Evolution of the intra-arc Taupo-Reporoa Basin within the Taupo Volcanic Zone of New Zealand

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ABSTRACT

The spatial and temporal distributions of volcaniclastic deposits in arc-related basins reflect a complex interplay between tectonic, volcanic, and magmatic processes that is typically difficult to unravel. We take advantage of comprehensive geothermal drill hole stratigraphic records within the Taupo-Reporoa Basin (TRB), and integrate them with new ⁴⁰Ar/³⁹Ar age determinations, existing age data, and new mapping to develop a four-dimensional model of basin evolution in the central Taupo Volcanic Zone (TVZ), New Zealand. Here, exceptional rhyolitic productivity and high rates of extensional tectonism have resulted in the formation of at least eight calderas and two subparallel, northeast-trending rift basins, each of which is currently subsiding at 3 to 4 mm/yr: the Taupo fault belt (TFB) to the northwest and the TRB to the southeast (the main subject of this paper). The basins are separated in the northeast by a high-standing, fault-controlled range termed the Paeroa block, which is the focus of mapping for this study, and in the southwest by an along strike alignment of smaller scale faults and an associated region of lower relief. Stratigraphic age constraints within the Paeroa block indicate that a single basin (~120 km long by 60 km wide) existed within the central TVZ until 339 ± 5 ka (Paeroa Subgroup eruption age), and it is inferred to have drained to the west through a narrow and deep constriction, the present-day Ongaroto Gorge. Stratigraphic evidence and field relationships imply that development of the Paeroa block occurred within 58 ± 26 k.y. of Paeroa Subgroup emplacement, but in two stages. The northern Paeroa block underwent uplift and associated tilting first, followed by the southern Paeroa block. Elevations (>500 m above sea level) of lacustrine sediments within the southern Paeroa block are consistent with elevations of rhyolite lavas in the Ongaroto Gorge, the outlet to the paleolake in which these sediments were deposited, and indicate that the Paeroa block has remained relatively stable since development. East of the Paeroa block, stratigraphic relationships show that movement along the Kaingaroa Fault zone, the eastern boundary of the central TVZ, is associated with volcanic-tectonic events. Stratigraphic and age data are consistent with rapid formation of the paired TFB and TRB at 339 ± 5 ka, and indicate that gradual, secular rifting is punctuated by volcanic-tectonic episodes from time to time. Both processes influence basin evolution.

INTRODUCTION

Active convergent margins are characterized by tectonic, volcanic, and magmatic processes that influence basin development and provide an abundance of volcaniclastic and sedimentary material that fills accommodation space. Understanding the interplay between such processes requires knowledge of the geochemistry of arc systems, and the stratigraphic and structural architecture of the resultant basins. On a global scale, the geochemistry of arc systems is well known (Pearce and Peate, 1995). However, few well resolved stratigraphic and structural architectural models of arc-related basins have been developed (Cas and Wright, 1987; Busby and Bassett, 2007; Manville et al., 2009; Sohn et al., 2013). In most such settings, high frequencies of eruptions can provide readily datable and identifiable time horizons that allow for high resolution (e.g., 10 to 100 k.y.) interpretation of a basin’s evolution (e.g., Houghton et al., 1995; Smith et al., 2008). However, these same rates of volcanic production, in combination with varying vent locations, positions of available accommodation space, and extreme post-eruptive sedimentation rates, generally result in rapid lateral facies changes and burial of strata, greatly complicating the stratigraphic architecture (Busby and Bassett, 2007). Furthermore, these basins often host large-scale hydrothermal systems, post-depositional modification through hydrothermal alteration can add complexity by overprinting both subsurface and exposed deposits (Steiner, 1963, 1977; Browne, 1978; Grindley et al., 1994).

Quaternary basins of the central Taupo Volcanic Zone (TVZ) (Fig. 1) are no different in their complexity than arc-related basins elsewhere. However, the tempo of their development is exceptional and affords an excellent opportunity to capture their evolution in high fidelity. This area undergoes secular rifting, some parts at >10 mm/yr (Wallace et al., 2004), coupled with an exceptionally high rate of caldera-forming silicic volcanism (3.8 km³/kg. over the past 1.6 m.y.), and frequent smaller scale explosive and effusive eruptions (1 per 900 yr over the past ~61 k.y.; Wilson et al., 2009). This activity has resulted in the development of young, deep (>3 km) basins with a plethora of dateable time horizons (Houghton et al., 1995; Wilson et al., 2009). Although much of the older strata and structure is buried, more than 400 geothermal exploration and production drill holes provide stratigraphic and petrographic data to depths of 3.3 km (e.g., Browne et al., 1992; Rosenberg et al., 2009). Synthesis of subsurface stratigraphy with field and geophysical data provides a

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The northeast-trending TVZ is the most recent (past ~2 m.y.) manifestation in a ~17 m.y. record of similarly oriented arc volcanism associated with subduction of the Pacific plate beneath the North Island of New Zealand (Fig. 1) (Mortimer et al., 2010). From the Late Miocene to ~6 Ma, the locus of volcanism was located farther northwest along the line of the Colville arc. However, subduction of the Hikurangi Plateau at the Hikurangi subduction margin ~10 Ma induced extension within the overriding plate (Reyners, 2013). Initially, this extension was focused along the Hauraki Rift, which is a north-northwest–trending feature that has been active since at least ~7 Ma, parallels basement terrane boundaries, and presumably intersects the TVZ near the Whakamaru caldera (Fig. 1) (Wilson et al., 1986; Hochstein and Ballance, 1993). Since ~6 Ma, extension has been localized along the axis of the arc as it rapidly migrated to the southeast, concomitant with rollback of the subduction hinge (Reyners, 2013). This migration is indicated by the southeastward younging of volcanism (Black et al., 1992; Adams et al., 1994; Houghton et al., 1995), geothermal activity (Rowland et al., 2010; Mauk et al., 2011), and fault-controlled volcaniclastic basins formed in Mesoozoic metasedimentary basement rocks (Villamor and Berryman, 2006).

