HUKA GROUP GEOLOGICAL CHARACTERISATION AND INTERPRETATION, WAIRAKEI-TAUHARA GEOTHERMAL FIELD, TAUPO

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ABSTRACT

Understanding the stratigraphic architecture and evolution within geothermal fields is important for the interpretation of geological controls on system hydrology.

In this study, we sample core and use whole-rock immobile element variations (Ti/Zr) to identify lithofacies from within the Huka Group (HG) in the Wairakei-Tauhara Geothermal Field (Wairakei-Tauhara), Taupo Volcanic Zone (TVZ).

Facies associations indicate HG deposition occurred within paleo-Lake Huka. Deposition commenced with a thick ignimbrite deposited in the Lake (Waiora Ignimbrite). Mass ignimbrite emplacement was followed by <120 kyr of smaller-scale volcaniclastic and sedimentary deposition in the subsiding basin (Waiora Volcaniclastics). Volcanic quiescence is marked by the dominant deposition of lacustrine siltstone beginning with the lower HFF (LHFF). Siltstone deposition was briefly exceeded by eruption of the middle HFF (MHFF) phreatomagmatic unit. Continued lacustrine deposition (UHFF) becomes increasingly fluvial as rivers transgressed the filling basin.

1. INTRODUCTION

The Wairakei and Tauhara Geothermal Fields (Wairakei-Tauhara) are located in the central Taupo Volcanic Zone (TVZ) on the northeast edge of Lake Taupo (Fig. 1). The geothermal system is hosted within a structural basin near the southern end of the Taupo-Reporoa Basin. The basin developed in response to regional extension and episodes of caldera collapse, filling with 3 km of low density pyroclastics, sediments and lavas (Downs et al., 2014).

Over sixty years of drilling at Wairakei-Tauhara has provided extensive stratigraphic data. As drilling has progressed since 1950, numerous unpublished reports and published reviews have provided several lithological- and petrographic-based classification schemes (e.g., Grindley, 1965; Healy, 1965; Steiner, 1977; Healy 1984; Rosenberg et al., 2009a; Bignall et al., 2010).

Publically available stratigraphic interpretations by Rosenberg et al. (2009a) (updated by Bignall et al., 2010) follow up on pioneering work by Grindley (1965). An extensive drilling programme at Wairakei-Tauhara from 2006 – 2013 (Fig. 2) has provided new stratigraphic information, which is reflected to a large extent in Rosenberg et al. (2009) and the review by Bignall et al. (2010). Recent (2006 – 2013) drilling included continuous core drilling which provided unprecedented detail on lithological variations from within the Huka Group (HG), comprising material above the Wairakei Ignimbrite (350 ka; Downs et al., 2014), including Waiora and Huka Falls Formations, and below Oruanui Formation (~25.4 ka Wilson, 2001; Vandergoes et al., 2013). Continuous core has provided an opportunity for focused lithofacies and chemical analysis of the HG. Outcomes from our investigations are expected to contribute to better characterising the HG and its evolutionary depositional processes in the Wairakei-Tauhara geothermal area, and the implications for evolution of the broader TVZ .

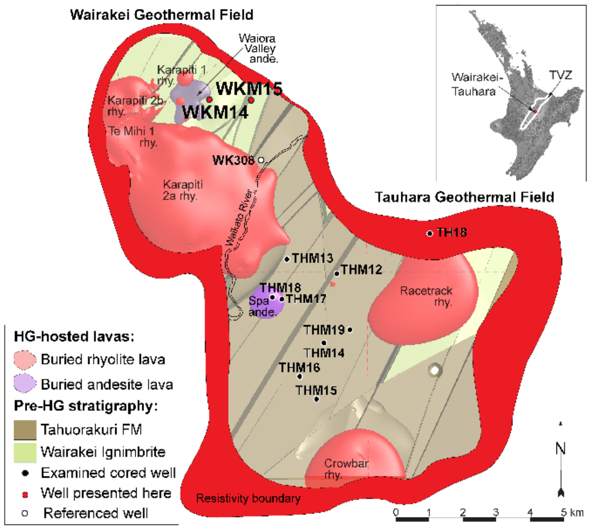

Figure 1: Insert: location of the Wairakei-Tauhara within the TVZ. Main: architecture of Wairakei-Tauhara geothermal fields defined by a resistivity boundary (Risk, 1984) and the locations of wells/cores and HG-hosted subsurface lavas mentioned in the text (Contact Energy, 3D Field Geological model).

