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Fieldtrip Guides

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FIELDTRIP 2

EARTHQUAKES AND ERUPTIONS AT OKATAINA VOLCANIC CENTRE

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OVERVIEW

This field trip will focus on new research findings that show different levels of volcano-tectonic interactions around Okataina Volcanic Centre (Fig.1). Recent paleoseismic studies have found evidence for close time associations between individual eruptions and surface fault ruptures during the last ~15,000 years (Berryman et al., 2004, 2006; Nairn et al., 2005; Villamor et al., 2007; Berryman et al., submitted; Canora et al., in prep; unpublished data). On a larger scale, new geological and geophysical information has improved understanding of the geometrical relationships between major volcanic features such as caldera structures and tectonic features such as rift grabens (Acocella et al., 2003; Spinks et al., 2005; Seebeck et al., 2007). We will also briefly discuss new active fault data for the Rangitaiki Plains, based on LIDAR information (Begg and Mouslopoulou, 2007), as well as new results for the 2006-2007 Matata Earthquake Swarm (Bannister et al., 2007).

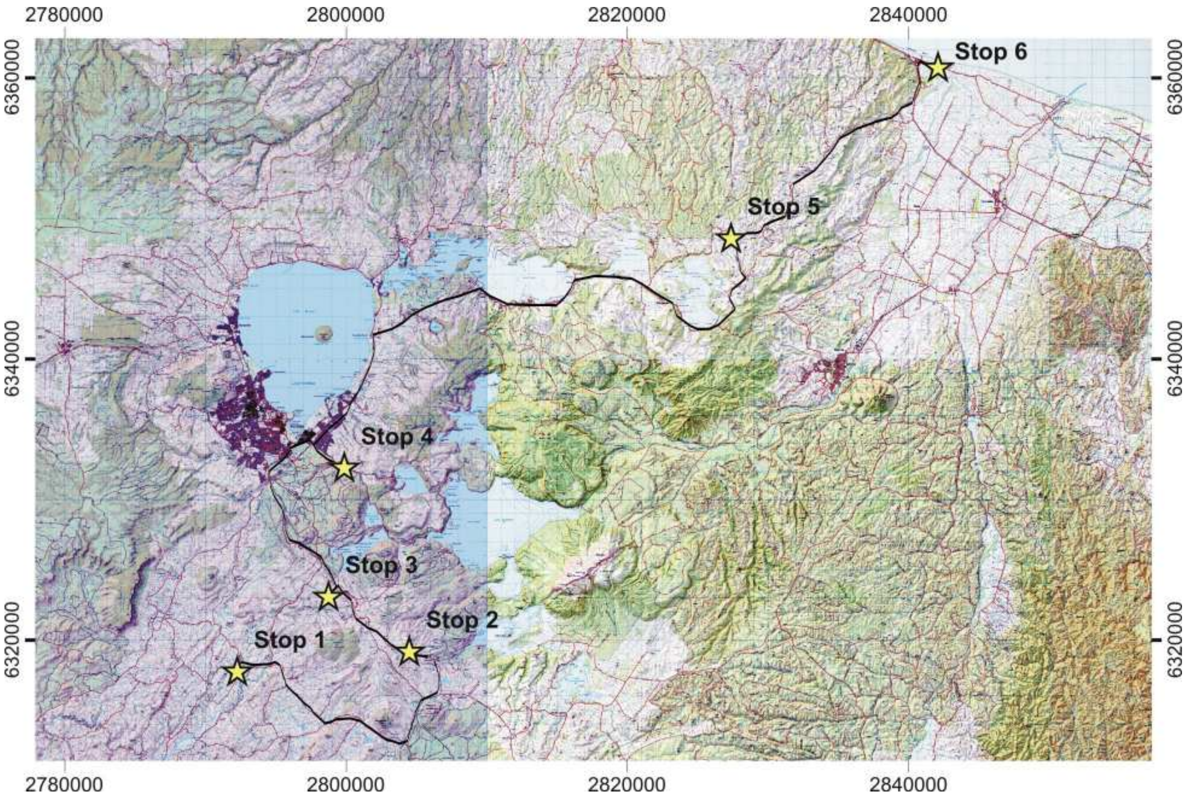

Figure 1. Field stop locations (NZ Map series 260, maps U16, V16 and V15)

INTRODUCTION

The Taupo Volcanic Zone (TVZ) is the late Pliocene-Quaternary volcanic arc associated with the Hikurangi subduction margin (where the Pacific plate is subducted beneath the North Island of New Zealand; Wilson et al., 1995) (Fig. 2). The TVZ is also regarded as the southern, onshore, continuation of the Havre Trough, an extending basin NNE of New Zealand defined by active normal faulting and volcanism (Wright, 1993). While a well defined backarc basin to the west of the Kermadec subduction zone exists along most of the Havre Trough (with the active volcanic arc located to the east of the tectonic basin; Gamble and Wright, 1995), extension onshore occurs within the volcanic arc itself. Extensional faulting within the TVZ has the character of a continental rift, here called the Taupo Rift (Acocella et al., 2003; see Villamor and Berryman, 2006, for other nomenclature). Composition of volcanic centres varies along the rift with predominantly rhyolitic volcanism between Taupo and Okataina volcanic centres, and andesitic volcanism dominating south of Taupo and north of Okataina (Wilson et al., 1995).

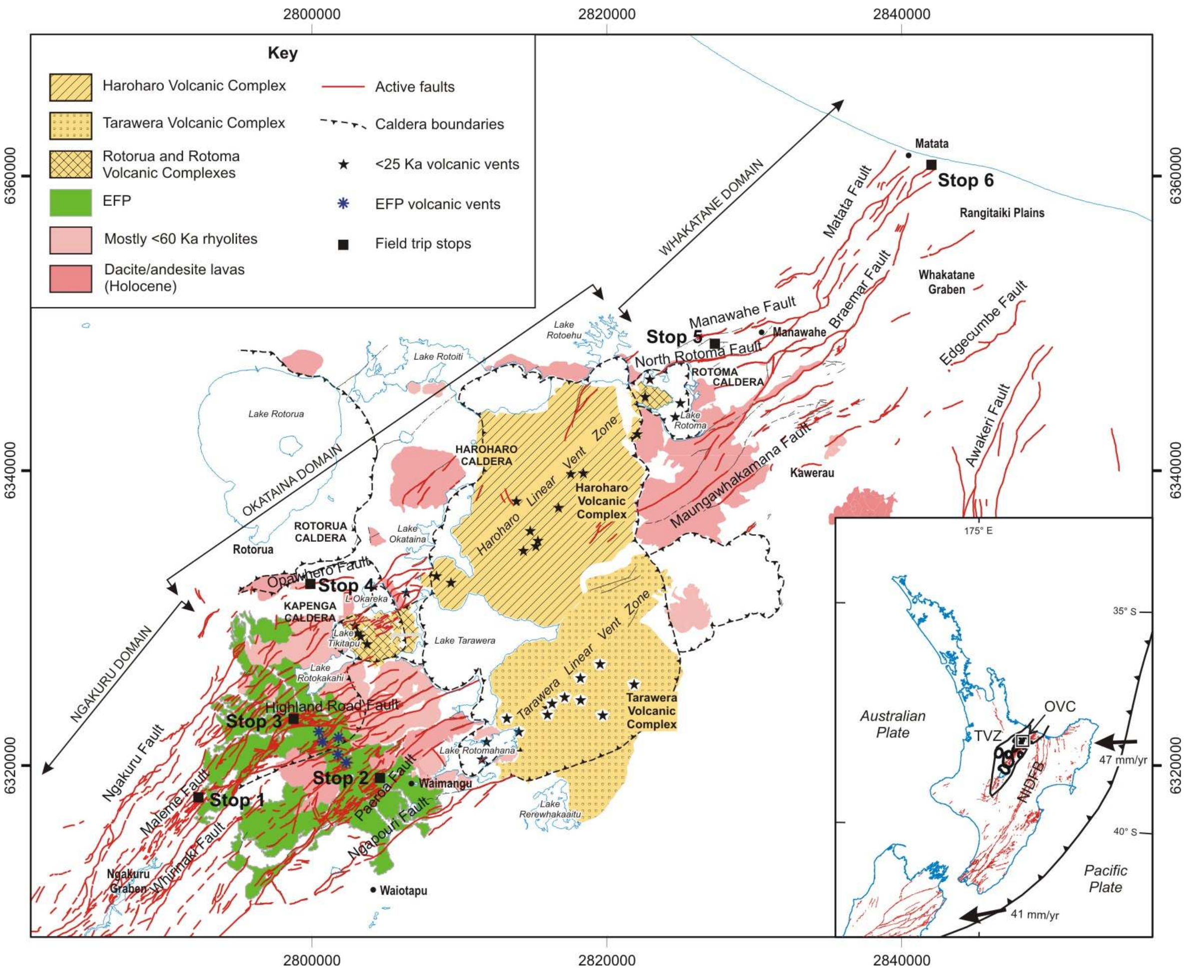

Figure 2. Regional tectonic map of the northern sector of the Taupo Rift. Okataina Volcanic Complex (from Nairn, 2002) is located between the Ngakuru (to the south) and Whakatane (to the north) rift domains. Inset: New Zealand plate boundary with location of the Taupo Volcanic Zone (Dashed line); main rhyolitic calderas (bold line; Nairn, 2002); and active faults (from Nairn, 2002, and GNS active faults database, 2007, http://data.gns.cri.nz/af/)

