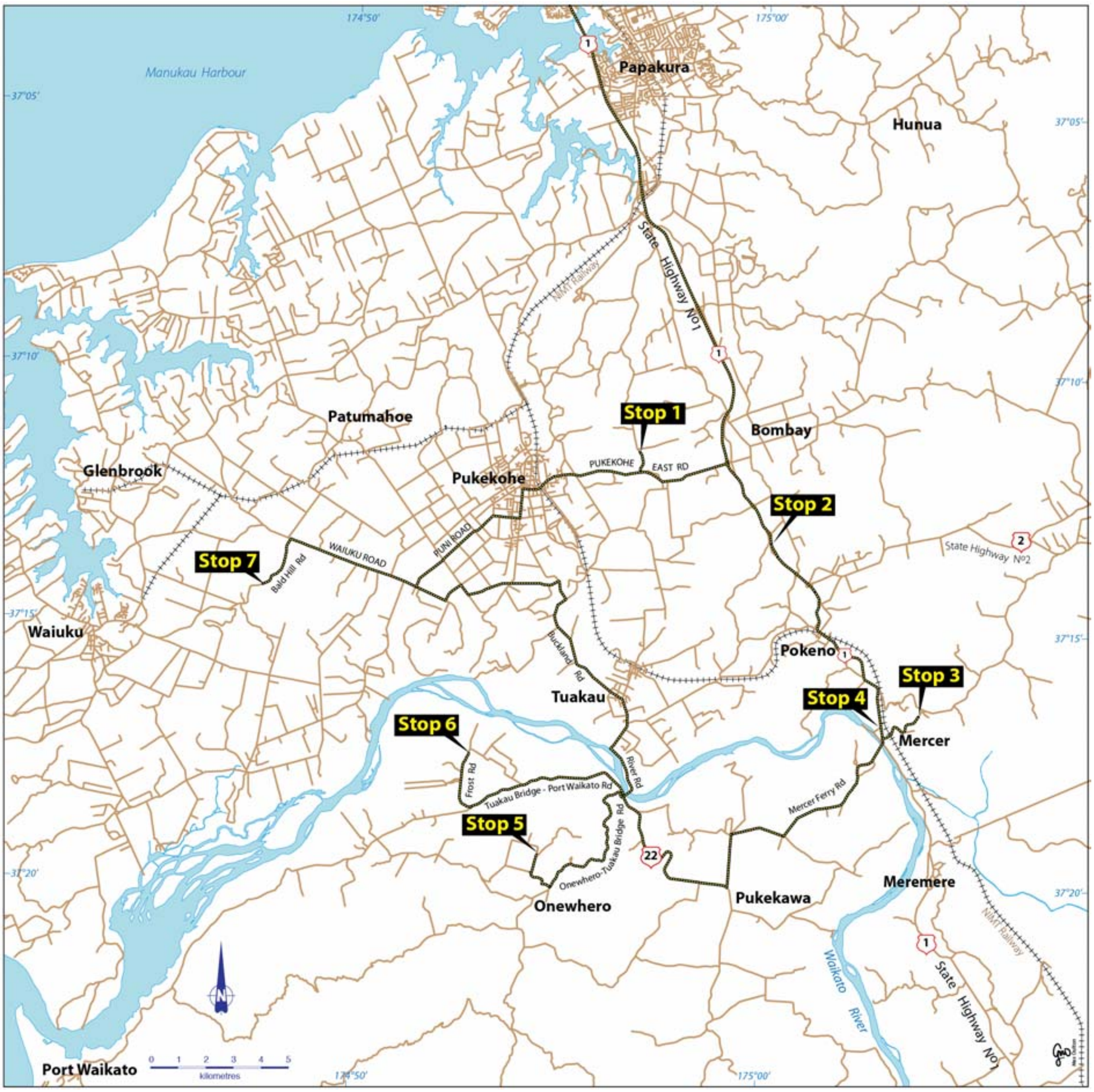


**Fig. 6** *Fieldtrip route and stops on the South Auckland Volcanic Field*

### Stop 1 Pukekohe East tuff ring

The Pukekohe East tuff ring is one of the best preserved tuff rings in the SAVF (Figs 6 & 7) but the deposits are poorly exposed. The tuff ring is oval in shape, about 1.1 km long and 0.8 km wide, has a flat floor and is breached to the west. The tuff ring deposits are about 50 m thick at the eastern side. It has been dated at 0.68 Ma (Briggs et al., 1994a).

**Fig. 7** *Pukekohe East tuff ring looking towards the breached western rim. The broad lava shield of Pukekohe Cone is in the middle distance, and the upstanding block of Mesozoic basement rocks on the south side of the Waikato Fault are seen in the far distance.*

We will stop at the Pukekohe East historic church to view the tuff ring. The church was built in 1863 which was a time of skirmishes with local Maori, and three bullet holes can be seen in the church walls.

**Stop 2 Bombay Quarry (Exit 474 Ridge and Nikau Roads)**

The complexity of the broad shields in the central part of the SAVF is well exposed in Holcim's Bombay Quarry where multiple lava flows are intercalated with scoria spatter cones and Quaternary sands, and then overlain by a thick tuff ring (Fig. 8). A rhyolitic tephra layer occurs at the base of the tuff ring which has been suggested to have been derived from the Mangakino caldera in the Taupo Volcanic Zone 1 to 1.2 million years ago (Alloway et al., 2004).

The Jones Block, exposed recently on the northern side of the quarry, further highlights the stratigraphic complexity and the "polygenetic" nature of the Bombay shield. Several unconformities are exposed in the quarry, including the Jones Block section (Alloway et al., 2004). Another feature of the quarry is that there are multiple but separated vents, and we can discuss the definition of a polygenetic centre at this site.

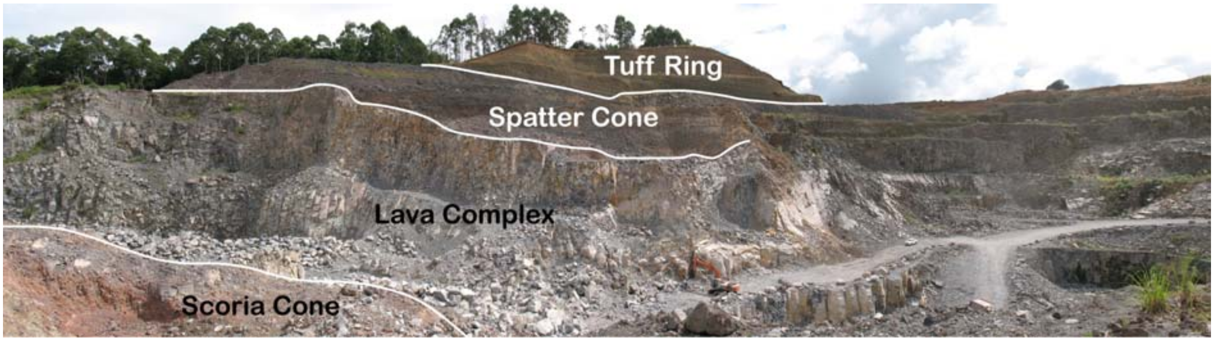


**Fig. 8** *Pukekohe East tuff ring looking towards the breached western rim. The broad lava shield of Pukekohe Cone is in the middle distance, and the upstanding block of Mesozoic basement rocks on the south side of the Waikato Fault are seen in the far distance.*

Access to this quarry is highly restricted because of safety reasons in a working quarry, and we will only be able to view the quarry from outside the gate. Hard hats, high-vis vests, and steel toe-capped boots must be worn to enter the quarry, and for this reason we are not allowed to go further than the overview site. Please abide by these restrictions.

**Stop 3 Kellyville maar**

The Kellyville maar has been dated at 1.48 Ma (Briggs et al., 1994a) and commenced with an early phreatomagmatic phase which produced a tuff ring, followed by a later magmatic phase that formed two scoria cones (Glass Hill and School Hill) inside the tuff ring (Gibson, 2011)(Fig. 9). School Hill cone lies approximately at the centre of the tuff ring and is thought to be the first vent position, and Glass Hill is situated 330 metres to the west and is thought to overlie the second vent position.

The maar was infilled by diatomite up to 8.5 m thick, determined from drill-holes carried out by Winstone Aggregates in 1972 (Waterhouse, 1980). The diatomite shows laminated bedding with carbonaceous layers containing fossil leaves and seed imprints (Fig. 10). SEM studies showed the presence of the freshwater diatom species Stephanodiscus novae zealandiae and Cyclotella stelligera (pers.com. V.C.Cooper, in Gibson 2011), which both have age ranges from Cretaceous to Recent and are therefore not age determinant.

The maar has since been breached on its western side by the wandering Waikato River.

The Kellyville maar is underlain by the Mercer Sandstone and the Koheroa Siltstone, both formations within the Waitemata Group (Edbrooke, 2001b), which can be seen outcropping on State Highway 1. The Mercer Sandstone and Koheroa Siltstone are both found as lithic fragments in the tuff ring deposits, especially in the earlier vent clearing phases when the magma supply was unsteady and pulsating with variations in magma/water ratios. This deposited lithic-rich, coarse air-fall material around the vent. Stages of stronger fragmentation caused finer grained material to be deposited in alternating layers of coarse ash surge and fine ash fall layers. Many large juvenile and lithic ballistics are found in the lower sections of the 34 m stratigraphic section through the tuff ring exposed on Koheroa Road (Fig. 11). This section records the middle and later stages of the eruption, and a fining upwards succession from fine to coarse lapilli with occasional block and bomb layers to alternating laminated fine to coarse ash beds. Some beds in the upper section show low angle cross bedding and discontinuous lensoidal pinch and swell structures, indicating a predominance of surges and associated fall, derived from an open vent. The cause of the end of the eruption was most likely due to a decrease in magma supply rate and eventual withdrawal of the intruding magma body.

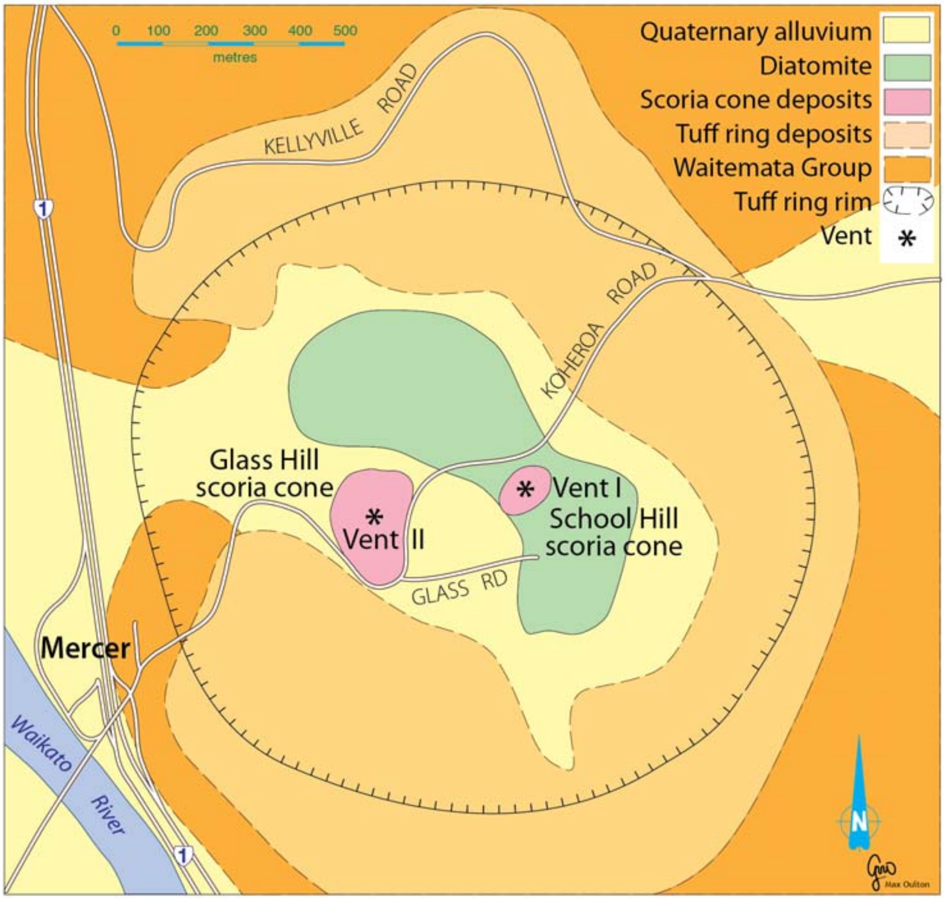


**Fig. 9** *Map of Kellyville maar (after Gibson 2011).*

The magmatic phases of the eruption may have occurred sometime later when the external water supply was depleted and subsurface water interaction was low enough to produce the scoria cones.

We will walk down section viewing the upper fine-grained surge deposits, then the lower lithic-rich deposits, and finally arrive at the diatomite within the tuff ring.

**Fig. 10** *Bedded and jointed diatomite, Kellyville maar*

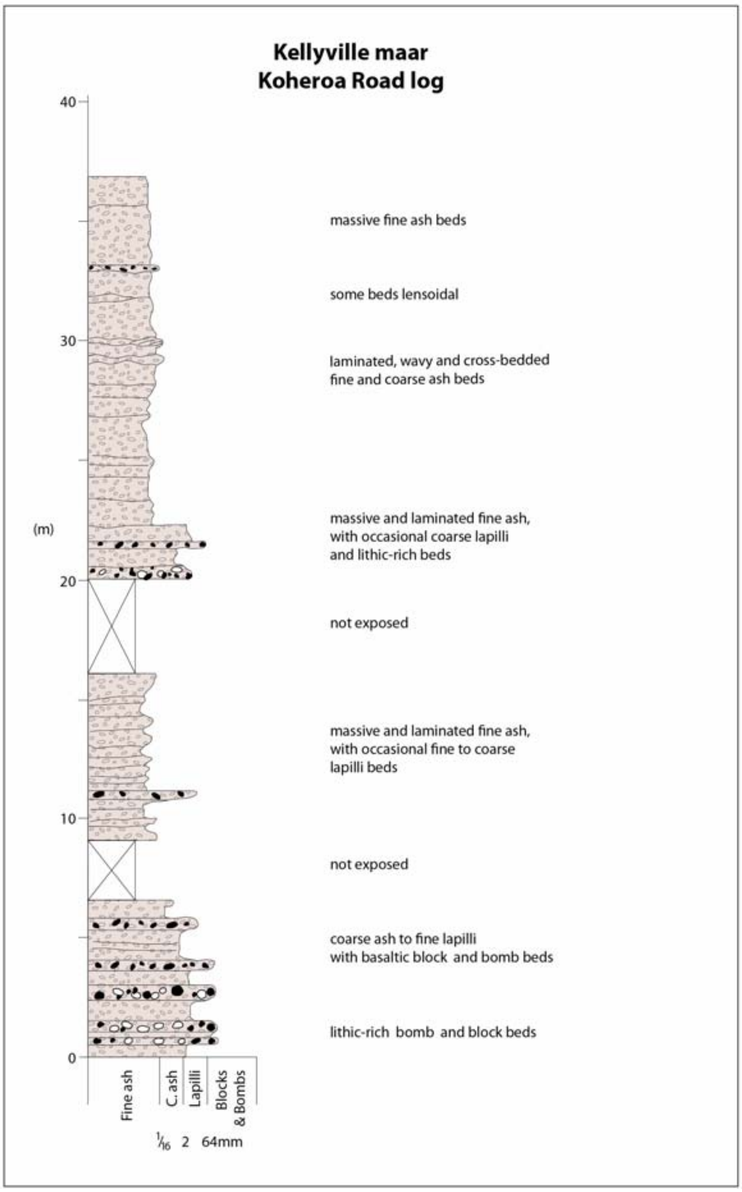


**Fig. 11** *Simplified stratigraphic column through the maar deposits on Koheroa Road, Kellyville maar (after Gibson 2011).*

**Stop 4 Lunch at Mercer**

**Stop 5 Onewhero maar**

The Onewhero tuff ring is situated south of the Waikato Fault and is the largest tuff ring in the SAVF with a topographic rim to rim diameter of 2.7 km (Fig. 12). It has been dated at 0.88 Ma (Briggs et al., 1994a) and described by Gibson (2011). Tuff deposits are about 750 m in width around the entire tuff ring. The floor of the tuff ring ranges from 95 to 110 m a.s.l. The inner slope angles of the tuff ring range from 14 to 25°, whereas the outer slope angles are about 7°, although these angles have been modified by erosion and partial collapse. The Miller Road Stream has cut through the northeast side of the tuff ring, exposing a section about 30 m high (Fig. 13). Several localities near the stream provide access to stratigraphic sections of variable height. We will only have time to visit the lower part of the section (Fig. 14).

