Three-dimensional geological model of the greater Lake Tarawera catchment

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CONTENTS

FIGURES

TABLES

EXECUTIVE SUMMARY

The Rotorua Te Arawa Lakes Programme aims to protect or restore lake water quality in all 12 lakes of the Rotorua area. The eight lakes in the greater Lake Tarawera catchment (Tarawera, Okataina, Okareka, Tikitapu, Rotokakahi, Rotomahana, Rerewhakaaitu and Okaro) are part of the Programme. Bay of Plenty Regional Council (BOPRC) investigations in the greater Lake Tarawera catchment include assessments of land use and the discharge of nitrogen to lakes and streams. As part of these investigations, BOPRC contracted GNS Science to develop groundwater models of the eight lake catchments within the greater Lake Tarawera catchment.

This report describes a three-dimensional geological model of the greater Lake Tarawera catchment that characterises the complex, largely volcanic, geology in the area. The model simplifies the geology into 13 hydrogeological units that were based on geological units from the QMAP geological map. These units include: ignimbrite sheets (4 model units), other pyroclastics (4 model units), rhyolite and dacite lava or domes (4 model units), alluvial sediments (1 model unit) and lake sediments (1 model unit). The base of the model is delineated by the base of Whakamaru Group. Major faults and caldera boundaries, identified at the ground surface in the QMAP geological map, provide structural control for the model. Data used to build the model includes geological maps, a digital terrain model with lake bathymetry, BOPRC drill hole data, published cross-sections and information derived from discussions with volcanic geologists. The resulting model extends over an area of 386 km^2 and has a grid resolution of 80 by 80 m. The vertical extent of the model is between -2600 m RL (below mean sea level) and 1100 m RL.

The degree of fracturing, and the connectivity of fractures, controls groundwater flow in welded ignimbrite (e.g., Whakamaru Group, the deepest aquifer in the study area) and rhyolite units. Only a limited number of BOPRC wells have been drilled in areas of rhyolite surface outcrops, but good groundwater flow is expected in fractured zones of the rhyolites. Grain size is a control on groundwater flow in unwelded ignimbrites and other pyroclastic model units (e.g., Pokopoko Pyroclastics, Earthquake Flat Formation), with coarser deposits permitting higher permeability. Aquitards can include fine-grained basal tephra layers at the base of ignimbrite and other pyroclastic units (e.g., the Onuku Pyroclastics that can have a thickness of several meters). Thick, well developed palaeosols may also act as aquicludes between units.

The next phase of the greater Tarawera lakes investigation includes the development of a catchment-scale groundwater flow model. This mode will incorporate the geological model layers identified in this report, aquifer properties estimated from a BOPRC drilling programme and water budget components (e.g., catchment water inflows, lake inflows and stream flows) before modelling the effects of land use on water quality.

1.0 INTRODUCTION

Bay of Plenty Regional Council (BOPRC) and research providers including GNS Science are currently working under the Rotorua Te Arawa Lakes Programme in a range of lakes and lake catchments in the Rotorua area with aims to protect, or restore, the water quality of these lakes. The greater Lake Tarawera catchment includes eight lakes (Tarawera, Okataina, Okareka, Tikitapu, Rotokakahi, Rotomahana, Rerewhakaaitu and Okaro) that eventually drain into the Tarawera River (Figure 1). Of these lakes, the greater Lake Tarawera catchment was identified as the top priority for investigation in considerations of options for groundwater assessment (White, 2008).

These lakes are commonly hydraulically linked to their catchment via the groundwater system (Gillon *et al*., 2008) and much of the water and nutrient that reaches these lakes does so via groundwater. In addition, lake catchments are linked through the groundwater system. Land use is known to impact groundwater quality, in particular leaching of excess nitrogen, in these catchments. Therefore, an assessment of groundwater flow paths in the greater Lake Tarawera catchment is important for understanding the effects of land use on lake water quality.

