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Field Trip Guides

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Field Trip Guides – Contents

Field Trip 7

Caldera Volcanism in the Taupo Volcanic Zone

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INTRODUCTION

Central TVZ is the most frequently active and productive Quaternary silicic system on Earth (HOUGHTON *et al.*, 1995) characterised by intense and volumetrically dominant rhyolitic volcanism that is expressed largely as major calderas and caldera complexes. Caldera-forming silicic volcanism in TVZ began at c. 1.6 Ma, and at least thirty-four caldera-forming eruptions have occurred since then during three main periods: 1.68-1.53 Ma, 1.21-0.68 Ma, and 0.34-present (HOUGHTON *et al.*, 1995). Six of the calderas identified in central TVZ (Okataina, Taupo, Rotorua, Reporoa, Ohakuri and Whakamaru) have formed in the last 350 ka. These comprise both multiple event caldera complexes (Okataina, Taupo and Whakamaru) and single event calderas (Reporoa, Ohakuri and Rotorua). The Okataina and Taupo caldera complexes, located at the boundaries of the central part are the most productive rhyolitic volcanoes on earth, with eruption rates of c. 0.1 m^3s^{-1} and c. 0.2 m^3s^{-1} respectively, averaged over the last 65 ka (WILSON, 1993). Remote sensing and structural data obtained on deposits younger than 300 ka along TVZ show that it comprises a number of segments with variable dextral components of shear, and significantly that pure extension is restricted to those segments containing the Okataina and Taupo caldera complexes (ACOCELLA, *et al*., 2003). The diversity of calderas within modern TVZ thus provides an opportunity to examine the role of rift architecture in controlling the location and development of caldera volcanism (SPINKS *et al*., in press),

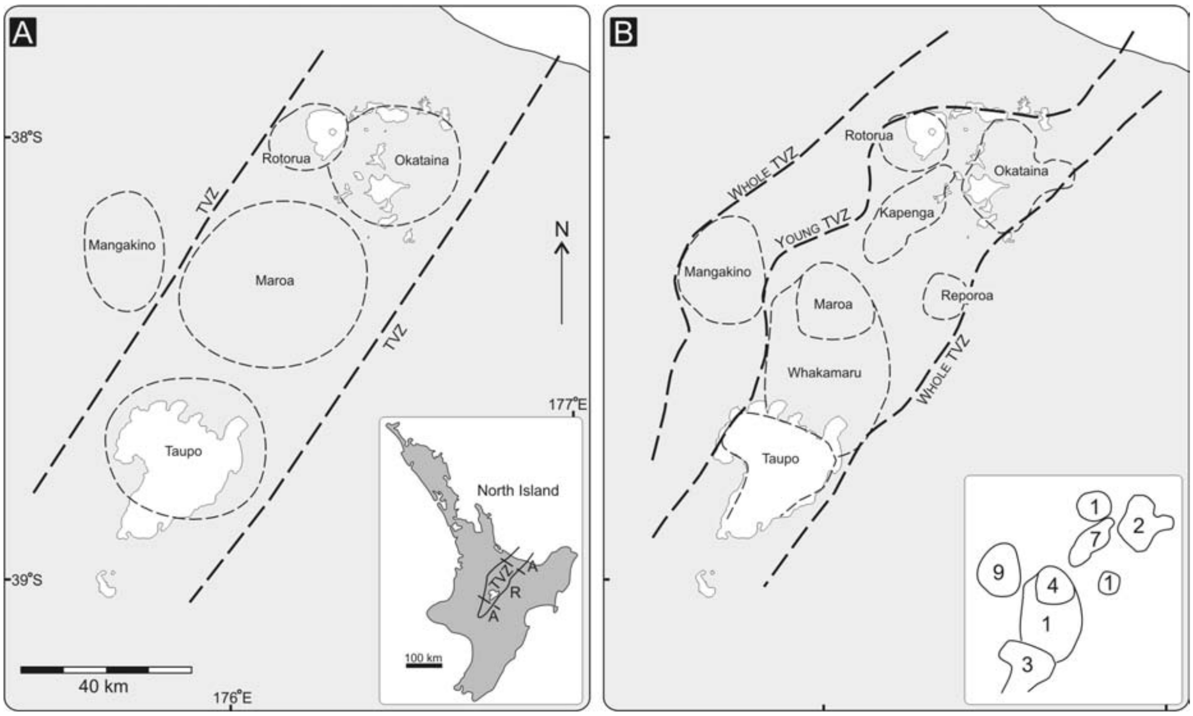

Figure 1 A: Rhyolitic centres of the Taupo Volcanic Zone (from Cole, 1990); **B:** Calderas of the Taupo Volcanic Zone (from Wilson et al., 1995). Numbers in inset represent known ignimbrites or ignimbrite groups erupted from each caldera.

Terminology

Rhyolitic volcanism in central TVZ is traditionally divided into 'volcanic centres' or 'calderas' and their associated vents. COLE (1990) described four composite rhyolitic volcanic centres in TVZ), while more recently (e.g. HOUGHTON *et al*., 1995; WILSON *et al*., 1995) recognised eight caldera centres (FIG.1). These terms are used interchangeably in the literature while none are suitably defined. In particular, a 'volcanic centre' is a rather subjective concept based on some arbitrary spatial association of vents and adjacent caldera structures. In some situations (as in COLE, 1990) the term is used for broad areal groups of associated extrusive and explosive volcanics, and are thus larger than calderas. In other situations the term is used for a constrained group of volcanics associated with one volcano and is usually within a caldera (e.g. Maroa Volcanic Centre). In this field guide, the terms 'caldera' or 'caldera-complex' are used only to define the collapse structure, and volcanic centre is used in the latter sense for a specific space-time association, usually within a caldera or caldera complex.

CALDERA RECOGNITION IN TVZ

The eight documented calderas in TVZ are expressed at the surface by clustering of known or inferred vent locations and/or at depth by geophysically defined basement depressions. High production rates in TVZ and concomitant rapid burial makes caldera delineation in TVZ difficult, and only four of the currently recognised calderas (Taupo, Okataina, Rotorua and Reporoa; those corresponding to modern TVZ) are sufficiently exposed to enable analysis of surface morphology. Other collapse structures have been buried and/or destroyed by subsequent activity. Specifically, 'Kapenga volcanic centre' was first postulated entirely on geophysical evidence (ROGAN, 1982; WILSON *et al*., 1984), and while at least seven ignimbrites are attributed to it (HOUGHTON *et al*., 1995), no deposits are unequivocally related to any proposed caldera-forming events or documented collapse structures. The Mangakino and Whakamaru calderas also have effectively no surface expression, and recent work within the proposed Maroa Caldera does not indicate any separate caldera-forming event or caldera structure associated with the Maroa Dome Complex (LEONARD, 2003). Further calderas may be implied by extensive ignimbrite deposits exposed at the surface (e.g. Ohakuri Ignimbrite; GRAVLEY, 2005), and in drillhole samples (e.g. Rautawhiri Breccia; BROWN, 1994) but source areas do not provide evidence of caldera structure at the surface. Even where calderas are exposed at the surface, caldera structure is often obscured by caldera infill, including both intra-caldera ignimbrite and post-caldera volcanism. In addition, coincidence with intense regional faulting at some calderas forms complex structures where the relative contributions of volcanism and tectonism in landscape development are intimately associated and potentially difficult to resolve. Our current recognition of calderas is shown diagrammatically in FIG. 2.

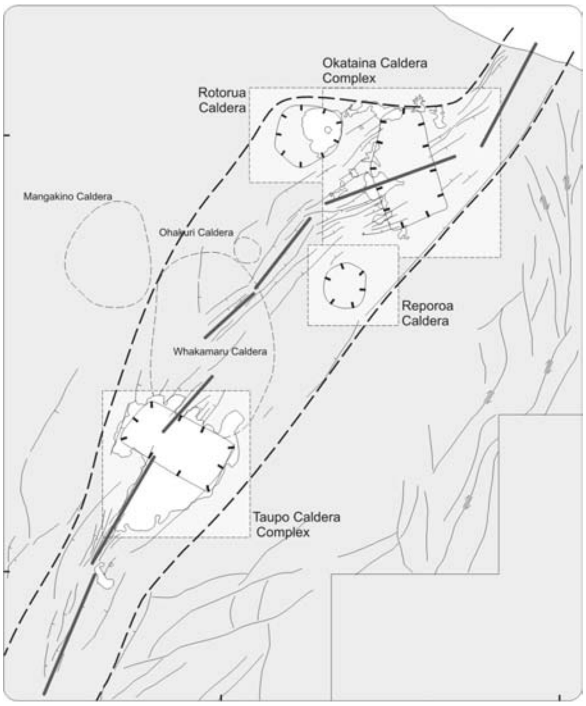

Figure 2 Summary of regional structure of TVZ and the location of currently recognised calderas. The highlighted calderas are the four 'modern' calderas (<300 ka) of Spinks et al (in press). The solid lines indicate rift segments of Acocella et al (2003).

Geophysical Analysis

Geophysical techniques, particularly gravity analysis, help elucidate the geometry and extent of caldera structures at depth. Gravity response is a function of density contrasts between lithologies, and for calderas, where dense basement rocks are deeper within the caldera than outside the caldera margins, burial by a potentially thick succession of intra-caldera, low-density pyroclastic material leads to a negative gravity anomaly. A caldera is therefore expected to have a negative gravity anomaly that will reflect the shape of the collapse structure at depth.

TVZ is characterised by a broad gravity low, and superimposed on this are several large negative residual gravity anomalies up to 75 mGal which indicate the presence of thick sequences of low-density volcaniclastic sediments and effectively mark the location of the rhyolitic calderas (ROGAN, 1982; DAVY & CALDWELL, 1998). Major well-defined negative gravity anomalies are coincident with the Okataina and Taupo caldera complexes, and an extensive region of gravity lows extends between these structures. These partly coincide with documented calderas and as such may provide a more accurate depiction of the buried caldera structures such as Whakamaru and Mangakino. While it is somewhat justifiable to consider much of the basement depression in the central TVZ (inside the -40 mGal contour for example) representative of caldera collapse, the gravity signal records zones of relatively low-density material, and these could similarly be accounted for by progressive filling of tectonic structures from various adjacent sources.

POST 350KA CALDERAS IN TVZ

In the following sections the post 350ka TVZ calderas (Whakamaru, Reporoa, Ohakuri, Rotorua, Okataina, Taupo) are considered in light of existing volcanological, geochemical and geophysical data, and new morphological and structural data, derived from DEM analysis and field studies, to assess the influence of the structural framework on caldera shape and development.

Whakamaru Caldera and Maroa Dome Complex

The proposed Whakamaru Caldera has no clear topographic margin and was proposed by WILSON *et al.* (1986) on the basis of the thickness and distribution of the Whakamaru-group ignimbrites, exposed east and west of central TVZ (FIG. 3). Whakamaru group ignimbrites constitute the largest eruptive episode in TVZ history, with a exposed volume of at least 1000 km^3. These ignimbrites extend north to the southern margin of OVC, east and west to the boundaries of TVZ and south to partially form the eastern walls of Taupo Caldera. Several episodes of collapse occurred at Whakamaru Caldera, with dome emplacement between collapse events. Other caldera boundaries are defined based on drillhole thickness of Whakamaru ignimbrite and are thick inside the structure (Wairakei, Mokai, Tauhara, Rotokawa) and thin (outflow sheets) outside the structure (Broadlands, Waiotapu) (BROWN 1994).

The proposed Whakamaru caldera is defined to the west by the Western Dome Belt, a 32 km long curvilinear chain of simple and compound silicic domes inferred from field evidence to post-date the Whakamaru eruptions (WILSON *et al.*, 1986). WILSON *et al.* (1986) divided the Western Dome Belt into 1) the Western Dome Complex (WDC), comprising the domes south of the Waikato River, and 2) the North-western Dome Complex (NWDC), north of the Waikato River, They are regarded as the result of post-collapse volcanism localised along the western caldera margin. Eruption of the domes has clearly been controlled by an N-S-trending fault system which has subsequently ruptured to displace the domes. Domes immediately east of the faults are probably younger features. Given that the domes and faults are aligned along a lineation oblique to the regional trend, if the lavas of the WDC are post-collapse features, then faulting likely relates to continued movement along the margins of the Whakamaru Caldera.

Domes of the NWDC curve around from an N-S orientation associated with the WDC, to trend NE at the northern end of the complex. The semi-continuous fault pattern suggests these faults too may reflect the caldera margin, but could equally reflect the northwestern margin of TVZ.

Maroa Dome Complex is an accumulation of youthful simple and composite silicic domes. Dome are strongly aligned along NNE trends and extensively faulted along the same lineation, indicating the same regional structure is responsible for controlling vent locations and subsequent deformation. Vent and fault lineations are sub-parallel with faulting in the Kapenga graben to the NE.

Reporoa Caldera

Reporoa Caldera (NAIRN *et al*., 1994) is located at the northern end of the Taupo-Reporoa depression ~15 km E of the Kapenga segment axis (FIG 2), originally interpreted as part of a large fault angle depression between the Taupo and Kaingaroa fault belts (MODRINIAK & STUDT, 1959). It was redefined by NAIRN *et al.* (1994) as a caldera and the source of the 0.23 +/- 0.01 Ma (HOUGHTON *et al*., 1995) Kaingaroa Ignimbrite, with a total eruptive volume of 100 km^3 (NAIRN *et al*., 1994; BERESFORD & COLE, 2000a). Kaingaroa Ignimbrite extends radially for 20-30 km beyond the caldera, mostly to the east of Reporoa Caldera where it caps the Kaingaroa Plateau (FIG. 4).

Pre-caldera volcanism in the Reporoa area comprises rhyolite lavas unrelated to the Kaingaroa magma system or the formation of Reporoa caldera (BERESFORD & COLE, 2000a) and older ignimbrites from caldera sources to the west (RITCHIE, 1996; WILSON *et al*., 1986; BERESFORD *et al*., 2000a). Minor (<2 km^3) post-caldera rhyolite domes are geochemically and isotopically distinct from the Kaingaroa magma system (BERESFORD, *et al.,* 2000). Lithic componentry data for the Kaingaroa Ignimbrite presented by BERESFORD & COLE (2000a) identify multiple stages in the eruption event: 1) an initial single vent phase; 2) a multiple vent or ring fracture phase on the eastern side with asymmetric caldera collapse leading to eastward-directed pyroclastic flows; 3) piston collapse accompanied by radially directed pyroclastic flows.