2. THE HUKA GROUP IN WAIRAKEI-TAUHARA

Eleven cores intersecting HG in Wairakei-Tauhara (Fig. 1; TH18, THM12, 13, 14, 15, 16, 17, 18, 19) were examined as part of the current study; however, results from two wells (Fig. 1; WKM14 and WKM15) are presented here. Stratigraphy of these wells is derived from the drilling report by Rosenberg et al. (2009b) and a 3D Field Geological model prepared by GNS Science for Contact Energy.

In detail, the HG (Fig. 2) consists of the Waiora Formation (WF), which includes the Waiora Ignimbrite member (Grindley's (1965) Wa_1 member) and a succession of approximately 7 volcanic beds comprising the Volcaniclastics member (Grindley's (1965) $Wa_{2\text{-}5}$). The intersected Ignimbrite is 100 m thick and conformable in Wairakei; however, drilling intersects >1500 m in Tauhara (3D Field Geological model) suggesting significant syn-emplacement paleo-topography existed and post-emplacement deformation since occurred.

The Volcaniclastics member has a more constant thickness (400 m, ± ~100 m) across the Wairakei-Tauhara field than the Ignimbrite member. In detail, they are highly lithologically variable (Fig. 2) which made it difficult for Rosenberg et al. (2009a) and Bignall et al. (2010) to apply Grindley's (1965) scheme throughout Wairakei-Tauhara. As a result, these authors resorted to some simplifications such as consolidation of members Wa3 and Wa4 into Wa3-4. Pumice lapilli-tuffs, brecciated lavas and volcanic-derived sediments from WF are relatively permeable and have served as shallow production targets at Wairakei. Minor, relatively impermeable horizons of WF are represented by interbedded siltstone beds and some intact lavas (Wood, 1994).

Overlying the WF is the Huka Falls Formation (HFF): lower (LHFF), middle (MHFF) and upper (UHFF) members (Rosenberg et al., 2009a). In WKM14/15, each HFF member is 20 – 60 m thick. Siltstone comprising the LHFF, UHFF and undifferentiated HFF serve as impermeable aquiclude cap rocks. The MHFF hosts shallow hot fluids and is a similar pumice-vitric lapilli-tuff composition to much of the Waiora Volcaniclastics. As shown by Dean et al. (2012), shallow steam zones hosted within HFF and near the interface of WF-HFF were targeted for early production at Wairakei. Relatively impermeable horizons within upper WF separated shallow steam-zones from deeper liquid-dominated geothermal aquifers. The latter (geothermal aquifer at mid-depth in WF) were heavily affected by cooling due to infiltration of shallow groundwater resulting in declined productivity of some wells. As a measure to prolong the productive life of some production wells, production casing was deepened to isolate the sections of the reservoir in WF subject to cooling.

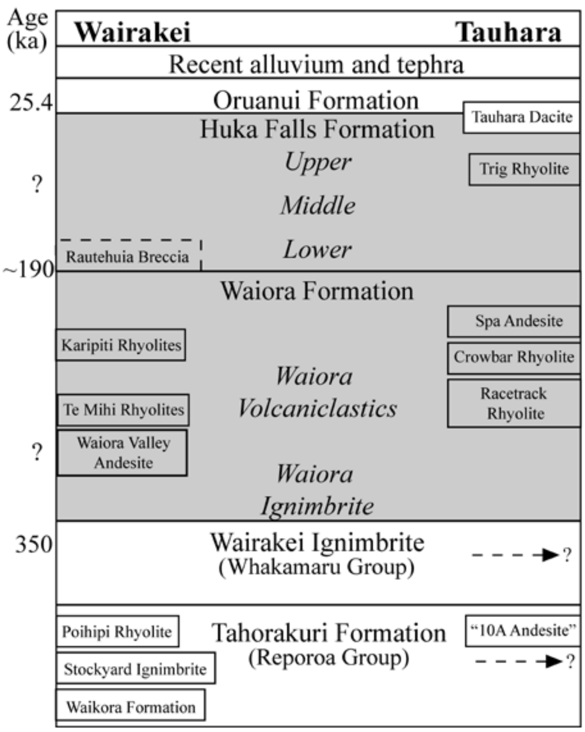

Figure 2: Illustration of stratigraphy throughout Wairakei and Tauhara. Huka Group is grey and members are italicised. Interbedded lavas and local units are in boxes. Figure and ages modified from Bignall et al. (2010) after Rosenberg et al. (2009a).