The TVZ is segmented both structurally and volcanically. Arc-related composite cone-building andesitic volcanism aligned along the axis of the rift occurs to the northeast and southwest of a central 120 km long, 60 km wide segment.
Figure 2. Geologic map of the Taupo-Reporoa Basin (TRB) showing the distribution of lavas, and volcaniclastic and sedimentary strata. New mapping within the Paeroa block is outlined; deposits outside the Paeroa block and Reporoa caldera are modified from Leonard et al. (2010). The eastern and western boundaries of the TRB are delineated by the Kaingaroa Fault zone and Paeroa, Orakei Korako, Whakaheke, and Kaiapo faults, respectively. New $^{40}\text{Ar}/^{39}\text{Ar}$ age determinations and sample locations are shown for reference. See Figure 3 for the stratigraphic key, legend, and descriptions of all units. Map is in the World Geodetic System 84 reference grid.
<table>
<thead>
<tr>
<th>Stratigraphic Architecture</th>
<th>Age</th>
<th>Source</th>
<th>Rock Type &amp; Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surficial deposits</td>
<td>625 ±0.2 ka</td>
<td>Taupo</td>
<td>Taupo formation ignimbrites, with minor fall deposits &amp; lacustrine sediments (see Manville, 2001; Wilson, 2001; Manville et al., 2004; Wilson et al., 2009).</td>
</tr>
<tr>
<td>Hydrothermal breccia</td>
<td>Unknown</td>
<td>Taupo</td>
<td>Hydrothermal eruption breccia - Multicolored, alteration-induced clast-supported, sparse to moderately common, fragmental deposits up to 2-m size, angular clasts, poorly-sorted, silicified, pumice-absent, crystal-poor, &amp; sparse matrix.</td>
</tr>
<tr>
<td>Mihi Breccia</td>
<td>281 ±19 ka</td>
<td>Locally sourced</td>
<td>Mihi Breccia - Lenticular, locally flow-banded, pumice-rich, biotite-rich, matrix-supported breccia.</td>
</tr>
<tr>
<td>Kaingaroa Formation</td>
<td>710 ±60 ka</td>
<td>Kapenga</td>
<td>Kapenga formation ignimbrites, with minor fall deposits &amp; lacustrine sediments (see Manville, 2001; Wilson, 2001; Manville et al., 2004; Wilson et al., 2009).</td>
</tr>
<tr>
<td>Okahuri Formation</td>
<td>* ~280 to 290 ka</td>
<td>Kapenga</td>
<td>Kapenga formation ignimbrites - Unwelded, common crystal-poor pumice, cream-colored matrix &amp; pumice (see Karhunen, 1993).</td>
</tr>
<tr>
<td>Mamaku Formation</td>
<td>* ~300 ka</td>
<td>Kapenga</td>
<td>Kapenga formation ignimbrites - Unwelded, common crystal-poor pumice, cream-colored matrix &amp; pumice (see Karhunen, 1993).</td>
</tr>
<tr>
<td>Pokai Formation</td>
<td>Unspecified</td>
<td>Unknown</td>
<td>Pokai Formation - Lenticular, locally flow-banded, pumice-rich, biotite-rich, matrix-supported breccia.</td>
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<tr>
<td>Chimp Formation</td>
<td>Unspecified</td>
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<td>Chimp Formation - Lenticular, locally flow-banded, pumice-rich, biotite-rich, matrix-supported breccia.</td>
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<tr>
<td>Matahina Formation</td>
<td>321 ±7 ka</td>
<td>Okataina</td>
<td>Matahina Formation - Lenticular, locally flow-banded, pumice-rich, biotite-rich, matrix-supported breccia.</td>
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<tr>
<td>Rautawiri Breccia</td>
<td>Unspecified</td>
<td>Unknown</td>
<td>Rautawiri Breccia - Lenticular, locally flow-banded, pumice-rich, biotite-rich, matrix-supported breccia.</td>
</tr>
<tr>
<td>Paihoa Subgroup:</td>
<td>340 ±4 ka</td>
<td>Whakamaru</td>
<td>Paihoa Subgroup - Lenticular, locally flow-banded, pumice-rich, biotite-rich, matrix-supported breccia.</td>
</tr>
<tr>
<td>Paihoa Subgroup:</td>
<td>710 ±60 ka</td>
<td>Kapenga</td>
<td>Paihoa Subgroup - Lenticular, locally flow-banded, pumice-rich, biotite-rich, matrix-supported breccia.</td>
</tr>
<tr>
<td>Waiotapu Formation</td>
<td>950 ±30 ka</td>
<td>Mangakino</td>
<td>Waiotapu Formation - Lenticular, locally flow-banded, pumice-rich, biotite-rich, matrix-supported breccia.</td>
</tr>
<tr>
<td>Akatarewa ignimbrite</td>
<td>1.18 ±0.2 Ma</td>
<td>Mangakino</td>
<td>Akatarewa ignimbrite - Lenticular, locally flow-banded, pumice-rich, biotite-rich, matrix-supported breccia.</td>
</tr>
<tr>
<td>Ahuora ignimbrite</td>
<td>1.21 ±0.4 Ma</td>
<td>Mangakino</td>
<td>Ahuora ignimbrite - Lenticular, locally flow-banded, pumice-rich, biotite-rich, matrix-supported breccia.</td>
</tr>
<tr>
<td>Ongatiti Formation</td>
<td>1.45 ±0.5 Ma</td>
<td>Mangakino</td>
<td>Ongatiti Formation - Lenticular, locally flow-banded, pumice-rich, biotite-rich, matrix-supported breccia.</td>
</tr>
</tbody>
</table>

Figure 3. Stratigraphic architecture, descriptions, and key for all deposits discussed within the text and shown on all maps, cross sections, and illustrations (unless otherwise indicated). The asterisk indicates new age dates discussed in the text, and the dagger symbol denotes our description of deposits from the Paihoa block. The thick boxes (Akatarewa ignimbrite, Chimp Formation) represent units that are mentioned in the text, but are not displayed in any figures. See references noted by deposits for more detailed descriptions and information.
dominated by rhyolitic volcanism, the central TVZ (Fig. 1) (Wilson et al., 1995). Structurally, the axis of the rift is offset along strike by transfer (accommodation) zones that align with caldera margins, geothermal fields, and inferred deep-seated basement faults, some of which align with faults of the north-northeast–trending Hauraki Rift (Rowland and Sibson, 2001, 2004).

The volcanlastic filled basins typically are interpreted as developing gradually through secular rifting (Villamor and Berryman, 2001; Nicol et al., 2006), which increases in magnitude from ~3 to >15 mm/yr from southwest to northeast, respectively, along the axis of the TVZ (Wallace et al., 2004). However, within the central TVZ, an additional, episodic basin-forming process adds complexity to the structural and stratigraphic history of the region. Over the past 1.6 m.y., the central TVZ has undergone at least 25 large (30 to >1500 km$^2$) rhyolitic eruptions, resulting in the formation of at least eight calderas centers (Wilson et al., 2009). These calderas range in diameter from ~10 to 40 km, and are superimposed upon, and in some cases perhaps intimately associated with the formation of, fault-controlled rift basins (Gravley et al., 2007; Rowland et al., 2010; Allan et al., 2012). The modern foci of rhyolitic volcanism are the Okataina and Taupo volcanic centers (Fig. 1) (Nairn, 2002; Wilson et al., 2009).

Currently, the central TVZ is geographically divided into two parallel northeast–elongate basins. The northwestern basin is the Taupo fault belt (TFB), which exhibits a classic rift morphology (Rowland and Sibson, 2001), is seismically very active (Bryan et al., 1999), and has subsided at a rate of 3 to 4 mm/yr since at least ~61 ka, based on studies of its paleoseismology (Villamor and Berryman, 2001). The southeastern basin is the TRB (Fig. 2), which, in contrast to the TFB has very limited geomorphic evidence for faulting and is seismically less active (Bryan et al., 1999), but nonetheless has subsided at an equivalent rate of 3 to 4 mm/yr since at least ~1.8 ka, based on the mapping of paleolake shoreline elevations (Manville, 2001). The kinematics of the TFB are reasonably well understood in terms of orthogonal rifting, perhaps with a minor component of strike-slip (Rowland and Sibson, 2001; Acocella et al., 2003). Little is known of the kinematics of the TRB, or its contribution to the tectonic and magmatic evolution of the TVZ; however, the TRB is of considerable interest for the following reasons.

1. New Zealand’s high temperature (>250 °C) geothermal resources currently under exploration or development are mostly located within, or on the perimeter of, the TRB (Figs. 1 and 2). The total estimated resource in this basin exceeds 2000 MW (Bibby et al., 1995). The rich database of drill hole stratigraphy obtained during more than 50 years of geothermal exploration, and high resolution local- and regional-scale geophysical imaging (aeromagnetics, gravity, resistivity, magnetotellurics) has facilitated development of reservoir- (e.g., Rae, 2007; Rosenberg et al., 2009) and crustal-scale geological models (e.g., Heise et al., 2007, 2010). However, the 3-D stratigraphic and structural architecture of the TRB and its temporal evolution remain poorly resolved.

2. The timing and rapidity of tectonism, volcanism, and magmatism that strongly influence basin development within the TVZ are unknown (gradual versus punctuated; Villamor and Berryman, 2001; Rowland et al., 2010). Comprehensive mapping, reevaluation of drill hole stratigraphy, and geochronology allow for the evolution of the TRB to be understood in terms of interconnected tectonic, volcanic, and magmatic processes.

3. The TRB occupies an equivocal position in the tectonic configuration of the Hikurangi subduction margin, between the TFB to the west and the right-lateral North Island fault system to the east. Whereas the TFB accommodates near orthogonal extension, the latter feature accommodates the margin-parallel component of oblique plate motion between the Pacific and Australian plates at the Hikurangi subduction margin (Beanland and Haines, 1998; Villamor and Berryman, 2001). It is not clear from current studies whether the TRB is undergoing near orthogonal extension, or whether it is a transtensional feature. The TRB’s position on the eastern margin of the TVZ, coupled with its extraordinary heat output, support the possibility that it is an incipient rift jump in the context of a southeastward migrating arc.