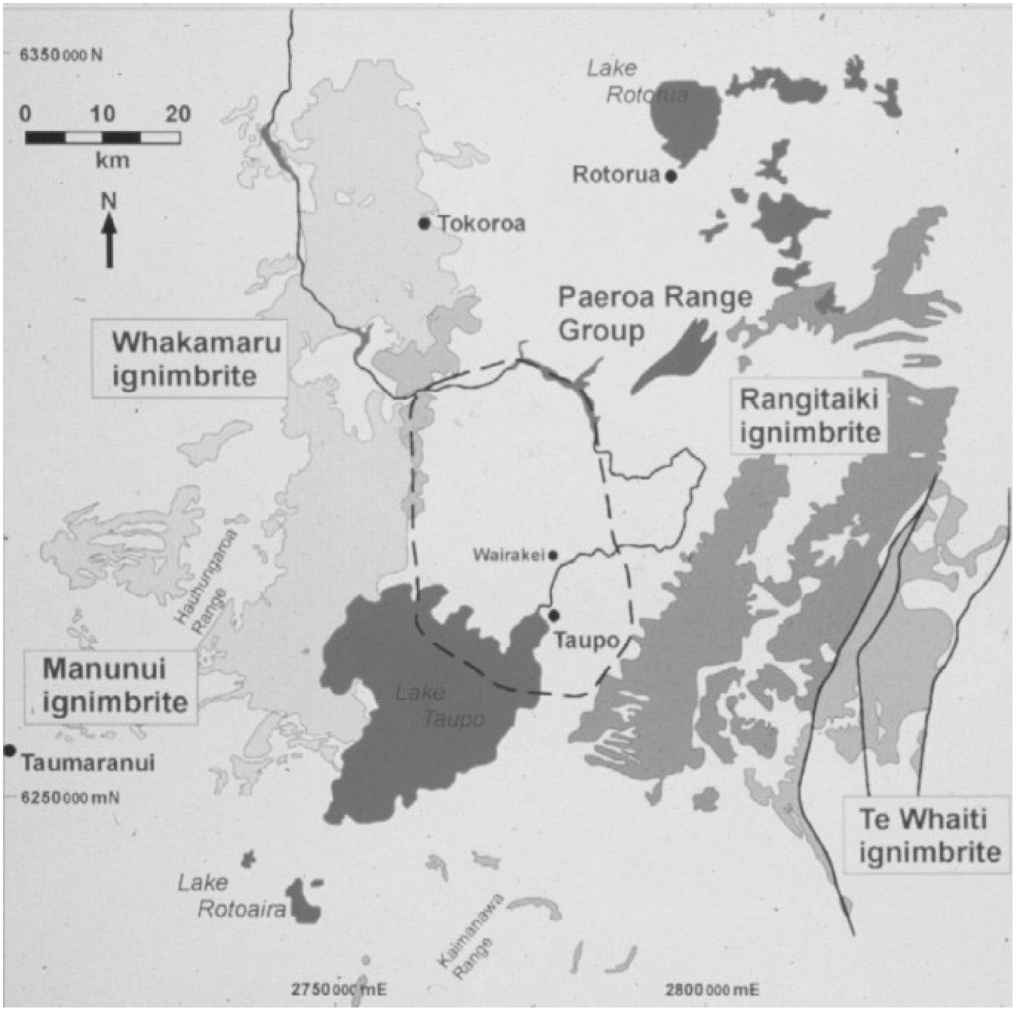

Figure 3 Map showing the distribution of outcrop of the Whakamaru group ignimbrites (from Brown, et al., 1998). The dashed line represents the outline of the Whakamaru caldera as proposed by Wilson et al (1986).

The caldera has a small but clear negative gravity anomaly (NAIRN *et al*., 1994; STAGPOOLE, 1994; STAGPOOLE & BIBBY, 1999) and a low Vp anomaly consistent with low density, low Vp caldera fill (SHERBURN *et al*., 2003). The gravity anomaly corresponds well with the topographic expression of the caldera, with a gentle and largely open western margin and a steep eastern margin, consistent with asymmetric collapse (BERESFORD & COLE, 2000a). Gravity data partly define the buried southern margin, which NAIRN *et al.* (1994) consider to coincide with a small rhyolite dome. NAIRN *et al.* (1994) also interpret post-caldera rhyolite domes and a buried dome complex inferred to exist by magnetic studies (SOENGKONO & HOCHSTEIN, 1996) to have erupted along fractures related to the caldera rim and a supposed inner caldera ring fault.

New DEM and field data (SPINKS *et al.,* in press) show that Reporoa caldera is located several km eastwards from the eastern boundary of the area of active tectonism within TVZ, most of the active faults being restricted to the Kapenga graben. Kaingaroa Ignimbrite extends eastward from the caldera, capping the Kaingaroa Plateau and forming a clear geomorphic fan on a sequence of older ignimbrites extending to the axial ranges. The asymmetry of Kaingaroa Ignimbrite distribution is partially an artefact of the heavily faulted terrain to the west of the caldera. Distribution of the Kaingaroa Ignimbrite in this area is strongly controlled by normal faulting (BERESFORD, 1997) and the situation is analogous to that for the Mamaku Ignimbrite from Rotorua Caldera, which is poorly exposed within the adjacent active rifting zone.

Reporoa is a morphologically simple sub-circular caldera (FIG. 4), with approximate dimensions of 11 x 13 km and well-preserved 250 m high collapse scarps along the northern boundary. The N-S long axis of the caldera (eccentricity E = 0.81) is oblique to the regional trend of faults to the west; in the east a NE-trending fault scarp merges with the N-S trending eastern caldera margin. The flat-floored caldera has a well defined topographic margin in the north and east, but is open to the west and south. The caldera margin is neither dissected by younger faults nor does it truncate older structures. Reporoa has contained lakes at various stages in its history, evidenced by lacustrine sediments and terraces above the current basin floor (MANVILLE, 2001 *and refs within*). Minor lineaments within the caldera may record modern subsidence or reflect the lacustrine history of the basin.

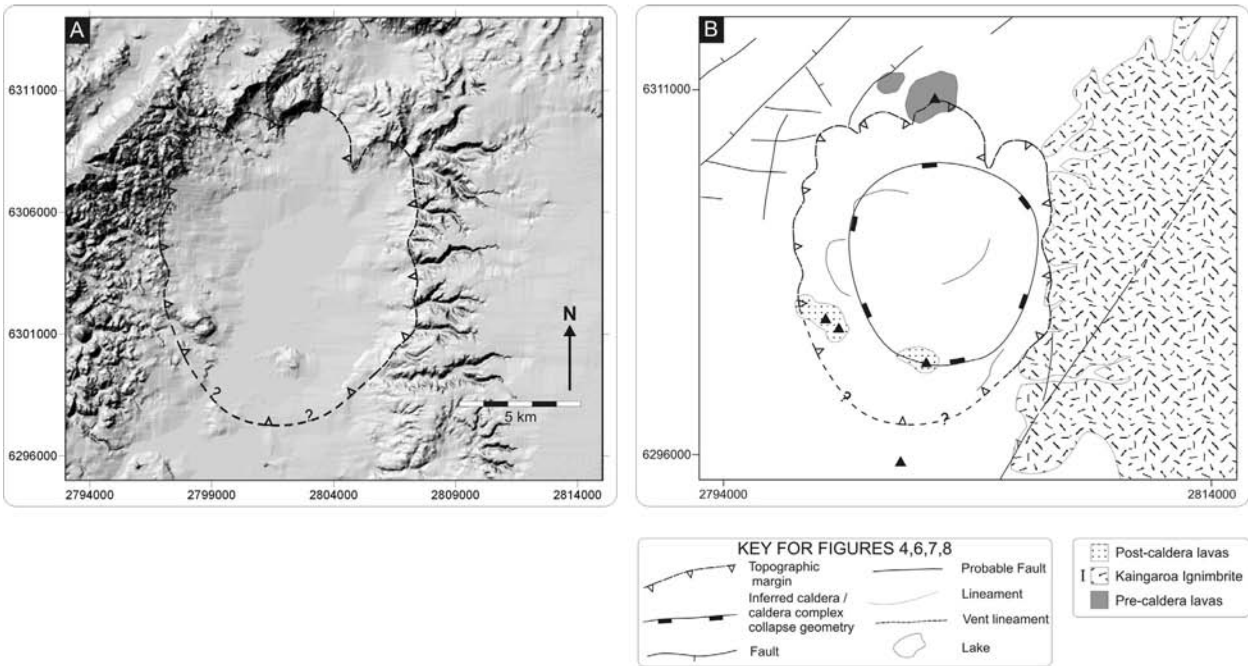

Figure 4 Reporoa Caldera. **A:** Shaded relief image generated from a 1:50,000 scale DEM; Grid coordinates are shown in the New Zealand map grid (NZMG). **B:** Structure map of the Reporoa Caldera derived from analysis of DEM data. Also shown are pre- and post-caldera lavas and the Kaingaroa ignimbrite related to caldera formation. (from Spinks et al, in press)

BERESFORD & COLE (2000a) interpret the eastern margin of Reporoa Caldera as coinciding with the Kaingaroa fault forming the eastern margin of the Taupo-Reporoa Basin. In fact, this fault is much more likely to continue sub-parallel to regional structure and pass obliquely beneath the Kaingaroa Plateau. BERESFORD (1997) inferred a 'hole' in the pre-caldera stratigraphy where proximal flows of the Kaingaroa Ignimbrite were restricted; middle and upper units of the ignimbrite maintain a near uniform thickness across the plateau. This 'hole' likely represents the down-faulted area west of the NE-trending Kaingaroa Fault, restricting early flows, and explaining the lack of early flow units of the Kaingaroa Ignimbrite. A NE-trending structure is visible northeast of Kaingaroa plateau, dividing two opposing drainage networks, and may be reflected in a subtle elevation change (west side downthrown) across the plateau.

Rotorua Caldera

Rotorua caldera is perhaps the most conspicuous caldera in TVZ, accentuated by its large, sub-circular caldera lake, Lake Rotorua (FIG. 5). The caldera is located 15-20 km NW of the junction between Okataina and Kapenga rift axes (FIG. 2), and formed during and immediately following the eruption of the c.240 ka Mamaku Ignimbrite (SHANE *et al*., 1994; HOUGHTON *et al*., 1995; BLACK *et al*., 1996; MILNER *et al*., 2002; WILSON *et al*., 1984), with a minimum eruption volume (including intra-caldera ignimbrite) of 145 km^3 DRE (MILNER *et al*., 2003). Some authors have proposed earlier events at Rotorua caldera to account for older ignimbrites in the area (WOOD, 1992), or that Rotorua is not a caldera at all (HUNT, 1992), but a detailed study by MILNER *et al.* (2002, 2003) confirm Rotorua as a single-event caldera, and the source of the Mamaku Ignimbrite.

A number of pre-caldera rhyolite domes are exposed in the vicinity of Rotorua Caldera. MILNER *et al.* (2002) showed that those on the rim of the caldera are geochemically distinct from each other and from the Mamaku magma system. The post-caldera Ngongotaha and Pukehangi rhyolite dome complexes, and lavas exposed at

Kawaha Point are geochemically similar to the Mamaku Ignimbrite system and may reflect a final eruptive phase from the Mamaku magma system (MILNER *et al*., 2002). Smaller rhyolite domes are geochemically distinct and thought to be much younger.

Stratigraphic evidence outlined by MILNER *et al.* (2002) indicates caldera collapse occurred throughout the eruption and emplacement of the Mamaku Ignimbrite during a single eruptive episode. MILNER *et al.* (2002) describe asymmetric caldera collapse deepest in the southwest of the caldera, with a component of downsag expressed in the overlying Mamaku Ignimbrite. Mamaku Ignimbrite geochemistry indicates the eruption of a single, compositionally zoned magma reservoir, represented by three petrogenetically related pumice types. An andesitic juvenile component in upper parts of the Mamaku Ignimbrite are thought to reflect a discrete magma injected into the residual silicic chamber and tapped during later phases of the eruption during advanced stages of caldera collapse (MILNER *et al*., 2003).

Rotorua Caldera is characterised by an N-S elongate negative residual gravity anomaly to the west and southwest of Lake Rotorua, including Rotorua city and the post-caldera rhyolite dome of Ngongotaha (ROGAN, 1982; DAVY & CALDWELL, 1998; HUNT, 1992). The surrounding gravity contours are not specifically concentric to the caldera margin, defining an asymmetric rise in basement towards the northeast and northwest caldera margins. The basement gradient is shallowest towards the east and steepest around the south-western margin.

DEM and field data show that Rotorua Caldera is located several km westwards from the present area of active tectonism within TVZ, with most of the active faults restricted to the junction between the Kapenga and Okataina segments (FIG. 2). To the south and east of the caldera, the Mamaku Ignimbrite surface is downfaulted and has been largely overprinted by volcanism and faulting. This is in contrast with the extensive ignimbrite surface to the north and west of the caldera reflecting the location of Rotorua Caldera west of the actively rifting portion of TVZ.

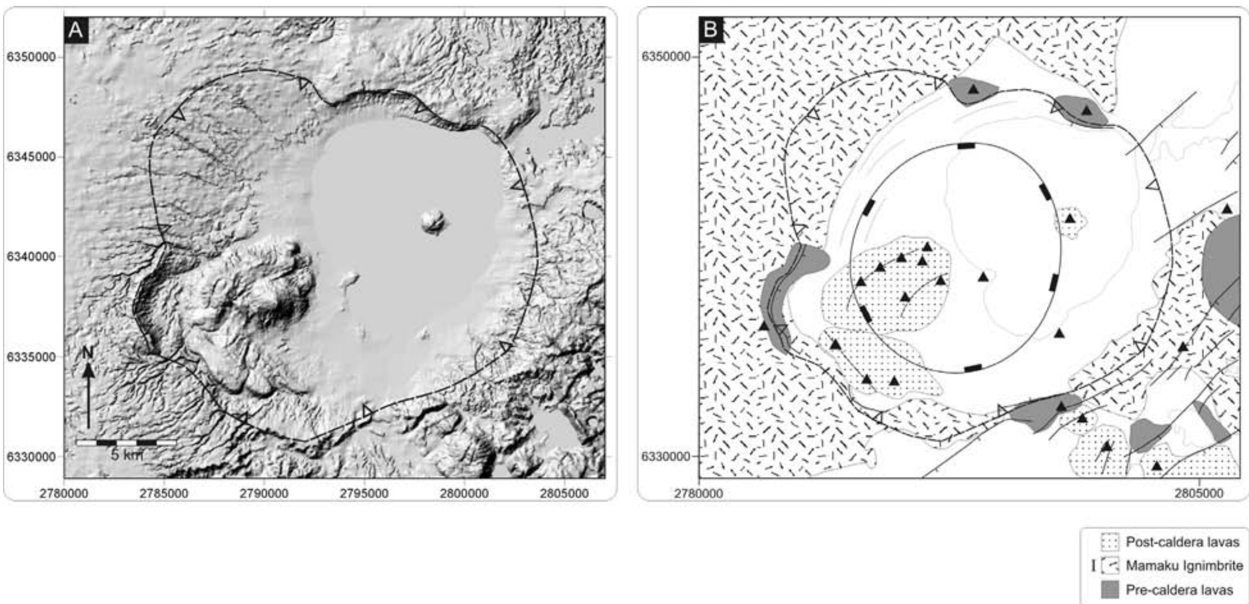

Figure 5 Rotorua Caldera. **A:** Shaded relief image of Rotorua Caldera. **B:** Structure map of Rotorua Caldera generated from analysis of DEM data. Also shown are pre- and post-caldera lavas and the Mamaku ignimbrite related to caldera formation (from Spinks et al., in press)

Rotorua is a simple sub-circular caldera with dimensions of approximately 20 x 16 km (FIG. 5). The caldera floor is dominated by the ~9 km diameter caldera lake and the youthful morphologies of post-caldera rhyolite dome complexes. Pre- and post-caldera rhyolite domes form prominent topographic features against the flat-lying ignimbrite plateau to the west of the caldera. The topographic margin is semi-continuous around the caldera and best expressed where formed by arcuate scarps in pre-caldera rhyolite domes or Mamaku Ignimbrite; elsewhere the margin is marked by the limit of the inwards dipping Mamaku Ignimbrite, referred to as the limit of deformation by MILNER *et al.* (2002). The southeast margin of the caldera roughly parallels NE-trending regional faults in the adjacent Okataina segment. The caldera margin does not truncate any regional structures and only in the NE is dissected by younger faulting. Other lineaments in the caldera are arcuate and relate to caldera bounding scarps and associated deformation, rather than to regional structure. In the northwest of the caldera several low scarps sub-parallel to the caldera margin are located within the area defined by MILNER *et al.* (2002) as having deformed by downsag into the caldera during collapse. The vents of the Ngongotaha and Pukehangi post-caldera rhyolite domes define several lineations within the caldera, interpreted by MILNER *et al.* (2002) as reflecting eruption along major dislocations bounding the area of deepest basement collapse.