The Okataina Volcanic Centre (OVC) is the most recently active of the eight large rhyolite eruptive centres in the Taupo Volcanic Zone (Fig. 2- inset). The OVC contains a complex of nested calderas that have subsided accompanying the eruption of large volumes of rhyolite magma during at least three ignimbrite episodes during the last 340 kyr (Nairn, 2002), while recently dated pre-caldera rhyolites range up to ~530 ka in age (Leonard pers comms. 2007). The most recent major caldera-forming episode occurred during eruption of the ignimbrite flows and interbedded airfall tephras that form the >100 km^3 Rotoiti Pyroclastics. The northern part of Haroharo caldera (Fig. 2) collapsed during the Rotoiti episode, which is dated at either ~50 ka, or 65 ka, depending on the preferred dating technique. Here we will use 60 ka (without prejudice).

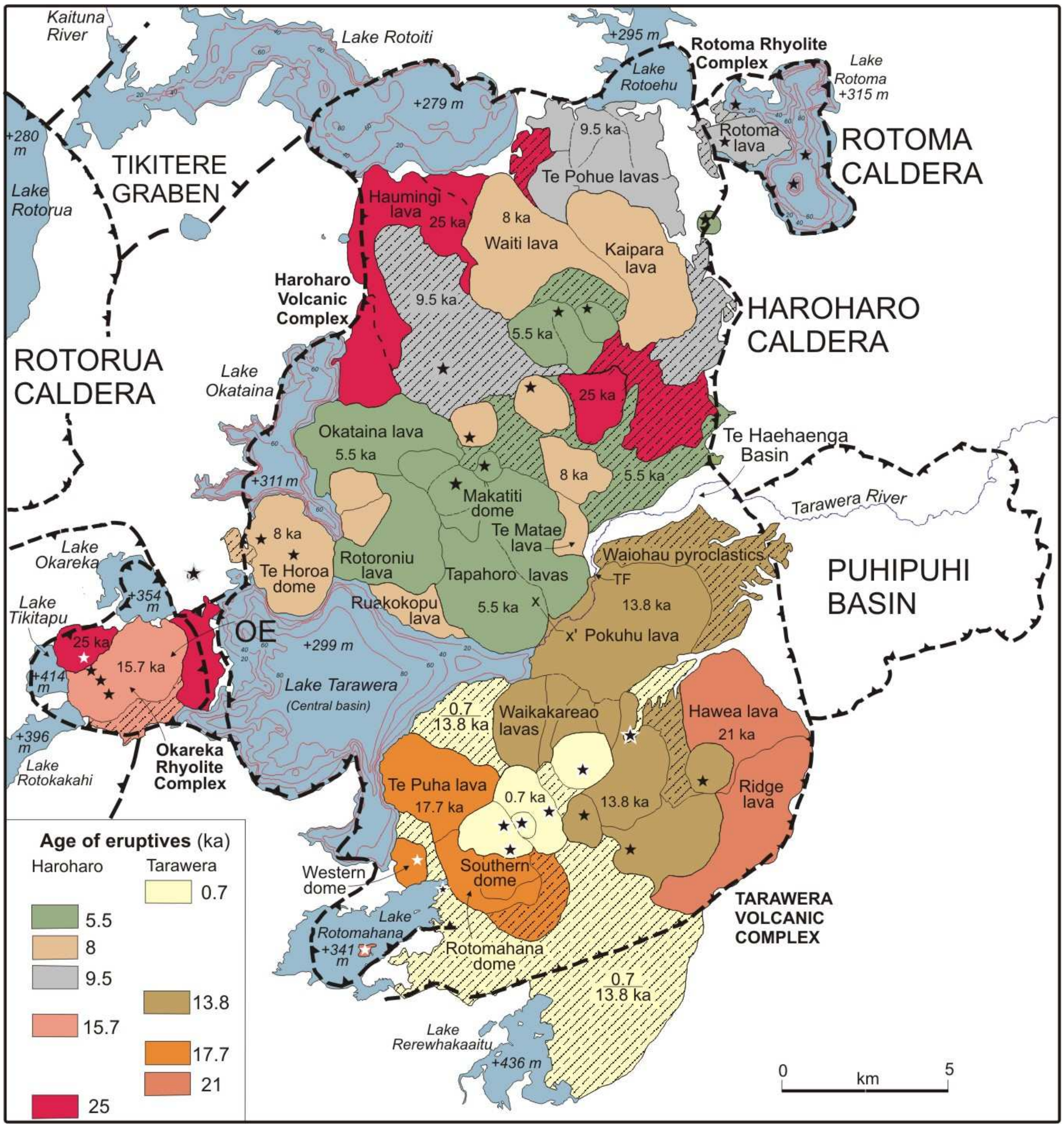

Figure 3. Map of the post caldera rhyolite lavas and associated pyroclastic deposits of the Okataina Volcanic Centre (modified from Nairn, 2002). See also Table 1. Stars are vent locations.

Since the Rotoiti eruption episode, many intracaldera eruptions (Fig. 3) have occurred from vents across the caldera floor, largely filling the caldera with piles of lavas and pyroclastics. Vents cannot be precisely located for the early (41-28 ka) intracaldera eruptions (Mangaone Subgroup pyroclastics (MSg); Jurado-Chichay and Walker, 2000; Smith et al., 2005a). However, many vents are known for the nine post-25 ka rhyolite eruption episodes (Table 1, Fig.3), and these define two broad linear zones (Fig. 2) that trend NE across the OVC (Nairn, 2002). Eruptions from these vent zones have built up the Haroharo complex in the northern part of Haroharo Caldera, and the Tarawera complex in the southern part (Figs. 2, 3). Eruptions occurred from multiple vents during each rhyolite eruption episode, with emission occurring simultaneously or sequentially from vents up to 11 km apart along the active vent zone (i.e., Nairn et al., 2001; Kobayashi et al., 2005). Only a single vent zone was active during each eruption episode; the rhyolite episodes at Tarawera and Haroharo have all been separated by >1000 years (Table 1). These relationships indicate that the post-25 ka rhyolite eruption episodes were fed by rhyolite dikes intruded beneath the vent zones (Nairn, 2002; Smith et al., 2005).

Eruption Episode	**Age (ka)**	**Magma volume (km3)**	
		Haroharo	**Tarawera**
Tarawera Basalt	AD1886	-	1
Kaharoa	0.7	-	5
Rotokawau Basalt	3.4	(0.5)	-
Whakatane	5.6	13	-
Mamaku	8.1	17	-
Rotoma	9.5	8	-
Waiohau	13.8	-	10
Rotorua	15.7	4	
Rerewhakaaitu	17.6	-	5
Okareka	21.4	-	8
Te Rere	25	13	-

Table 1. Calibrated ages, vent zones and magma volumes for the post-25ka eruption episodes from OVC (modified from Nairn 2002). All episodes are rhyolitic, except for the named basalts.