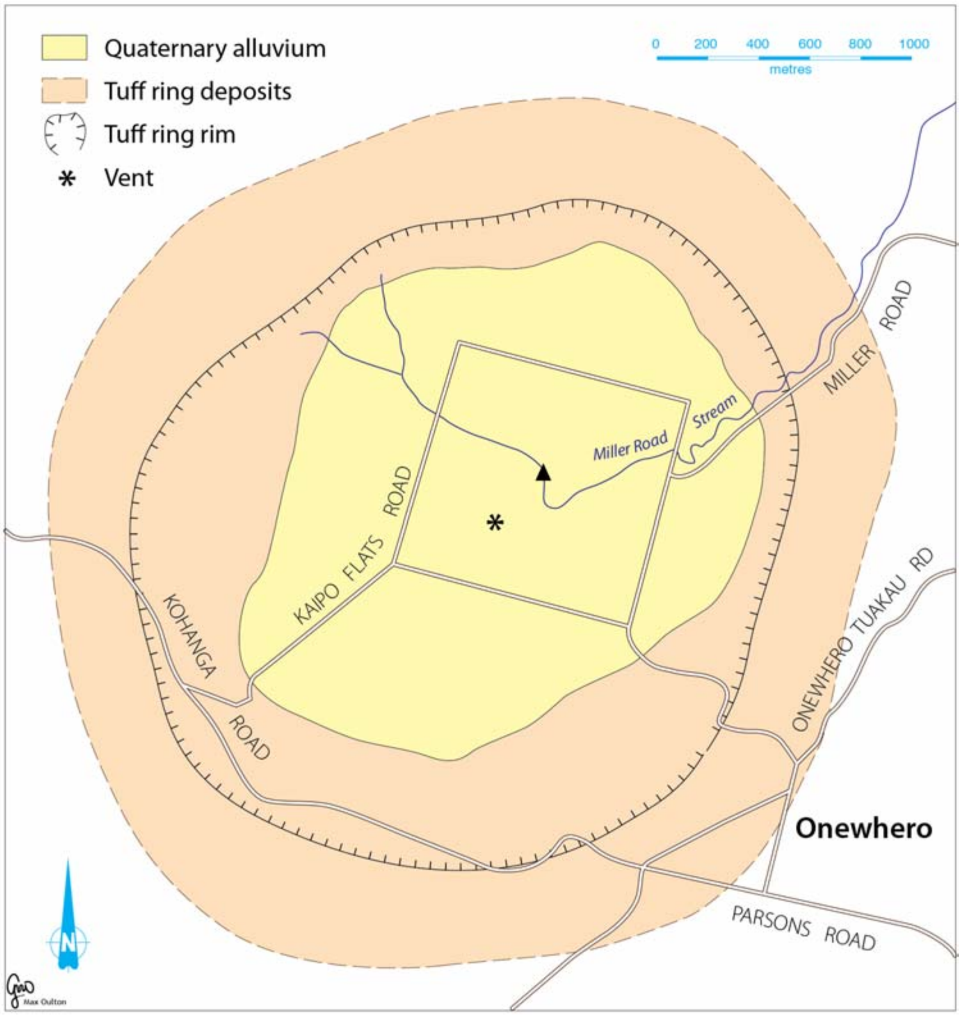


**Fig. 12** *Map of Onewhero maar (after Gibson 2011).*

**Fig. 13** *Exposed section on Miller Stream, Onewhero maar.*

The main underlying geological unit below the Onewhero tuff ring deposits is the Carter Siltstone of the Te Kuiti Group which has been identified as lithics within the tuffs. However, the Carter Siltstone is a tight siltstone with a low porosity and permeability, and is unlikely to have been the aquifer responsible for the eruption. Large free crystals of quartz, orthopyroxene and plagioclase are common as accidental crystals in the tuffs, and such large crystals do not occur in any of the underlying Te Kuiti Group formations but are the most abundant crystals in the Quaternary Waikato River alluvial deposits. The Waikato Fault is known to have been tectonically active during the Quaternary (Hochstein and Nunns, 1976), and so the large volume of external water required for phreatomagmatic activity may have been derived from when the Onewhero maar was formerly situated in the low-lying Waikato River valley prior to 0.88 million years ago. This implies that the block south of the Waikato Fault on which the Onewhero maar is constructed, has been uplifted about 100 m since 0.88 Ma.

The stratigraphically lower exposures at Miller Road typically consist of medium to well sorted, laminated, wavy and cross bedded alternating fine and coarse ash (Gibson, 2011). Basaltic blocks and bombs are common and reach up to 60 cm. Moderately to well sorted fine to medium lapilli beds also occur which can contain orange to red scoria and slightly vesicular basalt. Beds with both normal and reverse grading are observed. Gibson (2011) interpreted the lower sections to represent an energetic alternating fall and surge couplet dominated phase of the eruption with occasional ballistic fall-out represented by isolated lithic and juvenile clast blocks within finer deposits. Coarser beds of mainly juvenile clasts with uncommon lithics represent a drier stage of the eruption with lower fragmentation efficiency and energy of the eruption. Lithic clasts of Carter Siltstone at certain levels may indicate a downward shift in the fragmentation depth below the postulated Quaternary alluvium.

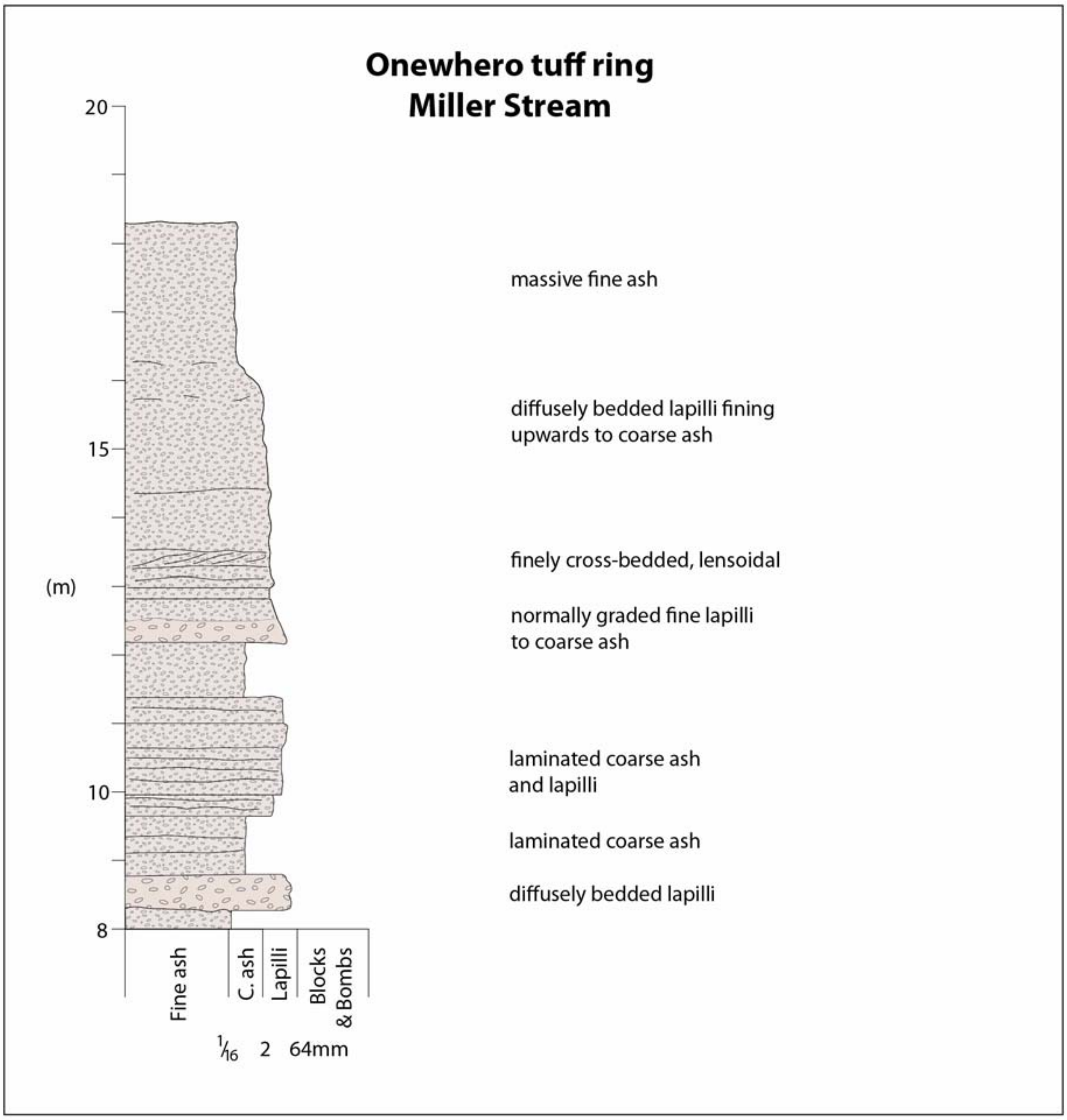


**Fig. 14** *Simplified stratigraphic column through the maar deposits on the northern side of Miller Stream, Onewhero maar (after Gibson 2011).*

Stratigraphically higher exposures include poorly sorted, diffusively bedded to massive beds, ranging widely in grain size from fine ash to blocks and bombs, intercalated with well sorted laminated and cross-bedded layers. The poorly sorted deposits with weakly developed bedding probably indicate a fall-dominated phase of the eruption while poorly sorted layers with alternating fine and coarse material may represent pulsing bursts of fall and surges resulting from a larger amount of water interacting with the magma causing pulsating explosions with high energy, and a trend of coarsening upwards through the tuff deposits (Gibson, 2011; Németh and White, 2003). Presumably the reason why the Onewhero maar is the largest in the SAVF is because of the unusually high volume of magma flux and a steady supply of water from an ancestral Waipa/Waikato River and its alluvial deposits which have high porosity, permeability and transmissivity. The absence of an associated magmatic phase and progression to a scoria cone suggests that the interaction between magma and water was continuous and that the ascending magma flux suddenly ceased before the water supply was depleted. The geochemistry of the basalt clasts show they belong to Group A of (Cook et al., 2005)

**Stop 6 Onepoto scoria cone**

Scoria cones are poorly exposed in the SAVF and all of them have been partly modified by erosion, but rare examples can be found at Onepoto scoria cone. Onepoto volcano is constructed by a series of lava flows that radiate from a central vent, surmounted by a scoria cone (Fig. 15). The flanking lavas of the volcano slope at about 10° and bedding in the scoria deposits in the cone dip at 28-30° (Fig. 16).

A small disused quarry near the summit of Onepoto scoria cone has exposed contrasting styles of eruption (Rosenberg, 1991). On the northern sides of the quarry the deposits are moderately to well bedded (30 – 100 cm thick), poorly to moderately sorted, medium to coarse lapilli and fine bomb-sized grey and dark brown scoria, alternating with finer grained beds, 10 – 30 cm thick, moderately sorted, massive or reversely graded brown to yellow palagonitised fine lapilli (Fig. 17, Frost Road quarry). Subangular to subrounded ballistic bombs and blocks occur up to 250 mm in diameter, and often have a degassed rind with a more vesicular core. Occasional bombs show bedding sags into underlying loosely packed lapilli. These deposits are interpreted to be strombolian in origin.

On the southern sides of the quarry (Fig. 17, Frost Road cutting) the deposits consist of angular to subangular lapilli and blocks of red oxidised scoria, which are usually agglutinated and weakly welded. Scoria is moderately to highly vesicular (46 – 67 %) and occasionally show fluidally-shaped surfaces (Rosenberg, 1991). The deposits are poorly sorted and massive with no bedding or textural changes, which implies that the deposits were formed from a steady sustained rate of accumulation typical of Hawaiian eruption styles, rather than the intermittent, discrete explosive bursts typical of strombolian activity. Two dikes up to 50 cm thick intrude the scoria but are poorly exposed.

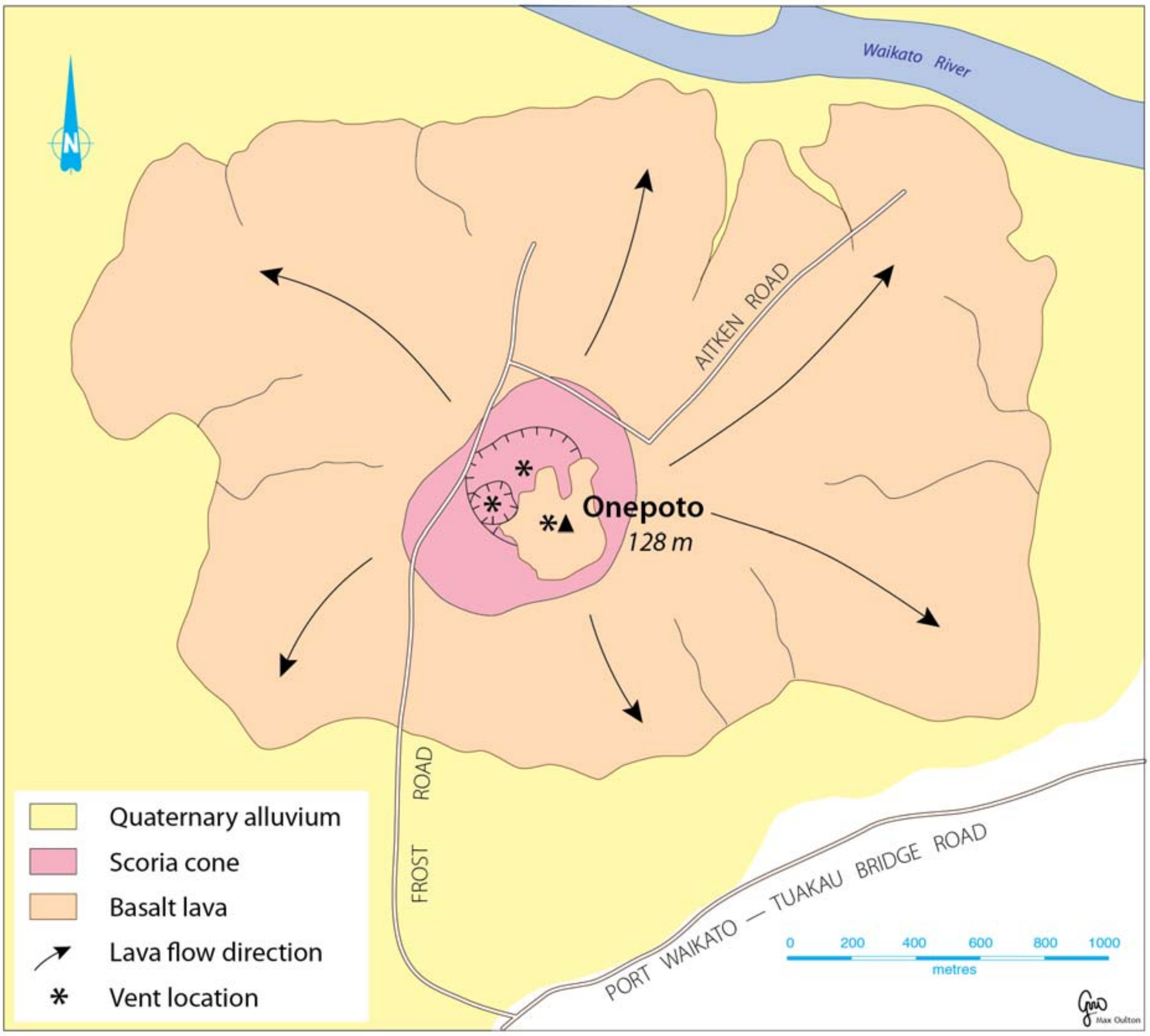


**Fig. 15** *Map of Onepoto scoria cone and lava apron.*

**Fig. 16** *Onepoto Cone and lava field.*

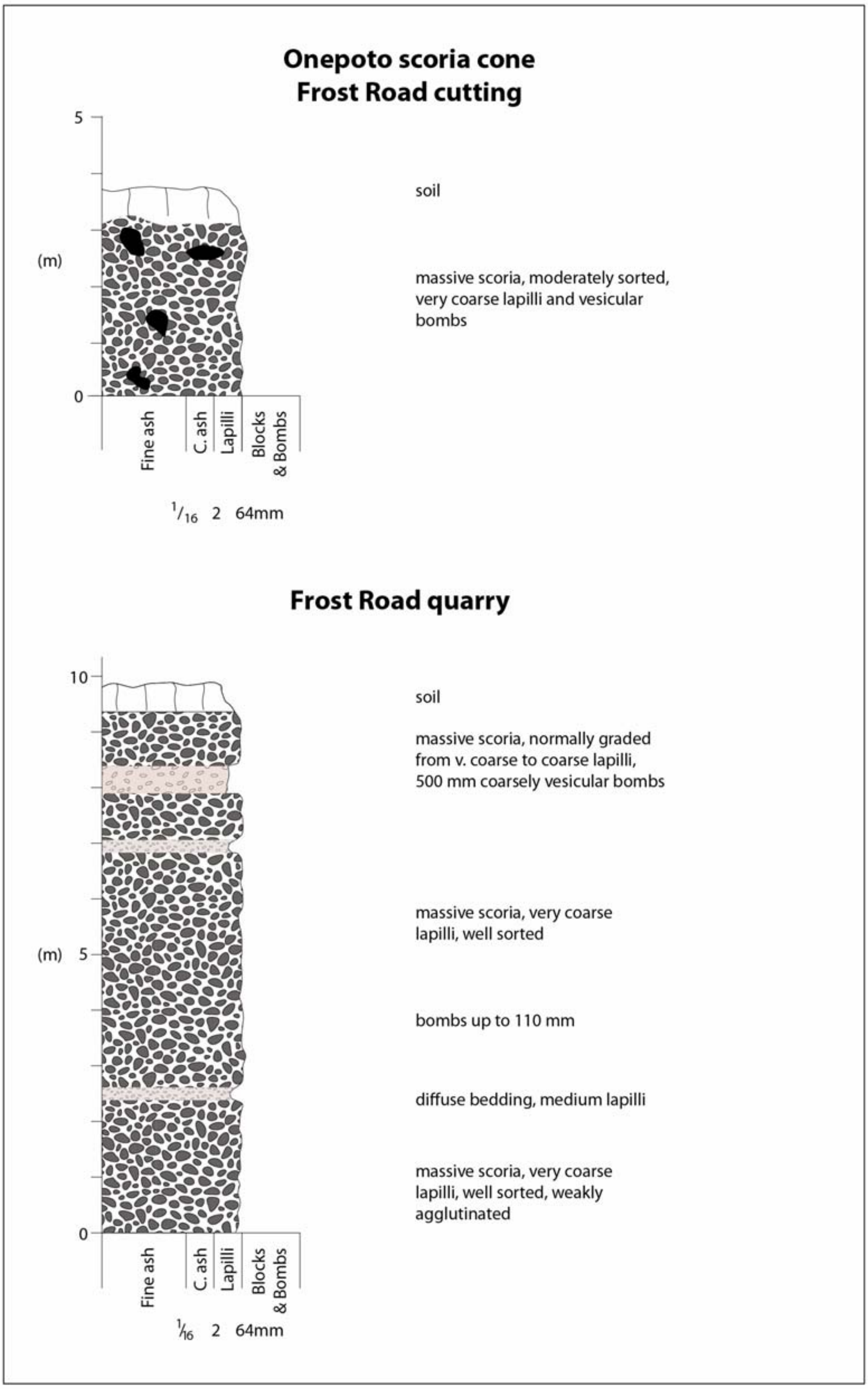


**Fig. 17** *Simplified stratigraphic column through scoria cone deposits, Frost Road, Onepoto Cone.*

**Stop 7 Barriball Road tuff ring**

The Barriball Road tuff ring provides an example of a tuff ring in which there is evidence for vent migration over the life of its construction (Ilanko, 2010; Rosenberg, 1991).

