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Influences of Geological Depositional Processes and Environments on Geothermal Strata from Wairakei-Tauhara Geothermal Field, New Zealand

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ABSTRACT

A detailed understanding of the strata in geological fields is an important input into drilling and resource management strategies. After >50 years of drilling, the petrography of the strata at the Wairakei-Tauhara Geothermal Field has been elucidated, and insights gained on physical characteristics essential for hydrological modelling in response to development. However, few studies have investigated the geological evolution and depositional setting of the strata, and none have detailed the influence of primary geological processes (e.g. explosive and quench fragmentation) on the near-surface hydrology of the geothermal system.

The Waiora and Huka Falls Formations (HFF), of the Huka Group, respectively form reservoir and capping strata for of the Wairakei-Tauhara system. Facies analysis indicates the Huka Group represents c.300 kyr of intra- and inter-basinal volcanic, volcaniclastic and sedimentary deposition in ancient Lake Huka, the precursor of present-day Lake Taupo located south of the Wairakei-Tauhara.

Over a ~100 kyr period, subaerial pyroclastic flows contributing to the 400 – 2500 m thick (typically ~1000 m) Waiora Formation were quenched and hydraulically reworked upon entering the lake. Subaqueously-erupted, water-supported mass flows also contributed multiple voluminous successions of highly fragmented and permeable, pumiceous pyroclastic deposits, grading from lithic breccia to fine-grained suspension cap. Contemporaneous, subaqueous lavas contain quenched-fractured breccia carapaces and contribute further coarse epiclastic sediments to the basin succession. Hydrovolcanic and sedimentary interactions resulted in fragmented vesicular deposits and fractured lavas underlain by dense breccias which facilitate permeable flow zones within the Waiora Formation reservoir.

Deposition of the overlying <300 m thick Huka Falls Formation occurred during a ~200 kyr period of relative volcanic/volcaniclastic quiescence. Lacustrine sedimentation formed amalgamated turbidite and massive mudstone successions, interrupted by sublacustrine phreatomagmatic event(s) that ejected up to 100 m of permeable pumiceous tuff into the lake. Recognising the physical character and distribution of the Huka Falls Formation mudstone, and that it provides an aquiclude for pressurised fluids migrating to the subsurface, has proven important for the resolving the hydrological evolution of the Wairakei-Tauhara geothermal system, management of near surface thermal fluid-groundwater aquifer interactions and effects of resource utilisation.

1. INTRODUCTION

Defining a detailed stratigraphic and structural architecture within geothermal fields allows conceptual 3-dimentional geological models to be developed and the physical and hydrological properties of strata to be examined for targeting and monitoring resources (Wood, 1994). Assessing the types of strata in geothermal settings can, however, be difficult due to high intensity hydrothermal alteration, commonly masking, homogenising or modifying macroscopic rock lithological properties. Alteration can lead to an oversimplified understanding of the field's stratigraphy (e.g. number of units, distributions, physical properties) and therefore the geothermal assessments made within that strata (e.g. permeability, thermal conductivity).

A primary goal of abundant drilling within geothermal fields in the Taupo Volcanic Zone (TVZ), New Zealand, in the last decade has been to characterise the nature and distribution of subsurface strata. Intersected sequences of dominantly volcanic deposits also provide a unique opportunity to assess the volcanic, structural and geothermal evolution of the TVZ. The Huka Group in Wairakei-Tauhara Geothermal Field (Wairakei-Tauhara), TVZ, contains a thick, shallow reservoir, the Waiora Formation, and a thin, shallow cap rock, the Huka Falls Formation. Understanding the physical properties and stratigraphic variations in the Huka Group by interpreting emplacement conditions, specifically the original geological transport processes and depositional paleo-environments of strata, is an important factor in understanding the shallow hydrology of the geothermal system.

Here, detailed macroscopic facies analysis of Huka Group drill core samples from selected areas of Wairakei-Tauhara has been undertaken to characterise the nature of the intersected ~700 m thick stratigraphic sequence. Facies analysis assesses the structure, fabric, associations and distribution of strata infer emplacement conditions to explain the primary depositional controls on the shallow hydrology. Inferred transport processes responsible for depositing the Huka Group are found to have been dominated by successive subaerial and subaqueous pyroclastic flows derived from magmatic and hydrothermal eruptions. Rapidly emplaced, thick deposits punctuated the ongoing 'ambient' alluvial and lacustrine sedimentation within the prevailing paleo-environment. Resulting deposits from high energy explosive magmatic and hydrothermal eruption processes provide high permeable conduits, such as pumice and lithic breccias, for geothermal fluid flow. Similarly, effusive lavas extrusion resulting in auto- and quench-brecciated extensive carapaces provides localised target zones of high permeability. Lacustrine and suspended volcanic fines emplaced during quiescence periods form thin laterally continuous beds that commonly act as aquicludes or aquitards throughout the dominantly permeable Huka Group. The shallow-intermediate hydrology (100 – ~1000 m) where most of the Huka Group occurs is controlled dominantly by the texture and structure of the primary lithology. At depth (>1000 m) in the lower Huka Group and underlying formations (e.g. Wairakei Ignimbrites) where compaction and cementation is high, extensional faulting and related fractures offsetting deep stratigraphy has been previously suggested as the dominant control on fluid migration.