A thorough understanding of the geological and hydrogeological conditions is required to identify groundwater flow paths through the catchment. Therefore, a groundwater investigation project by BOPRC and GNS Science commenced in the greater Lake Tarawera catchment in 2011 with a drilling programme (Thorstad *et al*., 2011; Rose *et al*., 2012; Lovett *et al*., 2012). The programme included exploratory drilling, aquifer testing, and groundwater sampling for chemistry and age dating to characterise the groundwater system.

This report is part of the first phase of a three-phase investigation to develop and apply groundwater models in the greater Lake Tarawera catchment that have relevance to the assessment of land use and nitrogen discharge to surface water including lakes and streams.

Phase 1 of the project, described in this report, is the development of a simplified 3D geological model of the greater Lake Tarawera catchment. This model identifies the key geological units (e.g., aquifers, aquicludes and lithologies identified by the drilling programme), relevant to groundwater flows within, and between, lake catchments. The complex geology of the area has been simplified into key model units based on the lithological and hydrogeological similarities of geological units. Major structures including the Okataina Volcanic Centre, associated with a long history of active volcanism, and faults are included in the geological model.

A groundwater flow model of the greater Lake Tarawera catchment will be developed in Phase 2. This model will reflect: the simplified geological model units developed in this report; groundwater inflows such as rainfall; groundwater outflows such as spring-fed streams and discharge directly to lakes; and groundwater transfers between lakes. These models will be applied, in Phase 3 of the project, to an assessment of the effects of land use on nitrogen discharge to surface water relevant to surface water quality in streams and lakes.

2.0 REVIEW OF GEOLOGY AND HYDROGEOLOGY IN THE GREATER LAKE TARAWERA CATCHMENT

2.1 HISTORY AND STRUCTURE

The Lake Tarawera catchment is located within the Okataina Volcanic Centre (OVC), the most recently active of the rhyolitic caldera complexes in the Taupo Volcanic Zone (TVZ) (Nairn, 2002) (Figure 2). The TVZ is a NE striking zone of volcanic and geothermal activity, which is on average 50 km wide and extends from Mt Ruapehu to beyond the Bay of Plenty coastline. The formation of this zone, which commenced approximately 2 Ma (Ma = millions of years before present day), is due to the subduction of the Pacific Plate beneath the Australian Plate with the North Island (Wilson *et al*., 1995) (Figure 3). The resulting rift zone, the Taupo Rift, is characterised by a narrow belt of active extensional faulting. The central part of the TVZ includes seven rhyolitic calderas or caldera complexes with associated rhyolite lavas and lava domes (Nairn, 2002; Seebeck *et al*., 2010) whereas the northeastern and southwestern extents of the TVZ are characterised by andesitic to dacitic effusive volcanism and the absence of rhyolitic calderas (Houghton *et al*., 1995).

Permian to Jurassic greywackes and argillite of the Waipapa and Torlesse composite terranes (and intrusive igneous bodies) form the basement of the TVZ (Sherburn *et al*., 2003; Adams et al. 2009). These basement rocks form the ranges at the flanks of the TVZ and the basement at 1 km to > 3 km beneath the volcanic cover of the Taupo Rift.

The OVC has a volcanic history going back hundreds of thousands of years (Nairn, 2002). The most recent volcanism was the 1886 Mt Tarawera eruption, whilst the oldest volcanic deposit that is likely to have erupted from the OVC is an ignimbrite named ‘Quartz-biotite Ignimbrite’ that has been dated at ~550 ka [ka=thousands of years before present day] (Cole *et al*., 2010). Since then, at least two major caldera-forming eruptions have occurred in the OVC: the 322 ka Matahina Formation ignimbrites and the 61 ka Rotoiti Formation pyroclastics (Leonard *et al.*, 2010). The main structural element of the OVC is the Haroharo Caldera Complex, a large basin structure created by at least two major eruption episodes. The southern part of this feature subsided during the Matahina Ignimbrite eruption and the northern part collapsed during the Rotoiti eruption (Nairn, 2002).