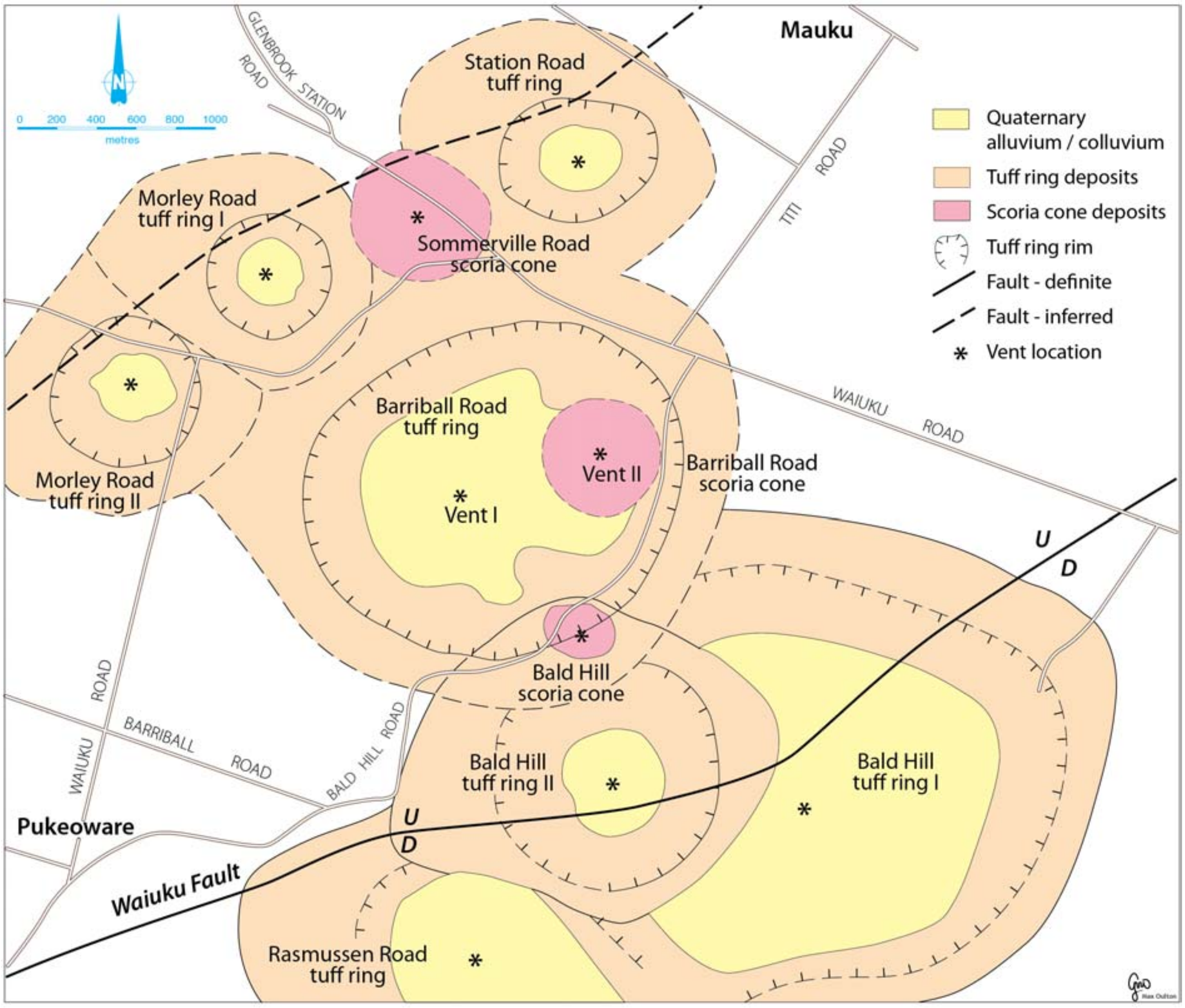


**Fig. 18** *Map of Barriball Road tuff ring (after Rosenberg 1991 and Ilanko 2010)..*

It consists of two overlapping tuff rings with a younger nested scoria cone. The Barriball Road tuff ring is situated between two ENE-striking faults (Fig. 18), the Waiuku Fault and an unnamed fault to the north recognised by Rosenberg (1991). The Bald Hill tuff rings I and II are aligned along the Waiuku Fault, and the Morley Road tuff rings I and II, the Sommerville Road scoria cone, and the Station Road tuff ring are aligned along the unnamed fault. The Barriball Road tuff ring is asymmetric and ellipsoidal, with the long axis of the ellipse aligned ENE, parallel to the two faults, and coinciding with the proposed location of vent 1 and the position of the summit of the Barriball Road scoria cone (vent 2). The location of the two vents may be related to another ENE-striking fault at depth.

The Barriball Road tuff ring has been dated at 1.0 Ma by Briggs et al. (1994) and has a maximum diameter of 2.1 km between the topographic high points on the rim. The maximum thickness of the tuff ring is about 50 m.

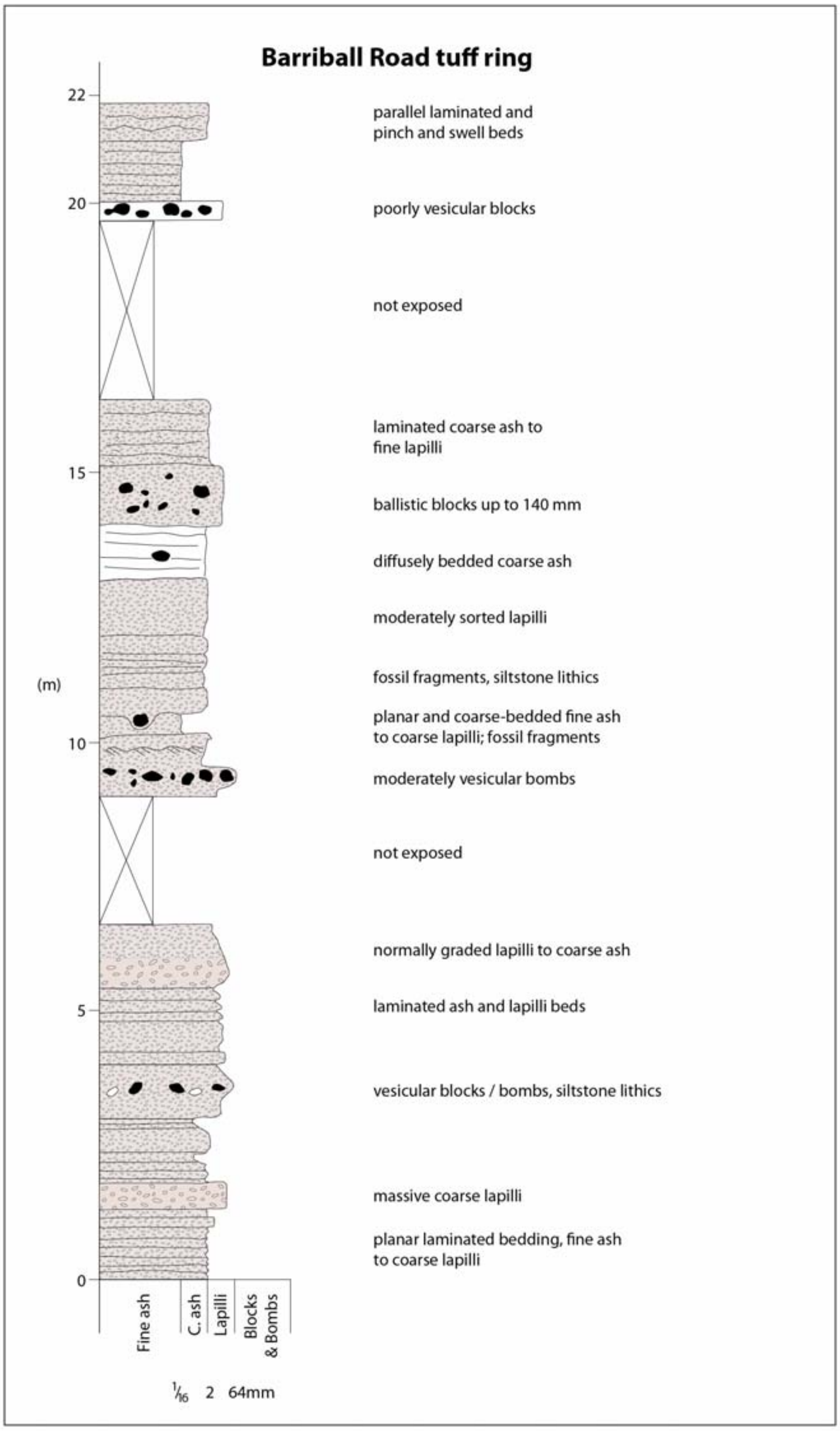


**Fig. 19** *Simplified stratigraphic column through the Barriball Road tuff ring (after Ilanko 2010).*

The initial stages of the eruption are not exposed but the stratigraphically lowest part of the succession contains diffusively planar bedded to massive, moderately to well sorted, alternating ash and lapilli, varying in thickness from 5 -100 cm thick (Fig. 19). Ash aggregates and armoured lapilli occur in some beds, and bedding sags are mainly absent. Pyroclastic morphologies and vesicularities are highly variable and may indicate both magmatic and phreatomagmatic fragmentation. The lower eruptive phase is considered to be mainly scoria-dominated fall deposits with occasional small ballistics with asymmetric bedding sags consistent with the direction of vent 1 (Fig. 20). Parts of this succession contain cyclic stratified ash-lapilli tuff couplets becoming finely laminated at their tops, possibly indicating that base surges have modified some of the fall deposits. Some beds have higher abundances of accidental crystals and lithics which may be linked to increased water:magma ratios.

**Fig. 20** *Asymmetric bedding sag structures, Barriball Road tuff ring.*

There is an angular unconformity with the overlying second eruptive phase, considered to result from a change in vent position, possibly due to blocking of the vent, and based on the difference in attitude of beds dipping normal to the position of the vent. Angular unconformities are common in maars and tuff rings and are often the result of slumping of dense wet pyroclastic sediments, but in this case a change in vent position is thought to have occurred because of the asymmetry of the maar (Fig. 18) and the apparent coincidence of the second vent position (vent 2) deduced from the attitude of the beds in the tuffs coinciding with the summit of the scoria cone. The second and upper eruptive phase is characterised by generally moderately to well sorted coarse ash to fine lapilli, with low angle cross-laminated to planar laminated bedding. Asymmetric bedding sags suggest an origin from vent 2. Occasional discontinuous layers contain dense basalt blocks and bombs, and both intact and broken gastropod and bivalve fossils. The second eruptive phase probably followed a change in vent location and increased water:magma ratios resulted in greater fragmentation and surge dominated deposits. The higher water:magma ratios resulted in beds with steeper dips, more like tuff cones, and extensive palagonitisaton. The formation of the scoria cone at vent 2 suggests a change to magmatic fragmentation, produced either by a lack of external water or an increased magma flux sufficient to prevent phreatomagmatic interactions.

The fossils in the Barriball Road tuff ring, identified as Polinices propeovatus, Glycymeris kaawaensis, and Dentalium solidum, are typical of those in the Kaawa Formation shell beds (Hollis, 1986). Local drillhole data suggest the shell beds lie about 170 m below the surface at Barriball Road (Greig, 1989). Based on this evidence and the presence of abundant accidental crystals of quartz, plagioclase, hornblende, and glauconite which are also typical of the Kaawa Formation sandstones, it is thought that the Kaawa Formation was the principal aquifer and source of external water for those tuff rings and maars in South Auckland which occur north of the Waikato Fault and west of the Drury Fault in the Manukau Lowlands downfaulted block. It also suggests that the fragmentation level for magma:water interaction was about 170 m below the surface.

We will visit a composite section showing the deposits of both the first and second eruptive phases.

**Return to Auckland**

## DAY 2 – AUCKLAND VOLCANIC FIELD

### Stop 2/1 – Pukaki maar

*Overview, and discussion on the climate and environmental record recovered from the maar lacustrine succession.*

Pukaki (Fig. 21) 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). The maar crater is at least 100 metres deep reaching about 70 m below sea level in its lake basin floor (Hayward et al., 2011b; Hayward et al., 2002). The maar crater was sheltered in most of its existence preventing major outflow and inflow allowing to develop a diatom-dominated sedimentation in the maar (Hayward et al., 2011b; Hayward et al., 2002). From tephrochronological studies it has been estimated as having a minimum age of 52 ka based on tephra recovered from the maar lake (Lindsay and Leonard, 2009; Lindsay et al., 2011) or 83.1 +/- 5.4 ka using model simulations of various tephra layers across the field (Bebbington and Cronin, 2010). Estimated minimum age of the oldest lake sediments based on sedimentation rates yields to a minimum of 65 ka (Lindsay et al., 2011). The maar basin contains 14 basaltic tephra layers derived from nearby monogenetic volcanoes of Auckland. In addition 25 more silicic tephra layers are known from the drill cores of the maar lake sourced from andesitic volcanoes of Ruapehu, Tongariro, Taranaki and the rhyolitic Taupo and Okataina caldera volcanoes (Hayward et al., 2011b; Sandiford et al., 2001).

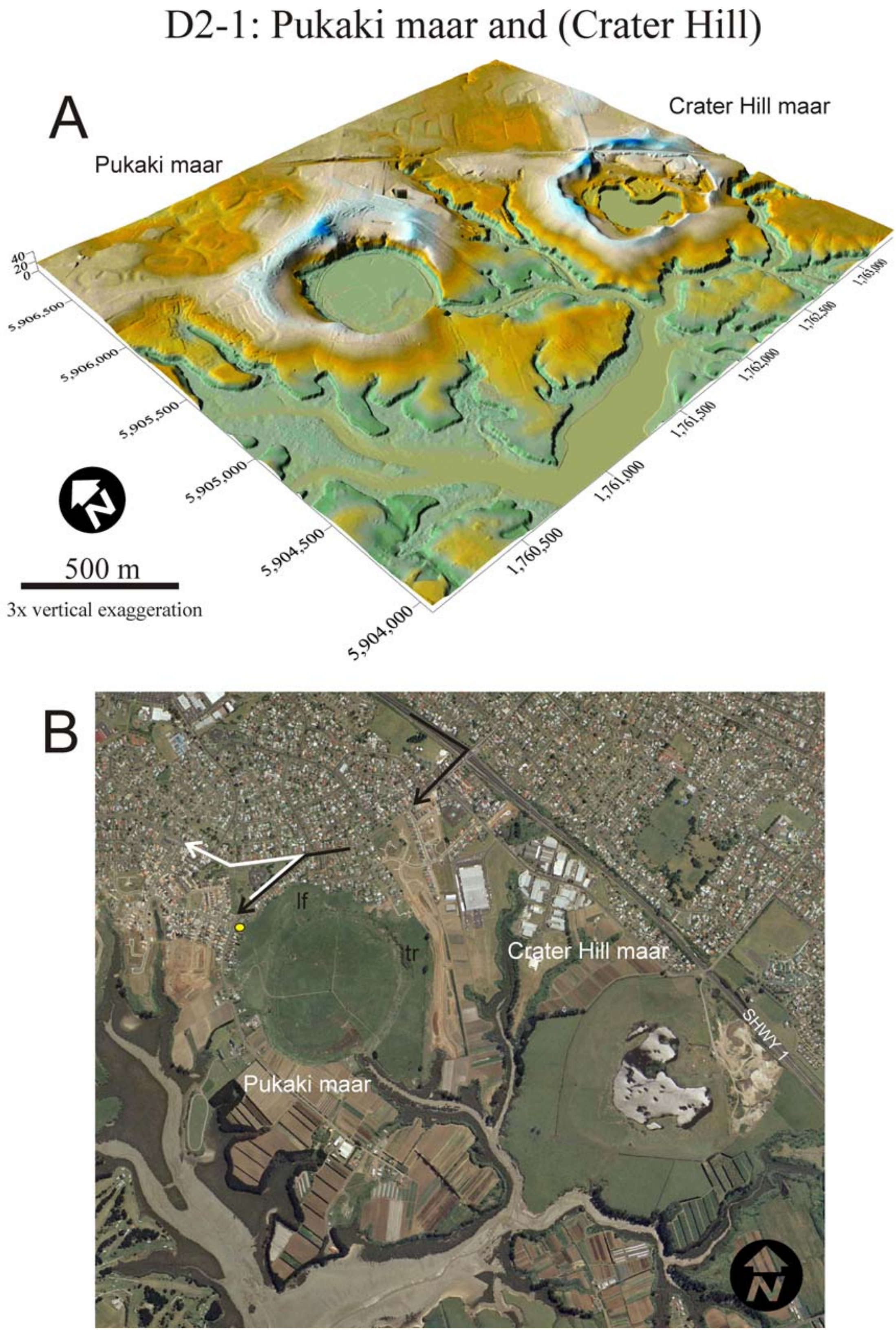


**Fig. 21** *DEM image of the Pukaki maar (A). Note the nearby Crater Hill tuff ring. The Crater Hill tuff ring's crater is filled with an intra-crater scoria cone. Puaki maar and Crater Hill tuff ring are clearly visible on GoogleEarth image (B).*

**Stop 2/2 – Maungataketake (Elletts Mountain) tuff ring**

*A complete coastal exposures of PDC dominated units forming the tuff ring. This site will offer an exceptional opportunity to discuss the volcanic hazards of PDCs. This site will also be a place to discuss the role of the mechanical properties of the substrate and its influence on crater formation.*