**Taupo-Reporoa Basin and Bounding Features**

As defined here and shown in Figure 2, the TRB extends along strike from the Taupo volcanic center in the southwest to the Waiotapu geothermal field in the northeast. In the northwest, the TRB is delimited by the active (last rupture at 20 ka or later; GNS Science Active Faults Database, http://data.gns.cri.nz/af/), and geomorphically well expressed ~25 km long Paeroa Fault, and its associated upstanding footwall block (Paeroa block; Fig. 2). Along strike beyond the southwestern limit of the Paeroa Fault the boundary is less obvious within more subdued topography, but is delimited by the active Orakei Korako, Whakaheke, and Kaiapo faults (Fig. 2). On its eastern margin the TRB is delimited by the currently inactive Kaingaroa Fault zone, which is discussed in more detail in the following (Fig. 2).

Geothermal drilling demonstrates that the top surface of the metasedimentary basement, in which the basin has formed, is at ~1 to >3 km depth (Wood et al., 2001; Rae, 2007; Rosenberg et al., 2010). Basin fill comprises predominantly Quaternary rhyolitic ignimbrites interbedded with lavas of all compositions, reworked volcanioclastic strata, lacustrine and fluviatile sediments, and paleosols (Figs. 2, 3, and 4A–4C) (Leonard et al., 2010). Silicic plutonic bodies have been proposed as being widely present (Evason et al., 1976; Stern, 1985); however, the only in-situ plutonic bodies identified are in the Ngatamariki geothermal field at 2.6 km or greater depth (Fig. 4B) (Browne et al., 1992; Arehart et al., 2002; Mighty River Power, 2013, written commun., drill hole data).

Quaternary strata within the TRB can be divided into four packages, the first three of which are relevant to our discussion (Figs. 3 and 5A–5D): (1) the Reporoa Group, which includes deposits that unconformably overlie metasedimentary basement through to but not including the 349 ± 4 ka Whakamaru Group (Gravley et al., 2006); (2) the Whakamaru Group, which corresponds with a regionally extensive and distinctive time horizon comprising ignimbrites dated at 349 ± 4 ka, and a geochemically and petrologically similar but slightly younger (339 ± 5 ka) suite of ignimbrites; (3) the Huka Group, which includes all strata between the Whakamaru Group and the 25.4 ± 0.2 ka Oruanui Formation; and (4) the Huka Group, which includes all strata between the Whakamaru Group and the 25.4 ± 0.2 ka Oruanui Formation.

The modern (past ~61 k.y.) TRB is volcanically quiescent, although it had an explosive past. In its northern part, the TRB encompasses the Reporoa caldera, which formed in association with eruption of the Kaingaroa Formation (Nairn et al., 1994) at 281 ± 21 ka (new age estimate discussed in the following). In the south, the TRB spans the southeastern part of the Whakamaru caldera, which formed during eruption of the regionally extensive ignimbrites of the Whakamaru Group at 349 ± 4 ka (Wilson et al., 1986). Stratigraphically important proximal members of the Whakamaru Group (Paeroa Subgroup) were erupted at 339 ± 5 ka from a source close to the present-day Paeroa
Fault (Keall, 1988; Grindley et al., 1994; Downs et al., 2013).

The TRB is generally interpreted as a simple fault-angle depression (i.e., half-graben) between westward dipping normal faults (Modriniak and Studt, 1959). However, the presence of calderas at its northern and southern extents (Wilson et al., 1986; Nairn et al., 1994), the morphology and geological complexity of its western boundary, and numerous intra-basinal faults, as inferred from offsets (>100 m) of stratigraphic contacts in geothermal drill holes (Figs. 4A–4C) (Henrys and Hochstein, 1990; Wood et al., 2001), suggest a more complex volcano-tectonic evolution.

**TRB Western Margin: Paeroa Block**

The Paeroa block is the largest exposed fault block within the central TVZ, extending >25 km along strike and rising to 500 m at its highest point above the adjacent TFB and TRB, between which it forms the major divide (Fig. 2). It is back tilted ~7° eastward, presumably as a result of footwall rotation around a horizontal axis in response to slip on the westward facing Paeroa Fault (Berryman et al., 2008). The Paeroa Fault is crustal in scale, strikes 040° to 050°, undergoes pure normal dip slip, and has slipped at a rate of 1.1 to 1.7 mm/yr, based on paleoseismology investigations of its northern splays and estimates derived from 550 ± 50 m displacement of the 339 ± 5 ka Paeroa Subgroup (Berryman et al., 2008). Although the elevation of the Paeroa block is generally attributed to tectonically induced footwall uplift (Villamor and Berryman, 2001; Berryman et al., 2008), structural resurgence has also been proposed (Healy, 1964). Whatever the cause, the upstanding Paeroa block preserves some of the best exposures of Quaternary strata within the TRB. The geology of the Paeroa block has received little new investigation since it was mapped at a reconnaissance level in the 1950s and 1960s (Grindley, 1959, 1961; Healy et al., 1964; Leonard et al., 2010). Correlation of outcrops within the block with subsurface data from the wider region is based on earlier work (Grindley et al., 1994), and open to reinterpretation based on improved geochronology (e.g., Wilson et al., 2010).

**TRB Eastern Margin: Kaingaroa Fault Zone**

The Kaingaroa Fault (Fig. 2), which defines the eastern margin of the TRB, is manifested as a topographic scarp along most of its extent and coincides with the eastern margin of the TVZ as defined from vent locations (Wilson et al., 1995).
It marks the western margin of the Kaingaroa Plateau, a broad (~30 km wide) area of low relief that abuts the axial ranges of the North Island and the attendant North Island fault system (Figs. 1 and 2). The surface of the Kaingaroa Plateau is capped by rhyolitic ignimbrites that are correlative with ignimbrites within the TRB (Figs. 4B, 4C). These ignimbrites unconformably overlie metasedimentary basement at an inferred depth of ~650 m, based on seismic reflection surveys (Stagpoole, 1994). Interpretation of resistivity and gravity data across the topographic scarp of the Kaingaroa Fault, in combination with geothermal drill hole stratigraphy from within the TRB, indicate that the basement is displaced by >2 km by several faults over a horizontal distance of ~6 km (Henrys and Hochstein, 1990; Bibby et al., 1998; Wood et al., 2001). Thus, the surface mapped Kaingaroa Fault is the easternmost structure within a narrow belt of faults referred to here as the Kaingaroa Fault zone. Limited observations (Wilson et al., 1986; Nairn et al., 1994; Tanaka et al., 1996) and geophysical interpretations (Stagpoole, 1994; Bibby et al., 1998) of stratigraphic relationships across the Kaingaroa Fault are consistent with the notion that the easternmost fault, and presumably the
Figure 5. Plan view stratigraphic time reconstruction of the Taupo-Reporoa Basin (TRB) and Taupo fault belt (TFB) displaying tectonic and volcanic features. TVZ—Taupo Volcanic Zone. In key, groups are differentiated: dark colors represent lavas and light colors represent volcaniclastic and sedimentary deposits. (A) Reporoa Group with a geothermal field inferred from Arehart et al. (2002). (B) Whakamaru Group and Paeroa Subgroup emplacement, and development of the TRB and TFB. (C) Huka Group with uplift and tilting of the southern Paeroa block. (D) Modern hydrothermal activity. The plus symbols represent buried lavas identified within geothermal drill holes that are inferred as being close to source.
entire fault zone, has been inactive since at least 281 ± 21 ka, that is since eruption of the Kaingaroa Formation (Fig. 2).

METHODS

Development of a basin-wide evolutionary model for the TRB necessitated definition of a new and high resolution stratigraphic architecture. To achieve this we used the following four-step process.