Faults within the OVC are part of the Taupo Rift that goes through the OVC from southwest to northeast. Faults of the Paeroa/Whirinaki/Ngapouri fault system (Figure 5) can be traced on the surface in a northeasterly direction to the caldera boundaries. Here, younger volcanic deposits cover possible fault traces, which indicates that the faults haven’t been active in the last few millennia. The faults reappear north east of the caldera system as part of the Maungawhakamana Graben, which extends into the Whakatane Graben with the Rangitaiki Plains (Nairn, 2002; White *et al.,* 2010). However, there is evidence that some faults are continuous through the caldera complex and that they have influenced the geometry and location of the caldera structures (Seebeck 2008; Seebeck *et al*. 2010). The faults are active and their slip rates are in the order of several mm/year.

2.2 MAJOR GEOLOGICAL UNITS IN THE STUDY AREA

The major geological units in the study area are summarised in the following sections. The geological nomenclature is based on the QMAP Rotorua geological map of the area (Leonard *et al.*, 2010). The major units are described in the order of approximate age, from oldest to youngest.

2.2.1 Okataina Rhyolites

Due to their similar lithological characteristics and limited hydrogeological information available for each rhyolite formation, all rhyolite formations identified in the geological map are described together. This group includes rhyolites mostly older than 322 ka, middle-aged (180 – 61 ka) rhyolites and the youngest (post-61 ka) Okataina rhyolites (cf. Nairn 2002).

The oldest rhyolites mostly pre-date Matahina ignimbrite (322 ka; Leonard et al. 2010) and are the oldest unit mapped in the greater Lake Tarawera catchment area (Leonard *et al.*, 2010). Outcrops are located outside of the Matahina and Rotoiti calderas, but downfaulting or erosion are likely to have buried or removed these deposits within the caldera boundaries (Leonard *et al.*, 2010; Leonard, 2013). The Mid to Late Pleistocene rhyolites sourced from the OVC have also been mapped at the ground surface only in areas outside of the caldera boundaries and may have been eroded or downfaulted within the calderas (Leonard *et al.*, 2010; Leonard, 2013). The young Okataina rhyolites are generally associated with the volumetrically substantial Q1 to Q4 pyroclastics (e.g. Mangaone-, Haroharo- and Mt Tarawera subgroups) and are exposed at the surface in areas inside, and outside, the caldera boundaries.

Beck (1955) describes the young rhyolites in the north of the Lake Tarawera catchment as "well jointed" and "probably permeable". Groundwater flow in all of these rhyolites is fracture dominated, as is likely to be the case for all rhyolites. However, permeability may vary as flow is affected by the size and amount of fractures and the linkage between them, e.g., "lithic rhyolite is usually well jointed and may contain scoriaceous zones and even cavities […], but some rhyolite is known to be almost impermeable" (Thomson, 1974). Gordon (2001) reports transmissivities between 500 and 1400 m^2/day for these, and other, rhyolites in the Bay of Plenty Region. Rose *et al.* (2012) derived hydraulic conductivities in the order of 10^{-3} and 10^{-2} cm/s (or 1 to 10 m/day) from the analysis of constant rate pumping tests and slug tests in what is assumed to be the carapace of a young rhyolite dome. This hydraulic conductivity is in the upper range for fractured igneous rock (Freeze and Cherry, 1979). Thorstad *et al*. (2011) conducted two aquifer tests and estimated hydraulic conductivity values for Mamaku Formation, a young (8 ka) pumiceous rhyolite lava, ranging between 0.2 and 3.6 cm/s (i.e., approximately 200 to 3100 m/day).

2.2.2 Whakamaru Group Ignimbrites

Whakamaru Group ignimbrites, approximately 340 thousand to 350 thousand years old are the oldest geographically continuous unit in the greater Lake Tarawera catchment area. The stratigraphic base of this unit defines the top surface of the base layer of the geological model. Whakamaru Group comprises several individual welded ignimbrites (e.g. Brown 1998), including Rangitaiki Ignimbrite which is mapped at the ground surface within the study area.