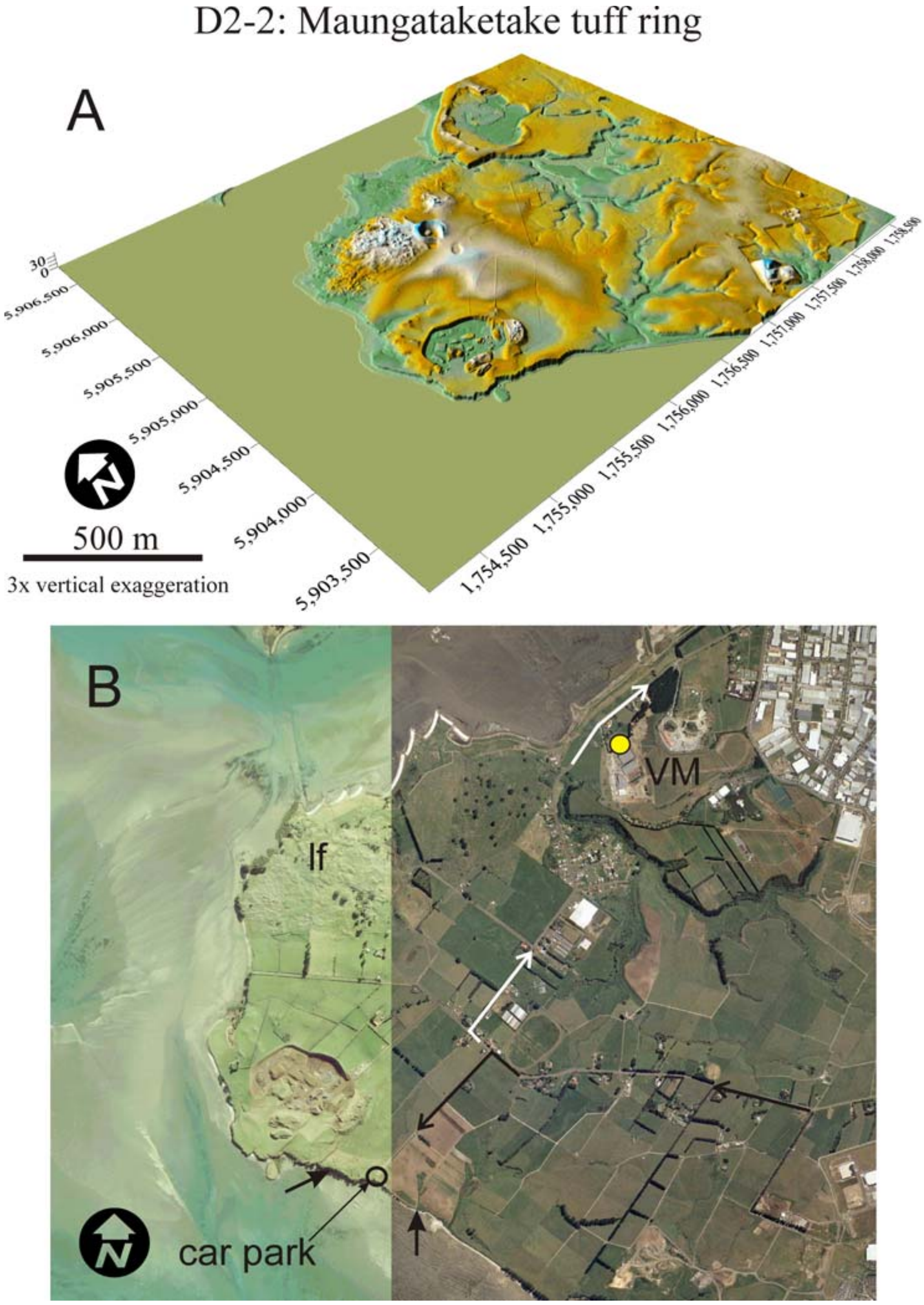


**Fig. 22** *DEM image of the area of the Maungataketake tuff ring (A). Note the nearby volcanoes just NE of Maungataketake on bioth the DEM and on the GoogleEarth image (B).*

Maungataketake is a scoria cone (Figs 22 & 23) 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). The measured ages from site form a huge range from about 33.5 ka to 177.1 ka, none of them viewed as reliable data (Lindsay et al., 2011).

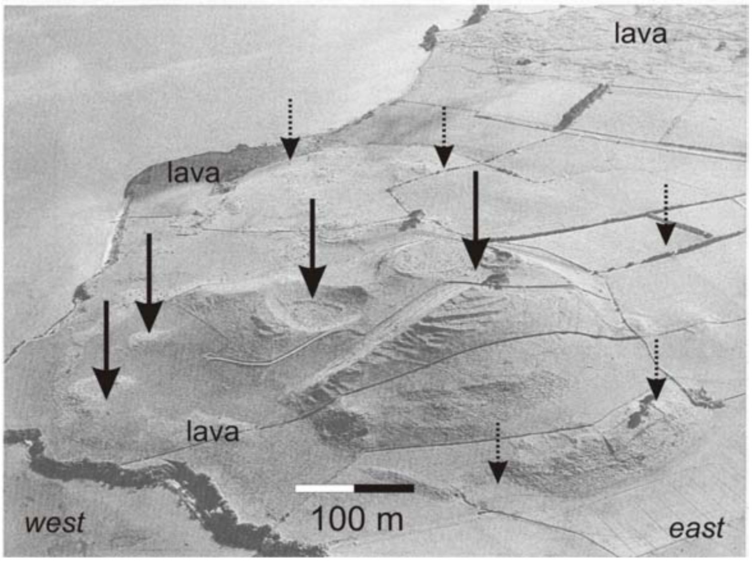


**Fig. 23** *Maungataketake in 1958 before quarrying. Note several craters of scoria and spatter cones (thick, black arrows) and tuff ring crest remnant (dotted arrows). Photo from Whites Aviation, National Archive Library, Wellington*

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 has 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

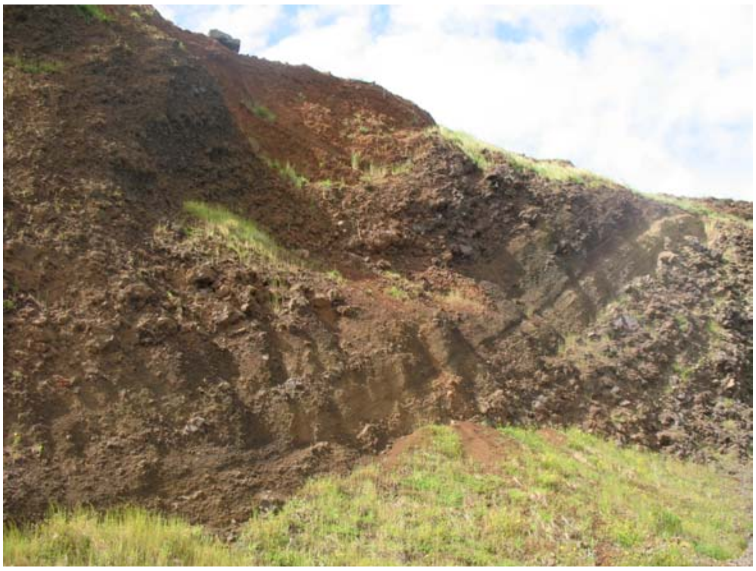

**Fig. 24** *Magmatic infill of the tuff ring crater of Maungataketake volcano.*

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.


**Fig. 25** *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.*

Maungataketake is a complex small-volume mafic volcano (Agustin-Flores et al., 2011; Agustin-Flores et al., 2012). 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 (Agustin-Flores et al., 2011). 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. 24). 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 (Agustin-Flores et al., 2011). 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 (Agustin-Flores et al., 2011) (Fig. 25). 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 (Agustin-Flores et al., 2011) (Fig. 26). A plastering effect over larger lapilli or bombs indicates a transportation direction from the centre of the Maungataketake vent (Fig. 26). Accretionary lapilli beds are thin (mm-to-cm thick) fine tuffs (Fig. 26) that are inferred to represent fall beds accompanied by successive base surges (Agustin-Flores et al., 2011).

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 (Agustin-Flores et al., 2011). 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.


**Fig. 26** 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.*

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 (Agustin-Flores et al., 2011) (Fig. 27). 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. 28) indicating that their removal might have been facilitated by shock waves accompanied with the phreatomagmatic explosive eruptions (Agustin-Flores et al., 2011).


**Fig. 27** *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.*

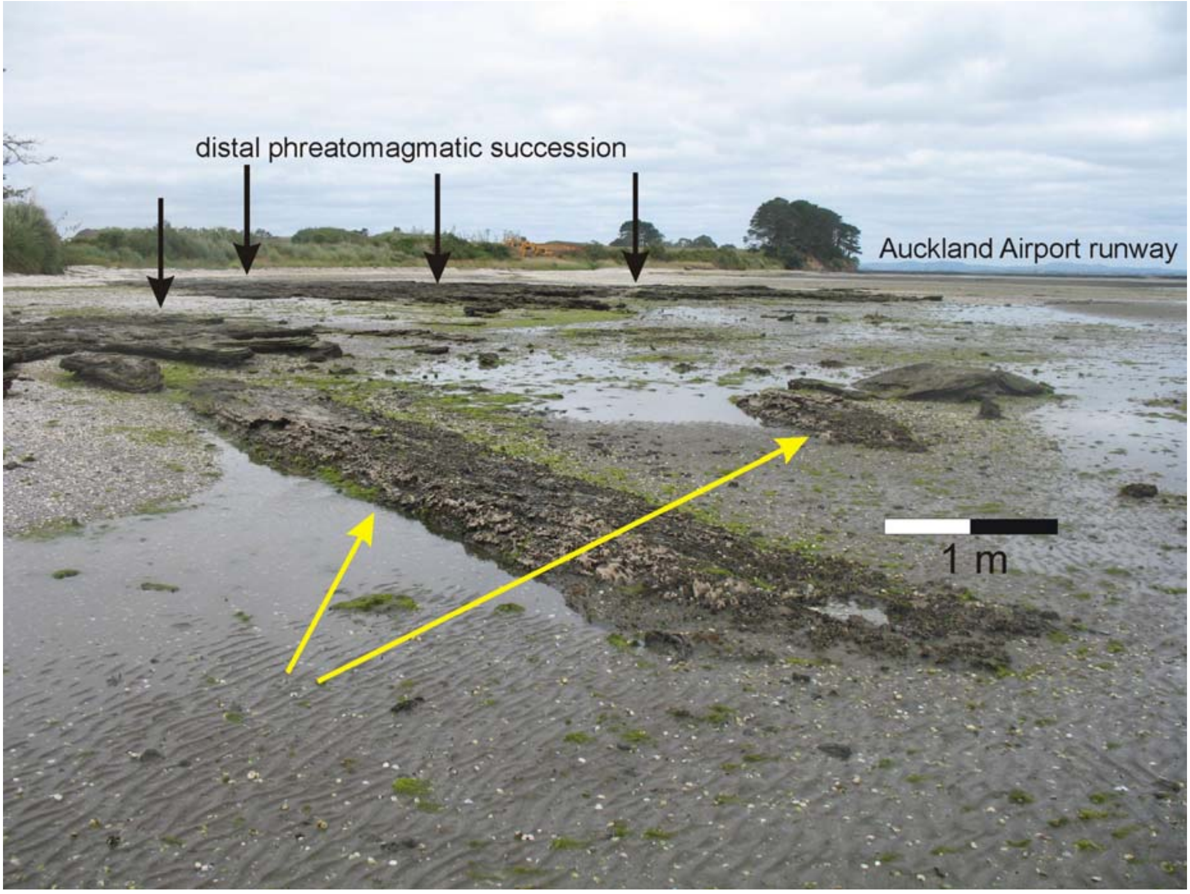


**Fig. 28** *Even in the distal units large (few metres scale) fallen logs (marked by yellow arrows) can be identified beneath the thin (dm-scale) veneer of the distal, base surge dominated phreatomagmatic succession about 1200 metres from their source.*

**Conference Dinner Site: Waitomokia tuff ring**

*This is a stop scheduled prior the Conference Dinner. The conference dinner will take place in a typical Auckland maar surrounded by a low tuff ring. The significant outcrop is on the road leading to the Villa Maria Vineyard which occupies the tuff ring crater (Fig. 29); this exposure shows the tuff ring rim perfectly.*

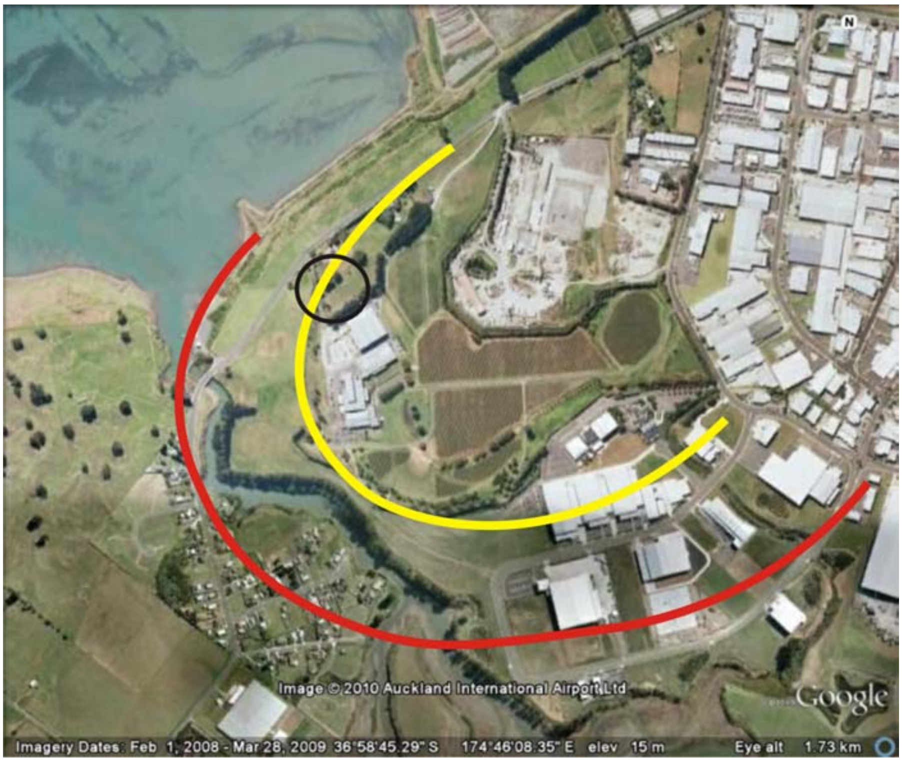


**Fig. 29** *Waitomokia tuff ring on a Google Earth image. The preserved crater floor is flat and surrounded by a crescent shaped tuff ring. The tuff ring crest is marked by a yellow line, while the lateral extent of the tuff ring is shown by a thick red line. Note the present day crater floor seems 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)*

Waitomokia tuff ring is a broad phreatomagmatic volcano with a minor, magmatic infill of lava spatter and clastogenic and normal lava flows in its NE-side that have largely been quarried away by now (Hayward et al., 2011b). These intra-crater cones commonly referred to a name of Moerangi or Mt Gabriel (Hayward et al., 2011b). It is an at least a 16 ka old tuff ring, shallow maar based on tephrochronology, however the age is considered to be moderately reliable (Lindsay et al., 2011). The tuff ring crest along a road cut in the NW-side of the tuff ring exposes an unconformity involving the proximal pyroclastic succession (Fig. 30). 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. 30A). On a steep depositional surface a younger phreatomagmatic pyroclastic succession formed a few metres thick succession 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. 31). 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. 30B). 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.

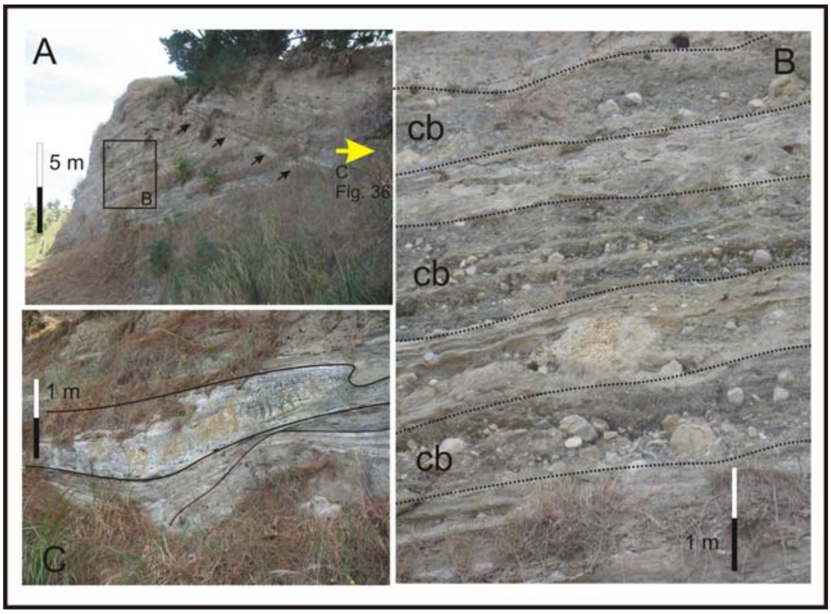


**Fig. 30** *Unconformity surface (arrows) in the tuff ring crest cross section at the Waitomokia tuff ring (A). The view is looking from the crater location. Rectangular field marks the view in "B". Yellow arrow points to the location from where the "C" view and about 20 m further away the Fig. 36 view 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. 30), 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. 31** *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 2/3: Mt Mangere (Te Pane a Mataaho) scoria cone complex**

*One of the largest scoria cones with multiple vent sites which offer a perfect vantage point to a small maar erupted next to this volcano. Lateral and vertical vent migration and the role of external versus internal controlling parameters will be the main subject to discuss at this site. A walk to the summit of the scoria cone will provide a superb view to the complex crater of this volcano.*