Outcomes from this research provide a geological context for explaining the types and distribution and permeability properties of strata comprising the Huka Group in Wairakei-Tauhara and explain the volcanic and environmental evolution of the TVZ during a prolonged (c. 300 kyr) period.

2. GEOLOGICAL SETTING

2.1 The Taupo Volcanic Zone

The TVZ is a rifted continental arc that concentrates dominantly silicic volcanism and geothermal systems in the central North Island of New Zealand (Fig. 1). Rifting in the central TVZ has been measured up to 9.6 mm/yr^{-1} (Wallace, 2004) resulting in crustal thinning and an anomalously high thermal gradient with temperatures at depth up to 310°C (Ellis and Mahon, 1977; Grindley, 1965). Initiation of rifting in the zone is likely contemporaneous with the onset of volcanism at c.2 Ma (Houghton et al., 1995; Wilson et al., 1995). Prolonged extension is accommodated by northeast-southwest-trending fault zones and local to regional tectonic and volcano-tectonic basins, many hosting lakes, which serve as depositional centres (e.g. Downs et al., 2014). Deposition in the zone is derived largely from 8 caldera centres generating numerous, widespread, voluminous pyroclastic deposits filling the depositional basins (Houghton et al., 1995; Wilson et al., 1995; Leonard et al., 2010). Concentrated deposition in the central TVZ has resulted in a 2.5 km thick sequence of low density pyroclastic and sedimentary strata (Bibby et al., 1995) hosting the geothermal systems. The high rate and relatively recent activity of volcanism in the TVZ has buried older eruptives which can only be assessed from drilling returns (core or cuttings). Abundant drilling within geothermal fields provides the opportunity to study the physical properties and the depositional history of the intersected units for understanding the local and regional geological evolution.

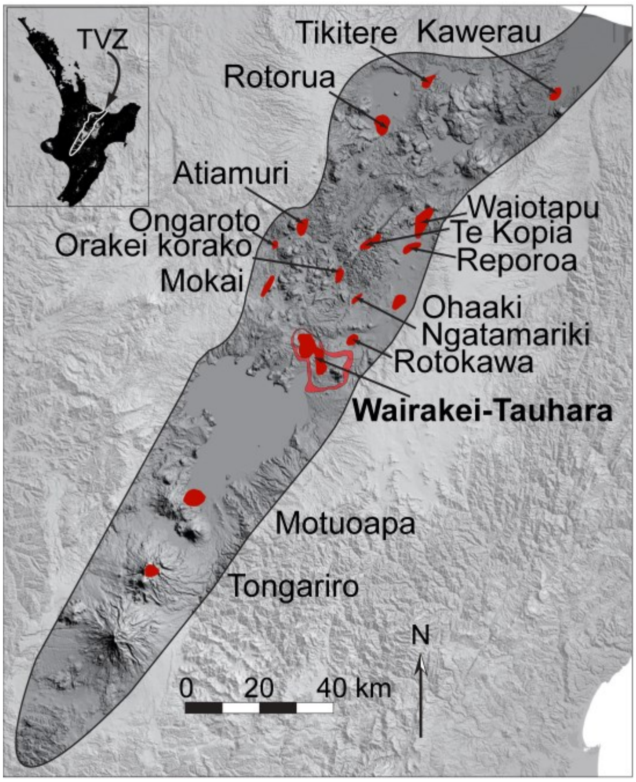

Figure 2: Locations of geothermal fields, including Wairakei-Tauhara, in the Taupo Volcanic Zone (TVZ). Insert shows the locality of the TVZ, central North Island, New Zealand.

2.2 Wairakei-Tauhara Geothermal Fields and the Huka Group

Wairakei-Tauhara Geothermal Fields are located in the central TVZ on the north-eastern shore of Lake Taupo (Fig. 2). The area of the fields are defined by a single resistivity boundary (Risk, 1984) and the two fields are delineated at the surface by the intersection of the Waikato River. Since early exploration of the Wairakei Field from 1949 (Wood and Browne, 2000) to the present day, >200 wells from a few tens of meters up to 3 km depth have been drilled providing a high-resolution insight into the subsurface stratigraphy (Milloy and Lim, 2012). Drilling has confirmed that major stratigraphic units are largely continuous between the fields (Fig. 3; Rosenberg et al., 2009a; Bignall et al., 2010). The stratigraphic sequence (Fig. 3) is underlain by greywacke basement that was intersected by drilling on the eastern margin of the field where it occurs at a shallow elevation (well TH17; Rosenberg et al., 2009a; Bignall et al., 2010). Details concerning the stratigraphic sequence and lithologies in Wairakei-Tauhara are covered in Rosenberg et al. (2009a) and Bignall et al. (2010).