The AD1886 Tarawera eruption occurred from a 17 km long basalt dike system (Nairn and Cole 1981) that bisected the Tarawera rhyolite massif. The AD1886 basalt fissure closely followed the 8 km vent lineation for the ~AD1315 (0.7 ka) Kaharoa rhyolite episode from Tarawera (Nairn et al., 2001), but extended across Rotomahana beyond the Haroharo caldera rim into the Waimangu area (Fig. 2). The Kaharoa rhyolites contain common basalt inclusions, and eruption of the 5 km^3 of rhyolite magma was demonstrably primed and triggered by intrusion of basalt into the rhyolite magma chamber (Leonard et al., 2002; Nairn et al., 2004). The syn-Kaharoa occurrence of large hydrothermal eruptions at Waiotapu (Fig. 2), apparently driven by a major pulse of heat and CO_2 gas, indicates that the Kaharoa basalt intrusion took the form of a dike that extended 21 km between Tarawera and Waiotapu (Nairn et al., 2005). Detailed studies of the older Tarawera eruptives (from the 21.4, 17.6 and 13.8 ka episodes, Table 1, have found evidence (ranging from blatant to cryptic) for basalt input into each Tarawera rhyolite episode (Nairn, 1992; Darragh et al., 2006; Shane et al., 2007, Shane et al., submitted). It now appears clear that intrusion of basalt magma has played a fundamental role in generating the Tarawera rhyolite magmas, and triggering them into eruption. All known (and inferred) basalt vents at OVC define dikes (Nairn, 2002) indicating that basalt magma rises from the mantle into the upper crust along near-vertical linear cracks. However, the dikes do not follow any mapped faults at OVC and appear to be controlled by separate structures.

In contrast to the Tarawera rhyolites, no evidence has yet been found for basalt in the post-25 ka rhyolite eruptives from the Haroharo vent zone (Nairn, 2002, Kobayashi et al., 2005; Smith et al., 2005, 2006). However, basalt scoria was erupted from vents in the northern part of OVC immediately before the 60 ka Rotoiti rhyolite episode (Pullar and Nairn, 1972; Nairn, 2002) and basalt intrusion appears to have been important in triggering the large Rotoiti magma body into eruption (Shane et al., 2005). Recent studies (Molloy et al., in press) of the Earthquake Flat Pyroclastics (EFP – see STOP 2), erupted at the end of the Rotoiti episode from vents on the SW margin of OVC (Fig. 2), have found compelling evidence for rejuvenation of the EFP magma body prior to eruption. The EFP magma had cooled and largely crystallized (stagnated) before it was heated and stirred (juxtaposing Fe-Ti crystals that record temperatures differing by up to 70ºC in a single pumice clast) immediately before it was quenched by eruption. Although evidence for basalt in the EFP eruptives is sparse (very rare microdiorite clasts have been found), the convective stirring was most likely driven by heat and volatiles transferred from underplating basalt magma. If so, basalt was intruded beneath much of OVC immediately before the Rotoiti-EFP eruptions, probably as an extensive dike swarm (Molloy et al., in press). Similar basalt intrusion is also likely to have been the fundamental cause of all the later eruptions on the Haroharo vent zone.

The Okataina Volcanic Centre (OVC) is located between two active segments of the Taupo Rift: the Ngakuru Domain to the south, and the Whakatane Domain to the north (Rowland and Sibson, 2001) (Fig. 2). Active faults run into the margins of the OVC from both southwest and northeast. Some fault traces overlap in space with the ends of the volcanic vent zones, but active faulting is much less common within the OVC than outside it (Fig. 2). The lack of mapped faulting within OVC may be in part due to the younger age (<25 ka; Fig. 3) of all ground surfaces within the caldera, in contrast to the >60 ka surfaces common outside the caldera. However, many rift faults have young (<10 ka) displacements that would be observed if they existed within the caldera, suggesting that the lack of intra-caldera faulting is real. The fault pattern (Fig. 2), and geophysical evidence for location or absence of possible melt in the crust (Ingham, 2005; Heise, et al., 2007; unpublished data, Hugh Bibby, pers. comm., 2007) suggests that although volcanic activity and faulting in the OVC area during the last 25,000 years have not been spatially coincident, they have been close enough to interact.

The Ngakuru Graben faults form a well-defined graben structure in the centre of the active Taupo Rift (Villamor and Berryman, 2001; Rowland and Sibson, 2001; Nairn, 2002). The graben contains five main faults, from east to west the Ngapouri, Paeroa, Whirinaki, Maleme and Ngakuru faults (Fig 2). Faults trend at 040º for most of their extension but bend to 060º as they approach the Okataina Volcanic Centre (Rowland and Sibson, 2001). The active graben is currently ~15 km wide but it was possibly much wider (up to ~80 km) at earlier stages, before faulting migrated inwards (Berryman and Villamor, 1999; Rowland, 2001) about ~300,000 years ago, when large rhyolitic eruptions also occurred (Berryman and Villamor, 1999; Villamor and Berryman, 2006). The extension rate at Ngakuru Graben is 7-12 mm/yr (Darby and Meertens, 1995; Villamor and Berryman, 2001; Wallace et al., 2004), with fault slip rates ranging from 0.1 mm/yr to possibly 3 mm/yr (Villamor and Berryman, 2001, Nicol et al., 2006). In many places faults are spaced at 1-3 km distances, much closer than the inferred 8-10 km thickness of the brittle crust (Bryan et al., 1999; Bannister et al., 2004), which implies that the surface fault traces have to join into a few major faults at depth.

The Whakatane Domain of the Taupo Rift is also to ~15 km wide and encompasses two regions of different geomorphic expression. Close to Okataina Volcanic Centre, normal faults display clear large fault scarps where they displace old (>350 ka) Okataina Rhyolites and Rotoiti Pyroclastics (~60 ka) (Nairn, 2002) (Fig. 2). In this area fault trends are bimodal with ~055º trends on the SE side (e.g. Maungawhakamana Fault) and ~ 070º on the NW side (e.g. North Rotoma Fault) (Nairn and Beanland, 1989; Rowland and Sibson, 2001). Further north, the rift structure is known as the Whakatane Graben (Nairn and Beanland, 1989, and references therein). There, large fault scarps displacing older volcanic deposits (~400-280 ka) form the NW side of the graben, while faults in the centre and SE side of the graben are mostly buried by the young volcanic sediments (<1.8 ka) that form the Rangitaiki Plains. The most recent displacements form small (mostly ~1 m) scarps. In the Whakatane Graben, fault trends also vary from ~030º on the NW side (Matata and Braemar faults) to ~055º on the SE side (Edgecumbe Fault).

The Whakatane Graben extends offshore, where faults have a dominant ~043º trend (Lamarche et al., 2006). Fault slip rates range from 0.3 to 3 mm/yr (Lamarche et al., 2006), which are similar rates to those in the Ngakuru area. Extension rates for the offshore Whakatane Graben have been defined as somewhat larger than further south, i.e., ~ 12-15 mm/yr (Wallace et al., 2004; Lamarche et al. 2006). Fault geometry and fault spacing offshore is very similar to those of the Ngakuru Graben (Villamor and Berryman, 2001; Lamarche et al., 2006). At the latitude of the Whakatane Graben the North Island Dextral Fault Belt (Fig 2) intersects with the Taupo Rift (Beanland, 1995; Mouslopoulou, 2006; Mouslopoulou et al., 2007) transferring the strike-slip displacement into the rift with a consequent increase in the extension rate of the rift north of the intersection (Lamarche et al., 2006; Mouslopoulou, 2006).

STOP 1 : Rehi Road: Maleme Fault Zone, axis of Ngakuru Graben

Faulting in the Ngakuru Graben

At this stop we will have a general view of the Taupo Rift and we will walk across the central axis of the Ngakuru Graben. Here the Maleme Fault Zone is represented by at least 11 fault strands that displace a ~20,000 year old volcano-sedimentary surface with a total displacement of 60 m (Villamor and Berryman, 2001) (Fig. 4). Evidence from paleoseismic trenches and geomorphic features from 25 fault traces across the whole Ngakuru Graben shows clustering of displacements in time and space (Nicol et al., 2006). For some individual fault traces, slip rate values can vary greatly with time (e.g., 0.1 to 1 mm/yr in Fig. 4) while others are constant. When slip rates are aggregated across a whole fault zone (i.e., across the several fault traces that comprise a fault zone), the total slip rate becomes more constant. This also happens when all slip rate values are aggregated for the whole rift. This clustering is a consequence of strong interaction between very closely spaced faults of the rift.