Ohakuri Caldera

The Ohakuri caldera is a newly recognised structure in the Whangapoa basin, 25kms SSW of Rotorua (FIG. 6), which is considered the source of the c. 240 ka Ohakuri pyroclastic deposits (GRAVLEY, 2005). It overlies the northern margin of the older Whakamaru caldera and lies adjacent to the axis of the modern Taupo Fault Belt. It is difficult to define either the topographic or structural caldera margins precisely because of subsequent deposition of volcaniclastic sediments, but its presence is inferred from distribution of air fall deposits, distribution of and transport directions within the Ohakuri ignimbrite, and from geophysical data.

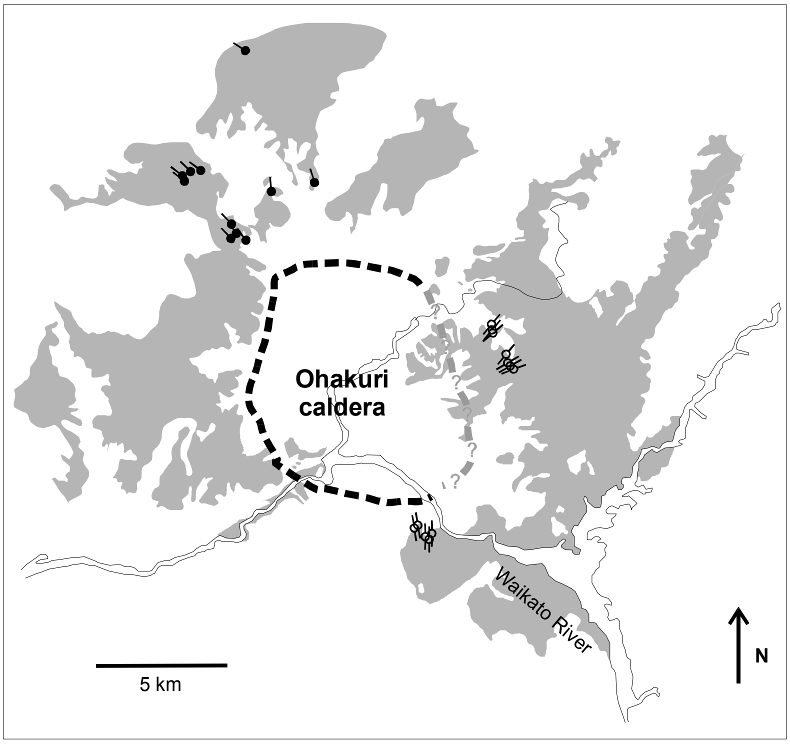

Figure 6 Ohakuri caldera and pyroclastic deposits (from Gravley, 2005). Filled circles represent uni-directional indicators from dune structures (with bar pointing in direct of flow). Open circles represent bi-directional indicators measured from channel structures.

Stratigraphic evidence presented by GRAVLEY *et al.* (2003) suggests that the Mamaku ignimbrite and the Ohakuri pyroclastic deposits were erupted in rapid succession, from the Rotorua and Ohakuri calderas respectively. They suggest that the most feasible way of achieving this linkage is through volcano-tectonic processes, in which contemporaneous faulting triggered almost concurrent events 25km apart.

Okataina Caldera Complex

Okataina Caldera Complex (OCC) is a complex of overlapping and nested collapse structures (FIG. 7), largely filled by the products of post-caldera rhyolite volcanism. The composite structure is the result of two main collapse events associated with the 0.28 ± 0.01 Ma Matahina Ignimbrite (BAILEY & CARR, 1994; date from HOUGHTON *et al*., 1995) and 65 ka Rotoiti eruption (NAIRN, 1981, 1989; date from HOUGHTON *et al*., 1995), and modified by substantial intra-caldera rhyolite volcanism (e.g. JURADO-CHICHAY & WALKER, 2000; NAIRN, 1989, 2002). Further older (>300 ka) and younger (>65 ka) collapse events are likely, but potential deposits and precise collapse margins are obscured and/or overprinted by subsequent activity. Magmatic volume estimates for the Matahina and Rotoiti events (including intra-caldera estimates) are 150 km^3 (BAILEY & CARR, 1994) and 120 km^3 (FROGGATT & LOWE, 1990) respectively; other eruptives from within and adjacent to OCC account for at least 150 km^3 (e.g. NAIRN, 1989; FROGGATT & LOWE, 1990; BELLAMY, 1991; JURADO-CHICHAY & WALKER, 2001). The Matahina and Rotoiti ignimbrites extend predominantly to the east and north, and appear related to overlapping but distinct sources in the southern and northern parts of the caldera complex respectively (NAIRN, 1989).

A number of rhyolite dome lavas scattered around the rim of the caldera-complex record volcanism in the Okataina area predating the first collapse event (NAIRN, 1989, 2002). No precise dates exist for these lavas, but BOWYER (2001) showed that they are chemically distinct and relate to discrete magma batches. Geochemical variation is small however, and no significant variability exists between pre-caldera lavas adjacent to the Okataina and Rotorua calderas; this would imply that these lavas are not related specifically to a Rotorua or Okataina 'volcanic centre'. Only one pre-caldera magma batch has a similar chemistry with the Matahina magma system (e.g. NAIRN, 1981; BOWYER, 2001).

Lavas and associated pyroclastics erupted between the major caldera-forming events are predominantly exposed to the southwest of the caldera where it intersects the Kapenga axial rift segment (FIG. 2) and relate to multiple magma batches (BELLAMY, 1991; BOWYER, 2001). Following the second caldera collapse event during the eruption of the Rotoiti Pyroclastics, a major phase of explosive volcanism ensued from sources within the caldera complex prior to the development of the two large rhyolite lava massifs that currently fill the caldera. Two main magma types were erupted during the explosive phase, generating 14 eruptive episodes (SMITH *et al.*, 2002); during more recent effusive activity multiple magmas were often involved with a single eruptive episode. The two documented caldera-forming events at Okataina are spatially overlapping but are significantly temporally separated (> 200 ka) and reflect geochemically distinct magma systems (BURT *et al.*, 1998). Both the Matahina and Rotoiti ignimbrites exhibit minor geochemical variation (BURT *et al.*, 1998) as likely by-products of weakly zoned magma chambers. Volcanism in the Okataina area from the earliest to the most recent eruptives, including the caldera forming events, therefore records the eruption of multiple discrete magma chambers rather than the progressive tapping of a single large chamber.

A distinct large negative residual gravity anomaly (ROGAN, 1982; DAVY & CALDWELL, 1998) and low Vp anomaly (SHERBURN *et al.*, 2003) define an N-S elongated depression consistent with the mapped caldera margin and filled with a large volume of low Vp, low density, volcaniclastic sediment. A clear low Vp anomaly at 4km effectively corresponds to a minimum depth extent of the collapse structure (SHERBURN *et al.*, 2003). Gravity data presented by NAIRN (2002) indicates a N-S elongate negative gravity anomaly roughly concentric to the topographic margin, and centered beneath Tarawera Volcanic Complex and the southern part of Haroharo Volcanic Complex. The contours open on the west side of the structure but gravity high's separate the structure from basement highs to the east and Rotorua Caldera to the west. Topographic embayments in the caldera complex margin are also peripheral to the main basement depression indicated by gravity and Vp data.

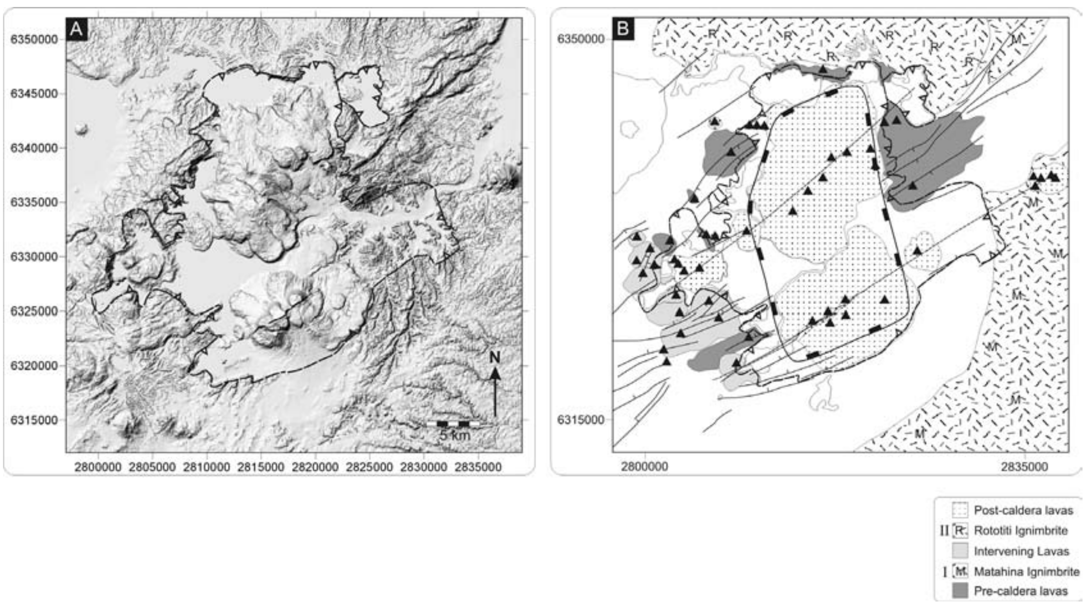

Figure 7 Okataina caldera complex. **A:** Shaded relief image of Okataina Caldera Complex; **B:** Structure map of Okataina Caldera Complex from analysis of DEM data. Also shown are pre- and post-caldera lavas and caldera-forming ignimbrites. I and II relate to the first and second caldera-forming events respectively (from Spinks et al., in press).

Morphotectonic analysis of the caldera using DEM and Remote Sensing data reveals that Okataina is significant in its location at a structurally complex transfer zone in the axial rift where the axes of adjacent segments are offset by more than 20 km. This major ENE-trending bend in the transtensional rift accompanies local rotation of the extension direction resulting in a zone of orthogonal extension. The OCC is a complex structure delineated by morphologically youthful intra-caldera volcanic features in juxtaposition with the older and more dissected terrain of pre-caldera lavas and ignimbrites forming the caldera margin. The 28 x 15 km caldera complex is strongly rectangular with a long axis trending N8°W, roughly perpendicular to the Okataina rift axis.

The topographic margin at Okataina is variably manifest as scalloped slump scars in pre-caldera rhyolite domes and ignimbrites, eroded caldera walls, rectilinear fault scarps coincident with regional faulting, and in the SW by the steep margins of post-caldera constructional rhyolite domes. As such, the composite topographic margin defines a depression considerably modified from the original multiple collapse structure. Distinct embayments occur on each side of OCC where it is intersected by regional faulting of the axial rift within the Okataina transfer zone. These are contiguous with two intra-caldera dome complexes forming two overlapping linear vent zones, which transect the caldera complex as the lateral continuation of the adjacent rift segment axes. The boundaries of individual collapse events are complex and largely overprinted by subsequent volcanism and tectonism, but caldera reconstructions suggest the major collapses are centered on the axes of the intersecting rift segments. Lakes at Okataina exhibit a moat pattern where they have ponded between the topographic rim of the caldera and caldera-filling post-caldera constructional volcanism; lakes filling earlier manifestations of the structure may have been much larger.

Taupo Caldera Complex

Taupo Caldera Complex (COLE *et al*., 1998) has been frequently active in the past ca. 65 ka (WILSON *et al*., 1986; HOUGHTON *et al*., 1995), while its poorly constrained early eruptive history indicates activity over ca. 300 ka (WILSON *et al*., 1986; COLE *et al*., 1998). The caldera-forming Oruanui eruption at 26.5 ka (calibrated; WILSON, 1993) generated a c.430 km^3 fall deposit, a 320 km^3 bulk volume non-welded density current deposits (mostly ignimbrite) and ~420 km^3 of caldera-fill material erupted, equivalent to ~530 km^3 of magma (WILSON, 2001). The Oruanui event is thus largely responsible for the modern caldera morphology (Fig. 8). WILSON (1993) has identified 28 separate eruptions since the Oruanui eruption, the most recent and largest of these, the caldera forming 35 km^3 Taupo ignimbrite eruption, occurred about 1800 years ago from vents near the Horomatangi Reefs in the eastern part of the lake (WILSON & WALKER, 1985; SMITH & HOUGHTON, 1995).

The early history (>65 ka) of volcanism in the vicinity of modern Lake Taupo is represented mainly by domes and limited pyroclastics scattered around the lake (SUTTON *et al*., 1995). Two ignimbrites exposed on the margin of the caldera are commonly attributed to a Taupo source (SUTTON *et al*., 1995; COLE *et al*., 1998), although their limited extent means their relationship to the current caldera complex is ambiguous. Pre-caldera rhyolite lavas form a series of headlands along the northern caldera margin and to the southwest of the caldera, while the large caldera-filling domes and flows characteristic of OCC are noticeably absent. Post-Oruanui activity has been studied in detail, and a sequence of 28 eruptions is now recognized (WILSON, 1993; SUTTON *et al*., 1995). Vents for the post-Oruanui explosive eruptions are inferred by isopach data to be concentrated along a NE-trending lineation in the eastern part of modern Lake Taupo (WILSON, 1993). Construction of a dome complex in this area during the post-Oruanui phase is suggested by lithic componentry data for the Taupo Ignimbrite (COLE *et al*., 1998) with its likely destruction during the Taupo eruption. Lithic componentry analysis of both the Oruanui and Taupo ignimbrites identifies different lithic suites, interpreted by COLE *et al.* (1998) as reflecting dissimilar sub-caldera geology beneath mutually exclusive collapse structures.

Petrological studies (e.g. SUTTON *et al*., 1995; 2000) show a complex magmatic system, involving the stepwise appearance of compositionally distinct magma batches with short crustal-residence times. Eruptives prior to the Oruanui eruption form distinct compositional and spatial groups, while a large isotopically homogeneous magma body was generated prior to the Oruanui caldera-forming eruption (SUTTON *et al*., 1995). Some of the pre-Oruanui domes exposed on the northern caldera margin, and widespread tephras erupted between 65ka and the Oruanui eruption, are the same composition as the Oruanui magma, and thus record the coalescence of a large magma chamber. SUTTON *et al.* (1995) also point out that compositionally distinct magmas were erupted during the same period from different areas around Taupo, and that ignimbrite pumice chemistry indicates additional magma batches may have been eviscerated during the Oruanui eruption. Eruptives of the post-Oruanui sequence form four temporally grouped magma types and are compositionally distinct from the Oruanui magma. The youngest magma, associated with the Taupo eruption, represents the largest homogeneous magma accumulation in the post-Oruanui sequence (SUTTON *et al*., 1995).