The Huka Group occurs at an intermediate depth (~100 – ~1500 m depth, upto 2500 m) above the 320 ka Wairakei Ignimbrite and below the 25.4 Oruanui Formation (Fig. 2; Grindley, 1965; Rosenberg et al., 2009a; Wilson, 2001; Vandergoes et al., 2013). The depositional period represented by the Huka Group represents c.300 kyr of geological evolution in the central TVZ. Huka Group includes the Waiora Formation (400 – 2500 m thick), a major geothermal aquifer in Wairakei-Tauhara, and the Huka Falls Formation (HFF) cap rock (<300 m thick) (Grindley, 1965). These formations occur to the north-east in the Reporoa basin, however, this study is restricted Wairakei-Tauhara area (Fig. 3). Subdivisions of the two formations were proposed by Grindley (1965) from a well in the Wairakei field (members in Fig. 2) and have been revised by Rosenberg et al. (2009a) to represent stratigraphy across Wairakei-Tauhara. Here, the Waiora Formation members are defined as consisting of a lower Ignimbrite member (member 1; 100 – >1500 m) overlaid by an undifferentated Volcaniclastic member (members 2 – 5; ~400 – 1000 m) (Fig. 2). Limited samples, hydrothermal alteration, segemnted uplfit and lithofacies variations precludes identification of the Waiora Formation source from the laterally few samples investigated here. Nonetheless, the lateral distribution of the Waiora Ignimbrite, inferred to be confined to the Wairkei-Tauhara area, and its thickness (100 - 1000 m) likely reflects a nearby (Fig. 1) caldera origin. Restricted core samples examined here intersect a relatively thin (~100 m), but conformable, section of the Ignimbrite member only.

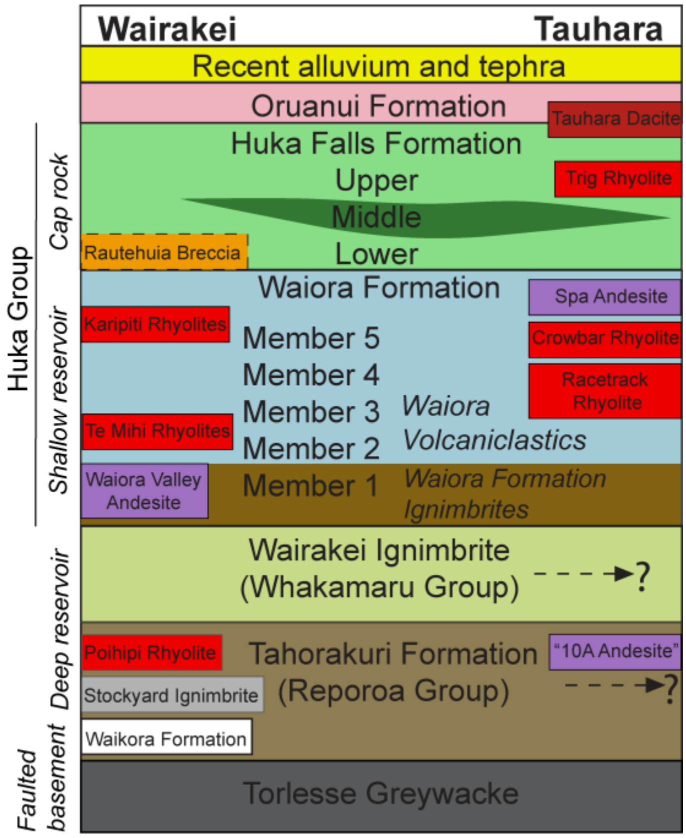

Figure 2: Summary of stratigraphy and their hydrological significance in Wairakei and Tauhara Geothermal Fields modified from Rosenberg et al. (2009a) and Bignall et al. (2010).

The HFF follows divisions proposed by Rosenberg et al. (2009a) consisting of a lower (LHFF) and upper (UHFF) siltstone and sandstone members surrounding a middle (MHFF) pyroclastic unit (Fig. 2). Bedded siltstones comprising the HFF reflect the location and deposition of an ancient form of Lake Taupo, Lake Huka, inferred to have been located between southern presant-day Lake Taupo to near Reporoa caldera (Manville and Wilson, 2004). The depositional processes and mechanisms associated with stratigraphic units within Wairakei-Tauhara have been briefly speculated in early driling reports and in more recent stratigraphic papers (e.g. Grindley, 1965; Healy, 1965; Steiner, 1977; Rosenberg et al., 2009a; Bignall et al., 2010), however, a detailed study of the Huka Group and its emplacement properties has not yet been undertaken. Further detail concerning the emplacement history and the potential influence of the lithologies on geothermal systems can be elucidated by carrying out a detailed facies analysis on the complex stratigraphy.