First, a comprehensive review and evaluation of lithologic descriptions from geothermal drill cores and cuttings was undertaken to construct the stratigraphic framework and structural architecture of the TRB (Figs. 3 and 4A–4D). The drill hole logs provide virtually the only stratigraphic record for the basin interior because young (25.4 ± 0.2 ka and younger) ignimbrites and sediments mask older units except for rare surface exposures of 100 ka and older rhyolite, dacite, and andesite lavas (Fig. 2). Regardless of location within the basin, or degree of hydrothermal alteration, the four packages of Quaternary strata defined earlier can be readily discerned in the drill hole records. In particular, the Whakamaru Group is the most distinctive marker horizon throughout the region and as a result, along with the Reporoa and Huka Groups, it is well located at depth throughout the TRB (Figs. 4A–4C). Although hydrothermal alteration limits geochemical and geochronological fingerprinting of units sampled from geothermal drill holes, further refinement of the stratigraphic framework is possible using petrography and zircon age spectra to aid in identification and correlation of altered units (Wilson et al., 2010).

Second, the Paeora block on the northwestern margin of the TRB was mapped to identify stratigraphic units and determine deposit geometries in the best exposed part of the TRB. During mapping, comprehensive descriptions of units were compiled (Fig. 3) and used to interpret volcanic sources, transport processes, and depositional environments. Juvenile pumice and lava samples were collected for 40Ar/39Ar dating and geochemical analysis, and lithic clast componentry was undertaken for comparison with previously described ignimbrites.

Third, Paeora block strata were correlated where possible, with units identified at depth within geothermal drill holes and exposed along the Kaingaroa Fault scarp. Correlations were based predominantly on lithological descriptions and juvenile clast petrology. Pumice is the juvenile mafic component from ignimbrites, and pumice petrography and geochemistry are widely used in correlating ignimbrites (Hildreth and Mahood, 1985). However, for the time frame from post–Paeora Subgroup (339 ± 5 ka) to 239 ka within the central TVZ, which spans ignimbrite ages within the major part of the Huka Group stratigraphy studied here, there is an overlap in major and trace element compositions, and petrographic characteristics for almost all deposits (Karhuinen, 1993; Beresford, 1997; Milner, 2001; Gravley, 2004). We have thus undertaken petrography to identify mineral assemblages and X-ray fluorescence (XRF) analyses to identify major and trace element trends, but such data are only used to complement and further support lithological descriptions for correlating strata.

Fourth, age control was established for the new stratigraphic architecture by supplementing existing data (Houghton et al., 1995; Wilson et al., 2009, 2010) with new 40Ar/39Ar ages on selected lavas and pumice clasts obtained from the Paeora block and rare surface exposures within the TRB.

XRF Techniques

Rhyolite lavas and juvenile pumice clasts (of at least 4 cm) obtained from exposed rhyolitic ignimbrites and lavas were used for individual XRF analyses. Samples were washed in deionized water to remove attached matrix or foreign material, and dried in an oven at 100 °C for several days before crushing. Clasts were crushed and altered material was removed. Samples were powdered using a tungsten carbide Teka mill. Powder (5 g) from each sample was dried at 110 °C for 24 h to remove meteoric water. Samples were then ignited at 850 °C for 12 h to determine loss on ignition by removing volatiles; 2 g of ignited sample were mixed with 6 g of 12:22 flux and fused into glass discs. Major and trace element geochemistry (Table 1; Table DR1 12:22 flux and fused into glass discs. Major and trace element

4Ar/39Ar Dating Techniques

Samples for age determinations were collected from seven rhyolite lavas and three rhyolitic ignimbrites exposed within the TRB (Table 2). Samples were crushed using a disc mill and plagioclase concentrates were prepared by hand-picking and using a LB-1 Barrier Frantz magnetic separator. Separates were etched with 0.1 M hydrofluoric acid to remove any adhering glassy material, then washed in acetone and deionized water. Final separates for irradiation were hand-picked to remove any crystals containing inclusions or with remaining adhering minerals or glass. Encapsulated packets of ~200 mg of plagioclase were irradiated for 1 h in the central thimble of the U.S. Geological Survey TRIGA reactor in Denver, Colorado (methods described in Dalrymple et al., 1981). Samples were shielded from thermal neutrons and neutron flux was measured using Taylor Creek sandine (TCR-2) fluence monitors with an assigned age of 27.87 Ma (Dalrymple and Duffield, 1988). The reactor vessel was rotated continuously during irradiation to avoid lateral neutron flux gradients. Fluence monitors were analyzed using a continuous laser system and a MAP 216 mass spectrometer (methods described in Dalrymple, 1989).

Argon was extracted from the plagioclase separates using a Molybdenum crucible in a Staudacher-type custom resistance furnace attached to the mass spectrometer. Heating temperatures were monitored with an optical fiber thermometer and controlled with an Accufiber Model 10 controller. Gas was purified continuously during extraction using two SAES ST-172 getters operated at 4A and 2.5A.

Detailed step-heating experiments were undertaken to yield plateau age spectra and isochron ages with regression intercepts (York, 1968) within error of the atmosphere. Degassing was done to 650 °C and steps utilized started at 700 °C. Significant 39Ar came off at 1400 °C so this was analyzed as a last step for calculating plateau ages. Analytical protocols for determining furnace blanks and mass discrimination followed those detailed in Calvert and Lane (2006). All ages are reported with 1σ errors including errors in neutron flux, but not including errors in decay constants or monitor minerals. Details of the experimental results are summarized in Table 2 and Figures 6 and 7 (see Figs. DR1–DR11 in the Supplemental File [see footnote 1] for complete age profiles).

RESULTS

Stratigraphic Summary

Deposits mapped within the Paeora block are shown in Figure 2. All are correlative with previously mapped or described formations. The overall stratigraphic architecture, ages, volcanic sources, and deposit descriptions are summarized in Figure 3. Strata of the Reporoa,
TABLE 1. REPRESENTATIVE MAJOR AND TRACE ELEMENT ANALYSES OF JUVENILE PUMICE CLASTS AND RHYOLITE LAVAS

<table>
<thead>
<tr>
<th>Sample Code</th>
<th>Rock Type</th>
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<th>Al₂O₃</th>
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<th>MgO</th>
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<th>P₂O₅</th>
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<td>99.86</td>
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Note: Analyses were performed by X-ray fluorescence. Major elements are recalculated anhydrous, but original loss on ignition (LOI) and totals are given.

Downs et al., 1998). Second, the older (349 ± 4 ka), lithological characteristics (Keall, 1988; Brown et al., 1998). In detail, aspects of the Whakamaru Group are widespread throughout the central North Island. Within the study area, these older ignimbrites blanket the Kaingaroa Group and are commonly penetrated by drilling in the Whakamaru Ignimbrites. The Whakamaru Group includes the Whakamaru ignimbrites and associated rhyolitic lavas, silicic pyroclastic deposits, and some rhyolitic vents. The Whakamaru Group is 1.7–2.5 km thick and consists of: (1) the Whakamaru Ignimbrites, which are 1.7–2.5 km thick and consist of well-stratified, predominantly pumiceous andesite and andesite-dacite tephra; (2) the central North Island volcanic field, which includes the Mihi ignimbrite, the Whakamaru Ignimbrite, and the Huka Ignimbrite; and (3) the northern North Island volcanic field, which includes the Whakamaru Ignimbrite and the direct west of the Whakamaru Ignimbrite.
TABLE 2. AGE DETERMINATIONS BY 40Ar/39Ar TECHNIQUES ON RHYOLITIC IGNIMBRITES AND LAVAS