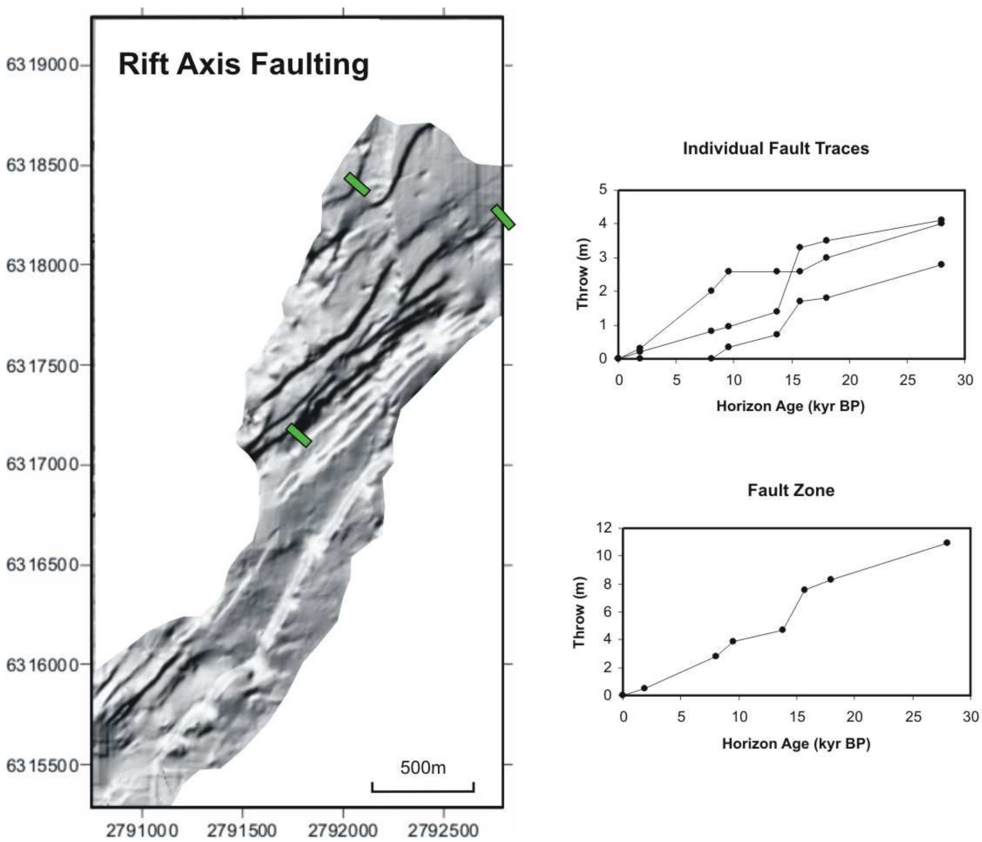

Figure 4. A) Shaded relief of the Maleme Fault Zone showing fault scarps and location of trenches. B) Displacement plots for individual trenches (upper plot) and for aggregation of all three trenches (Nicol et al., 2007).

STOP 2 : Waimangu Road: Volcanism in the southern part of the Okataina Volcanic Centre; Fault – volcano interactions; and Geophysical studies of the Okataina Volcanic Centre.

Volcanism in the southern part of the Okataina Volcanic Centre

The landscape of Stops 2 and 3 is dominated by the surface formed during the eruption of the Earthquake Flat Pyroclastics (EFP) at ~60 ka. The ~10 km^3 EFP deposits form low-angle pumiceous pyroclastic fans up to 150 m thick that radiate out from six vents that define a 5-km long northwest trending zone (Fig. 2) that overlies the inferred OVC outer ring fracture (Nairn, 2002; Molloy et al., in press). The intercalated fall beds extend beyond the pyroclastic flow fans, to form the distal “Rifle Range Ash” tephra, which directly overlies the analogous distal fall deposit (“Rotoehu Tephra”) of the Rotoiti Pyroclastics. The contact is sharp, conformable, and unweathered (Nairn and Kohn 1973), consistent with closely sequential deposition of the two tephras separated by a time gap as little as hours to weeks. The EFP deposits are important in providing a synchronous, originally planar, surface that extends across the Taupo Rift (Fig. 2), and that has been frequently displaced by subsequent rift faulting (Villamor and Berryman, 2001; Berryman et al., 2004; Nicol et al., 2006; Berryman et al., submitted). The EFP fans were partially dissected during the last Glaciation to commonly form a box canyon and interfluve topography. The original fan surface is preserved beneath MSg tephras (41-28 ka) on the interfluves, with the canyon floors first mantled by younger tephras. The 15.7 ka Rotorua Tephra was often the first tephra to be preserved on the canyon floors, as erosion ceased when the climate improved. The EFP fan and gully surfaces and their overlying tephras provide a stack of valuable time planes for determining the displacement history of post-60 ka Taupo Rift faulting (Berryman et al., 2004; Berryman et al., submitted).

From Stop 2, we can see the canyon-eroded and multiple fault-displaced EFP fan surface to the south, west, and north; pre-EFP rhyolite domes protrude through the EFP surface to the north and NE. The Tarawera complex is in the distance to the NE, with the summit area formed by ~AD1315 Kaharoa rhyolite domes, cut by AD1886 fissure craters. Makatiti dome (5.5 ka) forms the summit of the Haroharo complex to NNW, and marks one of the latest Haroharo vents. The Kaingaroa ignimbrite (240 ka) plateau surface is visible to the SE, with the Urewera greywacke ranges (Mesozoic) forming the far skyline beyond the volcanic zone. Maungakakaramea (Rainbow Mountain) and Maungaongaonga dacite domes (~150 ka?) are visible to the south, with part of the Reporoa caldera (source of the Kaingaroa ignimbrites) just beyond. To the SW, Paeroa mast marks the summit of the Paeroa Range with the Paeroa Fault scarp on the far side.

Fault – volcano interactions

Several cases have been recorded of Ngakuru graben faults rupturing at the same time as eruptions were occurring from OVC (Berryman et al., 2004; Nairn et al., 2005; Villamor et al., 2004; Berryman et al., 2006; Villamor et al., 2007; Canora et al., in prep). The faults we can see from stop 2 are part of the Paeroa Fault zone (Fig. 2), which forms the southeastern margin of the Ngakuru Graben. Recent paleoseismic studies in this vicinity (Berryman et al., 2004; Berryman et al. submitted) have been made in seven trenches excavated across 6 of the 11 strands of the Paeroa Fault zone. One of these trenches is shown on Figure 5. Analysis of the timing of faulting from this dataset shows that the Paeroa Fault zone has ruptured synchronously with the ~13.8 ka Waiohau eruption episode from the Tarawera vent zone (Table 1; Fig. 3) (Berryman et al., 2004), and with the ~9.5 ka Rotoma and ~15.7 ka Rotorua eruption episodes from the Haroharo vent zone (Berryman et al., submitted).

Studies of variation of fault offset along the Paeroa Fault zone as it approaches the Okataina Volcanic Centre (OVC) show that despite a change in faulting style (e.g. a predominately NW dipping single strand structure to a multiple strand graben structure), the faults within the zone are interacting and are kinematically related in a similar fashion to other fault zones in the Taupo Rift (e.g, Maleme Fault zone, Nicol et al., 2006). While the volcanic structures of the OVC (i.e. 1886 AD Tarawera basaltic dike) are shown to influence displacement on individual faults within the system, the overall cumulative displacement of the Paeroa Fault zone along strike is stable over a distance of 10 km towards the topographic caldera margin. This implies the volcanic centre has had no significant influence on the displacement rate of the Paeroa Fault zone over the past 60 kyr (Seebeck et al., 2007; Seebeck, in prep.).