3. HUKA GROUP ASSESSMENT

3.1 Methods

Detailed macroscopic lithological facies assessments were made from five deeper drill cores (wells TH18, THM16, THM18, WKM14, WKM15 to ~600 m depth) and one shallow sample (THM12 at 377 m depth) intersecting the Huka Group in a northern section of the Wairakei field (WKM wells) and in northern and central sections of the Tauhara field (THM, TH wells) (Fig. 3). Cores are 6 cm diameter and 1 m lengths with returns >95 %. No cutting samples were assessed due to their mixed, incoherent and uncertain nature necessary for lateral stratigraphic correlation and for identifying lithological variations. Lithostratigraphic variations were logged from physical core samples and from continuous core photographs (Glynn-morris & Winmill, 2009). Commonly identified lithologies were grouped into lithofacies groups (facies), each with unique characteristic facies associations. The identification of lithologies and assessments of microscopic textures were made by transmitted light microscopy of thin sectioned samples. Facies groups (Fig. 3) include: Siltstone (S), bedded brown silt and sand accumulations; 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). Graphic logs illustrate the facies sequence comprising the six examined cores in Fig. 3.

3.2 Huka Group lithostratigraphy

3.2.1 Northern Wairakei (WKM14, WKM15)

Two wells, WKM14 and WKM15, drilled c.1.5 km to ~600 m depth in northern Wairakei returned core samples providing the best, most complete insight into the Huka Group sequence in Wairakei-Tauhara (Fig. 3). Drilling intersects a 500 m thick, apparently conformable Huka Group sequence including all three HFF units (UHFF, MHFF, LHFF) and both Waiora Formation members (Volcaniclastics and Ignimbrites). Between the two wells, UHFF and LHFF are bedded siltstone lithologies; however, the contact in WKM14 is less conspicuous than the ~2 m gradational contact in WKM15. The contact in WKM14 may be gradational over ~70 m where siltstone is intermittently encountered within altered pumiceous tuffs. The volcaniclastic MHFF unit is thicker, stratified and contains coarser lithic and pumice clasts in WKM15 (Fig. 3), suggesting this well is more proximal than WKM14 to the source vent. Beneath the HFF, moderate hydrothermal alteration of fine grained volcaniclastic constituents in the Waiora Volcaniclastics makes identifying separate depositional units difficult. Characteristic horizons of noticeably fine grained tuff and siltstone lithologies represent low energy depositional conditions marking breaks between comparatively rapid volcanic emplacement episodes. Emplacement units are commonly underlain by coarse, normally graded breccia concentrations suggesting density grading occurred during deposition. These lithological boundaries identify ~6 major depositional units comprising the Waiora Volcaniclastics member that are largely correlatable between the two wells (Fig. 3). The lowermost drilled section intersects the Waiora Ignimbrites. The member is ~100 m thick in these samples and appears conformable with overlying stratigraphy (Fig. 3). In southern Tauhara, >1500 m of the member has been intersected (Rosenberg et al., 2009a). This lateral variation in thickness suggests either that emplacement occurred on significant paleo-topography or post-emplacement faulting has significantly modified stratigraphy. The Waiora Ignimbrites consist of ~10 weakly normally graded, ~5 m thick beds of medium rhyolite lapilli and common, weakly reversely graded and compacted chloritised pumice clasts (volcaniclastic pumice facies). The unit grades into a 20 m thick siltstone or fine tuff suspension cap (volcaniclastic mudstone facies). In WKM14, up to 40 m of the underlying Wairakei Ignimbrite is intersected. The unit consists of thinly bedded tuffs and siltstone suspension deposits above a massive lapilli-tuff ignimbrite.

3.2.2 Northern Tauhara (TH18)

Seven kilometers south-east of the Wairakei wells, well TH18 intersects a lithologically dissimilar sequence of the Huka Group (Fig. 3). Lithologies of the HFF were largely included in the clast-bearing siltstone facies (Fig. 3) due to the significantly higher volume of clasts (typically ~10 vol.%) than typically observed in the siltstone facies. The MHFF unit is difficult to distinguish here as the usual contrast between brown siltstone and grey tuff lithologies is not present. Instead, the MHFF is identified by a minor increase in volcaniclastic clast detritus (Ramirez pers. comm. 2009). Distinct beds of clast-supported, rounded, medium pebble clasts in the LHFF suggest the unit as has a fluvial origin (Fig. 3). Beneath the clast-bearing facies is typical LHFF consisting of massive to bedded siltstone facies. A 10 m intercalated contact separates LHFF siltstone from altered volcaniclastic lithologies. Over 90 m of reworked rhyolite lapilli-tuff overlies a local lava unit and its breccia component (Fig. 3). The reworked material is inferred to be a talus carapace from the underlying Racetrack Rhyolite, a 200 m thick, flow banded, vesicular lava and monomict breccia that sharply overlies and intrudes (as monomict hyaloclastite/peperite) a thick siltstone facies (Fig. 3). The lowermost 100 m of TH18 intersects several facies including hyaloclastite breccia, a small lava and undifferentiated, highly altered coarse lapilli-tuff.

3.2.3 Central Tauhara (THM12, THM16, THM18)

Wells drilled in Tauhara intersect various diverse lithologies suggesting units are localised (such as lavas and eruption breccias) and lateral widespread units are internally variable (e.g. ignimbrite facies). Core from THM12 intersects UHFF siltstone, MHFF pumice lapilli-tuff and polymict breccia. This sample is unique due to the presence of a ~20 m thick, coarse polymict breccia underlying the MHFF (Fig. 3). Similar breccias have been identified at other nearby wells (e.g. THM14), however, the unit is coarsest and most lithologically diverse in THM12 (Rosenberg et al., 2009b). The breccia is normally graded from block- and lapilli-sized clasts into lapilli and tuff clasts. Overlying the breccia is a 80 m pumice (~10 vol.%) lapilli-tuff in a vitric ash matrix.