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Grid reference*</th>
<th>Unit</th>
<th>Sample type</th>
<th>Plateau</th>
<th>Interpreted age</th>
<th>Isochron</th>
<th>Isochron</th>
<th>Total gas age</th>
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<td></td>
<td></td>
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<td>%39Ar gas age</td>
<td>Age</td>
<td>MSWD</td>
<td>%39Ar/39Ari</td>
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<td>GL1034</td>
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<td>Aratiatia rhyolite lava</td>
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<td>55 (3 of 10)</td>
<td>103 ± 6</td>
<td>0.3</td>
<td>103 ± 6</td>
<td>as for plateau</td>
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<td>GL1084</td>
<td>38.555, 176.26E</td>
<td>Orakei rhyolite lava</td>
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<td>MR9</td>
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<td>Mihi Plagioc assay</td>
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<td>243 ± 12</td>
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<td>2.2</td>
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<td>153</td>
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<tr>
<td>CR1</td>
<td>38.445, 176.17E</td>
<td>Kaingaroa Formation</td>
<td>Pumice: plagioclase</td>
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<tr>
<td>Cd110</td>
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<tr>
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Note: MSWD—mean square of weighted deviates.
*Grid references are in World Geodetic System 84.
†All errors are 1σ other than 40Ar/39Ar, which is 2σ.
Figure 6. Weighted mean plateau ages (WMPA) for all samples, except Mihi sample MR1, dated using 40Ar/39Ar techniques from the Taupo-Reporoa Basin (MSWD—mean square of weighted deviates). Gray boxes were used to calculate the WMPA, and black boxes were discounted. All samples have been scaled to an apparent age of 600 ka except for the Ngapouri rhyolite lava (sample 245). The WMPA for the Kaingaroa Formation (sample CR1) is displayed, but based on stratigraphic evidence an age of 281 ± 21 ka is considered more appropriate (see text for details).
are horizontal to sub-horizontal in other proximal locations within the southern Paeroa block. Gravley (2004) mapped a similar stratigraphic sequence of thin lacustrine beds (~10 k.y. of sedimentation) overlying the Ohakuri Formation within the TFB to the west. The lacustrine sediments within the Paeroa block are overlain by ignimbrite of the Kaingaroa Formation (Fig. 8D). Within the southern Paeroa block, decreasing lithic clast sizes (largest is >2 m across) and thinning of the Kaingaroa Formation to the west are consistent with it originating from a Repo- roa caldera source (Fig. 2). Both the Ohakuri and Kaingaroa Formations include accretionary lapilli–bearing beds, suggesting that abundant water was present during both eruptions (Beresford, 1997; Gravley, 2004).

Overlying the aforementioned formations is the Mihi Breccia (Fig. 2), an enigmatic composite of interbedded lacustrine, volcanioclastic, and pyroclastic density current deposits (Figs. 9A, 9B). Prismatically jointed (breadcrusted) pumiceous clasts, soft-sediment deformation, and abundant lithic clasts of lacustrine sediments (Fig. 9B) all support the notion that the pyroclastic density currents flowed into, or erupted beneath, a lake system. The Mihi Breccia thus records numerous shifts from low energy lacustrine sedimentation to rapid accumulation of primary and reworked volcanioclastic material (Fig. 3). The Mihi Breccia is considered equivalent to, but not correlative with, numerous subsurface rhyolite lavas and their pyroclastic equivalents that are interbedded with lacustrine sediments throughout the TRB (e.g., Rosenberg et al., 2009).

Additional deposits within the Paeroa block include a pumice-rich breccia of limited extent (Fig. 8E), a clast-supported hydrothermal eruption breccia (Fig. 9C), and a stratified basaltic lapilli tuff (Mangamingi basalt; Fig. 9D); all derived from sources within the southern Paeroa block.

Geochemistry

A large database of XRF analyses exists for rhyolitic ignimbrites encompassed by the Huka Group time frame (Karhunen, 1993; Beresford, 1997; Milner, 2001; Gravley, 2004). However, since overlap in the values of all major and trace elements is common in deposits erupted during this time frame, analyses of juvenile clasts were used only as a complement to lithologic descriptions for correlating deposits within the southern Paeroa block. Single pumice clast major and trace element geochemistry on the Ohakuri and Kaingaroa Formations overlap well with their respective fields, confirming correlations (Fig. 10; Table 1). Slight variations outside of the
defined fields are inferred to be related to weak hydrothermal alteration of clasts, or to primary variations that have previously been undetected. Three pumice types were geochemically identified by Gravley (2004) within the Ohakuri Formation; one is minor and has not been identified here.

Geochemical compositions of pumice and rhyolite lava clasts from the Mihi Breccia are delineated into two groups that correspond to signatures from nearby rhyolite lavas exposed within the TRB (Kairuru, Pukekahu, Deer Hill; Fig. 2). The first is a high silica group closely corresponding in composition to Kairuru, and the second is a lower silica group that encompasses Pukekahu and Deer Hill rhyolite lavas (Fig. 11; Table 1). Mihi Breccia juvenile clasts are texturally and petrographically similar to those exposed rhyolite lavas. In addition, a buried dome complex inferred to correlate with Kairuru is interpreted to be beneath the southern Paeroa block that yield ages of 965 ± 8 ka (at Ngapouri) and 490 ± 3 ka (at Trig 8566; Fig. 2). We use the age of 710 ± 60 ka from Houghton et al. (1995) for the Waiotapu Formation within the northern Paeroa block. Five members of the Whakamaru Group and Paeroa Subgroup have been dated, and the results are discussed in Downs et al. (2013). The oldest Huka Group eruptive identified within the southern Paeroa block is the localized pumice-rich breccia (Fig. 8E), which yields an age of 312 ± 4 ka from a juvenile clast (Fig. 6). However, this unit has only been identified in one locality and there are no stratigraphic or geochemical correlatives, and so we presume that this is a localized eruption.

Of central interest to this study are the ages of three closely spaced caldera-forming eruptions (Ohakuri, Kaingaroa, Mamaku, the last of which has not been identified within the TRB) and their timing relative to other ignimbrites within the Huka Group time frame (e.g., Gravley et al., 2007). Our new ⁴⁰Ar/³⁹Ar age determination for the Kaingaroa Formation, sampled at the southwest end of the Paeroa Fault scarp, is 298 ± 3 ka (Fig. 6); this contrasts with the previous determination of 230 ± 10 ka (Houghton et al., 1995). However, numerous fall deposits, at least five caldera-related ignimbrites (Matahina, Chimp, Pokai, Mamaku, Ohakuri), lacustrine sediments, and multiple paleosols (Karhunen, 1993; Manning, 1996; Gravley et al., 2007) occur between the Paeroa Subgroup at 339 ± 5 ka and the deposit sampled as the Kaingaroa Formation (Fig. 12). A time span of ~40 k.y. for such a complex and prolonged stratigraphic record coupled with existing age data (Houghton et al., 1995; Gravley et al., 2007) imply that an age of 298 ± 3 ka for the Kaingaroa Formation is unrealistic, and we therefore use it only as an upper age constraint on the Kaingaroa eruption. The three exposed post-Kaingaroa rhyolite lavas on the edge of, or just south of, the Reporoa caldera provide minimum age limits. The 264 ± 4 ka Deer Hill lava provides the lower age constraint. An age of 281 ± 21 ka, which is half-way between 264 ± 4 and 298 ± 3 ka, plus or minus half the total difference including their uncertainties, is thus adopted here for the age of the Kaingaroa Formation. This age is identical within uncertainty to the ~285 ka value, based on tephrostratigraphy and oxygen isotopic stratigraphy, for the age of the Kaingaroa Formation airfall deposit reported by Manning (1996).

Gravley et al. (2007) proposed an Ohakuri Formation age of 240 ± 11 ka, based on its stratigraphic position and ⁴⁰Ar/³⁹Ar age determinations relative to the Mamaku Formation. However, Ohakuri Formation ages are scattered beyond analytical uncertainties. The Ohakuri and Mamaku Formations are of geologically identical ages, as demonstrated by Gravley et al. (2007), and underlie the Kaingaroa Formation, and therefore are older. It is unknown how much older, but Gravley (2004) estimated that lacustrine sediments overlying the Ohakuri Formation in the TFB represented a ≤10 k.y. time frame, based on thicknesses and sedimentation rates. We have identified stratigraphically equivalent lacustrine sediments within the Paeroa block, and thus estimate the eruption ages of the Ohakuri and Mamaku Formations to between ~280 and 290 ka. This age range falls within uncertainty of the oldest Ohakuri age (275 ± 16 ka) reported by Gravley et al. (2007). The Pokai Formation (Fig. 3) within the TFB has been dated at 275 ± 10 ka (Gravley et al., 2007), but its top surface contains a well-developed paleosol with Mamaku and Ohakuri units overlying it. The Pokai Formation overlies two airfall tephra sequences that are interbedded

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**Figure 9.** Photographs of southern Paeroa block strata. Shovel used for scale is ~1 m long, hammer head is ~16 cm, and hammer is ~33 cm. All map references are in the World Geodetic System 84 reference grid. (A) Contact between lacustrine sediments and Mihi Breccia (38.47S, 176.26E). (B) Entrained lacustrine clasts within Mihi Breccia (38.48S, 176.26E). (C) Hydrothermal eruption breccia consisting of fine-grained laminated lacustrine sediment boulders (38.48S, 176.23E). (D) Mangamingi basalt (38.49S, 176.22E).
clusions, that is ~300 ka. The Pokai Formation age is likely to be somewhat younger than the Mihi Breccia.