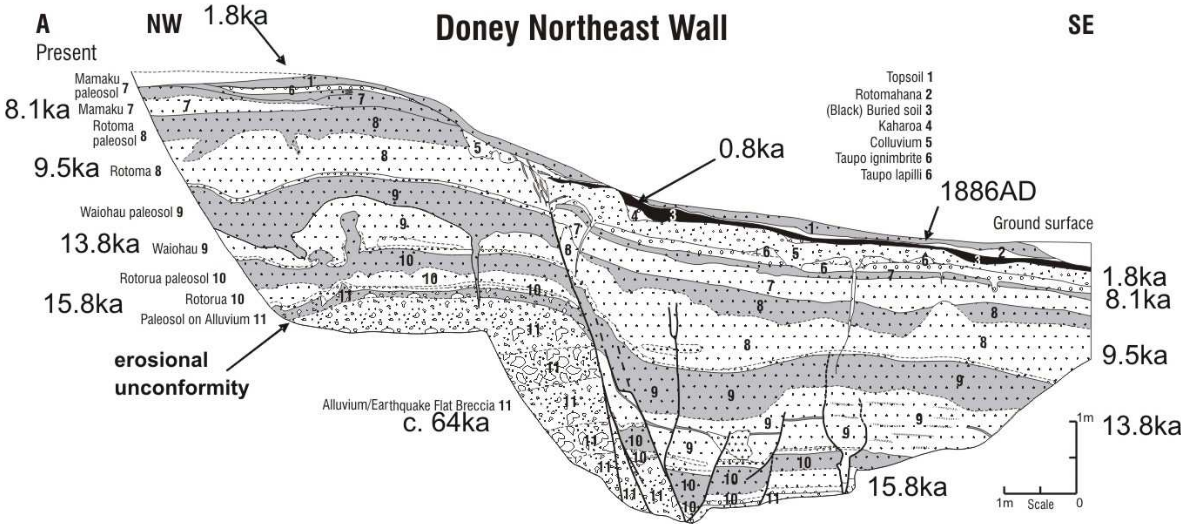

Figure 5. Doney trench: Trench log of one of the seven trenches excavated across the eleven strands of the Paeroa Fault zone in the Earthquake Flat area. Retro-deformation of the Doney trench (Berryman et al., submitted) shows that displacement occurred during the Waiohau eruption episode. Other trenches show displacements associated in time with the Rotoma and Rotorua eruptions. (Figure from Berryman et al., submitted)

Geophysical studies of the Okataina Volcanic Centre

Calderas are subcircular depressions with diameters many times larger than those of included vents and are commonly formed by subsidence associated with the removal of magma from a chamber during major eruptions (Cole et al., 2005 and references therein). The axial part of the Taupo Rift is characterized by several Quaternary elliptical calderas with varying elongation (oblique, perpendicular, and parallel) (Wilson et al., 1984; Seebeck et al., 2007; Seebeck, in prep.) with regard to the orientation of the Quaternary rift structures (NE-SW) and to the regional extension direction (N40°W).

The Haroharo Caldera is an approximately rectilinear depression of subsidence with clearly defined north and northeastern topographic margins (Fig. 6). Where well-expressed, the topographic caldera rim is strongly scalloped, indicative of slumping of over steepened rim scarps following the catastrophic collapse of the caldera floor during voluminous ignimbrite eruptions. The margins of the caldera are less clear to the south, where the collapse appears to be older (Nairn, 2002).

Gravity models of the caldera (Seebeck et al., 2007; Seebeck, in prep) indicate the major subsidence occurred in the south-central region of the caldera complex to depths of ~3 km between the Haroharo and Tarawera linear vent zones. These models are supported by the location of low Vp anomalies of Sherburn et al. (2003) and recent magneto-telluric studies (Bibby pers comms. 2007) and support the evolution of the caldera from elongation in a rift-parallel orientation (eruptions >60 ka) to a rift-oblique orientation during the Rotoiti eruption (60 ka) (Nairn, 2002). An inner ring fault proposed by Nairn (1989) is consistent with the seismic reflection interpretations of Davy and Bibby (2005) and gravity modeling and represents the major structural feature of the volcanic complex.

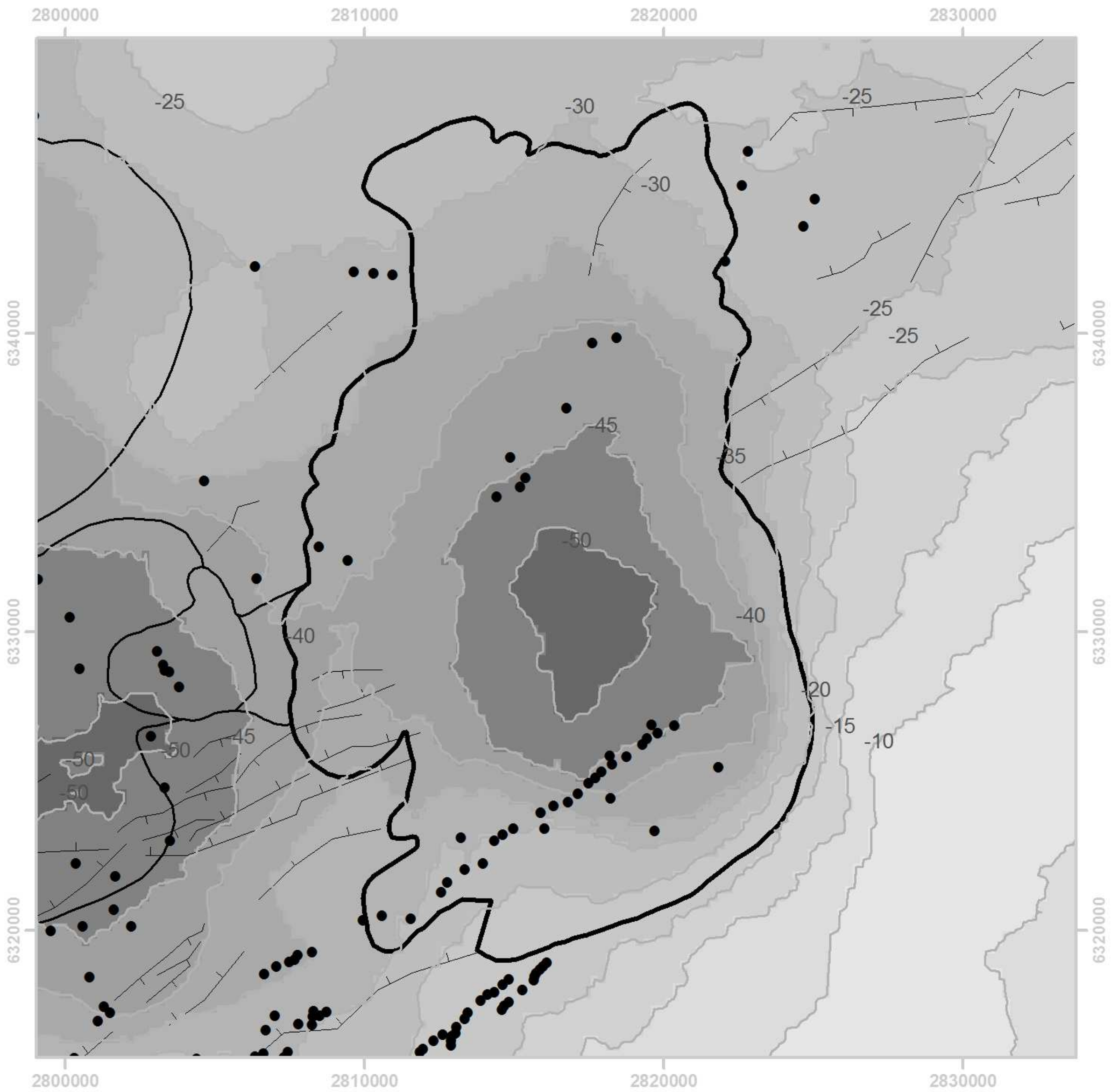

Figure 6. Map showing the residual gravity anomaly associated with the Okataina Volcanic Centre (Seebeck, in prep). Residual gravity anomalies (mGals) were created from the GNS Land Gravity Database and reduced to Bouguer anomalies using method of Reilly (1972)

along with the removal of the regional anomaly calculated by Stern (1979). A density of 2670 kg/m3 was used for the Bouguer and Terrain corrections. Also shown area OVC Topographic caldera boundaries (Nairn, 1989, 2002) (thick black line), adjacent calderas (thin black lines) (Wilson et al., 1984; Nairn, 2002), major Taupo Rift faults (ticked black lines) GNS active faults database (2004), and volcanic vent locations (filled black circles) Leonard and Begg (2007) unpublished QMAP Rotorua data. NZMG grid spacing 10 km.