Five km south-west, well THM16 consists of a localised bedded sequence (Fig. 3). In THM16 the HFF is absent and instead present there is the Crown Breccia: a thickly bedded volcaniclastic coarse lapilli-tuff and lithic breccia interpreted as a young hydrothermal eruption deposit (Rosenberg et al., 2009b). Beneath Crown Breccia is a 600 m thick sequence of similar bedded deposits assigned to the Waiora Formation. At least eight, discrete, lithic-rich beds (Vl) are identified including a 100 m thick unit of pumice lapilli-tuff (Vp) (Fig. 3). This sequence is lithologically dissimilar and localised in contrast to the laterally variable, but continuous pumice and tuff-rich Waiora Volcaniclastics deposits observed in WKM15/WKM15. Below the bedded Waiora Formation are two to three, highly silicified, normally graded and thinly bedded, lithic and pumice lapilli beds totalling 150 m assigned to the Waiora Ignimbrites (Rosenberg et al., 2009b).

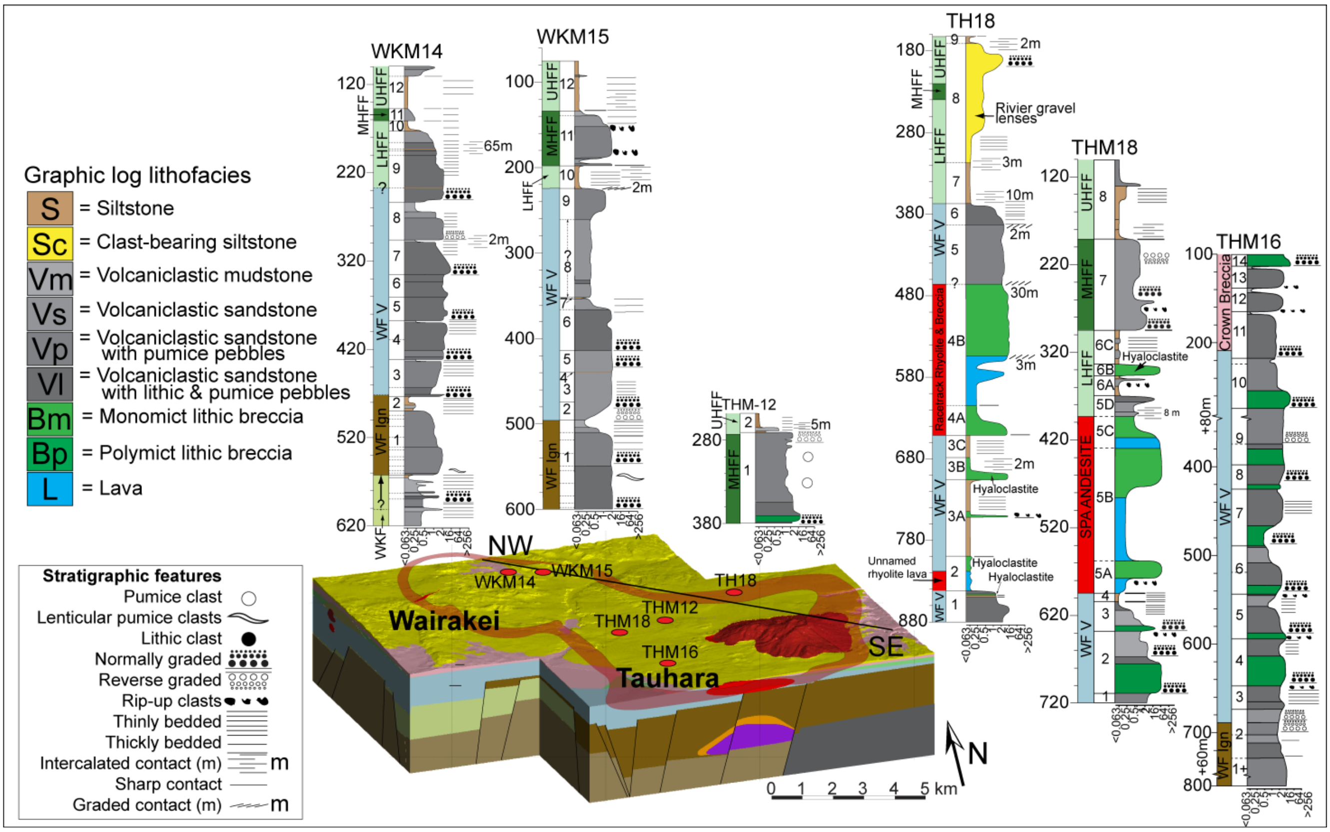

Figure 3: Graphic logs illustrating stratigraphy and lithologies as lithofacies in the six examined core samples from a conceptual geological model of Wairakei-Tauhara (see Fig. 2 for stratigraphy). Log colours reflect common lithofacies explained in the corresponding key.