A large trapezoidal-shaped negative Bouguer gravity anomaly is documented over the northern part of the lake (DAVY & CALDWELL, 1998) consistent with earlier onshore investigations (ROGAN, 1982). It is the most intense negative gravity anomaly in TVZ (DAVY & CALDWELL, 1998), and indicates a collapse structure filled with volcaniclastics of relatively low-density. The gravity anomaly is consistent with a caldera collapse structure elongate NW-SE, perpendicular to the axial rift zone in this segment. The gravity data do not facilitate identification of individual collapse structures, and DAVY & CALDWELL (1998) consider the structures are nested, with the Taupo eruption producing additional subsidence in the northeast part of the modern lake. Geophysical data also demonstrate differential subsidence towards the caldera in the southern part of the lake, and a NW-SE-trending structural boundary marking the southern caldera margin (DAVY & CALDWELL, 1998). Seismic reflection, gravity and magnetic data presented by DAVY & CALDWELL (1998) all suggest that a line between Karangahape Cliffs and Motutere Point marks a major structural boundary perpendicular to the trend of TVZ.

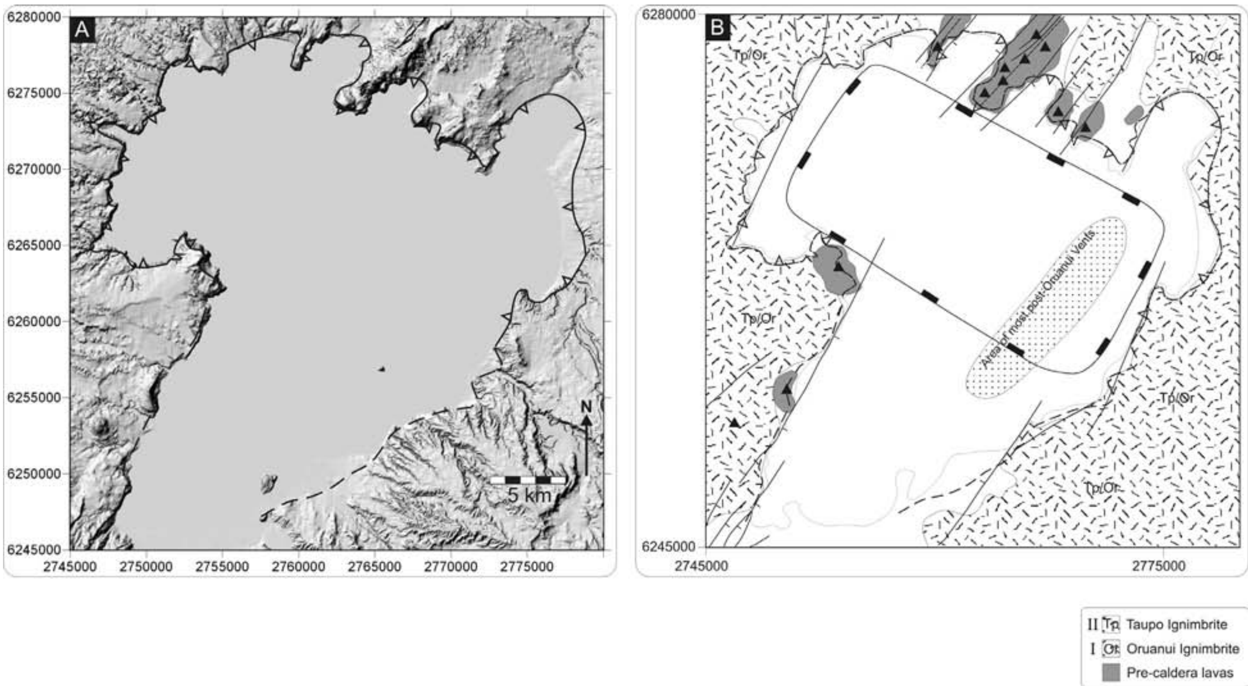

Figure 8 Taupo Caldera Complex. **A:** Shaded relief image of Taupo Caldera Complex; **B:** Structure map of Taupo Caldera Complex from analysis of DEM data. Also shown are pre-caldera lavas and caldera-forming ignimbrites and the location of the post-Oruanui vents (from Spinks et al., in press).

New DEM and field data show that Taupo is located within the axial rift zone of TVZ. The 28 x 16 km caldera complex is rectangular and a long axis trending N63°W, roughly perpendicular to the Taupo North rift segment (FIG. 8). The northern caldera margin intersects NE-trending regional faults controlling a series of peninsulas and embayments in the topographic margin. Pre-caldera lavas to the southwest and north of the modern lake are aligned along regional trends. To the east and west of the caldera, the planar ignimbrite surface is gently tilted toward the lake where the eastern and western margins are partially eroded but generally NE-trending linear features .

The southern part of Lake Taupo occupies a NE-trending fault-bounded depression intersecting the southern caldera margin; the western margin of this structure is a continuation of fault systems dissecting the Tongariro Volcanic Centre to the south. A prominent structural feature is the divergence in fault trend (~20°) to the south and north of the caldera complex. This bend effectively forms the boundary between the Tongariro and Taupo South rift segments. Vents for pre-caldera lavas to the south and north of the caldera complex lie along NE-trending lineaments; the vents for post-Oruanui eruptions mostly occur along the eastern edge of the caldera complex (WILSON, 1993).

Across-axis relationship between tectonism and magmatism

The characteristics of Modern TVZ calderas (i.e. <300 ka; Taupo, Okataina, Rotorua and Reporoa) clearly elucidate the complex eruptive and structural history of Okataina and Taupo in relation to Rotorua and Reporoa.

These data therefore show that caldera structures of Modern TVZ can be divided into two groups (1) extra-rift calderas (Reporoa and Rotorua) are simple, relatively small, sub-circular, monogenetic structures, without significant coupling to active regional structure, and where caldera-forming ignimbrites are associated with zoned magma chambers, and (2) intra-rift caldera complexes (Okataina and Taupo) are large, multiple collapse structures, with rectangular geometries and clear coupling to regional structure; here homogeneous magmas are erupted during caldera-forming events (FIG 9). This distinction demonstrates the role of active regional tectonics in influencing the location, structure and development of caldera systems within a rift zone.

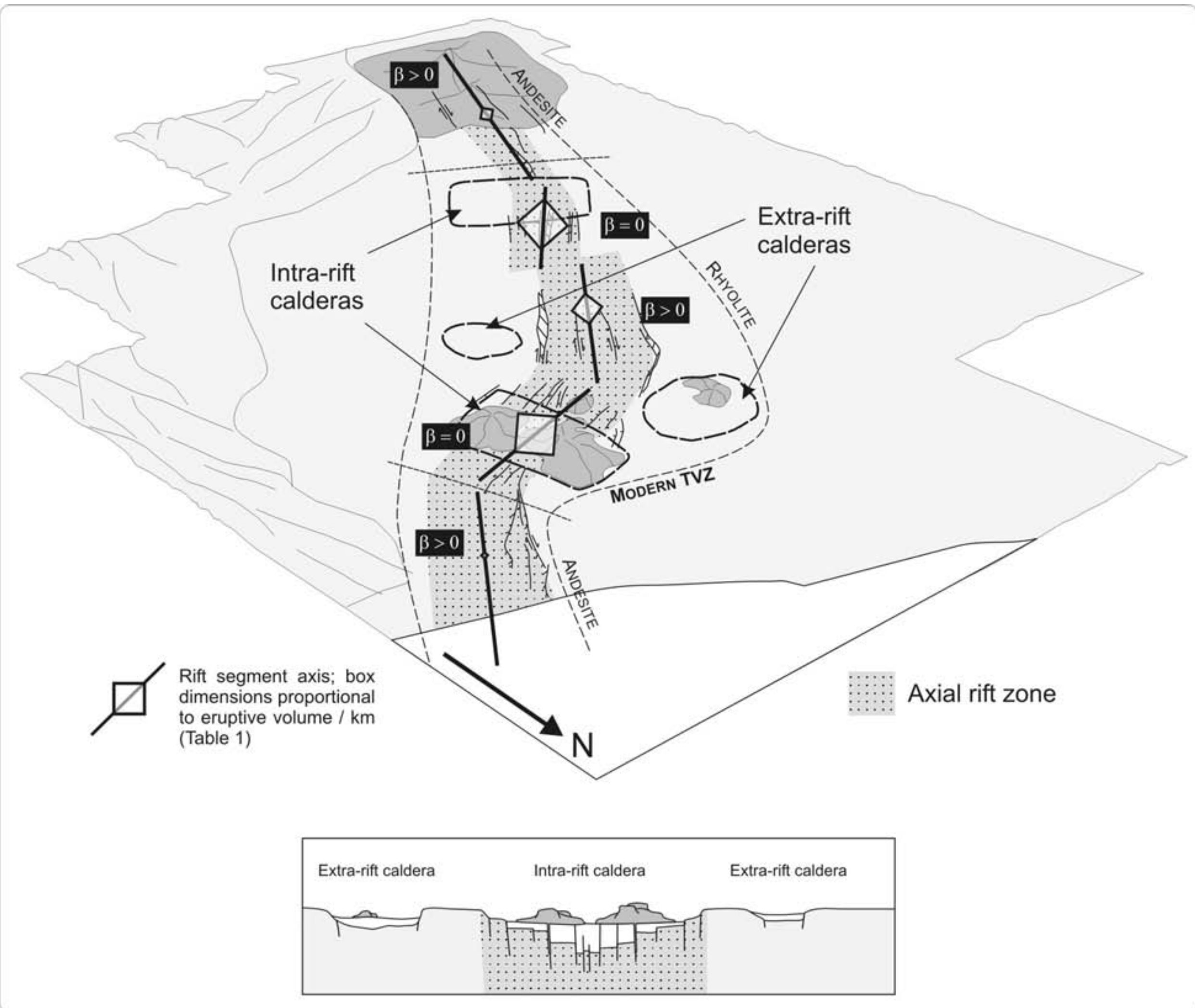

Figure 9 Schematic figure of TVZ (oblique map and section view) summarising the overall structural control on volcanism. The variation in the dextral component of extension (ß), the erupted volumes (proportional to squares), and the caldera structures in 'modern' TVZ, are reported as a function of segment trend (along axis) and the distance from axis (across axis). (from Spinks et al., in press)

TOUR ITINERARY

The tour is based in Taupo. Day 1 will concentrate on the Taupo and Whakamaru calderas and their deposits, day 2 on Maroa Volcanic Centre, Ohakuri and Rotorua calderas and their deposits, and day 3 on Okataina. A map of the tour route will be given out at the beginning of the tour.

DAY 1: FRIDAY 9 DECEMBER: BACKGROUND INFORMATION

Whakamaru Group Ignimbrites (From BROWN *et al*., 1998)
The term 'Whakamaru group' was introduced as an informal name by WILSON *et al.* (1986), and refers collectively to Whakamaru, Manunui, Rangitaiki, Te Whaiti, Wairakei, and the Paeroa Range Group ignimbrites, all of which share similar petrographic features and inferred or measured radiometric ages between 330 and 340 ka. The Whakamaru group ignimbrites crop out over two broad areas on the eastern and western margins of the TVZ, covering a total area of 13,000 km^2 (FIG 3), and having a collective volume of more than 1000 km^3 (WILSON *et al.,* 1986). On the western side of the TVZ they are known as the Whakamaru and Manunui ignimbrites, and on the eastern side of the TVZ as Te Whaiti and Rangitaiki ignimbrites. Along the central axis of the TVZ, Whakamaru group ignimbrites are largely buried by younger volcanic deposits, but occur in geothermal drillholes (e.g., Wairakei ignimbrite; GRINDLEY, 1965) and are correlated with part of the Paeroa Range Group ignimbrites which crop out along the Paeroa Fault Scarp (HOUGHTON *et al.,* 1995). In addition, a widespread fall deposit known as the Mt. Curl or Rangitawa Tephra is chemically and chronologically linked to the ignimbrites, but the crystal-rich nature of the fall deposit precludes it being a simple co-ignimbrite ash-fall and its volcanological relationship to the ignimbrites is not established.

Despite the overall similarity in appearance of the ignimbrites outcropping along the eastern and western margins of the TVZ, Whakamaru and Rangitaiki ignimbrites form a more crystal-rich textural end member that contain distinctive large resorbed quartz crystals, and common quartz-rich welded ignimbrite lithic fragments. Manunui and Te Whaiti ignimbrites, on the other hand, are typically more intensely welded, less crystal- and pumice-rich, and contain predominantly metasedimentary (regolith-derived) lithic fragments. Te Whaiti and Manunui ignimbrites tend to be distributed slightly further south than Whakamaru and Rangitaiki ignimbrites, which form thick welded deposits up to 60km from the inferred caldera margin.

There has been much speculation as to the relationship between Whakamaru and Manunui ignimbrites west of TVZ, and Rangitaiki and Te Whaiti ignimbrites east of TVZ; MARTIN (1965), BLANK (1965) and BRIGGS (1973) considered Manunui to be simply a fine-grained distal equivalent of Whakamaru ignimbrite, while GRINDLEY (1960) and MARTIN (1961) considered them to be separate ignimbrites, representing at least two eruptive episodes over a significant time period (Whakamaru and Rangitaiki ignimbrites overlying Manunui and Te Whaiti ignimbrites respectively). WILSON *et al.* (1986) provided good evidence that Whakamaru group ignimbrites represent at least three eruptive phases, with a total duration of 50-100 ka (1) Manunui/Te Whaiti ignimbrites; (2) Whakamaru/Rangitaiki ignimbrites; and (3) a possible phreatoplinian phase represented by parts of the Paeroa Range group and the Mt. Curl/Rangitawa tephra. While there is strong evidence that the ignimbrites were erupted during more than one episode, more recent Ar-Ar dating and field evidence (BROWN, 1994) indicate there is no significant time break between either Manunui and Whakamaru ignimbrites, or Te Whaiti and Rangitaiki ignimbrites, and they were all erupted over a relatively short period (<10 ka, cf. WILSON et al., 1986).

BROWN *et al.* (1998) considered Manunui ignimbrite equivalent to the stratigraphically lowest unit(s) of Whakamaru ignimbrite exposed along the Waikato River valley (i.e. unit A of in the work of BRIGGS (1976)). Similarly, east of TVZ, Te Whaiti ignimbrite corresponds to the lowermost parts of Lower Rangitaiki ignimbrite. No well-defined contact between Te Whaiti and Rangitaiki ignimbrites has been observed in the field and it may be gradational in nature. Manunui and Te Whaiti ignimbrites are generally only exposed in medial to distal areas where upper, less intensely welded units (Whakamaru and Rangitaiki) have been removed by erosion.

BROWN *et al.* (1998) postulated that the caldera for the Whakamaru group lies to the north of Lake Taupo. This was based on regional geophysical anomalies, and the distribution of ignimbrite outflow sheets in outcrop, and in drillholes.

Rangatira Point ignimbrite (From COLE *et al*., 1998)
The Rangatira Point ignimbrite has previously been referred to as the ‘brown ignimbrite’ (WILSON *et al*., 1986), ‘Rangatira Point ignimbrite’ (SUTTON, 1990) and the ‘welded ignimbrite of Rangatira Point’ (SUTTON, *et al*., 1995). The ignimbrite is not well exposed, but forms 10 - 15m high cliffs on the northern shore of Lake Taupo at Whakamoenga Point, and is best exposed on the shore platform.