Whakamaru Group (Figs. 3 and 12); thus, the Mihi Breccia ages were determined on two pumice clasts (filled symbols) used to confirm correlations of southern Paeroa block deposits with the Ohakuri and Kaingaroa Formations. Ohakuri and Kaingaroa fields (gray shaded areas) are from data collected by Gravley (2004) and Beresford (1997), respectively. SiO₂ values are recalculated to totals of 100%, after accounting for loss on ignition.

Figure 10. Selected trace element Harker variation diagrams of single pumice clasts (filled symbols) used to confirm correlations of southern Paeroa block deposits with the Ohakuri and Kaingaroa Formations. Ohakuri and Kaingaroa fields (gray shaded areas) are from data collected by Gravley (2004) and Beresford (1997), respectively. SiO₂ values are recalculated to totals of 100%, after accounting for loss on ignition.

with the Chimp Formation, all of which overlie the 349 ± 4 ka widespread ignimbrites of the Whakamaru Group (Figs. 3 and 12); thus, the Pokai Formation age is likely to be somewhat younger than the Mamaku and Ohakuri Formations, that is ~300 ka.

Mihi Breccia ages were determined on two stratigraphic units, although their spatial complexity within the Paeroa block makes their exact stratigraphic positions difficult to determine. The two ages from the Mihi Breccia give a minimum time range of 281 ± 9 ka to 239 ± 3 ka (Figs. 6 and 7). This range overlaps with the ages of the three post-Kaingaroa rhyolite lavas of Deer Hill at 264 ± 4 ka, Pukekahu at 263 ± 5 ka, and Kairuru at 247 ± 2 (Fig. 6), lending credence that these, and related geochemically (Fig. 11) and petrographically similar subsurface rhyolite lavas, are probable sources of the Mihi Breccia. Farther south, two rhyolite lavas exposed at the surface have been dated at 142 ± 4 ka (at Orakei) and 103 ± 6 ka (at Aratiatia; Fig. 6), although any correlative pyroclastic deposits are buried.

DISCUSSION

Evolution of the Paeroa Block

The pattern and distribution of strata within the TRB and surrounds vary along and across the strike of the predominantly northeast-southwest tectonic fabric. In particular, the geology of the Paeroa block varies abruptly along strike, and attests to a contrasting evolutionary history from north to south. The mapped distribution of formations within the southern Paeroa block is as expected for a tilted and somewhat eroded fault block: broadly, the units are elongate to the northeast and young to the southeast (Fig. 2). However, north of the east-west–striking fault that transects the Paeroa block, the Paeroa Subgroup is exposed and there is a lack of younger cover material. The interpretation of the southward slope of the surface of the northern Paeroa block is equivocal; it could represent a primary depositional feature of an ignimbrite fan (our data), a structural resurgence related to the Paeroa Subgroup magmatic system (Healy, 1964), tectonic tilting (Berryman et al., 2008), or some combination of all three processes. Eruptive activity proximal to this part of the block, particularly from the Reporoa caldera accompanying the Kaingaroa Formation, would most likely have resulted in emplacement of an ignimbrite sequence overlying the Paeroa Subgroup. The absence of such material, with the implication that any deposits were thin and consequently eroded away, leads us to infer that the northern Paeroa block has been a topographic high since Paeroa Subgroup emplacement at 339 ± 5 ka, in marked contrast to the southern Paeroa block (Fig. 13C).

The thicknesses and degree of preservation of younger formations within the southern Paeroa block (100 to 500 m thick), interior of the TRB (generally >1000 m thick), and TFB (unknown thickness) indicate that these areas provided the main post–Paeroa Subgroup accommodation space (Fig. 4C). Although all three areas may have had a shared flux of volcanoclastic materials, the role of the southern Paeroa block in accommodating these materials was shorter lived. Exposed stratigraphic positions and deposit geometries indicate that the Ohakuri Formation was emplaced into this southern Paeroa basin early, and was immediately covered by lacustrine sediments (Fig. 13D). The westward thickening wedge of Ohakuri Formation and the ~7° southeast dip of overlying lacustrine sediments show that these units underwent fault-induced uplift and tilting along the present-day southern Paeroa Fault. In contrast, similar aged lacustrine sediments also located proximal to the Paeroa Fault are horizontal to sub-horizontal. We use such evidence to interpret that most of the uplift and tilting of the southern Paeroa block occurred prior to emplacement of the overlying 281 ± 21 ka Kaingaroa Formation (Fig. 13E). This notion is supported by the observation that Kaingaroa Formation is notably absent at higher elevations along much of the southern Paeroa block: a high-standing physical barrier is inferred to have been in place at the time to obstruct and limit the westward flow of the parent pyroclastic density currents. Thus, based on the age dates discussed herein, the Ohakuri and Kaingaroa caldera-forming eruptions, sedimentation of lacustrine beds between these eruptions, and uplift of the southern Paeroa block is inferred to have occurred within a time frame of ≤10 k.y.
The construction of the entire Paeroa block from emplacement and uplift of the Paeroa Subgroup in the northern block (339 ± 5 ka), through subsidence, lacustrine sedimentation, and uplift in the southern block (281 ± 21 ka), is thus inferred to have occurred over 58 ± 26 k.y. Despite the age uncertainties, this line of reasoning draws into question the validity of using modern fault slip rates, as defined from offset surfaces and displacement of 61 ka or younger tephras (Villamor and Berryman, 2001; Berryman et al., 2008), to understand landscape-forming processes within highly productive magmatic rifts. Our chronostratigraphic considerations demonstrate that a minimum slip rate of at least ~11 ± 6 mm/yr is required to account for the maximum observed throw on the fault (500 ± 50 m; Grindley et al., 1994); however, this is an extraordinarily high rate for rifting (Nicol et al., 2006). A more likely scenario is fault displacement in association with eruptive episodes (Rowland et al., 2010). The evacuation of hundreds to thousands of cubic kilometers of volcanic material in association with caldera-forming eruptions provides a plausible mechanism for transient and anomalous slip on pre-existing faults (e.g., Wilson, 2001; Gravley et al., 2007; Allan et al., 2012).

**Figure 11.** Selected major and trace element Harker variation diagrams of Mihi Breccia juvenile pumiceous clasts and broadly coeval rhyolite lavas. Mihi Breccia juvenile clasts have a broad overlap with rhyolite lavas exposed within the interior of the Taupo-Reporoa Basin. Major oxide data are recalculated to total 100% anhydrous.

**Significance of Lacustrine Sediments**

The deposits of ephemeral and longer lived lakes have been documented within the central TVZ, and are likely a common phenomenon given the region’s temperate climate and propensity for drainage networks to be occasionally blocked by eruptive products (Smith et al., 1993; Manville, 2001; Manville and Wilson, 2004). Our age determinations indicate that lacustrine sedimentation within the Huka Group of the Paeroa block spans >50 k.y., but it is unknown if the deposits are the products of one large, long-lived lake or several smaller short-lived lake systems. The evidence for phreatomagmatic activity during the Ohakuri eruption (e.g., accretionary lapilli) and the widespread distribution of lacustrine sediments within the TFB and southern Paeroa block after emplacement of the Ohakuri Formation are taken to indicate that a regional-scale lake system existed prior to and subsequent to emplacement of the Ohakuri Formation (Gravley, 2004; Gravley et al., 2007).