4. HUKA GROUP EMPLACEMENT CONDITIONS

Wairakei-Tauhara geothermal system is dominantly hosted by low-density pumiceous tuffs including of the Waiora Formation aquifer which is hydrologically and thermally capped by siltstones of the Huka Falls Formation (Fig. 3). The ideal Huka Group stratigraphic architecture which hosts the geothermal system is the result of a unique sequence of interacting transport processes and depositional environments over c.300 kyr (Rosenberg et al., 2009a). A long record of bedded siltstones and reworked tuffs in the stratigraphic record indicate the prolonged existence of ancient Lake Huka. The ancient lake consisted of a single large lake or series of multiple smaller lakes in the Wairakei-Tauhara area prior to its destruction and the formation of Lake Taupo during the 25.4 Oruanui super eruption (Manville and Wilson, 2004).

Bedded siltstones beneath the Huka Group cap the Wairakei Ignimbrite in WKM14 (Fig. 3). Facies associations between siltstones and pumiceous tuffs of the Waiora Ignimbrite suggest the unit was deposited proximal to and/or within an aqueous setting (Fig. 4B). Furthermore, bedding in the Ignimbrite member suggests deposition was progressive. The origin of the bedding may have been controlled by subaerial pyroclastic flows entering the lake, which became sorted and density graded. Lacustrine processes may have been responsible for controlling the progressive deposition rather than source-controlled depositional ‘pulses’. A lack of evidence for erosional or reworked surfaces in the Ignimbrite member suggest emplacement was rapid and near continuous. The graded suspension cap consisting of fine tuff or siltstone represents a return to quiet, non-turbulent conditions in Lake Huka where fines were able to progressively settle out of the water column. Density grading and a suspension bed capping the 100 m thick unit support subaqueous deposition in northern Wairakei; however, the presence of welded areas of the ignimbrite unit (Grindley, 1965) and its significant thickness in Tauhara (>1500 m) suggest not all deposition was subaqueous or influenced by the prevailing lake environment.

The occurrence of a relatively thin lacustrine siltstone bed (~10 m) in WKM14 following the Ignimbrite member suggests there was a brief period of volcanic quiescence prior to the emplacement of the Waiora Volcaniclastics. Lithologies of the Waiora Vocaniclastics vary throughout the examined wells in Wairakei and Tauhara fields. This variation is explained by the unit consisting of localised units such as the local lavas and hydrothermal eruption breccias intersected in Tauhara wells (TH18, THM16, THM18). The sequence examined in the northern Wairakei wells (WKM14 and WKM15), a composite of pumice lapilli-tuffs, volcanic breccias and thin siltstone beds, is the most representative of the Waiora Formation throughout Wairakei-Tauhara. The sources of the pumice and lithic lapilli-tuffs comprising the Waiora Formation is unknown, however, the deposits are inferred to have been transported from both distal (subaerial setting) and local vent (subaerial and subaqueous?) settings. Minor epiclastic sedimentary deposits are also inferred to comprise lithic-rich zones of the Volcaniclastics member (Fig. 4B). Epiclastic sediments are sourced from large, local lava domes contemporaneous with Waiora Formation deposition (e.g. Karapiti, Waiora Valley, Racetrack lavas; Rosenberg et al., 2009a) (Fig. 4B; Wood and Browne, 2000). Lavas intersected in the examined wells range from 20 m to 200 m thick and from andesite to rhyolite composition. Without knowing the shape of the buried lava unit from other wells, the individual intersected thickness is a first approximation for differentiating lava flows (10s of meters) from lava domes (several 10s to 100s of meters). Textures in the lavas such as flow banding, brecciated zone and relationships with underlying and overlying strata provide further, although not unequivocal (cf. Milicich et al., 2013; Tian and Shan, 2011), evidence for identifying the lava types and emplacement localities (subvolcanic or extrusive). Racetrack Rhyolite and unnamed rhyolite in TH18 have characteristics consistent with (partial?) subaqueous dome and flow emplacement on top of Lake Huka siltstones, respectively (Fig. 4C). Spa Andesite has distinct brecciated layers suggesting composite flows occurred beneath Lake Huka from a near-by source vent.

The Huka Falls Formation marks a change from volcanic- to sedimentary-dominated deposition. The change is marked at the Wairoa Volcaniclastics-LHFF contact which is variable in space ranging from gradational (progressive or intercalated) to sharp between underlying tuffs and overlying siltstone (e.g. WKM14 and WKM15). The contact between tuff containing siltstone beds (the gradational zone) and the overlying massive LHFF siltstone, however, is relatively sharp. Here, the stratigraphic contact is made at this definite lithological change. The seemingly abrupt change to lake-dominated siltstone deposition in Lake Huka is not well understood. It is inferred to reflect sudden subsidence in the Lake Huka basin allowing the rate of suspension deposition to increase and a sudden period of quiescence in local pyroclastic volcanism. The quiescence period where HFF was accumulating was terminated when a vent beneath Lake Huka erupted the hydrovolcanic MHFF (Fig. 4A). The location of the underlying, laterally graded lithic breccia, most coarse in well THM12, highlights the nearest locality to the source vent (Cattell et al. in press). The explosive eruption is inferred to have been confined to the subaqueous setting which fed water-supported, turbulent, successive density currents rich in pumice and ash beneath Lake Huka. The thin MHFF in WKM14 and absence of the typical pumice lapilli-tuff unit in TH18 are inferred to represent shallow areas of the lake. Density currents are inferred to have been restricted to deeper areas of the lake (Cattell et al. in press). The presence of river gravels at TH18 further support its position as a shallow near-shore area of Lake Huka. A return to lacustrine deposition is recorded by the UHFF covering much of the Wairakei-Tauhara area.