The Rangatira Point ignimbrite is grey to brown, and lithic-rich. Pumices locally exceed 300mm diameter and maximum lithic (M_L) dimensions frequently exceed 70mm within well-defined fines-depleted lithic concentration zones associated with segregation pipes, some of which appear to be sheared during late stages of deposition. Intercalated surges and lithic breccias imply a proximity to source, but limited outcrop precludes meaningful assessment of lithic size distribution. The ignimbrite is divisible into two units, a lower brown pumice and lithic-rich ignimbrite and an upper 'sandy-black' pumice-rich ignimbrite. The lower unit contains a single brown rhyolitic pumice type whereas the upper unit is a vitric, fines-poor, dark grey and generally pumice-rich unit, that contains grey/orange, and subordinate highly vesicular black pumices which are flattened in welded sections. Pumices in the basal brown coloured unit at Whakamoenga Point are crystal-poor (5-7%) with oscillatory-zoned plagioclase, orthopyroxene, Fe-Ti oxides and trace quantities of quartz and hornblende (SUTTON, *et al.,* 1995).

The ignimbrite postdates the 0.32 - 0.34 Ma Whakamaru group ignimbrites and underlies lacustrine sediments of the pre-26.5 ka Huka Formation. No age determination is available for the ignimbrite itself, but chemically it belongs to a group of rhyolite lavas and pyroclastics which form the 'Marotiri' magma type of SUTTON *et al.* (1995). This magma type includes a welded ignimbrite at Kawakawa Bay which has been dated by Ar/Ar method at ca. 0.22 Ma (B.F. HOUGHTON, unpublished data), and a comparable age for the Rangatira Point ignimbrite is plausible. Spatially and/or chemically the Rangatira Point ignimbrite is distinct from widespread ignimbrites of locally similar physical appearance and comparable age in the TVZ (Kaingaroa; Pokai) and does not appear to have any other subaerial correlatives (BERESFORD, 1997).

Oruanui pyroclastic deposits (From WILSON, 2001)
WILSON (2001) describes the eruption in terms of 10 phases, nine mappable fall units and a tenth, poorly preserved, but volumetrically dominant, fall unit. Multiple bedding and normal grading in the fall deposits show the first third of the eruption was very spasmodic, with short-lived but intense bursts of activity separated by time breaks up to several months duration. Pyroclastic density currents were erupted through out the eruption with most deposited during phase 10. Lithic lag breccias also occur in phase 10 deposits indicating that this is when most of the ~140 km^2 structural caldera collapsed.

The 1.85 ka Taupo Eruption (From SMITH, 1998)
The 1.85 ka Taupo eruption was the most violent and complex rhyolitic eruption world-wide in the last 5000 years, and the largest caldera-forming eruption in the TVZ since the 26.5 ka Oruanui event. The pyroclastic sequence comprises seven units erupted over six contrasting phases of activity (FIG. 10). The term *unit* is here applied to a deposit of distinctive origin, and the term *phase* is used to denote the equivalent interval of time. The sequence includes three phreatomagmatic deposits emplaced during three phases (units 1, 3, and 4), to plinian phases (units 2 and 5), an intra-plinian ignimbrite unit (unit 6) emplaced during phase 4, and a final caldera-forming phase involving violent emplacement of ignimbrite (unit 7) over a very wide area. Most of the units of this eruption have been studied in some detail (WILSON & WALKER, 1985; and references therein) and a summary only is presented here.

Taupo eruption sequence and deposits
Unit 1, the 'initial ash', is a locally dispersed ($0.05km^3$), fines-rich deposit that represents minor phreatomagmatic activity in the opening stages of the eruption (WILSON & WALKER, 1985). Unit 2 (Hatepe plinian pumice) is a mostly uniform, well-sorted, moderately-sized plinian fall deposit with a bulk volume of $2.5km^3$ (WALKER, 1981). Fine ash beds within this unit in the northerly part of the dispersal area are interpreted as due to minor water-aided aggregation and locally-directed dilute density currents from the margins of the eruption column (TALBOT *et al* 1994).

Unit 3, the Hatepe ash represents a period of large-scale 'wet' activity when abundant external water gained access to the actively vesiculating magma (WALKER, 1981; HOUGHTON & WILSON, 1989). There is abundant evidence throughout this deposit of water-aided deposition and it has been described as an archetypal phreatoplinian deposit (SELF & SPARKS, 1978; WALKER, 1981). Previous studies have calculated a whole-deposit bulk volume of $1.9km^3$ for the Hatepe ash, based on whole-unit thickness contours. Over a significant part of its dispersal area, the top of the Hatepe ash is intensively eroded and it is inferred that the water for this gullying was ejected from the lake (WALKER, 1981). Previous workers have suggested that this gullying represents a break in the eruption sequence of no more than a few weeks.

Unit 4, the Rotongaio ash has been interpreted as the product of large-scale phreatomagmatic activity, and previously classified as phreatoplinian in style (SELF & SPARKS 1978; WALKER 1981). However, the Rotongaio ash is quite different to the Hatepe ash and all other deposits classified as phreatoplinian. It is strikingly fine grained throughout the dispersal area with little material coarser than 1mm, even in the most proximal exposures, and it is composed mainly of poorly to non-vesicular juvenile material. The unit is typically plane-parallel bedded on a mm to cm scale, and beds consist mostly of a range of small (1-3mm) ash aggregates or show vesicular ash textures. Also, the unit contains numerous intraformational gullies and rills produced by syn-eruptive erosion. Many thin beds have adhered to steep slopes indicating accumulation as cohesive ash, but thicker beds have typically slumped as a mobile ash-slurry. Water-reworked material is ubiquitous within the Rotongaio deposit and intercalated at a fine scale with the pyroclastic stratigraphy indicating penecontemporaneous fluvial erosion and resedimentation.

Unit 5 (Taupo plinian pumice) records the sudden return to a magmatic style of eruption involving rapid discharge of very gas-rich magma and fallout of pumice lapilli over a very wide area (WALKER, 1980). This unit is notable for its extremely wide dispersal and the very low rate of thinning with distance from vent, and was termed 'ultraplinian' by WALKER (1980). Clast disperal and thickness distance-decay data from this unit form an integral part of current numerical plume models. The unit is also the source of controversy because of Walker's use of crystal mass balance calculations from which he derived a volume three times larger (23 km^3) than that determined from thickness contours (7.7 km^3). Mapping of this unit and orientation of logs in unit 7 (Taupo ignimbrite) were used to first suggest Horomatangi Reefs and the vent location for the 1.85 ka eruption (FROGGATT *et al.*, 1981). Localised ignimbrite units (unit 6) were emplaced synchronously with Taupo plinian pumice during phase 5, due to small-scale collapse around the unstable margins of the eruption column (WILSON & WALKER, 1985).

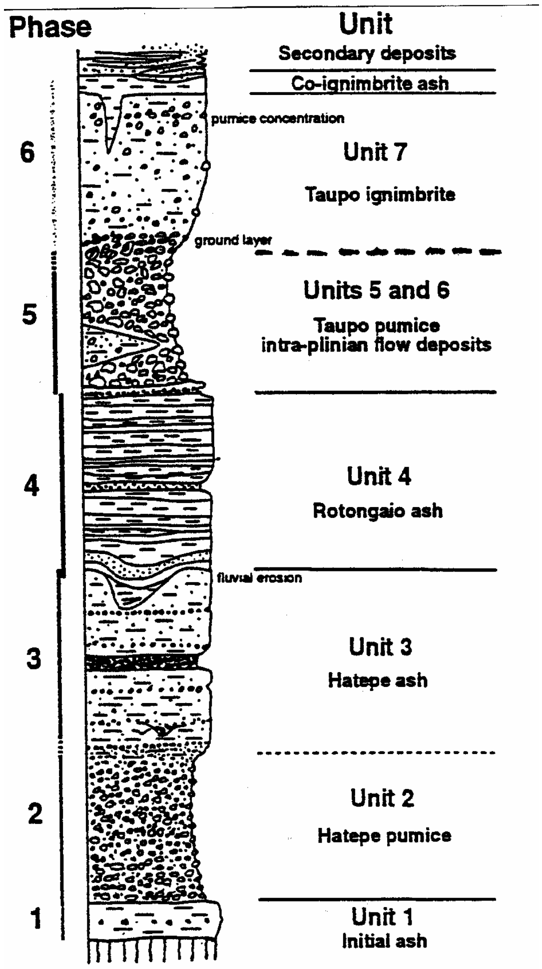

Figure 10 Generalised stratigraphy of the 1.85 ka Taupo eruption sequence showing the six eruptive phases and associated depositional units (from Smith, 1998).

Unit 7 (Taupo ignimbrite, 30 km^3) was emplaced as the climactic phase of the eruption triggered by incipient caldera collapse and unroofing of the magma chamber (WILSON, 1985). Wilson (1985) suggests the flow was erupted over only 400 s as a series of pulses, and that these coalesced to form a single concentrated flow which travelled radially outwards for at least 80km and up to 300 m/s. The unit is spread very thinly (the archetypal low-aspect ratio ignimbrite) and exhibits considerable lateral facies variation due to the violence of emplacement. More recent workers have suggested that many of the features of the Taupo ignimbrite are better explained by transport not as a thin, dense flow, but as a relatively dilute and turbulent current (DADE & HUPPERT, 1996).

Post-Eruption Events

Vent collapse and ignimbrite emplacement mark the end of the explosive eruption sequence, but stratigraphy throughout the central North Island records the continuing impact on the eruption. Deposits of fine grained co-ignimbrite ash elutriated from the pyroclastic flow are rare and preserved mainly in fissures in the ignimbrite which must have opened up soon after emplacement. A range of debris flow, fluvial and lacustrine secondary deposits overlie and extend beyond the area directly impacted by the eruption, and most of this material seems to have been derived from erosion of the non-welded ignimbrite (SMITH, 1998). Vent collapse and ignimbrite emplacement largely emptied the caldera of water. It is estimated that at current inflow rates the lake would have taken 20 years to refill (NORTHEY, 1983). The lake initially rose to 34m above the present day level, but later fell as the outlet river was able to cut through the eruption deposits (WILSON & WALKER 1985).

During the refilling of the lake a small lava dome was extruded onto the lake floor (eruption Z of WILSON, 1993) to form what is now Horomatangi Reefs. Pumiceous blocks which floated from the carapace of this extrusion were blown by the predominant westerly winds and deposited along the eastern shores of the lake (WILSON & WALKER, 1985).

DAY 1 ITINERARY

Stop 1: Taupo Overview (U18/773767)
In fine weather this lookout affords a magnificent view across Lake Taupo to the andesite massifs in the south and the greywacke Kaimanawa Ranges in the east (see GRINDLEY, 1960 for geology of the area). The northern half of the lake depression has been formed mainly by caldera collapse whereas the southern part cannot be related to recent (<50 ka) volcanism and is in the main of tectonic origin. Beyond the NE corner of the lake south of the dacite cumulo-dome complex of Tauhara (LEWIS, 1968) lie two flat near horizontal surfaces. The lower of these is the upper surface of Taupo Ignimbrite and the higher more dissected surface of the 26.5 ka Oruanui Ignimbrite. Both surfaces show clear evidence of down-faulting and post-eruptive subsidence, especially post-Taupo ignimbrite.

Stop 2: Napier-Taupo Road (U18/881680)
This is an excellent roadside section of the deposits of the 1.8ka Taupo eruption. See FIG 10 for sequence.

Stop 3: Airport turnoff (U18/772693)
Blocks from the Taupo lithic lag deposit. The dominant lithic lithology in the Taupo ignimbrite is rhyolite (73.5%), followed by ignimbrite (8.5%), andesite-dacite (6%), sediments (5%), obsidian (4%), hydrothermally altered clasts (2%) and greywacke (1%). However, different sites have different assemblages, suggesting derivation from different sectors around the vent.

Stop 4: Te Ti Point, Wharewaka (U18/772710)
A brief stop to look at large blocks of ignimbrite from the Taupo lithic lag along the shore of Lake Taupo.

Stop 5: Punatekahi (U18/737785)
At least two coalescing scoria cones have been formed by strombolian eruptions (BROWN *et al.,* 1994). A 3-D view of one scoria cones has now been exposed by quarrying (Byford's Quarry). There are three facies - outer wall, rim/inner wall and crater fill. Outer wall beds dip at 15-32^o radially outwards from the vent and comprise lapilli and bomb beds. Inner wall facies dip radially towards the vent at 20^o and consist of alternations of poorly to moderately welded scoria beds which have commonly been remobilised rheomorphically downslope. Rim deposits dip at more shallow angles (0-5^o) and are highly welded. The crater fill facies is now largely covered by debris from the quarrying operation.

Stop 6: Whakamoenga Point (U18/716698)
This stop is in the Rangatira Point ignimbrite. All pumice samples from the ignimbrite are rhyolites (SiO_2 = 72.8 - 75.0%) and have amongst the highest K_2O (3.5 - 4.0%) and Rb (119 -136 ppm) abundances of any TVZ rhyolite. Our analyses show some degree of variation greater than previously documented (SUTTON *et al.,* 1995), but most lie within the field of the Marotiri-type rhyolite compositions of SUTTON *et al.* (1995). The remarkably similar chemistry and mineralogy of the Marotiri rhyolite lavas and Kawakawa Bay and Rangatira Point pyroclastics suggests derivation from a similar magma source.

(Lunch: Acacia Bay?)

Stop 7: Oruanui ignimbrite (Basal sequence: T17/582872; Ignimbrite: T17/591863)
No one outcrop clearly exposes all of the 26.5 ka Oruanui eruption sequence (Wilson, 2001). The two road cuttings visited at this stop are just over 1 km from one-another and the first provides good exposure of the early phases of the eruption, whereas the second is in the voluminous ignimbrite deposited during eruption phase 10.

Stop 8: Maraetai Damsite (T16/495134)

A good section of the upper part of the Whakamaru Ignimbrite is exposed in the Waikato River gorge at Maraetai Dam. Detailed studies have been made by MARTIN (1965), HATHERTON (1954), EWART (1965), BRIGGS (1973, 1976) and BROWN *et al*. (1998).

The ignimbrite varies from densely welded to non-welded in a simple cooling unit. The number of flow units is debatable (see background information) as contacts between them are gradational over several metres, but are usually marked by a zone of horizontal joints. It is suggested that the time intervals between successive eruptions were short, so that each unit while flowing stirred up and mixed the upper part of the preceding one thus accounting for the gradational contact. The complex jointing in the lower part is probably due to greater plasticity at the time of welding and consolidation, with differential settling on the underlying surface.

Detailed petrological studies by EWART (1965) showed vertical variations in chemistry and mineralogy in the lower part of the ignimbrite (mainly from sub-surface cores) but there is relatively little mineralogical variation in the section exposed at Maraetai. Phenocrysts of plagioclase (An_{31}) and quartz are abundant, with minor hornblende, biotite and magnetite. Sanidine phenocrysts are found only at the top of Ewart's Bottom Sheet and above (subunits D-F of BRIGGS 1976).

Drive back to Whakamaru and turn right along SH32 to Poihipi Road.

Stop 9: **Ben Lomond obsidian** (T17/674867)
A brief stop will be made along Pohipi Road to collect obsidian from a lava flow fission-track dated by KOHN (1973) as 0.12±0.02 Ma and K/Ar dated (HOUGHTON *et al*., 1991) at 105±9m 108±17 and 97±11 Ka. This obsidian is associated with the rhyolite dome on the north rim of the Taupo Volcanic Centre (SUTTON *et al.,* 1995).

Continue along Poihipi Road to Wairakei, join SH1 to Taupo.