The scale of this lake, and its longevity (at least 10 k.y.), would have required the existence of a long-lived dam across the major central TVZ drainage, the Waikato River (Figs. 13D, 13E).

Although the course of the Waikato River has undoubtedly changed over time (Manville and Wilson, 2004), it has drained the central TVZ to the west via the Ongaroto Gorge (Fig. 2) for at least 349 ± 4 k.y., based on the coincident location of a paleo–Waikato River gorge filled with Whakamaru Group ignimbrites (Martin, 1965). The Ohakuri Formation is of sufficient volume (~100 km³) to have overwhelmed drainage networks, and may have blocked the Ongaroto Gorge or upstream tributaries of the Waikato River. However, dams constructed from the unwelded Ohakuri Formation are unlikely to have prevailed for more than a few decades (e.g., Manville, 2001; Manville and Wilson, 2004). The Ongaroto Gorge walls consist of rhyolite lavas of the Western Dome Belt (Fig. 2), and have K-Ar age determinations ranging from after 349 ± 4 to 187 ± 14 ka (Houghton et al., 1991; Leonard et al., 2010). We think that a more likely control on base level involved such lavas, which presumably blocked the paleo–Waikato River at the present-day Ongaroto Gorge to provide a long-lived (>10 k.y.) barrier (e.g., Crow et al., 2008), or several barriers, in the appropriate location to allow formation of a regional lake.

Rhyolite lavas proximal to the Ongaroto Gorge have elevations of ≥500 m above sea level, consistent with the highest elevations of exposed lacustrine sediments within the southern Paeroa block. Since uplift and tilting are interpreted to have occurred prior to 281 ± 21 ka, the southern Paeroa block has remained relatively stable with respect to the inferred
Ongaroto Gorge barrier. Farther east in the TRB interior, geothermal drill holes commonly penetrate equivalent lacustrine sediments at depths to 900 m (although to 1300 m depth at Wairakei-Tauhara; Rosenberg et al., 2010) (Fig. 4A). Despite hydrothermal alteration making specific correlations tenuous, it is clear that the similarly aged lacustrine sediments within the TRB have subsided compared with those in the southern Paeroa block, and are continuing to subside at 3 to 4 mm/yr, as estimated for the past ~1.8 k.y. (Manville, 2001).

Evolution of the Kaingaroa Fault Zone

Faults composing the Kaingaroa Fault zone are considered to be former strike-slip faults of the North Island fault system reactivated as dominantly normal faults to accommodate TVZ extension (Stagpoole, 1994; Bibby et al., 1998). Some have proposed that these faults are periodically reactivated on a time frame used to infer gradual migration of the linked eastern TRB and TVZ margin (e.g., Stern, 1987). However, we argue that this fault zone reactivates on a punctuated and episodic basis over limited line length, for the following reasons.

The relatively uniform thicknesses of the Reporoa and Huka Groups (commonly ~1000 m for each) within individual geothermal drill holes throughout the TRB (Figs. 4A–4C) support the concept of a long-lived subsiding basin. If a gradual eastward migration of the linked TRB and TVZ margin were occurring, then progressively younger sediments and a thinner Quaternary cover sequence would be expected in an eastward direction across the TRB, but this pattern has not been observed in drill hole records (Figs. 4A–4C).

Sparse age constraints for movement along the Kaingaroa Fault zone are used to infer that the age of fault reactivation youngs to the north-east, and that the easternmost fault has been inactive since at least 281 ± 21 ka Kaingaroa Formation emplacement (Stagpoole, 1994). In the southern part of the TRB, the 712 ± 27 ka Rolles Peak andesite lava (Fig. 2) has not been displaced by the fault zone. North along the fault zone, the 349 ± 4 ka Whakamaru Group is exposed on the scarp near the Ohaaki geothermal field, but is displaced to depths of ~800 to 1300 m within the field (Fig. 4C). Farther north, the 281 ± 21 ka Kaingaroa Formation mantles the easternmost fault, as defined geophysically (Stagpoole, 1994), and is displaced to ~1250 m depth within the adjacent Reporoa caldera (Fig. 4A). The Kaingaroa Formation is the youngest displaced unit along the fault zone; therefore, the eastern margin of the TRB and TVZ has not migrated for at least the past 281 ± 21 k.y. (Fig. 2).

Thus, movement along the Kaingaroa Fault zone appears to be closely coincident with caldera-related eruptions (Whakamaru Group, Kaingaroa Formation), and we define the fault zone as a composite volcano-tectonic feature.

Evolution of the Taupo-Reporoa Basin

Prior to uplift of the Paeroa block, the central TVZ consisted of a single basin that extended from near the present-day Kaingaroa Fault zone to the western margin of the old TVZ bound-

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**Figure 12. Simplified stratigraphic column with a summary of caldera-forming ignimbrites within the northwestern (Taupo fault belt) and southeastern (Taupo-Reporoa Basin) parts of the central Taupo Volcanic Zone, including the deposits that divide the ignimbrites, and relevant age determinations and estimates. Compiled from field studies by Karhunen (1993), Manning (1996), Gravley et al. (2007), and this study.**
ary as defined by Wilson et al. (1995) (Figs. 5A and 13A, 13B). Parts of this basin are interpreted to be superimposed upon a region of earlier subsidence, as indicated by a deepening of metasedimentary basement to the southwest. This earlier period of subsidence appears to be aligned with the ~7 Ma Hauraki Rift, particularly in the Whakamaru caldera area (Figs. 1 and 4A) (e.g., Modriniak and Studt, 1959; Wilson et al., 1986). Rapid development of the Paeroa block, dividing the single central TVZ basin into TFB and TRB, was broadly contemporaneous with an eastward focusing of subsidence within the northern TVZ, as interpreted from stratigraphic relationships (Gravley et al., 2010), drill hole stratigraphy at the Kawerau geothermal field (Fig. 1) (Milicich et al., 2013), and patterns of fault growth in the offshore TVZ (Lamarche et al., 2006). The shift in the locus of tectonism in the northern TVZ ~370 ka (Gravley et al., 2010) predates the 349 ± 4 ka onset of major caldera-forming volcanism (>3000 km³ of erupted material in eight caldera-forming events within a 68 ± 25 k.y. time span; Fig. 12) within the central TVZ. The close timing (~21 k.y.) between the onset of major caldera-forming volcanism and rift localization and basin

Figure 13. Time-series reconstruction of the central Taupo Volcanic Zone (TVZ). (A) Emplacement of abundant andesitic lavas (older than 1.9 Ma) and some rhyolitic ignimbrites in a single basin. (B) Continued filling of the basin with Reporoa Group strata represented by numerous rhyolitic ignimbrites (i.e., Waiotapu Formation) and reworked (i.e., lacustrine, fluvial) equivalents. (C) Whakamaru caldera collapse at 349 ± 4 ka and Paeroa Subgroup emplacement at 339 ± 5 ka with subsequent uplift of the northern Paeroa block. (D) Ohakuri caldera collapse with subsequent tilting of the southern Paeroa block. (E) Reporoa caldera collapse at 281 ± 21 ka and continued lacustrine sedimentation from a rhyolite lava dam formed within the Ongaroto Gorge. (F) Continued basin development with episodes of rifting, effusive and explosive eruptions, and lacustrine sedimentation. See Figure 3 for color legend.
reorganization in the central and northern TVZ, respectively, suggests interactions between tectonic and magmatic processes over considerable distances (Rowland et al., 2010). Could such phenomena relate to migration of the arc?