5. INFLUENCE OF EMPLACEMENT CONDITIONS AND DEPOSITS ON THE GEOTHERMAL SYSTEM

The Huka Group contains both the main geothermal reservoir (Waiora Formation) and its cap rock (Huka Falls Formation) (Fig. 4). An understanding of its composition and distribution is important to the characterisation, development and sustainability of the geothermal system. A recent study at Wairakei-Tauhara has highlighted the influence shallow stratigraphy (e.g. variably welded ignimbrites and beneath lava domes) has on migration path of upwelling geothermal fluids (Sepúlveda et al., 2012).

The lowermost Waiora Ignimbrite member is a distinct stratigraphic marker. Its distribution, stratigraphic affiliations and source location are all poorly understood due to the lithologically variable, hydrothermally altered and buried nature of the unit (Wood, 1994). Its permeability reflects both primary depositional variations in welding (welded to non-welded and compacted) and post-depositional digenetic and hydrothermal modifications. Non-welded areas may correspond with thinner zones in Wairakei where syn-depositional compaction was less than in Tauhara where the unit is over ten times thicker. The distribution of welding may also correspond to where material was emplaced to deep areas (>150 m) of Lake Huka (e.g. WKM14, WKM15) which may have retarded welding. Further assessments on a lateral range of wells intersecting the unit in Wairakei-Tauhara are underway to better understand the origin and properties of this unit.

An Wairakei-Tauhara, textures and facies associations suggest many of the now buried lava domes interacted with the aqueous environment resulting in auto-brecciation and quench fragmentation carapaces (Fig. 4C). Resulting carapaces are highly fragmented and their formation likely provided significant loose epiclastic material to the contemporaneous Waiora Volcaniclastic member (Fig. 4B). Coarse breccia carapaces underlying thick, high density lavas serve as discontinuous conduits for fluids entering from out-field into the lower permeability system (e.g. Racetrack Rhyolite) as well as migration within the system (e.g. Karapiti lavas; Rosenberg et al., 2009a) (Bignall et al., 2007; Mielke et al., 2010; Sepúlveda et al., 2012). Lithostratigraphic assessments interpret the Waiora Volcaniclastic member as a composite succession (~6 emplacement units; Fig. 3) of pumice lapilli-tuffs and lithic breccias. Coarse, low density lithologies in the member with high intrinsic permeability act as shallow reservoirs in the shallow aquifer zone, while thin beds of finer units (siltstone, fine tuff beds) and intact lavas serve as local aquicludes within the reservoir (Fig. 4B).

Explosive volcanism dominantly filled the ancient lake basin which occupied the Wairakei-Tauhara area over c.300 kyr with low density, highly fragmented pumiceous pyroclastic material (e.g. the single MHFF emplacement unit). Thick siltstone units accumulated in Lake Huka during periods of quiescence formed the HFF reservoir cap rock, while thin beds throughout the Waiora Formation highlight the long-lived nature of the lake. Hydrothermal eruptions excavating the older cap rock such as Crown Breccia (THM16; Rosenberg et al., 2009b) serve as local pressure relief zones for migrating fluids in the upper sections of the underlying Waiora reservoir (Fig. 4A). These localised zones consist largely of clays with a compressibility lag forming localised zones of subsidence following pressure declines (Allis et al., 2009; Bromley et al., 2009). A subsidence zone near THM12 known as Rakaunui Bowl (Bromley et al., 2009) coincides with the locality of the coarse MHFF breccia interpreted as a near-vent lag-type breccia. This zone of subsidence may be a hydrothermal eruption crater, but instead likely corresponds with the explosive excavation of underlying stratigraphy forming the (magmatic) MHFF source vent.

Explosive magmatic eruptions in Wairakei-Tauhara reflect the dominant viscous magma composition and its volatile content. Explosivity is amplified by secondary magma-water quench interactions upon eruption (e.g. phreatomagmatic) or during transport (e.g. littoral explosions). The long existence of Lake Huka provided a sufficiently wet environment for these interactions reflected in the high volume of fragmented tuffs (explosive), brecciated deposits and the presence of hyaloclastite/pereritic subvolcanic intrusions (effusive). The highly fragmented nature of these deposits makes them ideal reservoir rocks due to initial high porosity and permeability for geothermal fluid migration.