DAY 2: SATURDAY, 11 DECEMBER: BACKGROUND INFORMATION

Maroa Volcanic Centre (from LEONARD, 2003)
Maroa Volcanic Centre (Maroa; FIG. 11) is located within the northeastern part of the older Whakamaru caldera. Maroa and the Western Dome Belt (WDB) represent the major locus of volcanism in the area of Whakamaru caldera from 305 to ~200 ka. Dome lavas make up the majority of Maroa volume, with the large Maroa West and East Complexes (MWC and MEC, respectively) erupted mostly over a short 29 kyr period starting at 251 ka. There are five mappable Maroa pyroclastics deposits. The Korotai (283 ka), Atiamuri (229 ka), and Pukeahua (~ 229 – 196 ka) pyroclastics are all ~1 km^3. The Putauaki (272 ka) and Orakonui (256 ka) pyroclastics total ~ 4 km^3 from a petrologically and geographically very similar central Maroa source. The ~ 220 ka Mokai pyroclastics outcrop partly within Maroa but their source remains unclear, whereas the ~ 240 ka Ohakuri pyroclastics appear to have come from a caldera just north of Maroa. The ages of the Mamaku, Ohakuri and Mokai pyroclastics are equivocal. The Mamaku and Ohakuri pyroclastics appear to be older (~ 240 ka) than the age previously accepted for the Mamaku pyroclastics.

Maroa lavas are all plagioclase-orthopyroxene bearing, commonly with lesser quartz. Hornblende +/- biotite are sometimes present and their presence is correlated with geochemical variation. All Maroa deposits are rhyolites (apart from two high-silica dacite analyses) and are peraluminous and calcic. They all have the trace element signatures of arc-related rocks typical of TVZ deposits. Maroa deposits fall geochemically into three magma types based on Rb and Sr content: M (Maroa-type), T (Taupo-type) and N (Northwestern Dome Complex-type).

The distinction between Maroa and Taupo Volcanic Centres is somewhat arbitrary and is best considered to be the easting directly north of Ben Lomond, north of which most volcanism is older than 100 ka and M and N type, and south of which most volcanism is younger than 100 ka and T type. The remaining boundaries (north to include Ngautuku, west to include Mokauteure and east to include Whakapapa domes) are arbitrary, and include the farthest domes linked closely, spatially and magmatically, to the other Maroa domes.

The rate of Maroa volcanism has decreased exponentially from a maximum prior to 200 ka. In contrast volcanism at Taupo and Okataina has increased from ~ 64 ka to present. The oldest Maroa dome (305 ka) constrains the maximum rate of infilling of Whakamaru caldera as 39-17 km^3/kyr. This highlights the extraordinarily fast rate of infilling common at silicic calderas and is in agreement with international case studies, except where post-collapse structural resurgence has continued for more than 100 kyr. The majority of caldera fill, representing voluminous eruption deposits in the first tens of thousands of years post collapse, is buried and only accessible via drilling. The WDB and Maroa are petrologically distinct from one another in terms of some or all of Rb, Sr, Ba and Zr content, despite eruption over a similar period. Magma sources for Maroa and the WDB may have been partly or wholly derived from the Whakamaru caldera magma system(s), but petrological distinctions among all three mean that Maroa and the WDB cannot be considered as simple magmatic resurgence of the Whakamaru caldera.

Maroa's distinct Thorpe Rd Fault is in fact a fossil feature which hasn't been active in almost 200 kyr. In addition, the graben across Tuahu Dome was likely created by shallow blind diking. Several recent studies across TVZ show structural features with some associated dike intrusion/eruption. Such volcano tectonic interaction is rarely highlighted in TVZ but may be relatively common and lie on a continuum between dike-induced faulting and dikes following structural features. Although rates of volcanism are now low in Maroa magmatic intrusion appears to remain high. This raises the possibility of a causative link between faulting and volcanism in contrast to traditional views of volcanism controlled by rates of magmatic ascent. Probable future eruptions from Maroa are likely to be of similar scale (< 0.1 km3) and frequency (every ~ 14,000 years) to most of those over the last 100 ka. Several towns lie in a range of zones of Maroa volcanic hazard from total destruction to possible ash fall. However, the probability of a future eruption is only ~ 0.6 % in an 80 year lifetime.

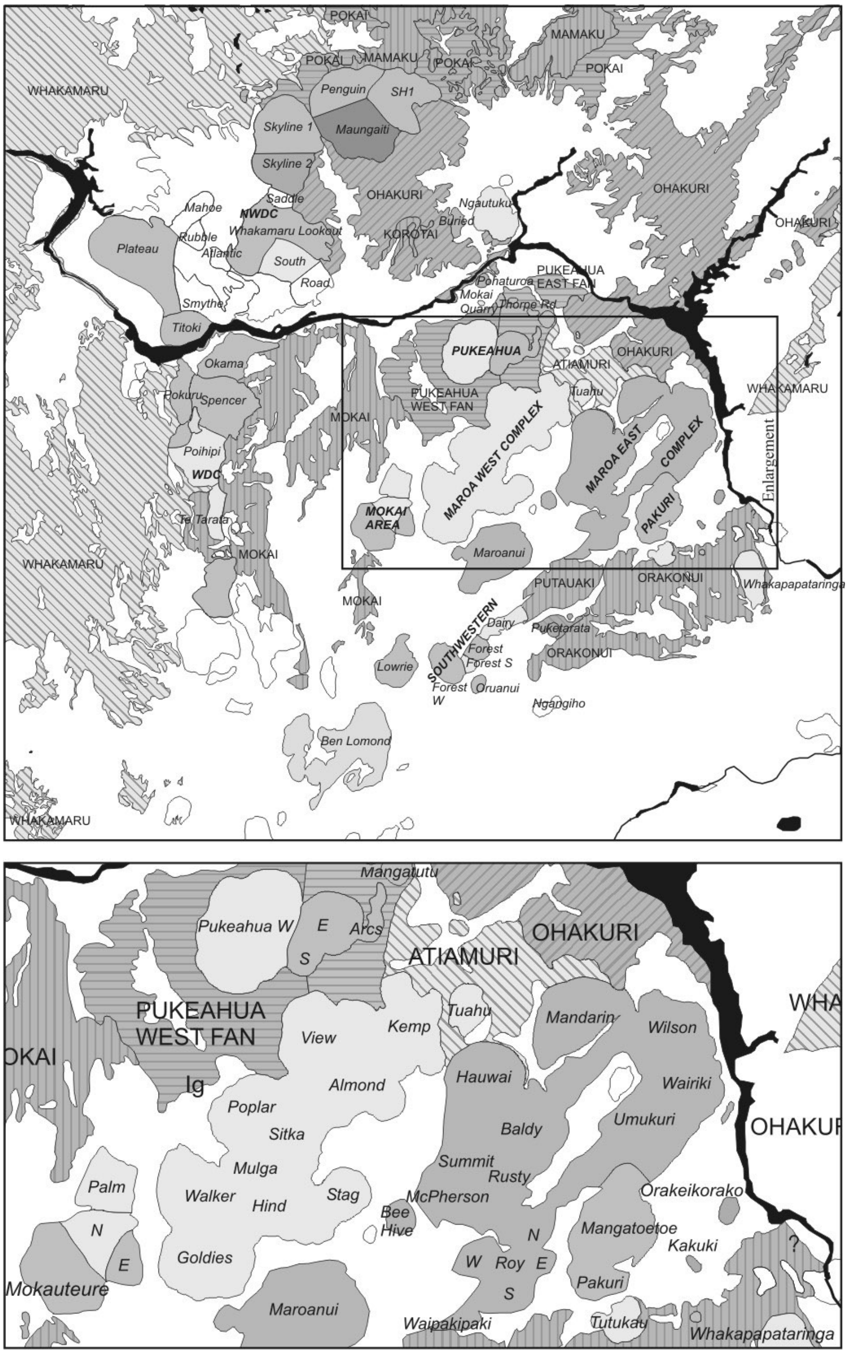

Figure 11 Map of Maroa-related deposits. Hatching distinguishes pyroclastics, with their names in capitals. Names of domes are italicised in lower case. Dome complex names are italicised in capitals. Inset (MWC/MEC domes) is enlarged below. Waikato River lakes are black.

Ohakuri pyroclastic deposits (From GRAVLEY, 2005)
The Ohakuri pyroclastic deposits are exposed within an area encompassing ~500 km^2. The pyroclastics were primarily distributed to the east and northeast, infilling a large portion of the Rotorua-Ohakuri volcano-tectonic depression between the Mamaku Plateau and the Paeroa Fault scarp. Within the volcano-tectonic depression, the Ohakuri pyroclastic deposits are exposed in NE-SW trending horst structures, with maximum thicknesses of ~ 200 m. The surface exposure in this area veils the great thickness of Ohakuri pyroclastic deposits in the subsurface, as the deposit has been identified in several drillholes to a depth of > 450 m. There are no Ohakuri pyroclastic deposits exposed east of the Te Weta fault block or north of the present-day Haparangi and Tumunui rhyolite domes where it is assumed that high ground in this area formed a backstop for the northeast travelling Ohakuri pyroclastic density currents (PDCs).

The base of the Ohakuri pyroclastic deposits can only be observed in the north and northwest sectors of the Ohakuri distribution. Here, the Ohakuri pyroclastic deposits form a thin veneer on top of the Mamaku ignimbrite slope which descends from the Mamaku Plateau down to the Whangapoa Basin. On top of the Mamaku Plateau, the exposure of the Ohakuri pyroclastic deposits thins rapidly. Southwest of the Mamaku ignimbrite slope and the Mamaku Plateau, a significant volume of Ohakuri pyroclastic deposits are exposed between the Whangapoa Basin and the Northwest Dome Complex. In this area they form conspicuous 50 to 100 m high conical hills that are juxtaposed against the slopes of the Northwest Dome Complex. Presumably, at the time of the Ohakuri eruption, this area formed a gentle slope off the existing Northwest Dome Complex, underlain by fan material, lavas and possibly Pokai ignimbrite. West of the Northwest Dome Complex (i.e. T16/68890834), only a thin veneer of Ohakuri pyroclastic deposits overlie the Pokai ignimbrite. To the south, the Ohakuri pyroclastic deposits are not exposed beyond the present-day Maroa Volcanic Complex (MVC). Age data from LEONARD (2003) indicates that the two linear dome complexes in the central MVC were constructed prior to the Ohakuri eruption. The northern sides of these two dome lineaments appear to have formed an insurmountable obstacle for the southward travelling Ohakuri PDC's.

Mamaku Ignimbrite (From MILNER *et al*., 2002)
The Mamaku Ignimbrite is the only ignimbrite currently recognized to have been erupted from Rotorua Caldera.

Outflow sheet

The Mamaku Ignimbrite is exposed in an outflow sheet of ~225 km^3 (in situ volume), dominantly in a 3100km^2 fan extending north and west of the caldera. Reconstruction of the original extents of the ignimbrite indicates that it may have originally covered up to 3900km^2 (283km^3). The ignimbrite is split into a basal tephra sequence and main ignimbrite sequence. The main ignimbrite sequence is divided into lower, middle and upper facies based on variations of welding, jointing, crystal content, lithic content, devitrification and vapour phase alteration.

The basal tephra sequence is a layered deposit up to 2.5m thick that comprises up to 14 pyroclastic fall and density current beds. The main ignimbrite sequence is predominantly massive and contains no definable flow unit boundaries. Vertical changes in the sizes and contents of pumice and lithic clasts impart crude layering in places and are all gradational with the surrounding ignimbrite. Boundaries between lower and middle, and middle and upper Mamaku Ignimbrite are also gradational over 1-2m and approximately 10m respectively. The lower (IMI) to middle Mamaku Ignimbrite (mMI) is signified by an increase in welding and crystal content. Welding decreases and devitrification increases with height above the zone of maximum welding in mMI and uMI is presented by ignimbrite in which the glass shards and pumice fragments have become totally devitrified.

Lithic lag breccias and areas of high lithic concentration are present in the top of uMI at localities at, and within, and caldera margin. Exposures of lithic lag breccias are poor, limited by extent of forest cover to an area at the southern caldera margin. Maximum thickness measured was only 1m.

Intracaldera

Only the upper part of Mamaku Ignimbrite is exposed inside the caldera, towards its northwestern and eastern margins, otherwise intracaldera ignimbrite is not exposed. In the eastern Rotorua City area intracaldera Mamaku Ignimbrite is >120m thick in a drill hole (WOOD, 1992), and 280m is interpreted from a seismic reflection profile (LAMARCHE, 1992), 0.5km and 1km north of the southern caldera boundary respectively. Gravity data (ROGAN, 1982) suggests there may be >1km thickness of deposits (probably Mamaku Ignimbrite) filling the caldera.

Chemistry

Pumice clasts in the Mamaku Ignimbrite are dacite to high-silica rhyolite and can be chemically divided into 3 types; high silica rhyolite (type 1), rhyolite (type 2) and dacite (type 3). All are petrogenetically related and types 1 and 2 may be derived by up to 20% crystal fractionation from the type 3 dacite. All three types probably resided in a single, gradationally zoned magma chamber. Andesitic juvenile fragments are found only in upper Mamaku ignimbrite and inferred to represent a discrete magma that was injected into the silicic chamber and is considered to have accumulated as a sill at the base of the magma chamber. The contrast in density between the andesitic and silicic magmas did not allow eruption of the andesite fragments during eruption of lower and middle Mamaku Ignimbrite. Caldera collapse during upper Mamaku Ignimbrite created withdrawal dynamics that allowed the andesitic magma to erupt.

DAY 2 ITINERARY

Stop 1: Puketerata (U17/753900)
The Puketarata eruption (17 ka, NEWNHAM ET AL., 2003) was the youngest from Maroa (BROOKER *et al*., 1993). It is one of the southernmost eruptions from Maroa and is chemically more similar to most Taupo eruptions. It produced a small tuff ring which was filled by a lava dome in the final stages of the eruption. In contrast, tuff rings associated with older Maroa eruptions have mostly been eroded away.

Stop 2: Whangamata Fault (Fault)
The Whangamata Fault is the southwestern continuation of the Paeroa Fault Zone and is the only fault with detectable post-26.5 ka displacement in Maroa. Many other faults and lineaments throughout Maroa show distinct topographic offsets but in the few cases where the timing of these can be constrained the faulting occurred at the time of major volcanism, prior to 200 ka (LEONARD, 2003). This stop is a good place to discuss the central Maroa deposits.

Stop 3: Atiamuri pyroclastics (U17/701036)
The Atiamuri pyroclastics (~ 1 km^3) are dominated by ignimbrite, and are the product of a small eruption that culminated in the extrusion of a lava dome about 1 km to the southeast (LEONARD, 2003). Ignimbrite deposits such as this were probably associated with many Maroa eruptions, but would have easily eroded away. This deposit has been protected by the surrounding older lava domes to the west and south, and a high block of Ohakuri pyroclastics to the north.

Stop 4: Ngautuku Road lookout (U16/738108)
This logging skid site perched on the northeastern flank of Ngautuku lava dome (160 ka, LEONARD, 2003) gives a great overview of the Ohakuri caldera through to the southern edge of the Rotorua basin to the northeast, and the Paeroa fault scarp to the east. Ngautuku is the northern-most dome associated with Maroa.

Stop 5: Korotai welded ignimbrite (U17/702093)
Highly welded zone within the Korotai pyroclastics (283 ka). Glassy fiamme are the result of hot flattening of juvenile pumice and vesicular obsidian clasts. This is a locally-derived ignimbrite deposit of ~1 km^3 sourced from a vent that is probably less that 2 km to the east (LEONARD, 2003).

Stop 6: Ohakuri Damsite (U17/798059)
Silicified Ohakuri Ignimbrite, which represents a "fossil" geothermal field, Geothermal activity occurred during the period <200ka to ~40ka ago (HENNEBERGER, 1983).