Current dating and stratigraphic relationships bracket the WF above the ~350 ka Wairakei Ignimbrite (Rosenberg et al., 2009; Downs et al., 2014), correlated with the regional Whakamaru Group (Wilson et al., 1986; Brown et al., 1998). The overlying HFF is constrained between a maximum age of ~190 ka, based on HFF lithics in a dated lava dome, and a minimum age of 25.4 ka for the overlying Oruanui Formation ignimbrite. U-Pb dating of magmatic zircons from the HG is being currently conducted and this is expected to further constrain the timing for key depositional events (M. Rosenberg pers. comm. 2013).

3. LITHOSTRATIGRAPHY AND EMPLACEMENT CONDITIONS

Examination of macroscopic textural and lithological features from core samples and lithofacies assessment is key for interpreting emplacement processes. Lithofacies are common distinctive rock bodies distinguished by lithologic and textural characteristics generated by depositional environments. Core logging of physical and photographed samples identified 9 common HG lithofacies groups (Fig. 3) summarising lithostratigraphy in graphic logs (Fig. 4).

Lithofacies include: Siltstone (S), bedded brown siltstone and sand detritus; Siltstone with clasts (Sc), bedded to massive siltstone including significant (>10 vol.%) detrital clast content; Volcaniclastic mudstone (Vm) and Volcaniclastic sandstone (Vs), vitric, vitroclastic and pumiceous volcanogenic silt- or sand sized units; Volcaniclastic sandstone with pumice clasts (Vp) and Volcaniclastic sandstone with lithic clasts (Vl, clasts <64 mm); Monomict (Bm) and Polymict lithic breccias (Bp, clasts >64 mm); and massive lavas (L). Since lithologies comprising lithofacies may be of variable origin (e.g., volcanic vs. epiclastic sedimentary), sedimentary grain size classification is used for descriptions as an arbitrary non-interpretative reference rather than interpretive volcaniclastic terminology.

Northern Wairakei Geothermal Field samples WKM14/15 only intersect lithofacies S interbedded in multiple, thick, graded Vm, Vs, Vp and Vl sequences (Fig. 4). The other lithofacies were intersected in the analysed wells from Tauhara Geothermal Field not presented here.

The lithostratigraphic variability of sequences intersected in northern Wairakei reflect a prolonged period of intense local volcanism interacting with prevailing sedimentary environments.

Emplacement of the Waiora Ignimbrite (Fig. 4A-B; WI, unit 1) was rapid. Transporting density currents are inferred to have transported material over variable topographic relief and interacted with prevailing lake environments. Graded bedding in the WKM14 and WKM15 holes may reflect eruptive pulses at the source vent or otherwise repeated reworking at the shoreline where pyroclastic flows entered the lake. The following <120 kyr of basin deposition included emplacement of 6 – 7 thinner volcaniclastic deposits (10 – 40 m thick) between quiescent periods that allowed lacustrine silts to be deposited (Fig. 4; WV, unit 2 – 9). Discriminating pyroclastic (magmatic or hydrothermal), autoclastic, and epiclastic sedimentary deposit types intersected by Wairakei wells can be difficult. The high abundance of pumice in or gradationally associated with emplacement units suggests units are dominantly pyroclastic, as pumice is easily modified and removed from reworked sedimentary deposits.

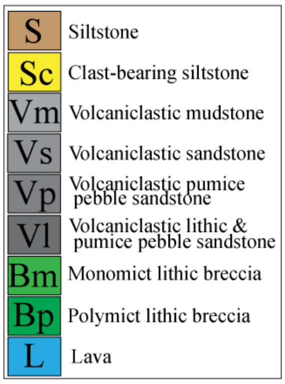

Figure 3: Summary of 9 common lithofacies identified in the Huka Group illustrated in Figure 4.