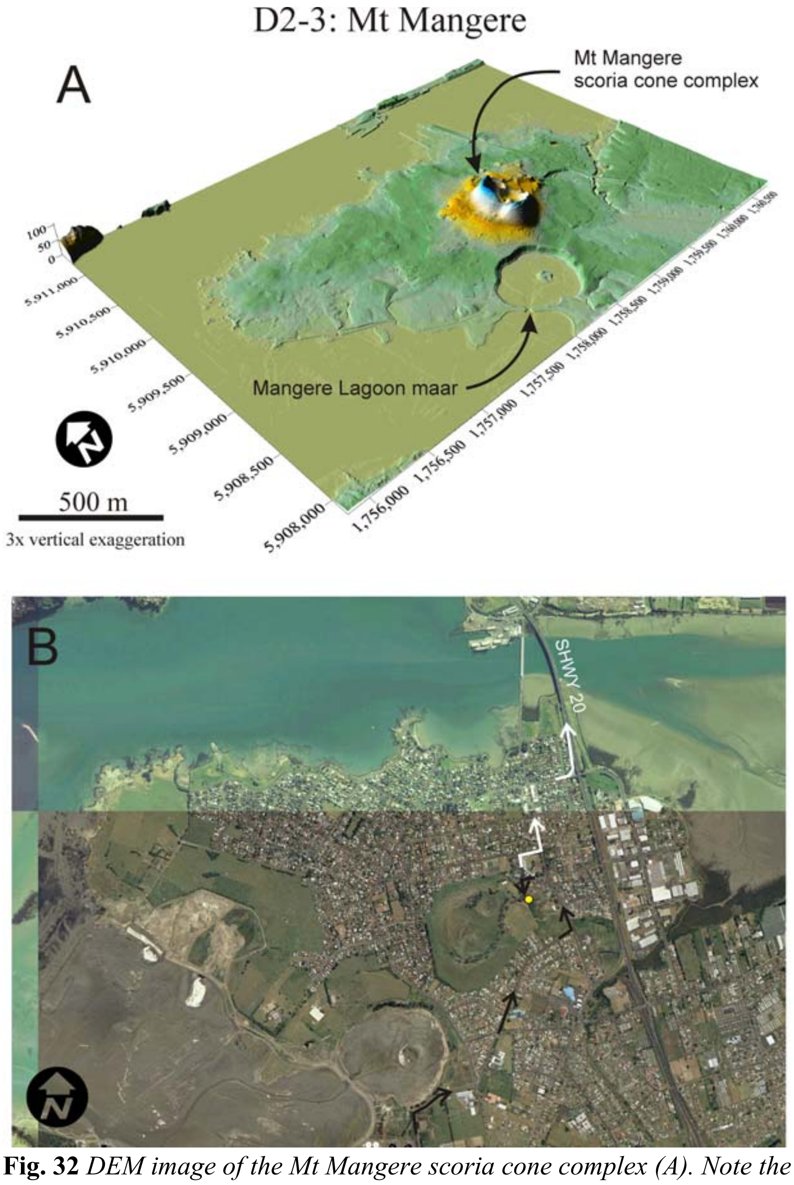


**Fig. 32** *DEM image of the Mt Mangere scoria cone complex (A). Note the nearby Mangere Lagoon shallow maar on the GoogleEarth image (B) SW of the scoria cone.*

Mt Mangere (Fig. 32) is one of the largest and best preserved scoria cones of the AVF. It forms a distinct cone of 106 m above sea level. The volcano is estimated to be in the age range of 22-35 ka on the basis of $C^{14}$ dates calculated from charcoaled vegetation beneath lava flows inferred to emitted from Mt Mangere (Lindsay et al., 2011). This age however considered to be moderately reliable only and further proofs need to have a better estimate for the eruption of this volcano (Lindsay et al., 2011). The volcano has an elongated, oval shape in map view formed by closely spaced individual vent sites. A smaller crater in the NE is adjacent to the main and broad crater. In the main crater however several vents can be distinguished with marked depressions and distribution pattern of welded agglutinated scoria and lava spatter ramparts (Fig. 33). In the middle of the main crater a basaltic plug form a morphological height that just composed of clastogenic lava flows and agglutinates. In the inner crater wall spindle bombs, lava blobs, and various gas expanded lava fragments are common beneath the grass cover. The main crater is breached away toward the east where a small lava flow removed and transported part of the crater wall about few hundreds metres from the crater rim. Lava emitted from the base of the scoria cone formed about a 5 $km^2$ lava field spread evenly in the flat syn-eruptive alluvial plain. The lava flows were low viscosity basalt flows formed pahoehoe type flow surfaces that can be observed along the coastline nearby.

**Fig. 33** *Intra-crater pyroclastic mo9unds and crater sites in teh main crater of the Mangere scoria cone*

Mt Mangere has no known phreatomagmatic pyroclastic base. Instead a small and shallow maar is located in its SW edge, called Mangere Lagoon (Fig. 34). The Mangere Lagoon, the individual vent sites of Mt Mangere and the oval shape elongated volcanic edifice of Mt Mangere form an alignment suggesting that these volcanoes erupted along a SW-NE aligned structural zone. Mangere Lagoon today is a shallow breached tuff ring with a crater rim succession of about 10 metres thick in its NW side. The tuff ring deposits quickly pinch out and can be traced maximum of about 500 metres away from the NE rim of the crater (Fig. 34). In the centre of Mangere Lagoon a small remnant of lava spatter (Fig. 34) suggests that eruption style has changed from pure phreatomagmatic to magmatic fragmentation in the final stage of the formation of Mangere Lagoon. The absolute age of the Mangere Lagoon is unknown, however it is considered to be older than Mt Mangere based on that lava flows from Mt Mangere cap the tuff ring of Mangere Lagoon (Kermode, 1992c; Lindsay et al., 2011).

**Fig. 34** *Mangere lagoon is a shallow maar with thin tephra ring.*

**Stop 2/4: Panmure maar (Wai Mokoia – Te Kopua Kai a Hiku)**

*This site will offer a 3D view of a flat, low-rimmed maar crater partially breached by the sea. The preserved crater rim deposits will offer discussions on PDC formation and associated bedforms as well as the potential to develop migrating vent sites in a broad crater of a low aspect ratio phreatomagmatic volcano.*

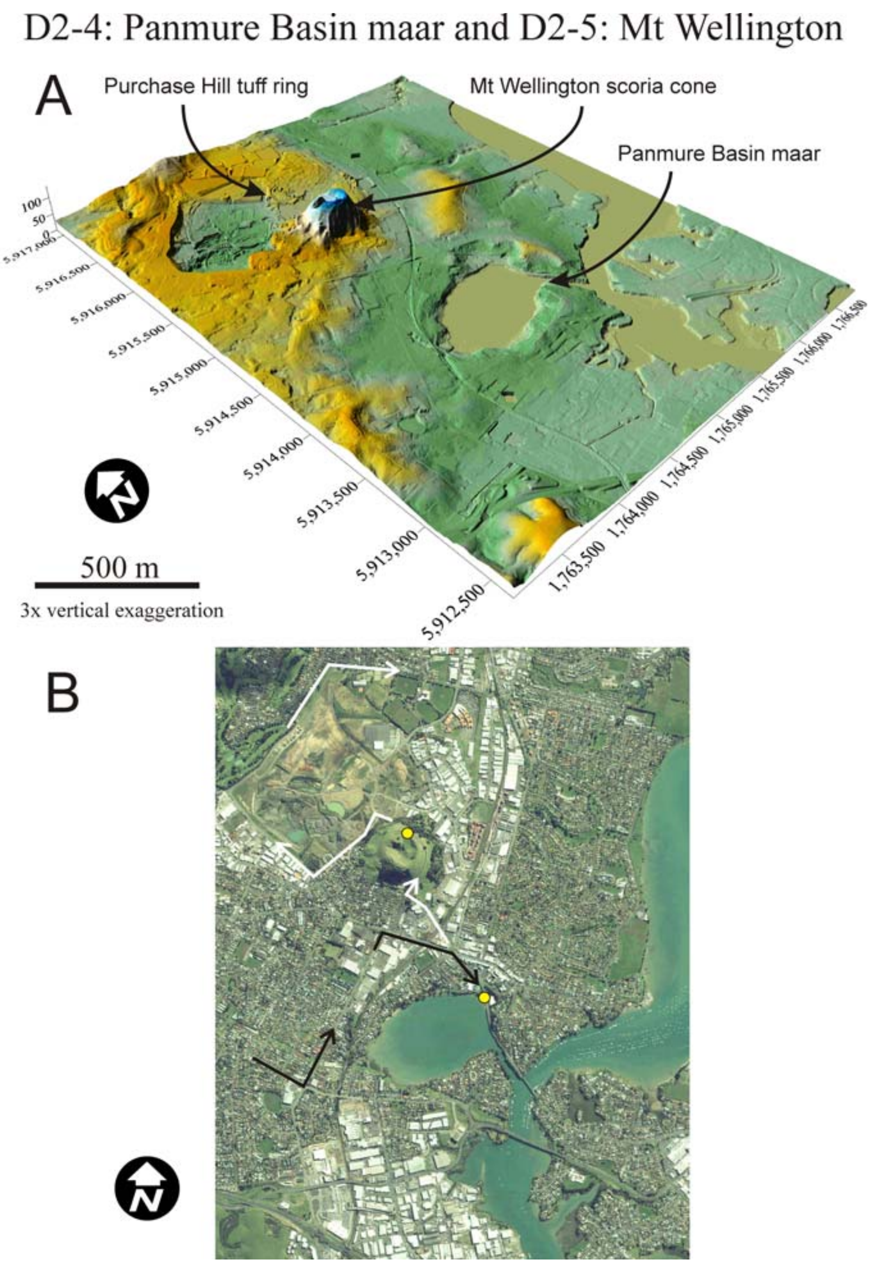


**Fig. 35** *DEM image of the Panmurei maar (A). Note the nearby position of the maar and the scoria cone of Mt Wellington on the GoogleEarth image (B).*

Panmure Basin (Fig. 35) , traditionally named as Te Kopua Kai a Hiku ("the eating place of the guardian taniwha Moko-ika-hiku-waru") (Hayward et al., 2011b) is an oval (100 x 600 m) depression connected to the sea through a narrow channel in its SW side (Fig. 23). The tephra ring surrounding the crater inferred to be breached during the las Ice Age about 8000 years ago, allowing sea access to the maar basin since then and form a marine lagoon. The depression is almost completely surrounded by a tuff ring, with its highest point ~50 m above the sea level in the SW (Fig. 36). NW of the basin the terrain is low and flat (Fig. 37). 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. 37). 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. 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). A general agreement is however that the phreatomagmatic volcano has to be at least 17 ka old (Lindsay et al., 2011). Panmure Basin is a nested and complex phreatomagmatic volcano (Cronin et al., 2009a) 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 (Cronin et al., 2009a) 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. 36** *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. 37** *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 (Cronin et al., 2009a; Hayward et al., 2011b). 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. 38). A cliff exposes a 20 m section of coarsely bedded, dune-containing and massive weakly consolidated phreatomagmatic pyroclastic deposits (Fig. 39). 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. 39). These deposits are commonly internally faulted and disrupted, reflecting near-vent syn-depositional collapse occurring throughout their emplacement.

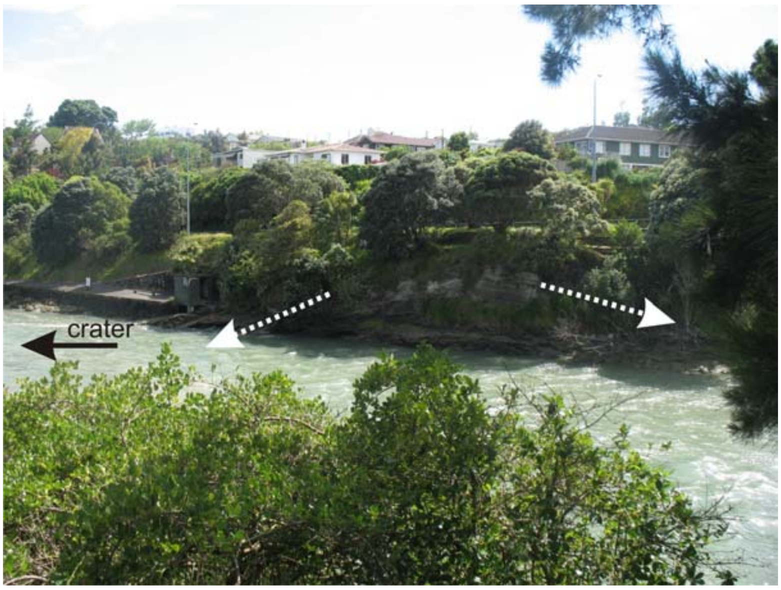


**Fig. 38** *The outflow of the Panmure Basin exposes the tuff ring crest, marked by inward and outward dipping proximal pyroclastic beds (dotted white arrows). The location of the crater is marked by a black arrow.*

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

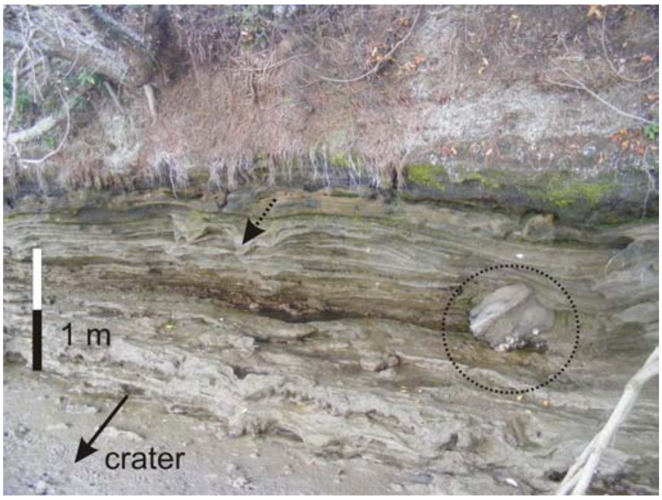


**Fig. 39** *Proximal basal phreatomagmatic pyroclastic unit in the southern margin of the Panmure Basin. Note the large accidental lithic bombs (circle) and bomb horizons causing impact sags on underlying tuff beds.*

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

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. 40). 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.

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 2/5: Mt Wellington (Maungarei) scoria cone lookout**

*Large, young scoria cone. This site will offer information on the erupted volumes calculated for the AVF. Scoria cone erosion and eruption mechanisms will be discussed.*

Mt Wellington (Fig. 41) is a large young scoria cone with lava spatter cones and multiple explosion pits in its main crater. The cone top is in 135 m above sea level. The steep sided cone suggest its young age, which has been confirmed by reliable C14 ages of charcoaled vegetation beneath lava flows emitted from the scoria cone. The age of the cone is about 10 ka old (Lindsay et al., 2011; Shane and Zawalna-Geer, 2011). The scoria cone initiated a major lava flow to the west that was partially captured by some paleo-valley leaving behind a thick (~ 25 m) accumulation of lava flows. These lava flows dammed stream valleys and created swampy areas behind them.

**Fig. 41** *Lava spatter cone in the main crater of Mt Wellington. In the background Rasngitoto Island is visible.*

North of Mt Wellington a broad tuff ring with strong anthropogenic modification can be seen (Fig. 41). This tuff ring is called Purchas Hill and its tephra ring is partially covered by eruption product of Mt Wellington (Fig. 42) (Hayward, 2006). Purchas Hill age has been confirmed by independent $C^{14}$ dates to be slightly older than Mt Wellington (Lindsay et al., 2011). The chemical composition of Mt Wellington and Purchase Hill in spite of their geographical proximity and nearly identical age is strikingly different and inferred to be sourced from two different magma batches (Smith et al., 2009). All together Mt Wellington and Purchas Hill closely resembling a complex dispersed vent volcanic system that produced nested phreatomagmatic and magmatic vents tapped different deep sources similar to those inferred for the largest and youngest volcano of the field, the Rangitoto (McGee et al., 2011; Needham et al., 2011). Such chemical behaviour associated with other eruption centres have also been noticed recently (Spargo et al., 2007).

**Fig. 42** *Lava flow over tuff ring unit inferred to be part of the Purchase hill phreatomagmatic volcano (above). The tuff ring deposits are unsorted, accidental lithic fragment rich typical proximal lapilli tuffs of maar volcanoes (below).*

**Stop 2/6: St Heliers tuff ring lookout (Te Pane O Horoiwi) and Brown's Island (Motukorea) nested tuff ring**

*Look out to the Motokorea tuff ring and Rangitoto. Discussion on landscape evolution with respect to sea level changes is planned.*

St Heliers (Fig. 43) has an estimated minimum age of 45 ka based on tephrochronology (Lindsay and Leonard, 2009; Lindsay et al., 2011). 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 ranges. 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 indicates 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

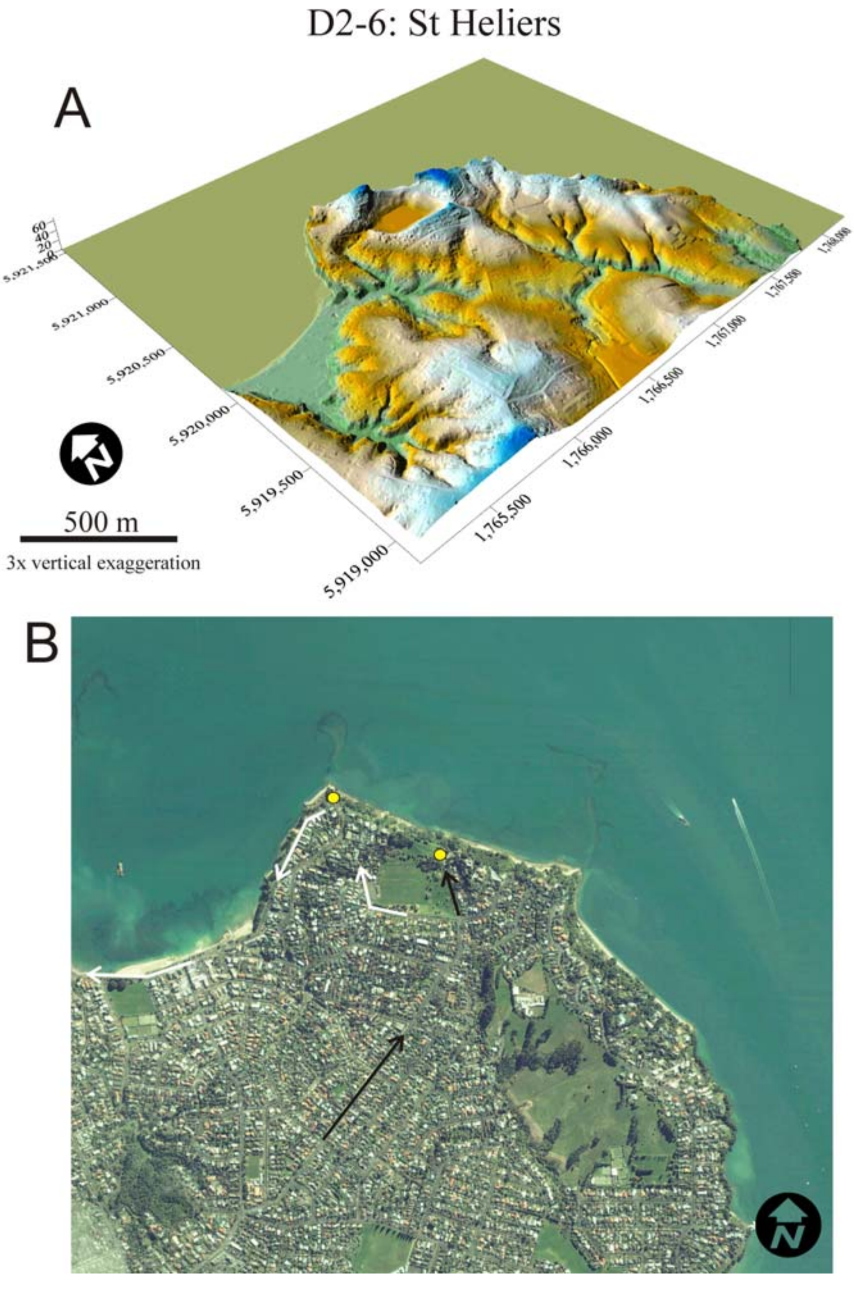


**Fig. 43** *St Heliers tuff ring on DEM (A) and GoogleEarth satellite image (B).*

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.