(Lunch Lake Ohakuri?)

Continue on to SH1, turn right, drive to Tar Hill.

Stop 7: **Road cutting near Tar Hill** (T16/690183)
Giant dunes within the Ohakuri pyroclastics in a road cutting along State Highway 1. The grain-size distribution within these deposits is similar to that of contemporaneous massive Ohakuri ignimbrite in other areas (GRAVLEY, 2005). A few hundred metres down the hill underlying Mamaku and Pokai ignimbrite are exposed.

Stop 8: Corner Parsons and Dunkirk Road (U16/798129)
An example of the massive and giant dune bedded facies of the Ohakuri Ignimbrite (GRAVLEY, 2005). The pyroclastic deposits provide evidence for transport and deposition from a turbulent density current erupted from a nearby source. The face of the outcrop is a giant dune bed with finer-scale cross-bedding within the structure. There are also large u-shaped channel structures that demonstrate the erosive capacity of the pyroclastic density currents. Accretionary lapilli are present, suggesting a phreatomagmatic origin.

Stop 9: Mamaku Ignimbrite near Horohoro (U16/871243)
A road-side outcrop of massive pink-purple vapour phase-altered Mamaku ignimbrite to the east of the Horohoro bluffs. This area is inferred to have been down-faulted or collapsed through magma withdrawal during or soon after the Mamaku and Ohakuri eruptions and as a consequence this is one of the few outcrops of Mamaku ignimbrite south of the Rotorua caldera (GRAVLEY, 2005).

Stop 10: Ngongataha Overview (U15917383)
An opportunity to discuss the structure of the Rotorua caldera. If weather is good there is the possibility of a distant view of Tarawera.

Return to Taupo

DAY 3: SUNDAY 12 DECEMBER; BACKGROUND INFORMATION

Rautawiri Breccia (From JACKSON, 2004)
The Rautawiri breccia is a welded volcanic deposit of mixed composition. It lies to the north-east of Taupo with the main outcrop formed by the eastern boundary of TVZ, the Kaingaroa fault. Stratigraphically it lies between the underlying Rangitaiki ignimbrite (330 ka) and the overlying Kaingaroa ignimbrite (240 ka) giving an approximate age. A unit found within Broadlands geothermal drill holes, 5 km north-west of the main Rautawiri outcrop also occupies this stratigraphic position and has previously been labelled as Rautawiri breccia. This unit however is unlikely to represent a continuation of the Rautawiri breccia at outcrop and is instead most likely unrelated.

The Rautawiri breccia consists of three distinctly different units, Rautawiri A, B and C (FIG. 12) which are not all present in all sections. Rautawiri A is a basal breccia of welded ignimbrite blocks, representing brecciation of an initial small welded pyroclastic flow by the onset of Rautawiri B eruptives. Rautawiri B is a rhyolitic pyroclastic flow that also contains these welded ignimbrite blocks, as well as primary rhyolitic pumice, obsidian, lithics and minor andesite towards the top of the deposit. Rautawiri C is a welded andesitic lava fountaining deposit, with elongate clasts of andesitic pumice, stacked without matrix. Large andesitic clasts show agglutination while welding in smaller clasts is due to postdepositional welding. A high rate of deposition to the south of the main outcrop has also led to rheomorphism and generation of secondary lava flows. Rautawiri C also contains primary rhyolitic pumice clasts that show mingling with the andesitic pumices on deposition. Lithics are common within the Rautawiri units and are dominantly angular greywacke, reflecting the shallow basement lithology on the edge of TVZ. The two primary magma types of Rautawiri breccia, andesite and rhyolite, are not directly related and were erupted from different vents. Their occurrence together in a single volcanic deposit is linked by a common fault trigger mechanism. This triggered simultaneous eruption of shallow level rhyolitic magmas and deep-seated andesitic magmas with the andesitic magmas erupting from two vents along a fault controlled fissure, running parallel to the Kaingaroa fault scarp. The Rautawiri breccia has been deposited by the complex interaction between multiple magmas erupting from multiple, fault activated vents.

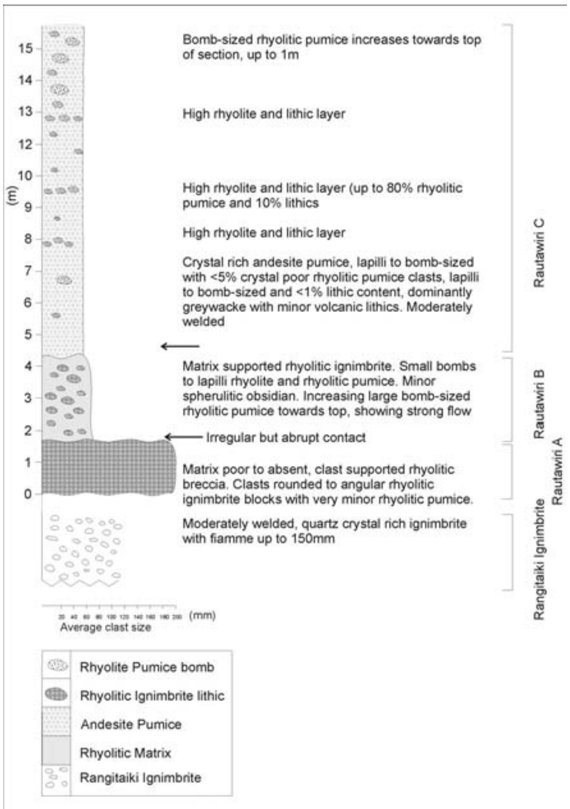

Figure 12 Composite stratigraphic section of the Rautawiri breccia (from Jackson, 2004)

Kawerau Ignimbrite (from SPINKS, 2005)
Kawerau Ignimbrite is a partially-welded pumice-rich ignimbrite that fills Puhipuhi Basin (FIG. 13) on the eastern side of the Okataina Caldera Complex and forms a thick terrace in and around the Kawerau township area. Puhipuhi Basin forms a volcano-tectonic embayment in the caldera complex margin where the local axial rift segment and caldera intersect. Within Puhipuhi Basin the Kawerau Ignimbrite is ~100 m thick, exposed on clear-felled knolls and locally forms jointed bluffs in thickest sections where it is valley ponded. Originally mapped as Kaingaroa Ignimbrite, it was subsequently separated and renamed Kawerau Ignimbrite (BERESFORD & COLE, 2000b), with an accepted age of 240 ka.

Further investigation of the Kawerau Ignimbrite during a current study into the development of the OCC (SPINKS, 2005) has revealed a much younger stratigraphic position. In Puhipuhi Basin the ignimbrite overlies ~280 ka Matahina and ~65 ka Rotoiti ignimbrites, and older tephras of the Mangaone Subgroup. Whole-rock and glass geochemistry tie the ignimbrite specifically to the 33 ka Unit I (Mangaone Tephra) phase of the subgroup, vastly increasing the eruptive volume of that unit (and the subgroup) and implying caldera collapse in this recent phase of OCC activity.

Two magma types are identified, with a large compositional gap between them interpreted to represent eruption of two distinct compositions. Vertical variation in the ignimbrite records rapid depletion of a subordinate dacite magma such that pumices of this composition are rare beyond proximal exposures. Lithic and pumice size distribution data indicate a source within southern OCC to the west of Puhipuhi Basin. Probable residual volume of the ignimbrite is <15 km^3, but estimates of the original volume approach >50 km^3 when intra-caldera volumes are considered.

Kawerau Ignimbrite thus represents the largest eruption from Okataina in the last 65 ka since the Rotoiti event. The recognition of a large partially welded ignimbrite with an emplacement age within the last 35 ka requires major revision to the accepted eruptive stratigraphy of the caldera complex and has significant implications for geologic hazard assessment in northern Taupo Volcanic Zone (TVZ).

DAY 3 ITINERARY

Drive along Broadlands Road, and take Tiriti (forestry) Road (to right).

Stop 1: Rautawiri Breccia (U17/014882)
We will look at 2 sections along the scarp E of Rautawiri Stream (described in JACKSON, 2004). Section R1 is an 8m vertical outcrop largely of Rautawiri B, at the southern end of the main exposure (just inside the forest). The basal contact of the Rautawiri Breccia is exposed here, where it overlies Rangitaiki ignimbrite. The second section (c.400m to the north) is a 10m exposure of Rautawiri B and C. Both Rautawiri B and C are regarded as welded airfall units by JACKSON (2004). The location will also provide an overlook of the Reporoa caldera.

Stop 2: Crater Road (V16/174196)
This now somewhat overgrown section illustrates the pyroclastic deposits associated with the 1305AD Kaharoa eruption from Tarawera (LEONARD *et al*., 2002)

Return along Ash Pit Road and turn left into Ngamotu Road. Turn left onto McKee Road.

Stop 3: Corner Tarawera/McKee Road (V16/375387)
A thick section through the Mangaone tephra sequence erupted from OVC between 32 ka and 26 ka (JURADO-CHICHAY & WALKER, 2000). The section includes Mangaone Tephra, Awakeri Tephra thick (c.5.5m) Omataroa Tephra (a well-sorted, shower-bedded, normally graded, coarse, plinian pumice bed) and Unit L. All of these units JURADO-CHICHAY & WALKER (2000) believe were erupted from the Puhipuhi Basin.

Continue along Tarawera Road, turn left into Cuming Road.

Stop 4: Viewpoint on Cuming Road (V26/301326)
This provides a good view of the Puhipuhi Basin with Kawerau Ignimbrite member of the Mangaone Formation partially filling the basin and underlying Matahina Ignimbrite which forms the surrounding cliffs. Puhipuhi dacites form the high point in the middle distance.

Lunch at Tarawera Falls (weather and time dependant)

Return to Kawerau and join SH30 to Lake Rotorua.

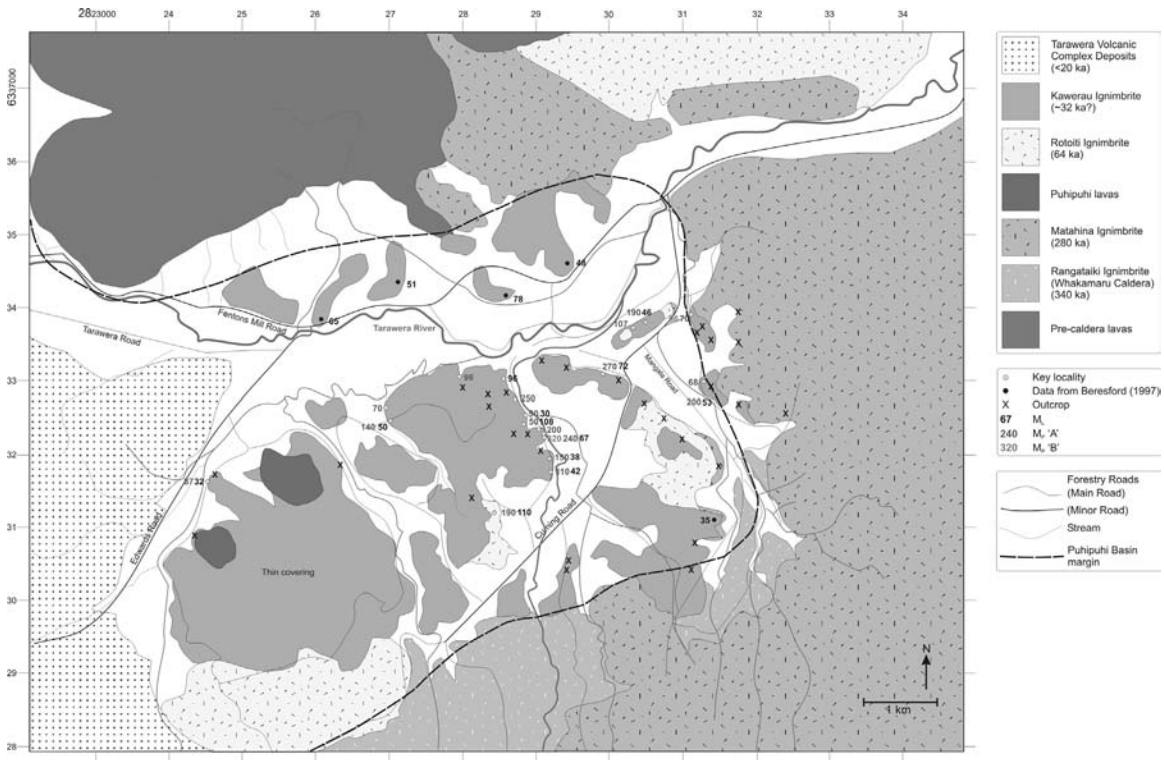

Figure 13 Geologic map of the Kawerau ignimbrite in the Puhipuhi Basin, on the eastern side of the Okataina Caldera Complex (from Spinks, 2005).

Stop 5: South shore of Lake Rotoma (V15/250420)
Matahina Ignimbrite exposed in cliffs on the south side of the road. Continue along SH30, past Lakes Rotoehu and Rotoiti to Rotorua, dropping anyone at Rotorua Airport who has a late afternoon departure. Lake Okataina (time dependant) – scalloped caldera walls, lake forms a moat between intra-caldera rhyolite lavas and caldera wall.

Stop 6: Kerosene Creek
This final stop of the tour is in a warm creek to relax with a cold beer before returning to Taupo.

REFERENCES

Acocella, V., Spinks, K.D., Cole, J.W. and Nicol, A. 2003. Oblique back arc rifting of Taupo Volcanic Zone, New Zealand. Tectonics, 22(4):1045 doi: 0.1029/2002TC001447

Bailey, R.A and Carr, R.G. 1994. Physical geology and eruptive history of the Matahina Ignimbrite, Taupo Volcanic Zone, North Island, New Zealand. N.Z. Jour. Geol. Geophys., 37: 319-344

Bellamy, S. 1991. Some studies of the Te Wairoa ignimbrites and the associated volcanic geology of the SW Okataina volcanic centre, Taupo Volcanic Zone. Unpublished MSc thesis, University of Waikato, Hamilton, New Zealand.

Beresford, S.W. 1997. Volcanology and geochemistry of the Kaingaroa Ignimbrite, Taupo Volcanic Zone, New Zealand. Unpublished PhD thesis, University of Canterbury, Christchurch, New Zealand.

Beresford, S.W. and Cole, J.W. 2000a. Kaingaroa Ignimbrite, Taupo Volcanic Zone, New Zealand: evidence for asymmetric caldera subsidence of the Reporoa Caldera. N.Z. J. Geol. Geophys., 43: 471-481.

Beresford, S.W. and Cole, J.W. 2000b. Kawerau Ignimbrite: a 0.24 Ma ignimbrite erupted from the Okataina caldera complex, Taupo Volcanic Zone, New Zealand. N.Z. J Geol. Geophys. 43 (1): 109-115.

Beresford, S.W., Cole, J.W., and Weaver, S.D. (2000). Weak chemical and mineralogical zonation in the Kaingaroa Ignimbrite, Taupo Volcanic Zone, New Zealand. N.Z. Jour. Geol. Geophys. 43(4): 639-680.

Black, T.M., Shane, P.A.R., Westgate, J.A. and Froggatt, P.C. 1996. Chronology and paleomagnetic constraints on widespread ignimbrites of the Taupo volcanic zone, New Zealand. Bull. Volcanol. 58, 226-238

Blank, H.R. 1965. Ash-flow deposits of the Central King Country, New Zealand. N.Z. J Geol. Geophys. 8: 588-607.