STOP 3: Tumunui Deer Farm: Paleoseismic trenching in Highlands Road Fault zone

We will open a trench across one of the strands of the Highlands Road Fault zone (located in EFP deposits near the axis of the Ngakuru Graben) in the week before this field trip. Therefore we are not able to provide any information on our findings in this guide, but we will have a handout ready on site. We hope to find some interesting volcano-tectonic relations to discuss, although we cannot guarantee what lies beneath the grass!!! In any case, we will show you how we analyse paleoseismic trenches and we will give you our preliminary interpretation on timing of faulting and hopefully of volcano-tectonic interactions in this new trench.

STOP 4: Tarawera Road - Displacement of the Opawhero Fault during and after the ~15.7 ka Rotorua eruption episode

At this stop a new road cut exposes the sharp fault plane of the 5 km long, ENE trending, Opawhero Fault, which forms the NW margin of theTaupo Rift in this area (Fig. 2). The fault displaces pumice fall beds of the ~15.7 ka Rotorua Tephra erupted from vents located about 6 km to the SE of this stop (Figs. 2, 3). The four Rotorua episode vents have a NW alignment over a distance of 1 km, between lakes Tikitapu and Tarawera (Nairn, 1980). The general sequence of the Rotorua episode is: (1) early plinian falls dominated by vesicular, clinopyroxene-bearing pumice; (2) late-stage fall units comprising dense, biotite-bearing pumices and ash; (3) extrusion of biotite-bearing Middle Coulee and Middle Dome lavas; (4) block-and-ash flows interbedded with dense biotite-bearing fall units (Kilgour, 2002; Smith et al., 2004). A minimum estimated eruptive volume for this episode is ~1 km^3 (Kilgour, 2002; Smith et al., 2004). Units 1 and 2 make up nearly all the Rotorua Tephra.

The Opawhero Fault lies >4 km to northwest of the closest Rotorua episode vent. At the road outcrop and on the fault footwall, old (>22 ka; probably <65 ka), >10m thick (base not exposed) weakly cross-bedded Te Wairoa Pyroclastics flow units are overlain by locally reworked deposits and loess with a distinctive bleached soil upper contact a few-cm thick. On the foot wall, this contact is overlain by ~4m-thick early plinian coarse pumice beds of the Rotorua Tephra (Fig. 7). The uppermost part of the sequence (~ 3-m-thick) contains a series of younger (Holocene) tephras. On the hanging wall, the stratigraphic sequence is similar, except that the Te Wairoa deposits are downfaulted below the road exposure level, and the plinian Rotorua deposits are >10 m thick (base not exposed).

The difference in thickness of the Rotorua plinian deposits across the fault plane implies that the Opawhero Fault moved during the pumice fall to accommodate the overthickened tephra on the hanging wall. The displacement must have been >6 m during the early phases of the Rotorua eruption episode (we discount ~2 m of offset that occurred after development of the paleosol on Rotorua Tephra). This (>6 m) is a very large displacement if compared with the expected coseismic displacement of 0.5-0.7 m for a 6 to 8 km long tectonic fault (M_W 5.9-6.1; using Webb's scaling relation for the TVZ; see Villamor et al., 2007 for details on this equation). Small discrete blocks of loess deposits, bleached soil and Rotorua deposits are dragged along the fault scarp suggesting possible multiple discrete offsets during the eruption (Fig. 7).

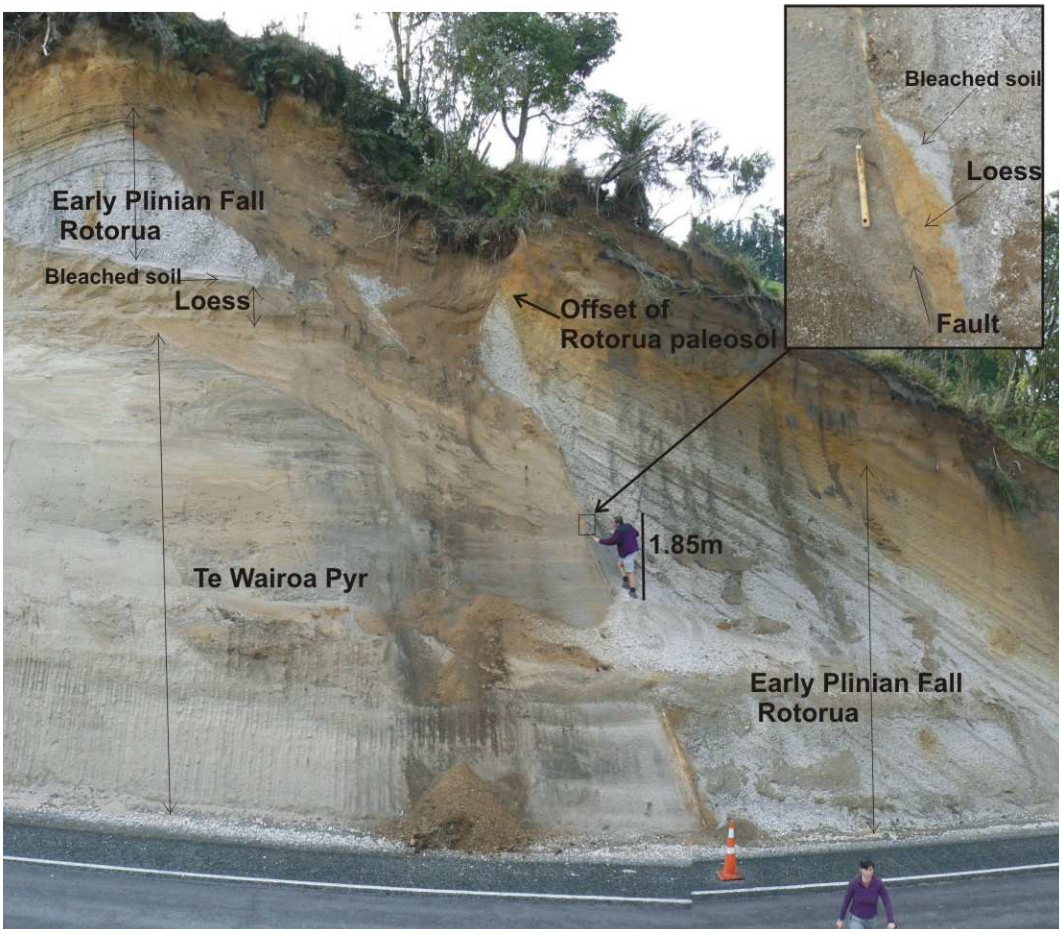

Figure 7. Exposure of the Opawhero Fault at Tarawera Road. Fault shows large displacement (~6m) during the pumice fall to accommodate the overthickened Rotorua Tephra on the hanging wall.

We do not yet fully understand the relationships exposed here. The observations can be interpreted as resulting from the steady or semi-continuous evacuation of magma during the plinian eruption, leading to steady or punctuated subsidence on the hanging wall. Based on these observations, it is difficult to conclude whether the displacements along the fault plane were associated with seismic events or displacements were aseismic. In the first case, subsidence could be associated with changes in crustal stress during the eruption. Stress changes can trigger a series of frequent small earthquakes (~ M_w 6.1 with coseismic displacements of ~0.7 m). The post-Rotorua displacement on the Opawhero Fault also seems to have a tectonic origin based on the poor exposure of the upper few metres of the road cut. This later would support a tectonic behaviour for the major displacement of the fault.

Alternatively, subsidence could be a consequence of accommodation into the space created by the emptying of the magma chamber. This latter explanation seems less likely since it would seem to require a large distance (~4 km) of lateral, underground transport of the magma to the vents. Although the location and subterranean extent of the Rotorua episode magma chamber is unknown, numerical modelling of crustal stress changes during eruptions, together with a paleoseismic trench exposing the most recent deformation, could rule out some scenarios.

STOP 5: Manawahe Rd: I**nteractions between the Manawahe Fault zone and volcanic eruptions at OVC.**

At the northern side of OVC, some Whakatane Graben faults align and overlap with the Haroharo Vent Zone, e.g., a trace of the Manawahe Fault zone (Fig. 2) that is exposed at this road cut (Fig. 8). Other faults are parallel to the vent zone but step over to the east. None of the faults are aligned with the Tarawera Vent Zone. The Manawahe Fault zone consists of at least three main strands with minor faulting between the strands (Fig. 2). To the south of the Manawahe Fault zone, the North Rotoma Fault is located close to the northern cliffs of Lake Rotoma and apparently controlled the location of the caldera rim here (Nairn 2002). The North Rotoma Fault has large offsets (~6-8 m) of the Holocene pumice alluvium that covers valley floors close to the lake. The Manawahe Fault zone and the North Rotoma Fault merge northeast of Manawahe township into the Matata Fault. The Matata Fault forms large scarps in the 280 ka Matahina Ignimbrite and older (Castlecliffian) sedimentary deposits on the western wall of the Whakatane Graben (Nairn, 2002; Nairn and Beanland, 1989).