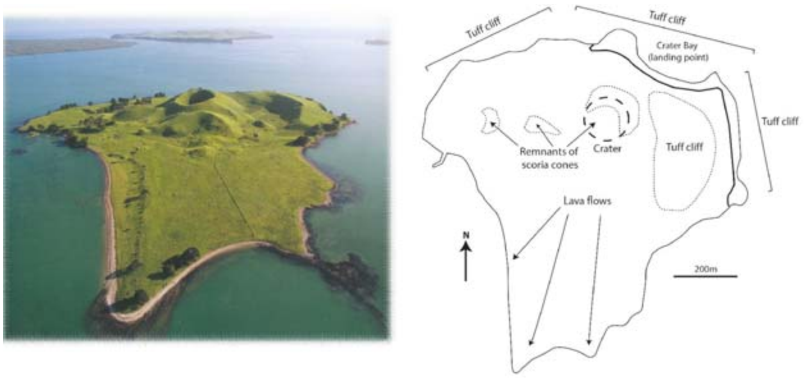


**Fig. 44** *Aerial photo (left) and sketch map (right) of Motukorea (Brown's Island). Sketch shows extent, orientation and direction of the tuff ring, scoria cones, crater and lava flows associated with Motukorea. Photo credit: Lloyd Homer*

From St Heliers a perfect view shows Browns Island or Motukorea (Fig. 44) 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.

The base of the pyroclastic succession is composed of an 8 m-thick tuff and lapilli tuff unit (Fig. 45). 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. 46). 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. 47). 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. 48). 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.

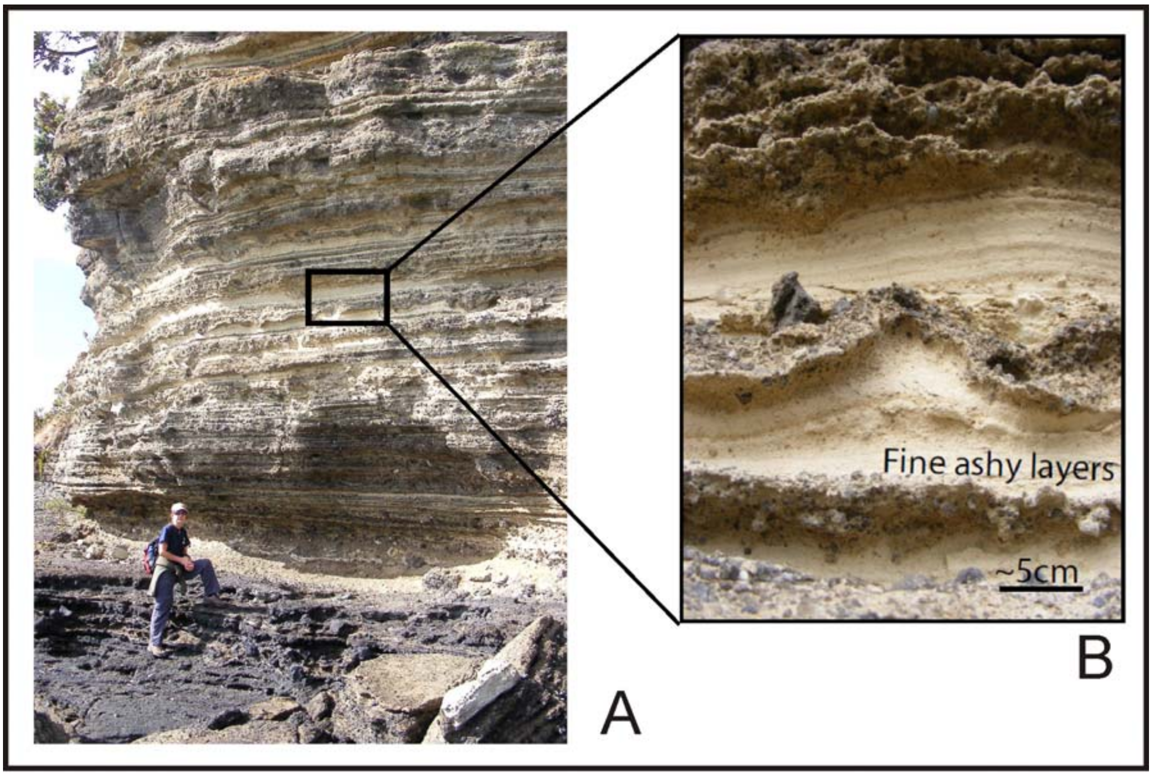


**Fig. 45** The *basal pyroclastic succession of Motukorea tuff ring is a bedded, dune-bedded accidental lithic-rich lapilli tuff and tuff unit (A) that is interbedded with bomb horizons (B) representing changing vent/conduit geometry and/or magma pulse that are clearing the instable volcanic conduit.*

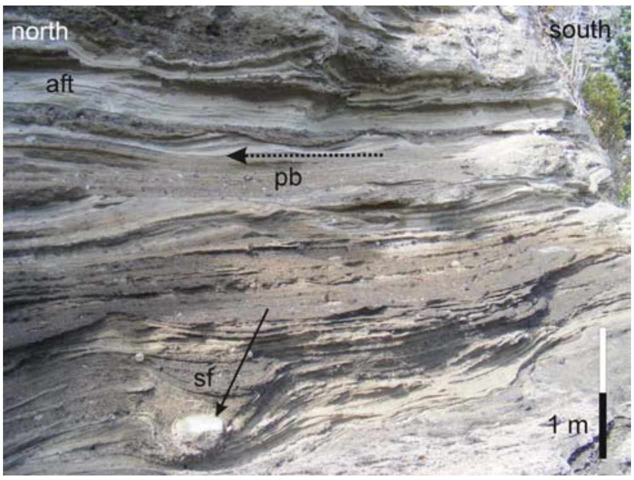


**Fig. 46** *Basal pyroclastic succession of Motukorea tuff ring with ballistic bombs and impact sags (arrow), scour filling (sf), parallel bedded tuff (pt) and accidental lithic rich fine tuff all characteristic for a typical subaerial tuff ring forming eruption. Dotted arrow represents base surge current movement inferred from dune geometry.*

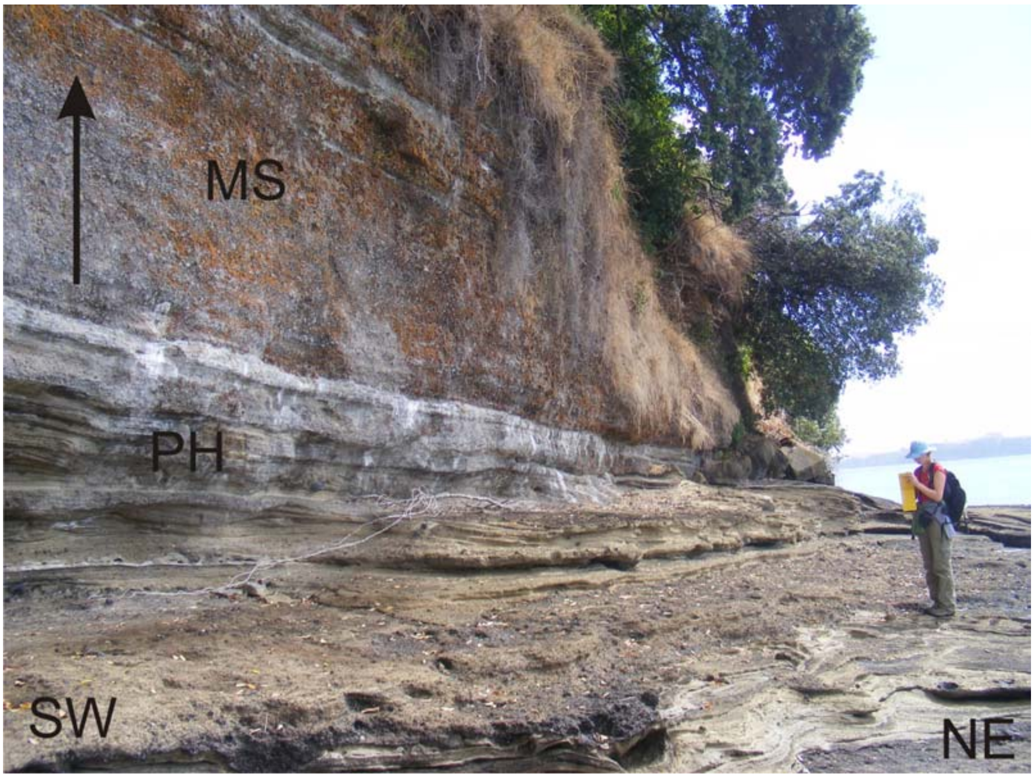


**Fig. 47** The *distal basal phreatomagmatic (PH) pyroclastic unit is overlain by a thick, scoriaceous, bedded Strombolian-style fall unit (MS) indicating abrupt eruption style change in the final stage of the eruption of Motukorea tuff ring.*


**Fig. 48** *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.*

## DAY 3 – AUCKLAND VOLCANIC FIELD

### Stop 3/1: Orakei maar

*Walk in the inner part of a low aspect ratio maar volcano, breached toward the sea. Its pyroclastic succession can offer discussions on vent opening, vent clearing and conduit dynamic processes which may influence the overall architecture of the accumulating pyroclastic successions around the vents.*

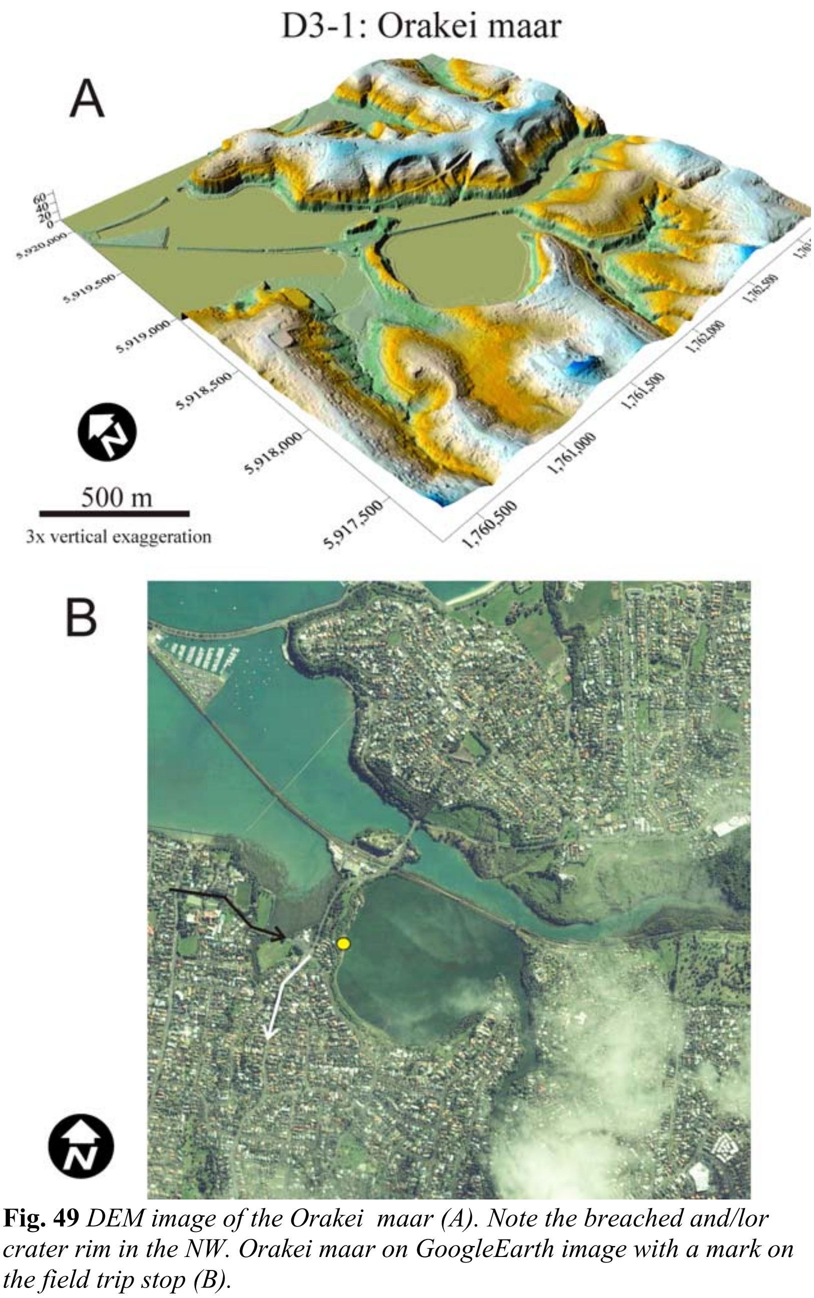


**Fig. 49** *DEM image of the Orakei maar (A). Note the breached and/lor crater rim in the NW. Orakei maar on GoogleEarth image with a mark on the field trip stop (B).*

Orakei Basin (Fig. 49) 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. 50). 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. 50** *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).*

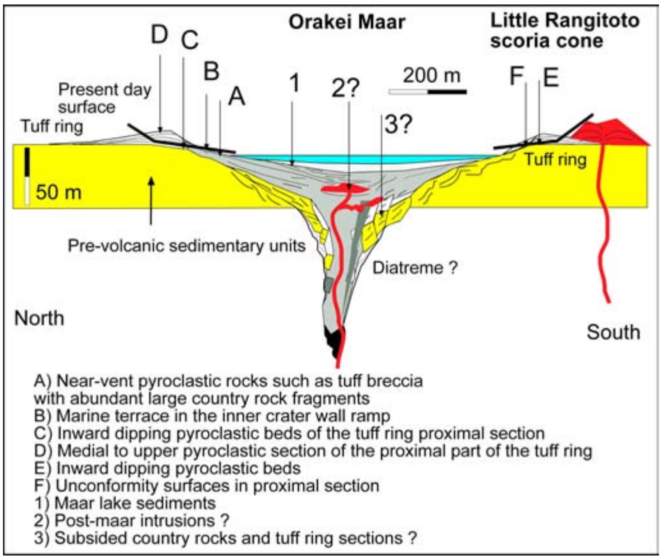


**Fig. 51** *Theoretical cross section through the Orakei maar (not to scale) Letters correspond to points of interest shown on Fig.50 .*

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. 51).

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. 51). 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.

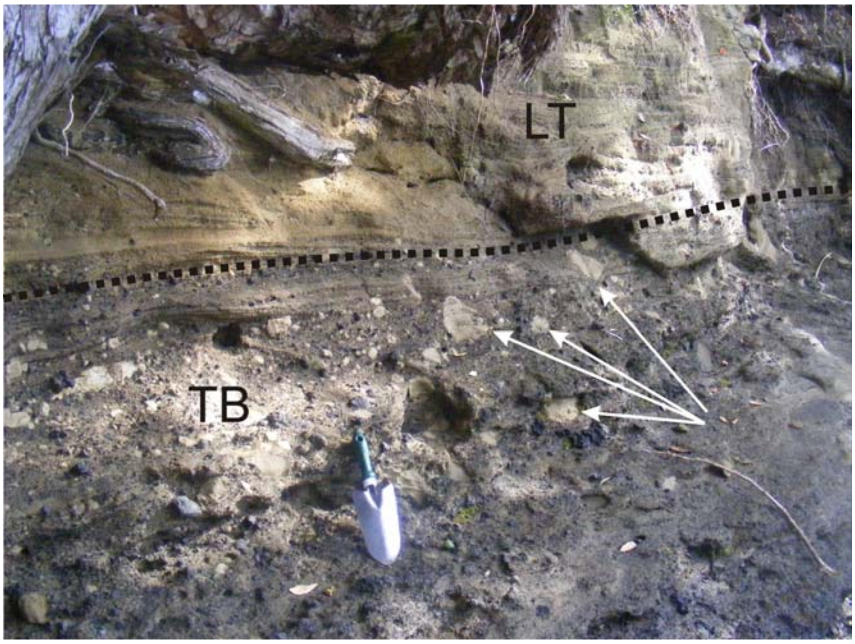


**Fig. 52** *Basal pyroclastic breccia (TB) unit in location A (Fig. 5) is interpreted to be a pyroclastic succession representing the initial vent opening phase. Abundant country rock fragments (arrows) and lapilli size juvenile pyroclasts with common impact sags indicates energetic explosive eruptions 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 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. 52). 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 50. 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. 53) 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

**Fig. 53** *Cauliflower bomb in the basal tuff breccia unit of Orakei maar.*

impure, i.e, comprising muddy slurry.

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. 54) that is inferred to reflect repeated transitions between development of a stable vent site, and periodic inward collapse and vent choking.