Rangitaiki Ignimbrite is described by Nairn (2002) as a moderately welded, dark grey, crystal rich tuff. The unit includes coarse tuffs, pumice breccias and air fall deposits. This ignimbrite is only mapped in the southern part of the catchment area, but it is assumed to extend continuously throughout the area with a thickness of up to 300 m. This assumption is based on the magnitude of the Whakamaru eruptions and the mapped extent of this unit beyond the catchment area (Hikuroa *et al.,* 2006; Leonard, 2013). Lithics of Whakamaru Group ignimbrites within Mamaku Plateau Formation support this assumption (Milner, 2001).

This unit is the deepest known aquifer. Based on aquifer tests, fracture-controlled flow provides the majority of groundwater available in this aquifer (Hadfield *et al.* 2001). Groundwater quality is generally good (Hadfield *et al.*, 2001). Thorstad *et al*. (2011) estimated a hydraulic conductivity value in the order of 10^{-3} cm/s (or approximately 1 m/day) for this ignimbrite north of Lake Rerewhakaaitu (Section 2.3). The transmissivity of Rangitaiki Ignimbrite in the Reporoa area is estimated in the range of 2 to 30 m^2/d (Piper, 2005).

2.2.3 Matahina Formation

Matahina Formation (Bayley and Carr 1994) ignimbrite erupted from the Matahina Caldera in the southern part of the Okataina Volcanic Centre at approximately 322 ka (Leonard *et al*., 2010). The ignimbrite is assumed to cover the entire greater Lake Tarawera catchment area outside of the Matahina and Rotoiti caldera boundaries with a thickness of approximately 100 – 200 m (Bailey and Carr 1994; Nairn, 2002). This thickness increases up to 700 m within the overlapping Matahina and Rotoiti calderas (Bailey and Carr 1994; Nairn, 2002). Outcrops of Matahina Formation ignimbrite are mapped mainly east of the greater Lake Tarawera catchment, but isolated outcrops exist in the southern part of the study area. The ignimbrite has been positively identified in one drill hole southwest of Lake Rerewhakaaitu with a thickness of 50 m (Rose *et al.,* 2012), Section 2.3. However, Matahina Formation has not been identified in any other of the 10 BOPRC groundwater investigation bores across the greater Lake Tarawera catchment (Thorstad *et al*., 2011, Rose *et al*., 2012, Lovett *et al*., 2012) and is absent at Waiotapu Geothermal Field (Hedenquist, 1983).

Matahina Formation comprises a basal pyroclastic fall deposit that is overlain by three pyroclastic flow units (Bailey and Carr, 1994). In the greater Lake Tarawera catchment the material is compacted to moderately welded, although densely welded ignimbrite has been identified outside of the study area (Nairn, 2002).

Gordon (2001) reports low primary porosity and low groundwater yields from the upper, unwelded part of Matahina Formation ignimbrite, whereas yields in the deeper, welded parts are greater. The ignimbrite is likely to show increased yield also in the compacted to moderately welded zones occurring within the study area. However, groundwater investigations at Rerewhakaaitu Road southeast of Lake Rerewhakaaitu by Rose *et al*. (2012) show few fractures and non-water bearing deposits in the upper 45 m of 50 m of Matahina Formation ignimbrite. Gordon (2001) reports transmissivities between 18 and 6000 m^2/day for unconsolidated deposits, (which is assumed to include the upper unwelded part of Matahina Formation) and transmissivities ranging between 6,000 and 12,000 m^2/d for fractured ignimbrite near Otakiri in the southwestern Rangitaiki Plains.

2.2.4 Pokopoko Pyroclastics and Millar Road Ignimbrite

This hydrogeological grouping includes Pokopoko Pyroclastics and Millar Road Ignimbrite (cf. Nairn 2002). Pokopoko Pyroclastics (>240 ka) pre-date Mamaku Plateau Formation, which unconformably overlies the pyroclastics in the north of the greater Lake Tarawera catchment. Pokopoko Pyroclastics consist of moderately compacted to welded pyroclastic flow units comprised of pumiceous ash, lapilli and blocks (Nairn, 2002). Millar Road Ignimbrite is highly welded and has a similar age to the Pokopoko Pyroclastics. However, this formation only occurs in limited outcrops north of Lake Okareka.