Devitrification of abundant glassy material forming clays, lithostatic compaction (e.g. Waiora Ignimbrites) and secondary mineral deposition in void spaces (silicification), particularly at depths >700 m, significantly reduces permeability (Mielke et al., 2010). Discontinuities in the rock structure such as faults, fractures and coarse breccia zones, particularly at intermediate to deep levels, are the most important structures for fluid migration and recharge (e.g. Rowland and Sibson, 2004; Rowland et al., 2012). Drilling identifies extensional faulting across Wairakei-Tauhara is accommodated by deep, offset, brittle stratigraphy. Movement of these deep accommodation zones is necessary for maintaining permeability in mineralised fault pathways.

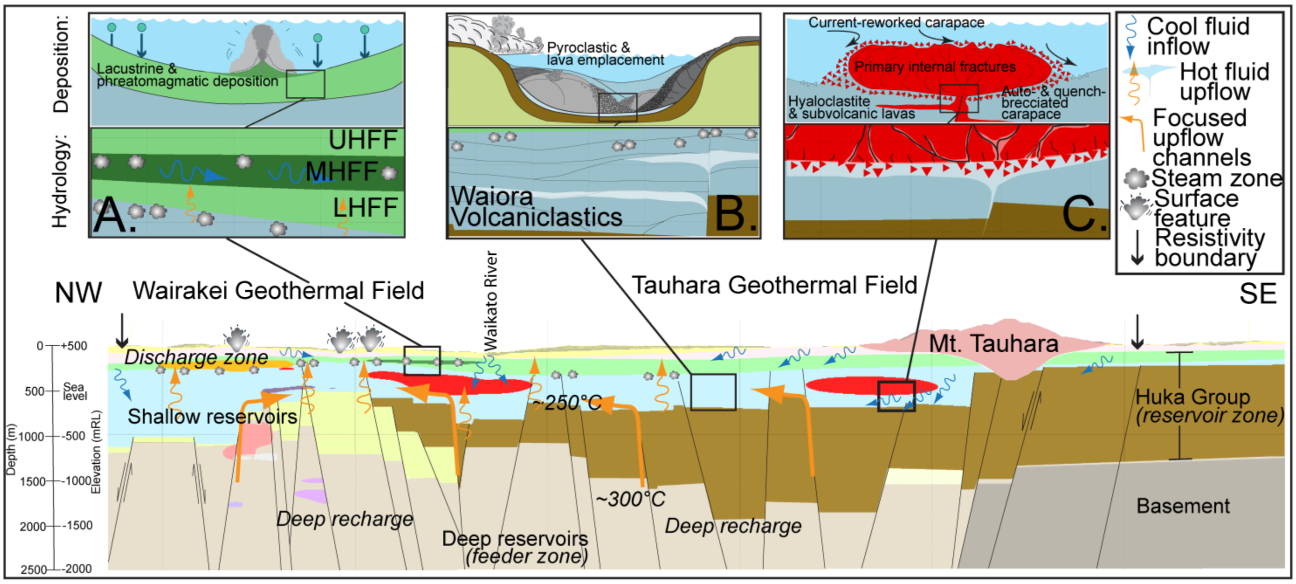

Figure 4: Main figure illustrates interpreted northwest-southeast, faulted stratigraphic sequence (Fig. 2) through Wairakei-Tauhara (Fig. 3) and conceptual interactions with migrating fluids. Cross section model from Contact Energy Ltd. and inferred hydrology modified from Bixley and Bromley, p.143 - 157, *in*: Rosenberg et al. (2010). Inserts (A – B) are inferred depositional conditions and resulting hydrology of emplaced units: A. Lacustrine suspension and subaqueous phreatomagmatic density currents respectively deposit the LHFF and MHFF forming discrete steam migration zones. B. Waiora Formation emplaced by local and regional subaerial pyroclastic flows (Ignimbrite and Volcaniclastic members) and subaqueous lavas (Volcaniclastic member) form a permeable reservoir. C. Lavas extruded into the subaqueous setting are fragmented enhancing their permeability.

6. CONCLUSIONS

Detailed facies analysis of the Huka Group reservoir (Waiora Formation) and cap rock (HFF) in Wairakei-Tauhara, New Zealand, identify a more complex lithological succession influencing the field's hydrology than the two stratigraphic formations alone may imply. The complex succession forms a composite of pyroclastic and lacustrine units emplaced in the rift basin hosting ancient lakes over a c.300 kyr period. At depth (>700 m) where hydrothermal cementation and compaction significantly reduce the permeability of host units, northeast-southwest extensional faults related to the rifting of the TVZ have been identified as concentrated fluid flow zones. At shallower elevations where much of the Huka Group occurs, coarser grained pyroclastic and brecciated lava carapaces are inferred here as reservoir and conduits for in-field fluid flow recharged from deep sources. The latter is common in the Wairakei Field. Fine grained lacustrine siltstones and ash suspension units in the Huka Group act as regional cap rocks (HFF) and localised aquicludes (Waiora Formation) influencing fluid migration. A detailed understanding of the emplacement history of stratigraphy in geothermal settings begins to explain the influence of lithology on hydrology and the lateral distribution and variations of units. The volcanological evolution also improves our understanding of the regional development of the TVZ.

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