The locus of modern magmatism related to subduction extends along strike from the andesitic cone of Ruapehu in the southwest to White Island in the northeast (Fig. 1), and manifests within the central TVZ as rhyolitic volcanism at the Taupo and Okataina volcanic centers (Nairn, 2002; Wilson et al., 2009), and the >2000 MW geothermal output within the TRB (Bibby et al., 1995; Rowland et al., 2010). Stern (1987) described the spatial and temporal distribution of arc front andesitic volcanoes, synthesizing the available geochronology, to postulate migration of an andesitic arc front across the central North Island and infer a secular rate of arc rotation. Inherent in Stern’s (1987) model is the notion that the migration of the andesitic arc front is gradual, and can be distinguished on the millennial scale. However, although the TRB appears to be currently aligned with the arc front, many of the thickest andesite lavas intercepted by drilling closely overlie metasedimentary basement rocks, indicating that one or more andesitic composite cones contributed some of the first volcanic extrusions to the TRB (e.g., at Rotokawa; Browne et al., 1992). An andesitic lava (Ngakoro andesite) in the Waio-tapu geothermal field (drill hole WT4; Fig. 4D) is bracketed by a 1.45 ± 0.05 Ma ignimbrite and the 1.21 ± 0.04 Ma Ongatiti Formation (Fig. 4A) (Wilson et al., 2010). At Ngatamariki and Rotokawa, early andesites are overlain by rhyolitic pyroclastic deposits of the Reporoa Group, which return U-Pb inferred eruption ages of 1.89 Ma and younger recorded from zircons (age data of Eastwood et al., 2013). Furthermore, there is broad overlap in the known ages of andesites from the western side of the TVZ to those on the east (Wilson et al., 1995, and references therein). Thus, despite the intuitive appeal of a gradually migrating andesitic arc front, any such arc front does not appear to have migrated for >1.9 m.y.

A more likely explanation for the rapid change in basin configuration within the central and northern TVZ is the interplay between secular rifting and the assembly and evacuation of large rhyolitic magma bodies (e.g., Rowland et al., 2010; Allan et al., 2012). Although a paired andesitic arc front, rhyolitic back-arc system is often promoted to explain the distribution and range of volcanism and gas chemistry within the central TVZ (Stern, 1987; Giggenbach, 1995), the available geochronology of all volcanic compositions within the TRB and wider TVZ does not justifiably such a discrimination. Vents of all compositions overlap spatially and temporally, and attest to a complex interplay between the silicic and mafic magmatic systems at mid-crustal depths, and secular rifting (Charlier et al., 2005; Rowland et al., 2010). These interactions are non-linear and may result in episodic landscape forming volcano-tectonic events from time to time (cf. Rowland et al., 2010).

### Basin Filling Rates

The interplay between tectonism, volcanism, and magmatism has resulted in rapid changes to accommodation space throughout the evolution of central TVZ basins, and so basin filling rates are likely to have varied by orders of magnitude over their lifetimes. A thick (at least 2 to 3 km) sequence of lavas, and andesitic and sedimentary strata in TRB geothermal drill holes, with abundant age dates (Fig. 3), allows for upper limits on filling rates within the TRB to be estimated. The oldest dated deposit at Waiotapu is the 1.45 ± 0.05 Ma ignimbrite penetrated at ~1000 m depth (Wilson et al., 2010).

Gravity studies have been used to interpret the presence of basement rocks beneath Waiotapu at ~2000 m depth (Modriñan and Sturt, 1959). If it is assumed that the 1.45 ± 0.05 Ma ignimbrite and basement rocks are separated by ~1000 m, then either basin fill started to accumulate significantly earlier than ~1.45 Ma, or filling of the basin occurred at a rapid rate prior to that time. Although in the TRB, the 1.45 ± 0.05 Ma ignimbrite has only been identified at Waiotapu, the thickness of Reporoa Group strata penetrated by drill holes throughout the TRB (Fig. 4A) would normally imply that significant time would be required for accumulation. This is supported by the 1.89 Ma and younger ages recorded from deep tuffs (at depths varying from 1.6 to 2.5 km) at Ngatamariki and Rotokawa geothermal fields (age data of Eastwood et al., 2013). These dates, when coupled with other age information from shallower lithologies, imply that these areas have never formed part of a caldera collapse area, and that average subsidence rates in these areas are only on the order of 0.8 to 1.4 mm/yr (cf. Waiotapu; Wilson et al., 2010).

Eruption of the Kaingaroa Formation deposits and accompanying formation of the Reporoa caldera at 281 ± 21 ka (Nairn et al., 1994; Beresford and Cole, 2000) can be used as an example of rapid filling within a localized basin formed within the northern TRB during caldera collapse. The intracaldera Kaingaroa Formation has a top surface penetrated by drill hole at ~1250 m depth (Nairn et al., 1994). However, the three surficial post-Kaingaroa rhyolite lavas dated by us record ages of 264 ± 4 ka (Deer Hill), 263 ± 5 ka (Pukekahu), and 247 ± 2 ka (Kairuru). Using the ages of the Kaingaroa Formation and the oldest rhyolite lava, a minimum sedimentation rate of ~31 mm/yr is estimated for the caldera filling rate. Considering the age uncertainties present, filling may have occurred more quickly. In contrast, a significant part of the stratigraphic architecture within the TRB reflects low energy lacustrine sedimentation with occasional localized small-scale effusive and explosive events (Fig. 13F). Shifts from dominantly pyroclastic and volcaniclastic deposition to low energy lacustrine deposition are not well established due to the scarcity of continuous core (as opposed to cuttings) in geothermal drill holes and the difficulty in distinguishing boundaries between low energy and high energy sedimentary regimes on a lithological basis (e.g., Rosenberg et al., 2009). Nonetheless, a long-term average rate of background lacustrine sedimentation for central TVZ lakes has been estimated as 0.28 mm/yr (Smith et al., 1993). These varying sedimentation rates reflect the processes that have resulted in basin formation and filling, and are intimately linked with tectonic, volcanic, and magmatic processes.

### CONCLUSIONS

New mapping within the Paeroa block, coupled with drill hole records and age dates within the TRB, have allowed for a basin-wide evolutionary model to be developed. While questions remain on the nature of tectonic, volcanic, and magmatic relationships across the TRB and TVZ, these processes are interconnected in controlling basin development and its stratigraphic architecture. The evolution of the TRB involves the following.

1. A single basal structure spanning the central TVZ began to develop during the onset of TVZ rifting and volcanism from ~2 Ma onward. The deposits in this early manifestation of TVZ basin development are represented by Reporoa Group strata, deposited until eruption of the 349 ± 4 ka Whakamaru Group ignimbrites. This group includes thick accumulations of andesitic lavas, indicating that composite cones existed throughout the TRB from before 1.9 Ma, and into the Huka Group time frame.

2. Whakamaru caldera collapse accompanied emplacement of the voluminous and regionally extensive ignimbrites defining the older part of the Whakamaru Group at 349 ± 4 ka, providing a useful time horizon.

3. Emplacement of the Paeroa Subgroup (the younger part of the Whakamaru Group) occurred at 339 ± 5 ka from a source near the present-day Paeroa Fault. Closely coincident with this eruption, the northern Paeroa block underwent rapid uplift, and/or the Te Weta block was downthrown. This abrupt event resulted in
separation of the TFB and TRB, and generation of an unknown amount of Paeroa Fault displacement.

4. Ohakuri caldera collapse accompanied emplacement of the Ohakuri Formation, here estimated to have occurred between ≈280 and 290 ka. Uplift and tilting of the southern Paeroa block occurred within ≤10 k.y. of this eruption.

5. Reporopa caldera collapse accompanied eruption of the 281 ± 21 ka Kaingaroa Formation ignimbrite. This eruption followed a period of brief post-Osakura lacustrine sedimentation, and uplift and tilting of the southern Paeroa block. The post-Osakura lake system lasted for >50 k.y., and was impounded by rhyolite lavas obstructing the paleo-Waikato River at the Ongarato Gorge.

6. The deposits mapped collectively as the Mihi Breccia were erupted and/or emplaced into a lake system over an extended time period from at least 281 ± 9 to 239 ± 3 ka.

7. Low energy sedimentation of lacustrine sediments and minor individual explosive and effusive eruptions continued to occur within the TRB until 25.4 ± 0.2 ka.

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