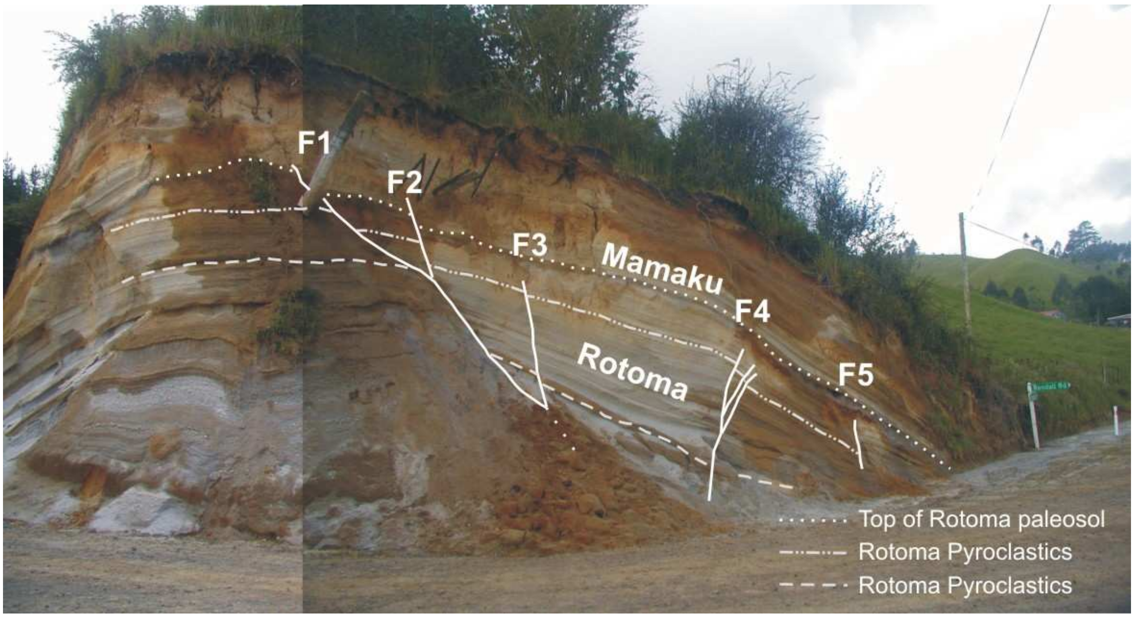

Figure 8. Exposure of fault planes of one the traces that forms the Manawahe Fault zone. Incremental displacement of markers within the Rotoma Tephra sequence shows that the fault ruptured during early to middle stages of the Rotoma volcanic episode.

The Stop 5 road cut is located ~5 km distance from the closest vent of the ~9.5 ka Rotoma eruption episode. One of the small fault traces of the Manawahe Fault zone is exposed and consists of 5 fault planes displacing pyroclastic fall deposits from the early to middle stages of the Rotoma episode (the late stage deposits are not present here) (Fig. 8). Rotoma episode eruptions occurred simultaneously or sequentially from multiple vents in Lake Rotoma, and extended over 12 km SE along the Haroharo vent zone (Nairn, 2002) (Fig. 2). An eruptive volume ≥8 km^3 has been estimated for the Rotoma episode (Smith et al., 2006).

The displacement of reference marker layers in the Rotoma stratigraphy (Fig. 8) at this stop shows that faulting may have occurred during deposition of the Rotoma Tephra, with additional displacement after deposition of the 8.1 ka Mamaku Tephra. The difference between the total offset values for the two markers within the Rotoma episode is 0.43 m for a summed offset of faults F1 to F4, suggesting at least one intra-Rotoma fault rupture. This interpretation is in agreement with observations from a paleoseismic trench across the middle strand of Manawahe Fault zone just south of the Manawahe township (Villamor et al., 2007). In the trench, located ~7.5 km from the closest Rotoma eruption vent, faulting is coincident in time with the early stages of pyroclastic deposition from the Rotoma eruption.

In July 2004 this area was hit by intense earthquake swarm activity. The Rotoehu earthquake swarm began on 18 July 2004 with the largest even being a M_L 5.4 centred near Lake Rotoehu (Fig. 2) (Hancox et al., 2004). From 18-25 July 2004 at least 40 earthquakes (two with M > 5 and seven of M > 4) occurred in the area. During the largest (M 5.4 and M 5) earthquakes on 18 July significant landsliding and ground damage occurred over ~70-300 km^2 around Lake Rotoehu and Lake Rotoma. No surface faulting was found. The amount of damage and landsliding was somewhat larger than other historical earthquakes in New Zealand because the slopes in the area were saturated when the earthquake occurred. In July 2004 heavy rain also produced intense landsliding and flooding in Matata township.

STOP 6: Whakatane graben: the 2005-2007 Matata earthquake swarm, new LIDAR based active fault mapping.

The 2005-2006 Matata Earthquake Swarm

In historical times, the Whakatane Graben has been one of the most seismically active areas of the onshore Taupo Rift together with the area north of Lake Taupo. In 1977 a mainshock - aftershock sequence occurred offshore of Matata starting with a M_L 5.4 mainshock on June 1 (Richardson, 1989). On March 2 1987, the M_L 6.3 (M_W 6.5) Edgecumbe Earthquake followed a series of 130 small earthquakes (February 21 to March 1) that were located in two areas, east of Matata and offshore of Oureki Point (Smith and Oppenheimer, 1989). A large foreshock of M_L 5.2 occurred a few minutes before the mainshock and numerous aftershocks followed for several weeks (Robinson, 1989). On July 5 and 6 1989 two main shocks of M_L 4.6 and 4.7, respectively, occurred in the same area where aftershocks from the 1987 have occurred. The two mainshocks were followed by several smaller events raising fears in the local population of a repeat of the 1897 Edgecumbe earthquake (Robinson, 1990).

Starting in 2005, an earthquake sequence of more than 1450 events (2 < ML < 4.5) is currently worrying the population of Matata again. Figure 9 shows the location of the epicentres of the earthquake swarm up to 1st October 2007. The sequence is ongoing with the largest event so far of M_L 4.5 on September 30 (Bannister et al., 2007). Earthquake locations have markedly improved with the increase in the density of the Geonet seismograph network, and with new approaches for relative earthquake location, using cross-correlation analysis and double-difference location techniques (Bannister et al., 2007). The location of the 2005-2007 Matata earthquakes define several NE trending lineaments that run onshore to offshore from west of Matata to 15 km north of the coast. Although these lineaments are parallel to the currently active faults, no active faults have been mapped onshore west of Matata (Nairn and Beanland, 1989; GNS Science Active fault database, 2007; http://data.gns.cri.nz/af/). However, offshore active faulting has been identified in the area where the 2005-2007 earthquake sequence is located (Lamarche et al., 2006).