Thorstad *et al*. (2011) derived hydraulic conductivity values in the order of 10^{-2} cm/s (or 10 m/day) from pumping tests in Pokopoko Pyroclastics northwest of Lake Tarawera. These hydraulic conductivity values are in the upper range for fractured igneous rock aquifers or in the upper to middle range for silty to clean sand aquifers, respectively (Freeze and Cherry, 1979). There is no information about permeability of the Millar Road Ignimbrite, but it is expected to incorporate fracture flow because it is highly welded.

2.2.5 Onuku Pyroclastics

Onuku Pyroclastics comprise “multiple non-welded, pumiceous fall and flow deposits” sourced from the OVC which in Waiotapu bore holes are up to 60 m and stratigraphically located between Matahina Formation (322 ka) and Kaingaroa Formation (230 ka) (Wood, 1994). Onuku Pyroclastics crop out only in the southern part of the model area, but Nairn (2002) suggests a thickness of 250 m for these deposits within the Matahina and Rotoiti calderas.

There is no information about the hydraulic properties of this formation. In the Rerewhakaaitu area, groundwater levels in Onuku Pyroclastics are shallower than in Whakamaru Group ignimbrites, therefore, Whakamaru Group ignimbrites are potentially recharged from Onuku Pyroclastics (White *et al.*, 2003).

2.2.6 Kaingaroa Formation

This unit, which erupted from the Reporoa Caldera south of the greater Lake Tarawera catchment at approximately 230 ka (Houghton *et al.,* 1995), has been mapped at the ground surface in the southern part of the catchment (Figure 5) where it reaches an estimated thickness of up to 200 m (Leonard *et al.,* 2010; Leonard, 2013). It is also assumed to occur within the Matahina Caldera structure (Nairn, 2002, Leonard, 2013), with an estimated thickness between 50 and 150 m depending on the distance of the ignimbrite from its source (Leonard, 2013).

The base of Kaingaroa Formation consists of several tephra layers that have a thickness of approximately 4 m (Nairn, 2002) and have been deposited on a palaeosol overlying Onuku Pyroclastics (Beresford and Cole, 2000). These are overlain by three ignimbrite units. The lower unit consists of at least 50 m of non-welded fine-grained ignimbrite that comprises several flow units (Beresford, 1997). This lower ignimbrite unit “comprises pink to yellow pumice lapilli and lithic clasts in an ash-rich matrix” (Beresford and Cole, 2000). The “sandy black” middle unit consists of a “lightly welded, dark grey to black pumice tuff” (Nairn, 2002). The upper ignimbrite unit is fine-grained, partially to densely welded and pumice poor (Beresford and Cole, 2000).

There is little information available regarding the hydrogeology of this formation. It can be assumed that the palaeosol underlying Kaingaroa Formation together with the basal tephra layers will act as an aquitard. The overlying ignimbrite units are likely to exhibit similar hydraulic properties as texturally comparable ignimbrite formations such as Mamaku Plateau Formation and Matahina Formation, but the actual properties will vary locally depending on the pore space and the degree of welding and jointing.

2.2.7 Mamaku Plateau Formation

Mamaku Plateau Formation comprises a massive, pink to grey ignimbrite that erupted approximately 240 ka from Rotorua Caldera (Leonard *et al*. 2010). It has been mapped in the northeast of the greater Lake Tarawera catchment area and extends below the surface across the entire study area north of the Rotomahana Fault with a thickness between 100 to 200 m (Nairn, 2002; Leonard, 2013). There is no evidence for Mamaku Plateau Formation in the study area south of this fault. Mamaku Plateau Formation was previously referred to as 'Mamaku Ignimbrite' and was renamed due to the name's similarity with Mamaku Formation, a Holocene (8 ka) tephra and lava formation erupted from the Okataina Volcanic Centre (Leonard *et al.,* 2010), Section 2.1.1.