**Fig. 54** *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.*

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. 55). 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 56, 57 and 58) and/or rimmed by a film of mud producing cored ash and lapilli textures (Fig. 59). 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. 55** *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.*

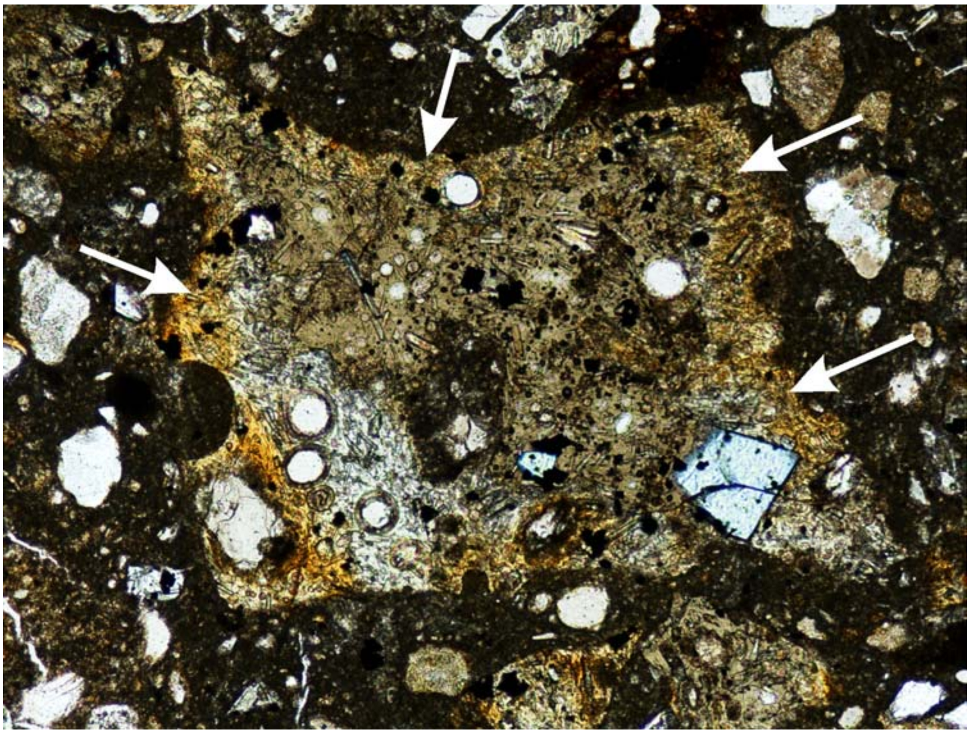

**Fig. 56** *Photomicrograph of a coarse ash particle from a coarser grained, juvenile particle-rich lapilli tuff bed from the upper section of the tuff ring succession at locality D. Note the advanced palagonitization (white arrows) of the sideromelane glass shard and its moderate vesicularity, but high microlite content. The long side of the view is about 1.2 mm.*

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.

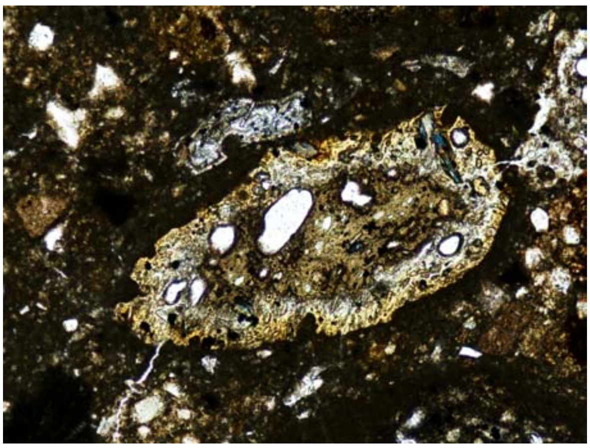

**Fig. 57** *Photomicrograph of a strongly palagonitized ash particle from the same locality as the sample from Fig. 11. The long side of the view is about 1.2 mm.*

In contrast, even in the stratigraphically high section of the tuff ring, accidental lihtic rich commonly fine grained tuff beds are common (Fig. 60). These beds exhibit over 90 vol % accidental lithic particle content (Fig. 61).

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.

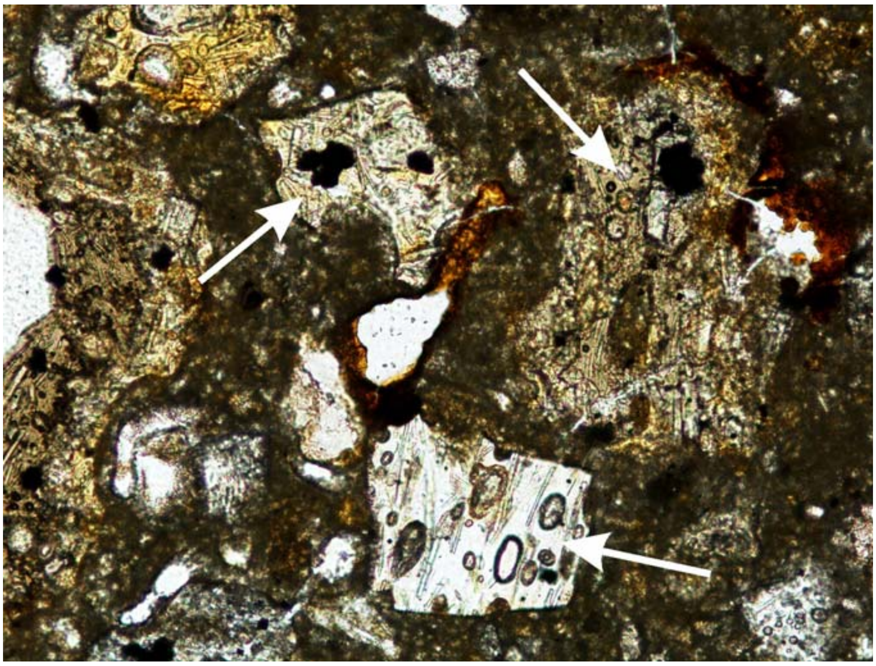

**Fig. 58** *Photomicrograph of a fine grained tuff bed showing great variety of shapes of interactive juvenile sideromelane glass shards (white arrows) in a muddy matrix. The long side of the view is about 500 micron.*

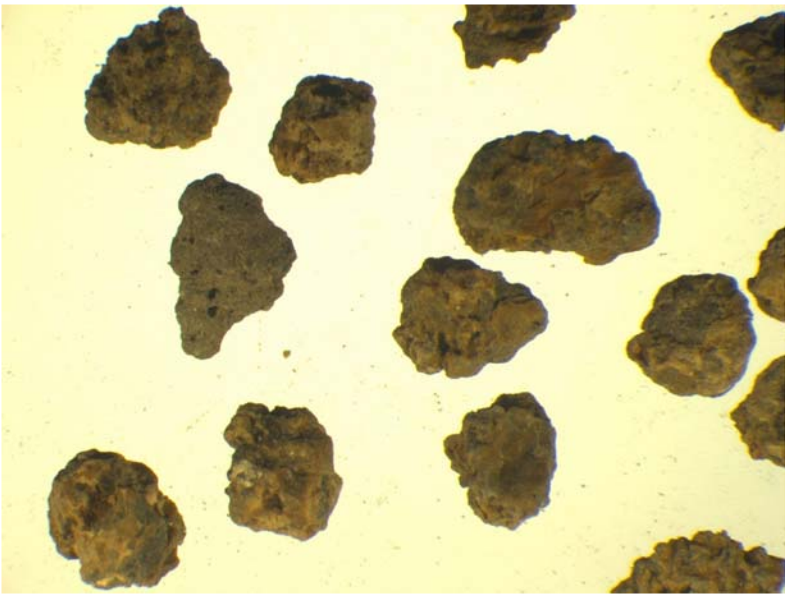

**Fig. 59** *Light microscopy image of juvenile coarse ash particles with palagonite and mud-coated rims. The long side of the view is about 9 mm.*

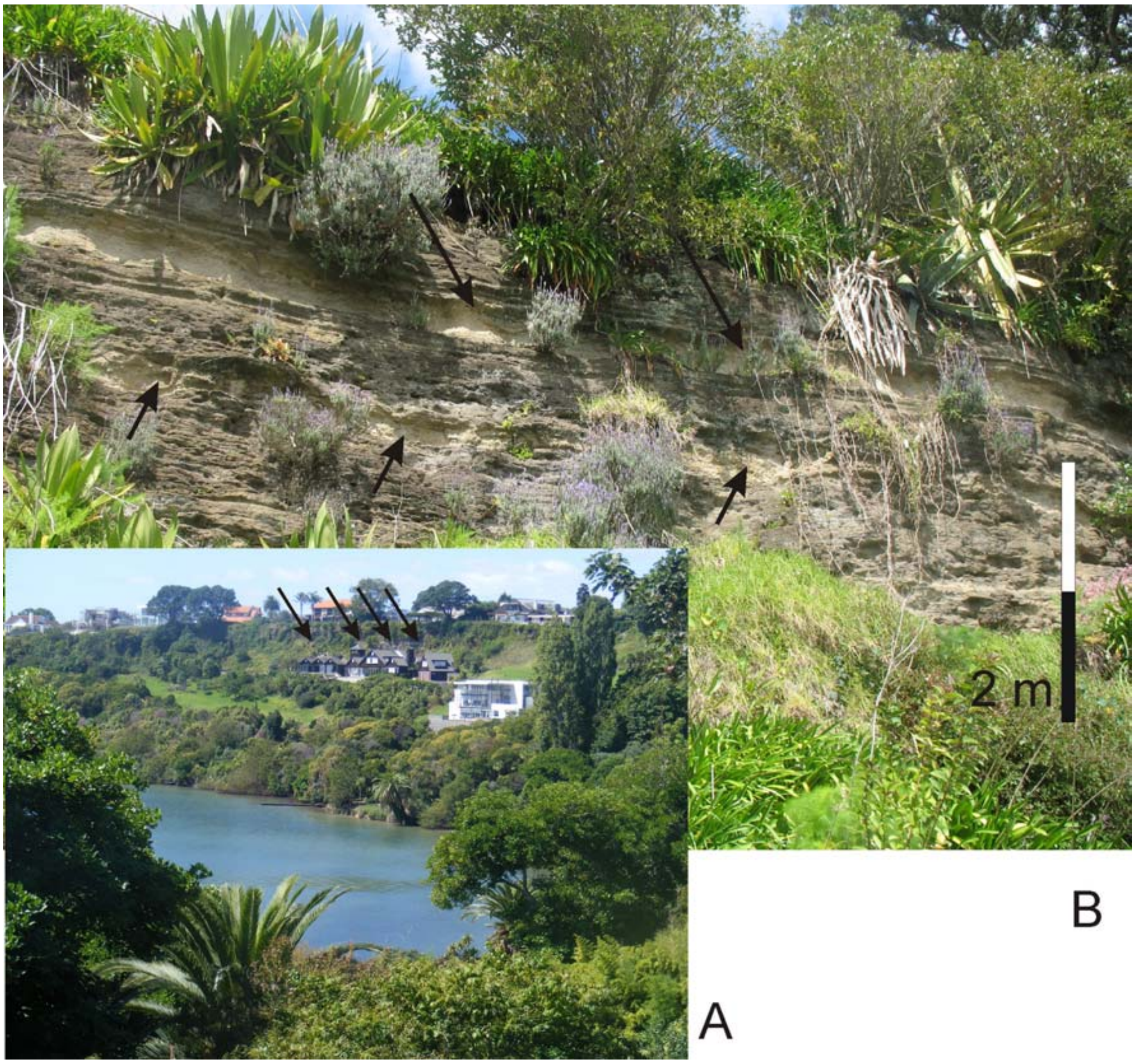


**Fig. 60** *Accidental lithic fragment rich marker bed (arrows) in the upper section of the tuff ring sequence in the eastern sector of the volcanic edifice (A). Note the white colour of two beds (arrows on B) and its laterally persistent nature.*

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.

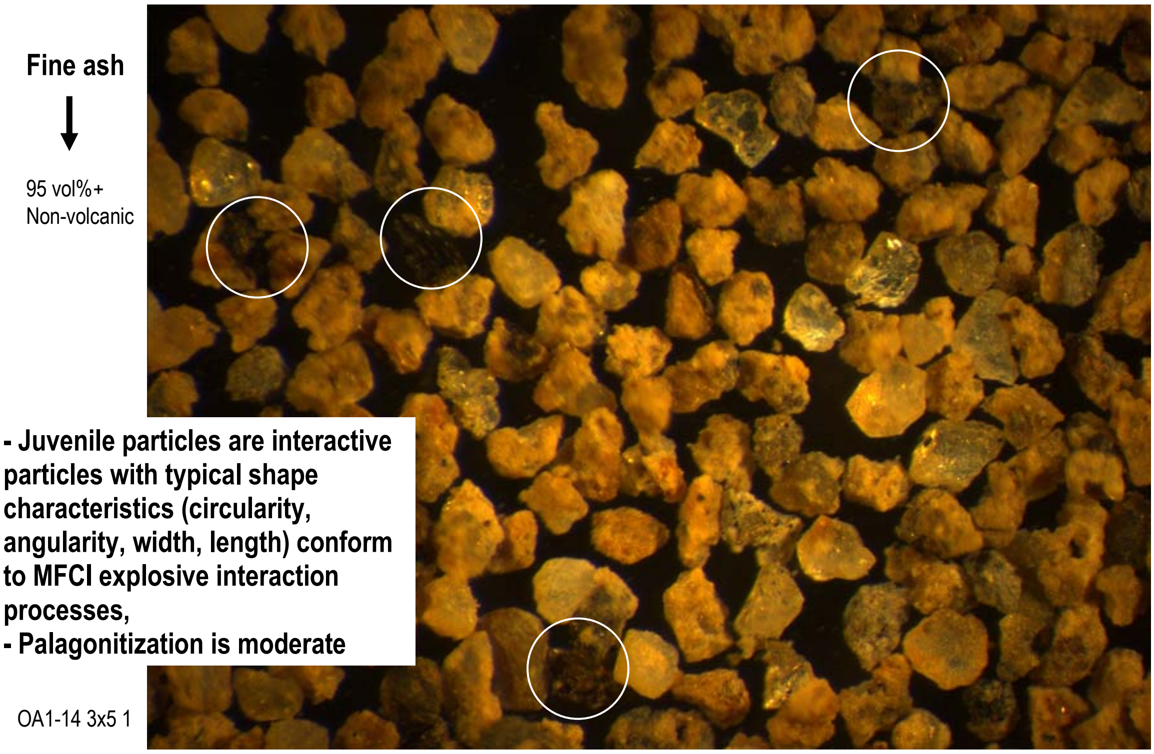


**Fig. 61** *Light microscopy image of fine tuff bed from the upper section of the tuff ring sequence. The tuff is composed of over 95 vol % of accidental lithic fragments (siliciclastic fragments from country rock units). Juvenile particles are sideromelane (circle). The long side of the view is about 3 mm.*

During eruption, lateral excavation of the country rock and vent migration is shown by at least one unconformity during the eruption sequence (Fig. 62). 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. 62). 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$^2$.

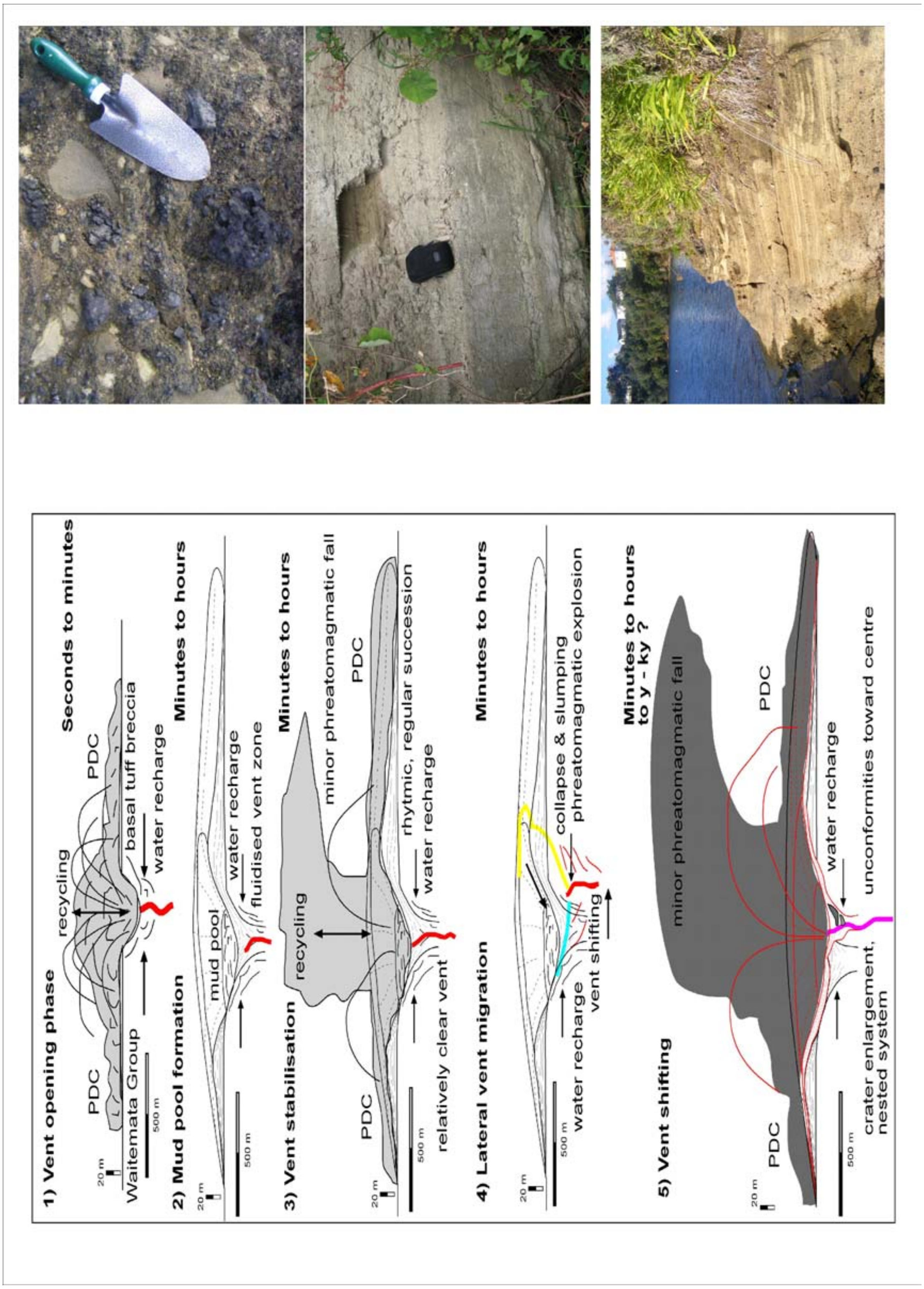


**Fig. 62** *Evolutionary model for the Orakei maar eruption. Field photos next to the evolutionary steps represent typical eruptive products and associated features*