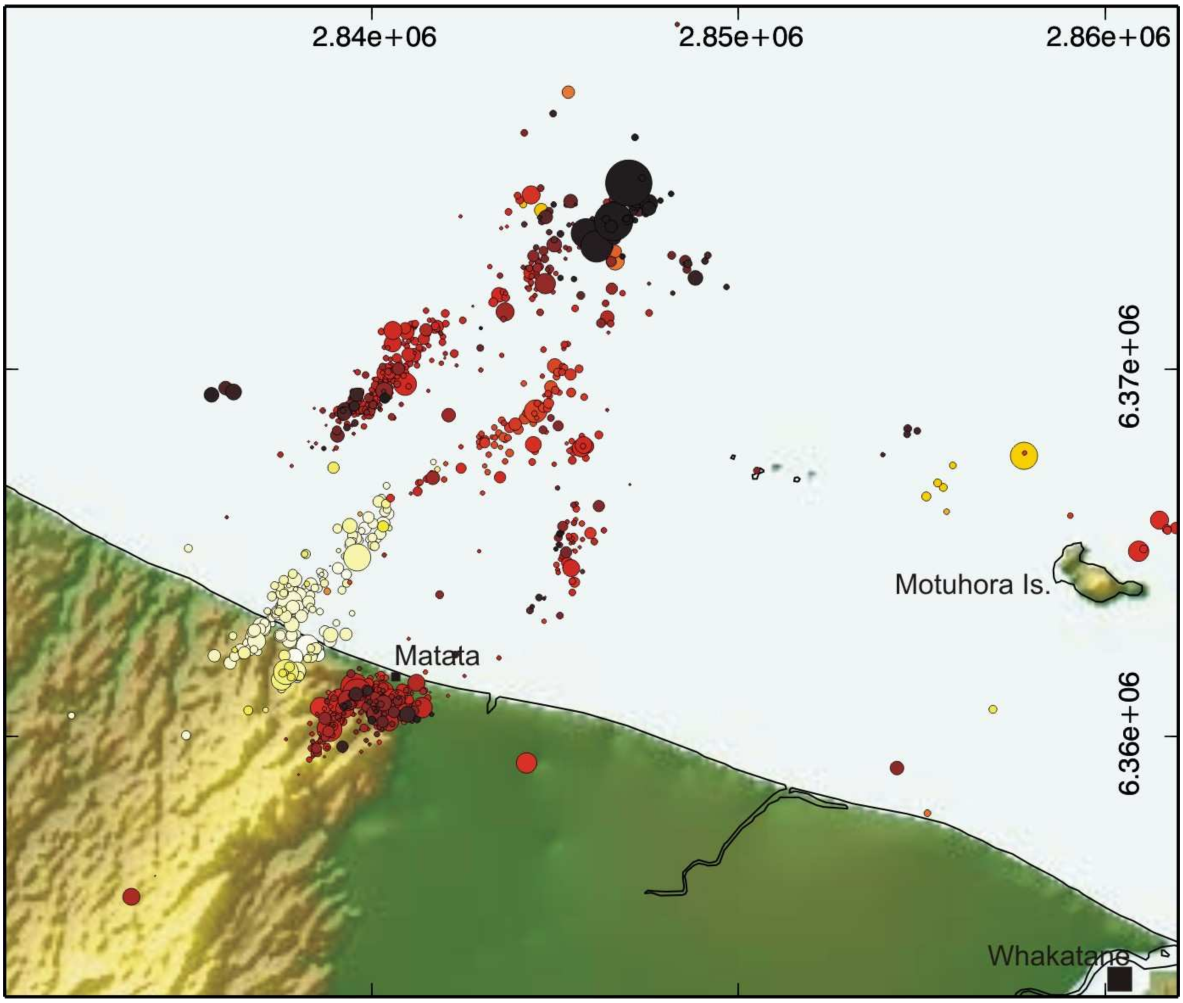

Figure 9. Location of 1450 earthquakes (2 < ML < 4 up to October 2007) of the 2005-2007 Matata (Bay of Plenty) earthquake sequence. Light to dark colours indicate time of occurrence (black circles are the latest October 2007 events, red circles are around March 2007, white circles are pre-March-2007 events). Earthquake locations are aligned in a NNE trend similar to the active faults of the western margin of the Whakatane Graben but they are

geographically located to the west of the active onshore rift (figure provided by Stephen Bannister; Bannister et al., 2007)

Mapping active faults in the Rangitaiki Plains

The occurrence of surface rupture associated with the 1987 Edgecumbe earthquake brought the attention of paleoseismologists to active fault mapping of the Rangitaiki Plains. Prior to the surface rupture in 1987 only a few active fault traces had been identified in the plains (Nairn and Beanland, 1989). To date, publicly available active fault mapping in the area shows a lesser density of fault scarps (see GNS Active fault database, 2007; http://data.gns.cri.nz/af/) than other areas of the onshore rift (e.g., Ngakuru Graben) and offshore Whakatane Graben (Lamarche et al 2006). High resolution (vertical resolution <0.1 m) LiDAR (Light Detection and Ranging) data collected recently across the plains by Environment Bay of Plenty Regional Council has allowed detection of numerous tectonic features that conventional databases can not resolve (Begg and Mouslopoulou, 2007) (Fig. 10). The density of the newly mapped active fault traces matches that of faults elsewhere in the rift. This new fault map will ease the correlation between onshore and offshore active faults.

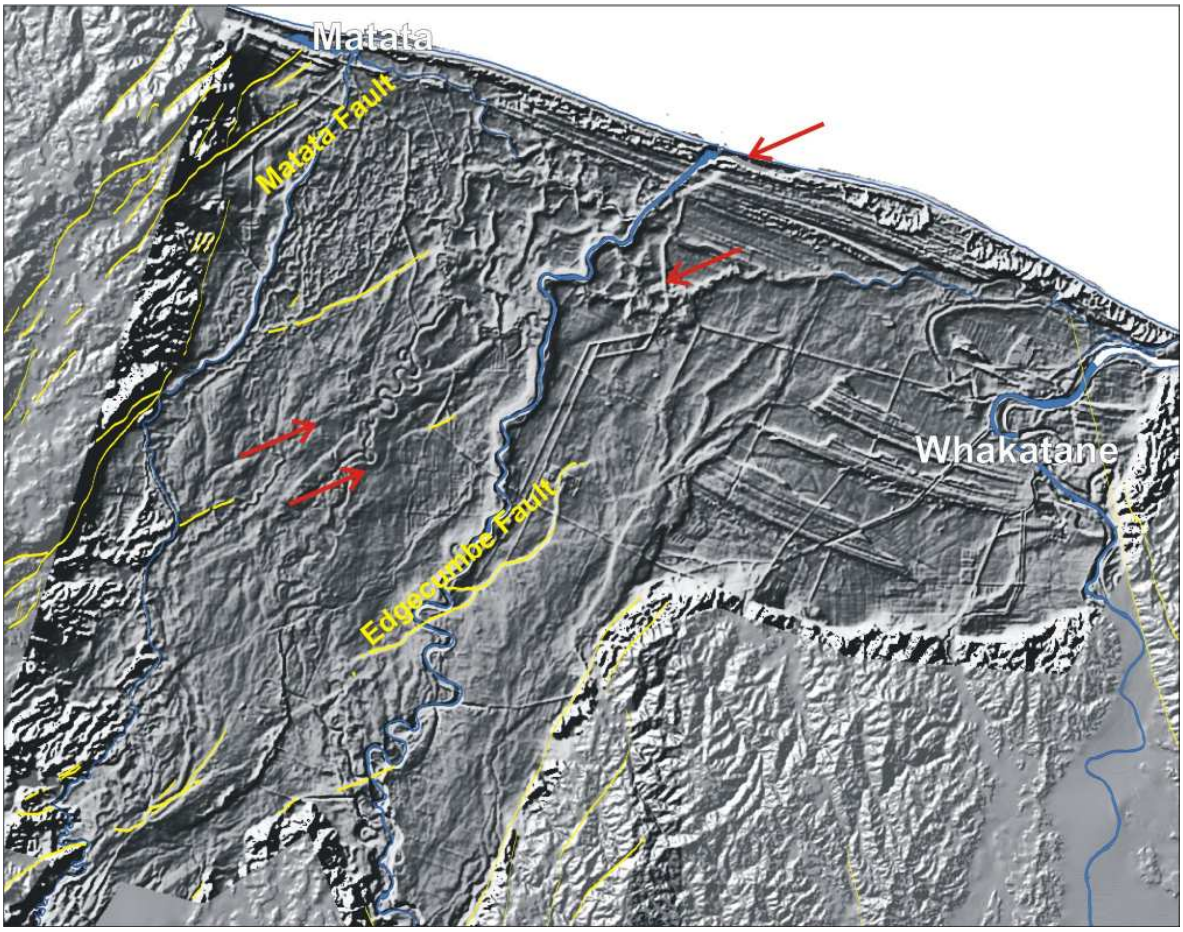

Figure 10. Digital terrain model of the Rangitaiki Plains produced with LiDAR data. Currently mapped active faults from GNS Active fault database (http://data.gns.cri.nz/af/) are shown in bold yellow lines. Some of the newly identified tectonic scarps are marked with red arrows. (Figure provided by John Begg; Begg and Mouslopoulou, 2007).

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