Bowyer, D.A. 2001. Petrologic, geochemical, and isotopic evolution of rhyolite lavas from the Okataina, Rotorua, and Kapenga volcanic centres, Taupo Volcanic Zone, New Zealand. Unpublished PhD thesis, University of Waikato, Hamilton, New Zealand.

Briggs, N.D. 1973. Investigations of New Zealand pyroclastic flow deposits. Unpublished PhD thesis, Victoria University of Wellington, New Zealand. 433p.

Briggs, N.D. 1976. Welding and crystallization zonation in Whakamaru Ignimbrite, Central North Island, New Zealand. N.Z. J Geol. Geophys. 19 (2): 189-212.

Brooker, M.R., Houghton, B.F., Wilson, C.J.N. and Gamble, J.A. 1993. Pyroclastic phases of a rhyolitic dome-building eruption; Puketarata tuff ring, Taupo volcanic zone, New Zealand. Bull. Volcanol. 55: 395-406.

Brown, S.J.A. 1994. Geology and geochemistry of the Whakamaru Group Ignimbrites and associated rhyolite domes, Taupo Volcanic Zone, New Zealand. Unpublished PhD thesis, University of Canterbury, Christchurch, New Zealand.

Brown, S.J.A., Smith, R.T. and Cole, J.W. 1994. Compositional and textural characteristics of the strombolian and surtseyan K-Trig basalts, Taupo Volcanic Centre, New Zealand: implications for eruption dynamics. N.Z. J Geol. Geophys. 37: 113-126.

Brown, S.J.A, Burt, R.M., Cole, J.W, Krippner, S.J.P., Price, R.C. and Cartwright, I., 1998. Plutonic lithics in ignimbrites of Taupo Volcanic Zone, New Zealand: Sources and conditions of crystallisation. Chem. Geol., 148: 21-41.

Burt, R.M., Brown, S.J.A., Cole, J.W., Shelley, D. and Waight, T.E. (1998). Glass-bearing plutonic fragments from ignimbrites of the Okataina volcanic complex, Taupo Volcanic Zone, New Zealand; remnants of a partially molten intrusion associated with preceding eruptions. J. Volcanol. Geotherm. Res. 84: 209-337.

Cole, J.W. 1990. Structural control and origin of volcanism in the Taupo volcanic zone, New Zealand. Bull. Volcanol., 52: 445-459

Cole, J.W., Brown, S.J.W., Burt, R.M., Beresford, S.W. and Wilson, C.J.N. 1998. Lithic types in ignimbrites as a guide to the evolution of a caldera complex, Taupo volcanic centre, New Zealand. J. Volcanol. Geotherm. Res. 80, 217-237.

Dade, W.B. and Huppert, H.E. 1996. Emplacement of the Taupo Ignimbrite by a dilute turbulent flow. Nature, 381: 509-512.

Davy, B.W. and Caldwell, T.G. 1998. Gravity, magnetic and seismic surveys of the caldera complex, Lake Taupo, North Island, New Zealand. J. Volcanol. Geotherm. Res., 81, 69-89.

Ewart, A. 1965. Mineralogy and petrogenesis of the Whakamaru Ignimbrite in the Maraetai area of the Taupo Volcanic Zone, New Zealand. N.Z. J Geol. Geophys. 8 (4): 611-677.

Froggatt, P.C., Wilson, C.J.N. and Walker, G.P.L. 1981. Orientation of logs in the Taupo Ignimbrite as an indicator of flow direction and vent position. Geology 9: 109-111.

Froggatt, P.C. and Lowe, D.J. 1990. A review of late quaternary silicic and some other tephra formations from New Zealand; their stratigraphy, nomenclature, distribution, volume, and age. N.Z. J. Geol. Geophys., 33: 89-109.

Gravley, D.M. 2005. The Ohakuri pyroclastic deposits and the evolution of the Rotorua-Ohakuri volcanotectonic depression. Unpublished PhD thesis, University of Canterbury, Christchurch, New Zealand.

Gravley, D. M., Wilson, C.J.N., Cole, J.W. and Leonard, G.S. 2003. Temporally and tectonically linked eruption and caldera collapse events in the central Taupo Volcanic Zone, New Zealand. Abstract, Geological Society of NZ Annual Conference, Dunedin 1-4 December 2003. Geological Society of NZ Miscellaneous Publication 116A: 63

Grindley, G.W. 1960. Sheet 8 – Taupo. Geological map of New Zealand 1:250:000. New Zealand Department of Scientific and Industrial Research, Wellington.
Grindley, G.W. 1965. The Geology, structure and exploitation of the Wairakei Geothermal Field, Taupo, New Zealand. New Zealand Geological Survey Bulletin 75. 131p.
Hatherton, T. 1954. The magnetic properties of the Whakamaru Ignimbrites. N.Z. J. Sci Tech.,358: 421-432.
Henneberger, H.C. 1983. Petrology and evolution of the Ohakuri hydro-thermal system, Taupo Volcanic Zone, New Zealand. Unpublished MSc (Hons) thesis, University of Auckland, New Zealand.
Houghton, B.F., Lloyd, E.F., Wilson, C.J.N. and Lanphere, M.A. 1991. K/Ar ages of obsidians from some rhyolite lavas in the Maroa-Taupo area, Taupo Volcanic Centre, New Zealand. N.Z. J Geol. Geophys. 34: 99-101.
Houghton, B.F., Wilson, C.J.N., McWilliams, M.O., Lanphere, M.A., Weaver, S.D., Briggs, R.M. and Pringle, M.S. 1995. Chronology and dynamics of a large silicic magmatic system: Central Taupo Volcanic Zone, New Zealand. Geology 23, 13-16
Hunt, T.M. (1992) Gravity studies in the Rotorua area, New Zealand. Geothermics 21: 65-74.
Kohn, B.P. 1973. Some studies of New Zealand Quaternary pyroclastic rocks. Unpublished PhD thesis, Victoria University of Wellington, New Zealand.
Jackson, R.S. 2004. The Rautawiri Breccia, Taupo Volcanic Zone, New Zealand. Unpublished BSc (Hons) project, University of Canterbury, Christchurch, New Zealand.
Jurado-Chichay, Z. and Walker, G.P.L. 2000. Stratigraphy and dispersal of the Mangaone Subgroup pyroclastic deposits, Okataina Volcanic Centre, New Zealand. J. Volcanol. Geotherm. Res., 104: 319-283.
Lamarche, G. 1992. Seismic reflection survey in the geothermal field of the Rotorua Caldera, New Zealand. Geothermics, 21: 109-120.
Leonard, G.S. 2003. The evolution of Maroa Volcanic Centre, Taupo Volcanic Zone, New Zealand. Unpublished PhD thesis, University of Canterbury, Christchurch, New Zealand.
Leonard, G.S., Cole, J.W, Nairn, I.A and Self, S. 2002. Basalt triggering of the c. AD 1305 Kaharoa rhyolite eruption, Tarawera Volcanic Complex, New Zealand. J. Volcanol. Geotherm. Res., 115: 461-486.
Lewis, J.F. 1968. Tauhara Volcano, Taupo Zone, Part 1 – Geology and structure. N.Z. J Geol. Geophys. 11 (1): 212-224.
Manville, V. 2001. Sedimentology and history of Lake Reporoa: an ephemeral supra-ignimbrite lake, Taupo Volcanic Zone, New Zealand. Spec. Pub. Int. Ass. Sediment. 30: 109-140.
Martin, R.C. 1961. Stratigraphy and structural outline of the Taupo Volcanic Zone. N.Z. J Geol. Geophys. 4: 449-478.
Martin, R.C. 1965. Lithology and eruptive history of the Whakamaru Ignimbrite in the Maraetai area of the Taupo Volcanic Zone, New Zealand. N.Z. J Geol. Geophys. 8: 680-702.
Milner, D.M., Cole, J.W. and Wood, C.P. 2002. Asymmetric, multiple-block collapse at Rotorua Caldera, Taupo Volcanic Zone, New Zealand. Bull. Volcanol. 64, 134-149
Milner, D.M., Cole, J.W. and Wood, C.P. 2003. Mamaku Ignimbrite: a caldera-forming ignimbrite erupted from a compositionally zoned magma chamber in Taupo Volcanic Zone, New Zealand. J. Volcanol. Geotherm. Res. 122, 243-264.
Modriniak, N and Studt, F.E. 1959. The geological structure and volcanism of the Taupo-Tarawera District. N.Z. J Geol. Geophys. 2 (4): 654-684.
Nairn, I.A. 1981. Some studies of the geology, volcanic history and geothermal resources of the Okataina volcanic centre, Taupo Volcanic Zone, New Zealand, Unpublished PhD thesis, Victoria University, Wellington, New Zealand.
Nairn, I.A. 1989. Sheet V16AC – Mount Tarawera, geological map of New Zealand, 1:50,000, Department of Scientific and Industrial Research, Wellington.
Nairn, I.A. 2002. Geology of the Okataina Volcanic Centre, Institute of Geological and Nuclear Sciences Geological Map 25: 156p + map.
Nairn, I.A, Wood, C.P. and Bailey, R.A. 1994. The Reporoa Caldera, Taupo Volcanic Zone: source of the Kaingaroa Ignimbrites. Bull. Volcanol. 56, 529-537
Newnham, R.M., Eden, D.N., Lowe, D.J. and Hendy, C.H. 2003. Rerewhakaaitu Tephra, a land-sea marker for the last termination in New Zealand, with implications for global climate change. Quaternary Science Reviews, 22: 289-308.
Northey, D.J. 1983. Seismic studies of the structure beneath Lake Taupo. Unpublished PhD thesis, Victoria University of Wellington, New Zealand.
Ritchie, A. 1996. Volcanic geology of the Waiotapu and related ignimbrites, Taupo Volcanic Zone. Unpublished MSc. thesis, University of Canterbury, Christchurch, New Zealand.
Rogan, M., 1982. A geophysical study of the Taupo Volcanic Zone, New Zealand. J. Geophys. Res., 87: 4073-4088.
Self, S. and Sparks, R.S.J. 1978. Characteristics of widespread pyroclastic deposits formed by the interaction of silicic magma and water. Bull. Volcanol. 41: 196-212.
Shane, P., Black, T. and Westgate, J. 1994. Isothermal plateau fission track age for the paleomagnetic excursion in the Mamaku Ignimbrite, New Zealand, and implications for late Quaternary stratigraphy. Geophys. Res. Lett. 21, 1695-1698.

Sherburn, S., Bannister, S. and Bibby, H. 2003. Seismic velocity structure of the central Taupo Volcanic Zone, New Zealand, from local earthquake tomography. J. Volcanol. Geotherm. Res., 122: 69-88.
Smith, R.T. 1998. Eruptive and depositional models for units 3 and 4 of the 1.85 Ka Taupo eruption. Unpublished Ph.D. thesis, University of Canterbury, Christchurch, New Zealand.
Smith, R.T. and Houghton, B.F. 1995. Vent migration and changing eruptive style during the 1800 ka Taupo eruption: new evidence from the Hatepe and Rotongaio phreatoplinian ashes. Bull. Volcanol., 57: 432-439.
Smith, V.C., Shane, P. and Smith, I.E.M. 2002. Tephrostratigraphy and geochemical fingerprinting of the Mangaone Subgroup tephra beds, Okataina Volcanic Centre, New Zealand. N.Z. J Geol. Geophys., 45: 207-219.
Soengkono, S. and Hochstein, M.P. 1996. Interpretation of magnetic anomalies over the Reporoa geothermal field, Taupo Volcanic Zone, New Zealand. Proceedings 18th N.Z. Geothermal workshop: 243-248.
Spinks, K.D. 2005. Rift Architecture and Caldera Geometry of the Taupo Volcanic Zone, New Zealand. Unpublished Ph.D. thesis, University of Canterbury, Christchurch, New Zealand.
Spinks, K.D., Acocella, V., Cole, J.W. and Bassett, K.N. in press. Structural control on volcanism and caldera development in the transtentional Taupo Volcanic Zone, New Zealand. J. Volcanol. Geotherm. Res..
Stagpoole, V.M. 1994. Interpretation of refraction seismic and gravity data across the eastern margin of the Taupo Volcanic Zone. Geothermics, 23: 501-510.
Stagpoole, V. M. and Bibby, H. M. 1999. Residual gravity anomaly map of the Taupo Volcanic Zone, New Zealand, 1:250 000, version 1.0. Institute of Geological & Nuclear Sciences Geophysical Map 13. Institute of Geological & Nuclear Sciences Limited, Lower Hutt, New Zealand.
Sutton, A.N., Blake, S. and Wilson, C.J.N. 1995. An outline geochemistry of rhyolite eruptives from Taupo volcanic centre, New Zealand. J. Volcanol. Geotherm. Res., 68: 153-175.
Sutton, A. N., Blake, S., Wilson, C.J.N. and Charlier, B.L.A. 2000. Late Quaternary evolution of a hyperactive rhyolite magmatic system: Taupo volcanic centre, New Zealand. J. Geol. Soc. London, 157: 537-552.
Sutton, R. 1990. The geology, petrography and geochemistry of the area surrounding Rangatira Point, northeast Lake Taupo, New Zealand. Unpublished B.Sc. (hons) thesis, Victoria University of Wellington, Wellington, New Zealand.
Talbot, J.P., Self, S., and Wilson, C.J.N. 1994. Dilute gravity current and rain-flushed ash deposits in the 1.8 ka Hatepe Plinian deposit, Taupo, New Zealand. Bull. Volcanol., 56: 538-551.
Walker, G.P.L. 1980. The Taupo Pumice: product of the most powerful known (ultraplinian) eruption? J. Volcanol. Geotherm. Res. 8: 69-94.
Walker, G.P.L. 1981. An ignimbrite veneer deposit: the trail maker of a pyroclastic flow. J. Volcanol. Geotherm. Res. 9: 409-421.
Wilson, C.J.N. 1985. The Taupo eruption, New Zealand. II. The Taupo ignimbrite. Phil. Trans. Roy. Soc., Lond. A314: 229-310.
Wilson, C.J.N. 1993. Stratigraphy, chronology, styles and dynamics of late Quaternary eruptions from Taupo volcano, New Zealand. Phil. Trans. R. Soc. Lond., A 205-306.
Wilson, C.J.N. 2001. The 26.5 ka Oruanui eruption, New Zealand: an introduction and overview. J. Volcanol. Geotherm. Res. 112: 133-174.
Wilson, C.J.N., Rogan, M.A., Smith, I.E.M., Northey, D.J., Nairn, I.A. and Houghton, B.F. 1984. Caldera volcanoes of the Taupo Volcanic Zone, New Zealand. J. Geophys. Res., 89: 8463-8484.
Wilson, C.J.N, and Walker, G.P.L. 1985. The Taupo eruption, New Zealand. Phil. Trans. R. Soc. London, Ser. A, 314: 199-228.
Wilson, C.J.N, Houghton, B.F. and Lloyd, E.F. 1986. Volcanic history and evolution of the Maroa – Taupo area, Central North Island. In: I.E.M Smith (Editor), Late Cenozoic volcanism in New Zealand. R. Soc. N.Z. Bull., 23: 194-223.
Wilson, C.J.N., Houghton, B.F., McWilliams, M.O., Lanphere, M.A., Weaver, S.D. and Briggs, R.M. 1995. Volcanic and structural evolution of Taupo Volcanic Zone, New Zealand: A review. J. Volcanol. Geotherm. Res., 68: 1-28.
Wood, C.P. 1992. Geology of the Rotorua Geothermal System. Geothermics 21: 25-41