**Stop 3/2: Mt Eden (Maungawhau) scoria cone lookout**

*Look out to the entire AVF. Discussion on scoria cone erosion, preservation and the late stage magmatic infills of phreatomagmatic volcanoes will be offered. Lava flow volume calculations and landscape evolution models will be discussed.*

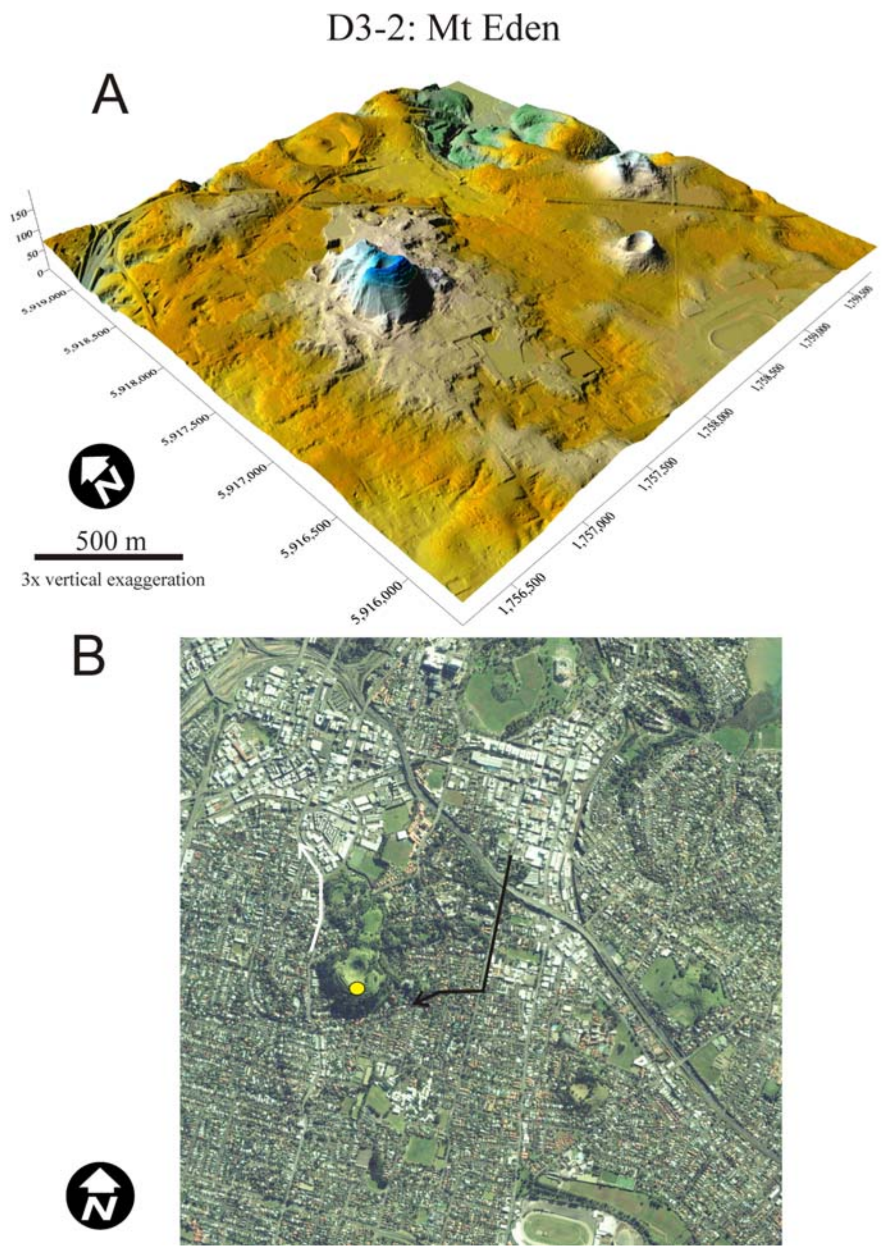


**Fig. 67** *DEM image of the Mt Eden scoria cone and its surroundings (A). andf the same region on GoogleEarth image (B).*

Mt Eden (Figs 67 & 68) 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. It is thought to be ~28 ka based on $C^{14}$ dating (Lindsay and Leonard, 2009; Lindsay et al., 2011). 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.


**Fig. 68** *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 3/3: Pupuke (Pupuke Moana) maar

*The oldest and largest fresh water lake-filled maar will offer good discussion points such as landscape evolution, pyroclast preservation potential and the number of vents, longevity and erupted magmatic volumes such phreatomagmatic volcanoes provide. In addition we will visit Pupuke lava flows on the coast that buried an ancient forest.*

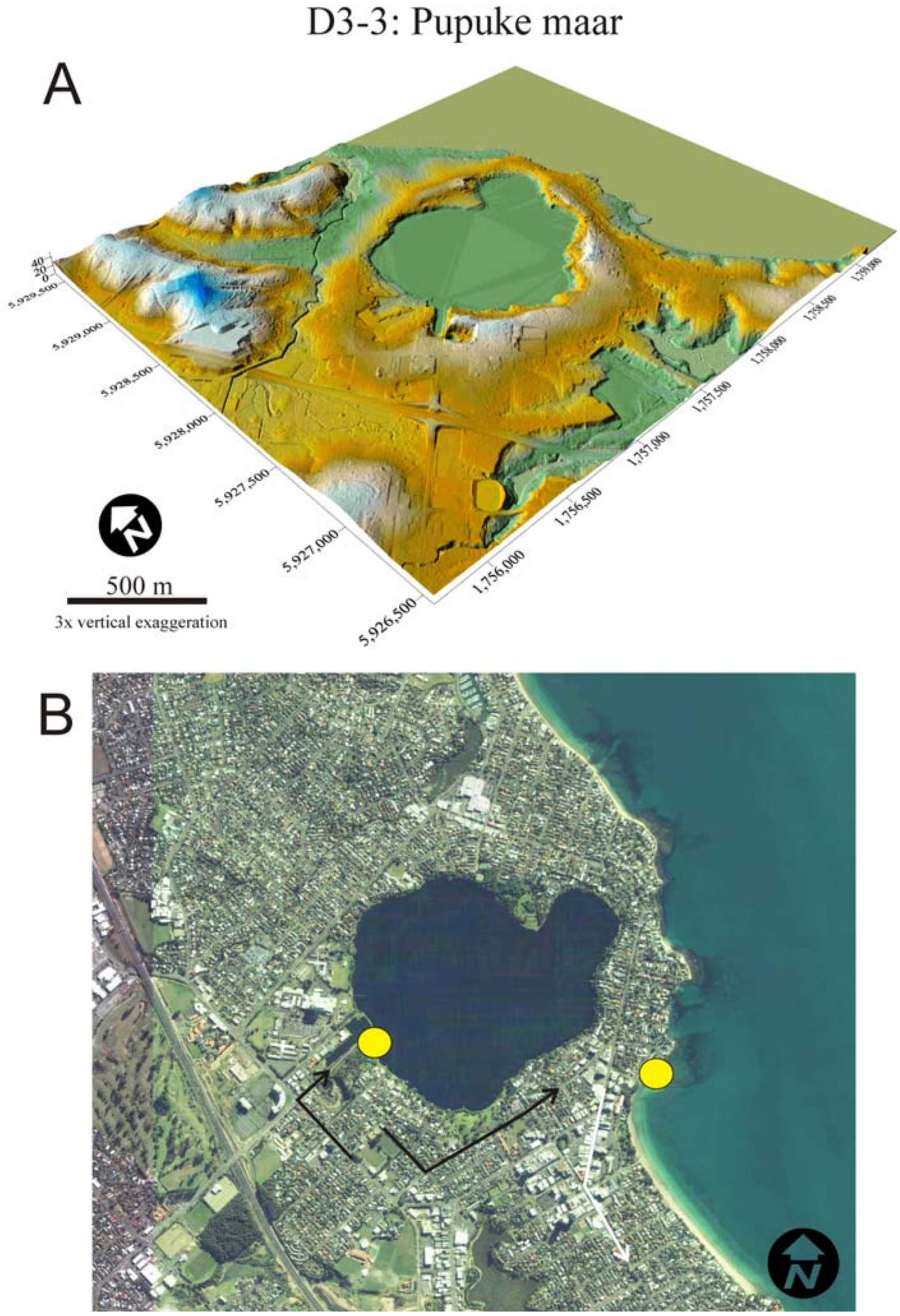


**Fig. 69** *Pupuke maar on DEM model (A) and on Google Earth image*. (B) . Dots mark field stops on the GoogleEarth image (B).

**Fig. 70** *An older phreatomagmatic eroded tuff ring rim surface overloain by a younger phreatomagmatic pyroclastic uni in the SW edge of the Pupuke maar rim.*

**Fig. 71** *Juvenile ash and lapilli-rich beds oiverlain a fine tuff bed in the Smales Quarry near the crater rim of Pupuke maar.*

Pupuke maar (Fig. 69) is a large water filled basin surrounded by a gentle sloping tuff ring in each direction. The maar is estimated to be in the age range of 200 to 260 ka old based on a range of K-Ar and Ar-Ar dates from juvenile pyroclasts and lava flows associated with the volcano (Lindsay et al., 2011). The volcano represents one of the oldest eruption centres in the field and generally considered to be the first volcano marked the start of the evolution of the AVF. Its age is in the same range as the nearby Onepoto and Tank Farm maars just about few kilometres to the SE from Pupuke (Lindsay et al., 2011). The basal volcanic section of the Pupuke volcano consist of an early lava shield that fed broad lava flows that are best exposed currently in the sea cliffs in the eastern side of the maar beneath its tuff ring. The initial lava shields were likely produced from multiple sources as chemical data suggested their distinct chemistry suggesting different sources. This lava shields are inferred to be related with local small scoria cones that were likely to be eroded today and/or destroyed by the subsequent maar-forming eruptions (Fig. 70). The source of the these lava flows are largely unknown however a recent quarry (Smales Quarry) in the SW side of the maar exposes a dark basalt plug indicating that the quarry itself likely to excavated an initial magmatic vent emitted lava flows that ponded behind scoria and lava ramparts that were rafted and breached to emit lava flows toward the NE (Fig. 71).

**Fig. 72** Accretionary lapilli-bearing tuff in the SW tuff ring of Pupuke maar.

Typical fine grained accidental lithic fragment-rich lapilli tuff and tuff units (Fig. 72) capping the basal lava flows and associated scoria cone remnants (e.g. near Smales Quarry). These pyroclastic successions are rich in accretionary lapilli, vesicular tuff layers, angular glassy pyroclasts and fine grained siliciclastic sediments from underlying rock formations. The bedding characteristics of these successions suggest that the present day exposures are the remnant of a medial to distal facies of a typical maar tuff ring suggesting a significant post-eruptive erosional enlargement of the maar forming the present day lake. This indirectly also supports the old age of the maar.

In the time the Pupuke maar formed the climate was colder than today, and sea level was lower. A broad coastal plain with drainage network hosted coastal vegetation that was partially destroyed by the erupted lava flows as evidenced as numerous tree moulds in the sea cliffs.

## Stop 3/4: North Head tuff cone

*North Head is typical open vent volcano with strong phreatomagmatic influence recorded in the preserved basal pyroclastic units that gradually changed to be normal scoria cone and lava spatter dominated capping units. This volcano will provide a significant base for discussion on the role of external versus internal controlling parameters influencing the resulting volcanic landforms.*

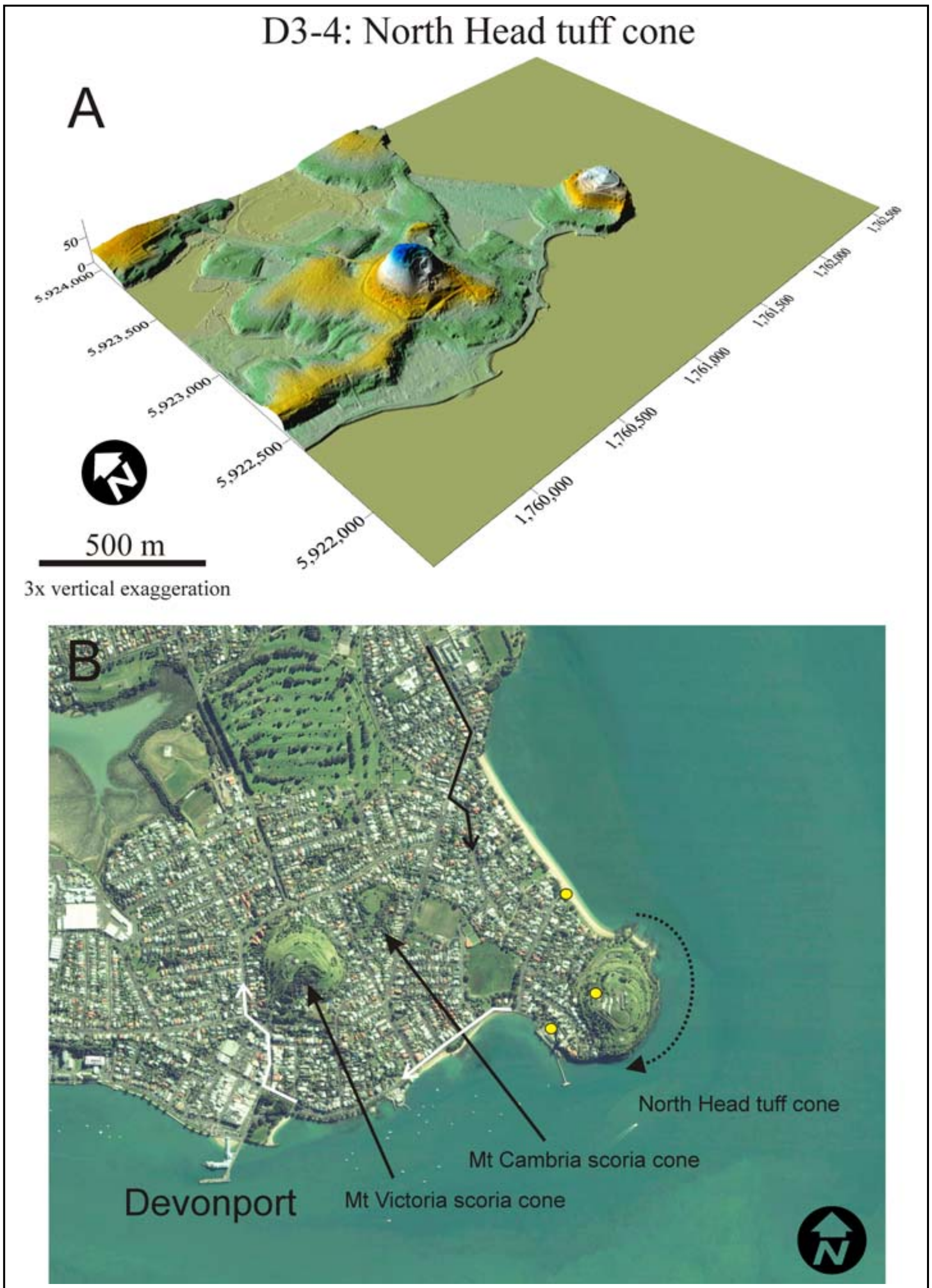


**Fig. 73** *Northhead tuff cone on DEM (A) and GoogleEarth images (B).*

North Head volcano (Fig. 73) 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. 74) 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. 75). 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. 76). In the medial section large fluidal shaped juvenile lapilli as well as various siliciclastic country rocks are more prominent (Fig. 77). 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. 74** *View of the North Head tuff cone landform from the south.*

**Fig. 75** *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. 76** *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. 77** *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 and South Auckland's monogenetic volcanoes. The majority of the SAVF and 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.

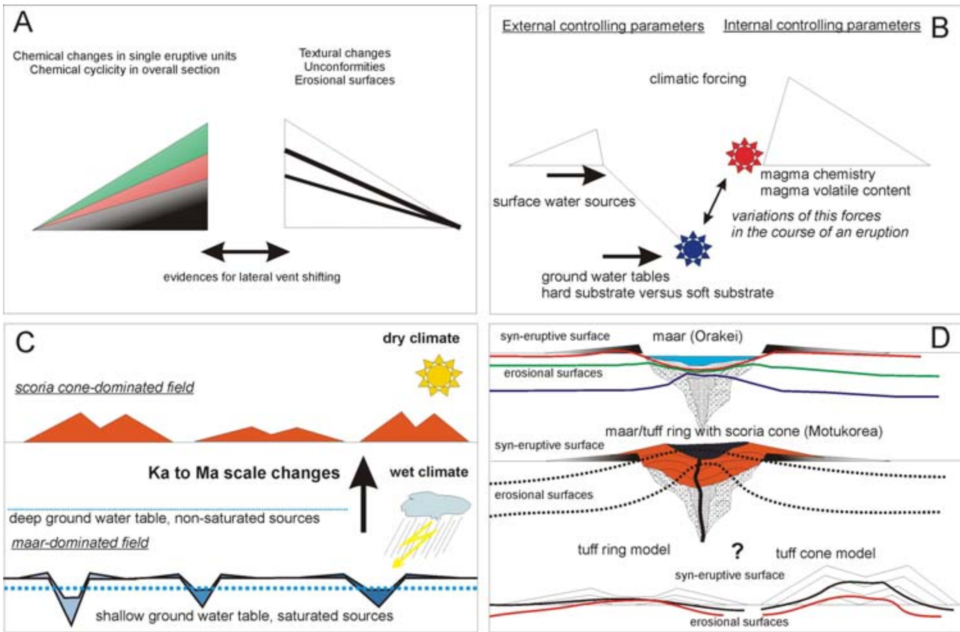


**Fig. 78** *Basic research questions to understand monogenetic volcanic fields (Németh, 2012) A) Monogenetic versus complex monogenetic volcanism, B) Role of internal versus external controlling parameters, C) Long term environmental changes recorded in volcanic field history, D) landscape evolution 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.*

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 South Acukland's and 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).

## 5. Conclusion

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

The SAVF and AVF are 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.

## 6. Acknowledgements

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