Following the pyroclastic-sedimentary basin-fill period,

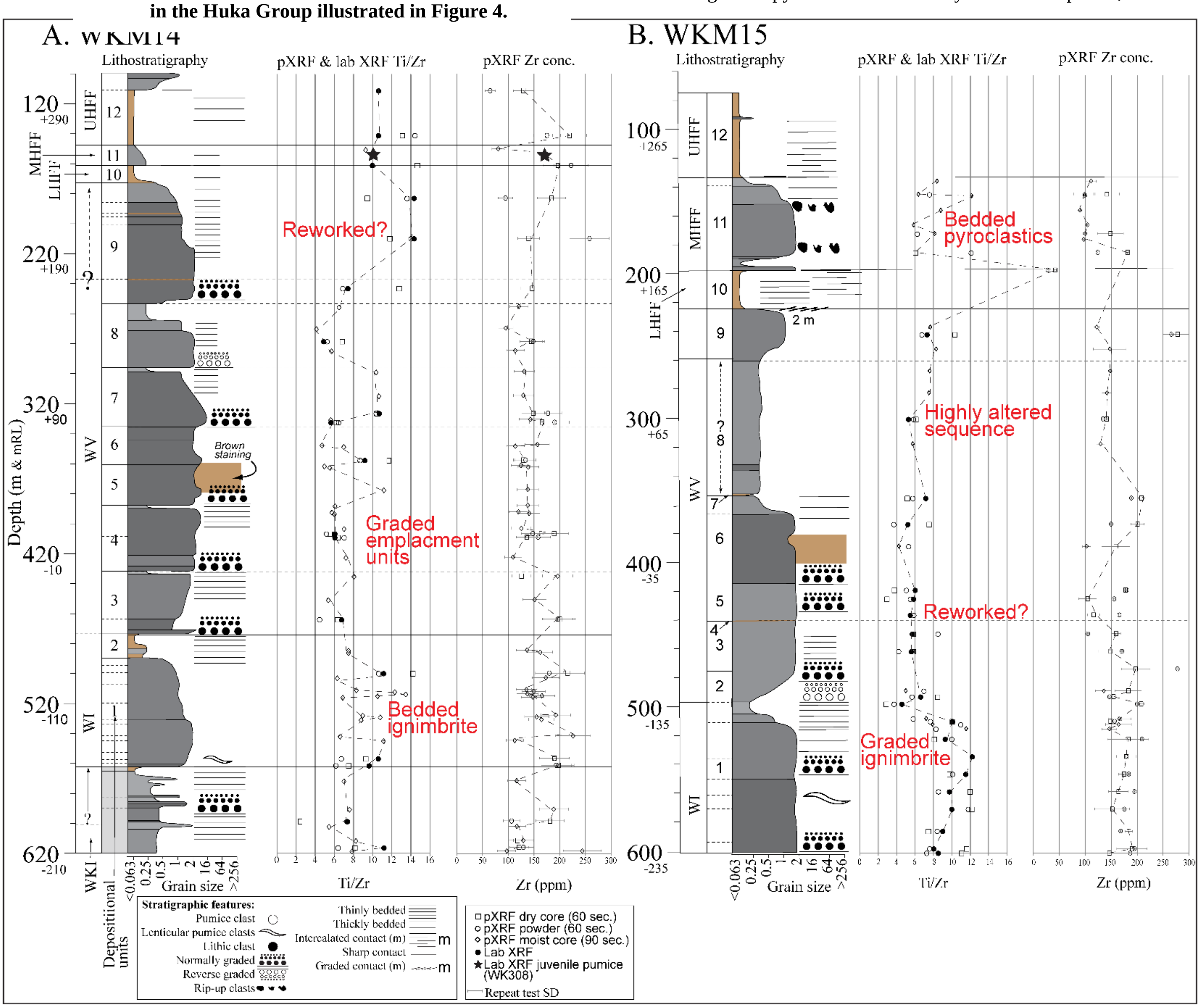

Figure 4. Graphic lithofacies logs and chemostratigraphic trends (Ti/Zr and Zr) of cored wells A. WKM14 and B. WKM15 from northern Wairakei Geothermal Field (Fig. 1). Vertical numbers are identified separate emplacement units that do not necessarily correlate between the wells. WKI = Wairakei Ignimbrite, WI = Waiora Ignimbrite member, WV = Waiora Volcaniclastics member, LHFF/MHFF/UHFF = lower, middle and upper members of the Huka Falls Formation. A fresh, juvenile MHFF pumice Lab XRF analysis is included (well WK308; Fig. 1).

lacustrine deposition dominated forming the HFF. The distribution of siltstones in the area reflects the footprint of ancient Lake Huka (Manville and Wilson, 2004). A widely (Fig. 4A; units 9 & 10) to narrowly gradational (Fig. 4B; units 9 & 10) or sharp lithological contact defining the WF-HFF boundary throughout Wairakei-Tauhara indicates the volcanic to sedimentary transition was spatially and temporally variable. Deposition of the LHFF was interrupted by a phreatomagmatic eruption likely sourced from a vent located in central northern Tauhara (near THM12; Rosenberg et al., 2009b). Bedding in the proximal to medial MHFF facies suggests the eruption was periodic and explosivity fluctuated while graded lateral facies indicate semi-coherent gravity flows transported pyroclastic material beneath Lake Huka (Cattell et al., 2014). Bedding in the MHFF is thick and weakly defined in WKM15, while WKM14 consists of a massive facies Vs only (Fig 4; MHFF, units 11). Progressive to intercalated grading between MHFF-UHFF (c.5 m) indicate that lacustrine sedimentation soon recovered and minor MHFF slumping occurred. Resuming UHFF lacustrine siltstone deposition grades into silty pebble deposits reflecting a change to lacustrine-fluvial deposition in the filling basin. Deposition of the HG was terminated and much of Lake Huka destroyed by the 25.4 ka Oruanui Super Eruption (Manville and Wilson, 2004).

4. CHEMOSTRATIGRAPHIC VARIATIONS

To confirm altered lithotypes (e.g., lithofacies V: pyroclastic vs. epiclastic sediments) whole-rock chemostratigraphic trends of immobile elements were analysed following the approach of Gifkins et al. (2005), after Barrett & MacLean (1994). Both traditional laboratory X-Ray Fluorescence (lab XRF) and new field-portable (pXRF) methods were used in this investigation to acquire concentrations of elements Ti and Zr. These elements have been identified by Youngman (1988) as immobile in Wairakei and therefore serve as unique alteration-resistant tracers reflecting magmatic affinity and entrainment. Data plots assessing for a consistent relationship between primary Ti and Zr indicate the elements are correlated, except when unconsolidated units are modified during transport (grading, winnowing and entrainment).

Lab XRF was the precise (consistent) and accurate (correct) benchmark. pXRF had low detection accuracy, but high precision in both homogenous (prepared) and inhomogenous (dry and moist core) sample types made the technique appropriate for comparing equivalent results analysed under constant conditions. The pXRF method was used for rapid, non-invasive collection of a large data set.

Low magnification (37×) Energy-Dispersive X-ray Spectroscopy (EDS) on rhyolitic tuffs confirmed constituents identified by earlier optical microscopy. EDS also demonstrated that Ti and Zr are principally concentrated in primary magmatic Ti-oxide (rutile, ilmenite) and zircon crystals. These phases occur in the rock as either free crystals (most common) or in a host clast (lithic or pumice). During primary or reworking transport, such as in low density flows, the high specific gravity of these free crystals (and heavy host lithic clasts) concentrate them near deposit bases. Bases of normally graded units are expected to have greater concentrations of Ti and Zr, while deposit tops may be Ti- and/or Zr-poor.

Results from ~50 lab XRF and ~150 averaged pXRF analyses (~4 analyses per target) define chemostratigraphic trends for WKM14/15. Relative to emplacement units identified by lithofacies assessments, internal chemostratigraphic trends use Ti/Zr and Zr concentrations to trace the distribution of the 'heavy' phases.

Lithologies of different primary composition (e.g., rhyolite vs. andesite) are easily identified in chemostratigraphic trends. Dominant rhyolitic compositions in the HG all have similar compositions (pXRF = Ti ~1500 ppm and Zr ~150 ppm). Successive rhyolitic units may be differentiated by internal grading controlling Ti/Zr trends. Mixed composition, lithic-rich bases (e.g., lithic breccias) are reflected as higher Ti/Zr values (>10) similar to those found by Gifkins and Allen (2001) in western Tasmania. Overlying lithic-rich bases, pumice- and vitric shard-rich rhyolitic caps typically have lower Ti/Zr values. Together these result in resulting in units with a negative trend with decreasing depth. Units forming positive trends that with decreasing depth may not have a lithic-rich base (present or analysed) or may be explained by reversely graded Ti-oxide- and zircon-bearing pumice clasts (Fig. 4; unit 11).

Only minor Ti/Zr variation occurs in sequential Waiora Volcaniclastics beds. This may be due to non-graded primary (massive) emplacement or post-emplacement (homogenisation) reworking (Fig. 4). Lithofacies V units conformable with lithofacies S have likely been exposed and reworked in the lake (e.g., Fig. 4B; units 3, 4 & 5). Commonly preserved density graded sequences consisting of a lithic-rich bases (Vl) capped by pumice lapilli-tuff (Vp) and fine tuff suspension (Vm-Vs) are perceived to have undergone minimal transport reworking due to their preserved stratification.

5. DISCUSSION

Characterising and understanding the depositional sequence in Wairakei-Tauhara area has value in terms of conceptual models of system hydrology at the scale of a geothermal system and regional models of the TVZ geological evolution. The presence of c.7 bedded or internally graded units comprising the WF indicate high intensity pyroclastic volcanism occurred over <120 ka. Subsidence of the structural basin accommodated basin filling rates. Chemical Ti/Zr trends in the Ignimbrite mimic the bedding variation supporting the presence of multiple, graded pyroclastic deposits.

Bedding, facies associations with lacustrine siltstones and possibly chemical homogenisation (limited Ti/Zr variation) may suggest that unconsolidated Waiora Volcaniclastics have been variably modified in the prevailing lake setting following initial emplacement (e.g., winnowed fines).

Identifying local vent localities (e.g., local subsidence bowls; Bromley et al., 2009) or correlating units with understood strata (e.g., Wairakei Ignimbrite with 350 ka Whakamaru Group; Wilson et al., 1986; Wood, 1994; Downs et al., 2014), thorough petrographic and chemical examination, will explain lateral variations and relationships within the complexities of the WF. Ongoing stratigraphic and dating is important for identifying the distribution.

The HFF siltstones represent a prolonged period of steady deposition (0.3 – 0.4 cm/yr; e.g., Nelson and Lister, 1995) in Lake Huka, while emplacement of the conformable MHFF was relatively instantaneous. The ~200 kyr volcanic hiatus (c.230 – 25.4 ka) that allowed Lake Huka to thrive (and the HFF to be deposited) is not yet well understood, but may be linked to the episodic nature of volcanism in the area and/or governing tectonic constraints. A study into identifying the extent, relationships and variations of Huka Group siltstone deposits across the central TVZ is necessary to understand the number of lakes, their temporal evolution and their structural controls. Milicich at al. (2013) recently proved at Kawerau Geothermal Field in northern TVZ that Huka Group sedimentary deposits (originally grouped by Grindley, 1986) are older and not related to the HFF at Wairakei (Grindley, 1965) indicating episodic lakes have occurred across the TVZ.

Better constraints of time marker units (particularly lavas) will identify the relative order of deposition and the rates accumulation/erosion associated with arc basin formation outlined here. Comprehension of both the timing of evolutionary processes constraining the tectonic history of the area and correlation of strata have value in predicting the geological controls on fluid flow in the geothermal system.

6. CONCLUSION

Detailed lithofacies analysis of the HG geothermal reservoirs identifies one thick and ~6 smaller pyroclastic units deposited in an ancient lake filled the subsiding basin over <120 kyr. Capping lacustrine siltstones pressurising the geothermal aquifer are lithologically distinct, but depositionally contemporaneous with the Volcaniclastics resulting in a spatially variable lithological contact.

Chemical analyses using a portable apparatus of altered HG core consistently confirmed lithostratigraphic observations and provided additional insights into emplacement and grading.

Understanding strata emplacement processes and distributions refine both our understanding of central TVZ geological evolution as well as the influence complex stratigraphy may have on geothermal systems.

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