The internal stratigraphy of the Mamaku Plateau Formation can be divided into a basal tephra sequence and three main ignimbrite units: lower, middle and upper (Milner *et al*., 2003). The lower sheet has a thickness of up to 45 m and is non-welded, non-jointed and mainly fine-grained. The middle unit is strongly-welded and jointed, whereas the upper section is characterised by a fine grain size and is semi-welded and not jointed (Milner *et al*., 2003). Hydraulic conductivity is likely to be the highest within the strongly-welded and jointed middle section. Rosen *et al*. (1998) consider the lower and upper units as permeable and the middle section as impermeable. Morgenstern *et al*. (2004), however, suggest that the middle section is an aquifer due to the existence of fractures in this sheet. The basal tephra sequence, on the other hand, is likely to be an aquitard (Thomson, 1974; Morgenstern *et al*., 2004; White *et al.,* 2007).

Transmissivity of the Mamaku Plateau Formation at Site 2 (Figure 4) is 4280 m/day (equivalent to an hydraulic conductivity value of approximately 0.83 cm/s, or 720 m/day) Thorstad *et al*. (2011). A transmissivity of 600 m^2/day was calculated for the Mamaku Plateau Formation from a pumping test conducted in a bore northwest of Lake Rotorua, i.e., an hydraulic conductivity of approximately 0.007 cm/s (or 6 m/d) for an assumed formation thickness of 100 m (Reeves *et al*., 2005).

2.2.8 Rainbow Mountain Dacite

Rainbow Mountain (Maungakakaramea) is a dacite cone of Middle to Late Pleistocene age (Nairn, 2002) located near the intersection of State Highways 5 and 38 in the southwest of the greater Lake Tarawera catchment. It has not been radiometrically dated but a stratigraphic age between 61 and 320 ka is inferred from a partial cover of Earthquake Flat Breccia (Nairn, 2002) and its lava that appears to overlie Rangitaiki Ignimbrite (Nairn, 1981).

Rainbow Mountain is located at the margin of the Waiotapu Geothermal Field and its lavas are substantially affected by hydrothermal alteration, which is likely to have reduced the bulk permeability in much of the edifice though formation of clays and other hydrothermal minerals.

2.2.9 Rotoiti Formation

Rotoiti Formation erupted from Rotoiti Caldera in the north of Okataina Volcanic Centre at approximately 61 ka (Wilson et al. 2007). The Formation has a large extent and consists of airfall and ignimbrite sub-units. The ignimbrites are non-welded of soft to firm consistency (Leonard *et al*., 2010).

There is no information available about the hydraulic properties of Rotoiti Formation, but it is expected to be highly porous and permeable, with finer grained zones within the sequence acting as aquicludes (Thomson, 1974). Permeability is also assumed to be similar to Oruanui Formation, as both units have similar lithological characteristics.

2.2.10 Earthquake Flat Formation

The 61 ka Earthquake Flat Formation, which is likely to have erupted immediately following the Rotoiti Formation (Nairn and Kohn, 1973; Wilson et al. 2007), is sourced from vents to the west of the greater Lake Tarawera catchment and is mapped only in the west of the study area (Leonard *et al*., 2010). Earthquake Flat Formation includes an airfall and an ignimbrite component. The ignimbrites are non-welded of soft to firm consistency (Leonard *et al*., 2010). The maximum thickness of this formation is approximately 120 m (Wood, 1994).

Wood (1994) describes Earthquake Flat Formation as “highly permeable”. Analysis of slug tests carried out by Lovett *et al*. (2012), estimated hydraulic conductivity values in the order of 10^{-3} cm/s (or 1 m/day) for pyroclastics that are very likely part of this formation. There is no other information available about the hydraulic properties of these deposits, but permeability is expected to be similar to Oruanui Formation as both units have similar lithological characteristics.

2.2.11 Oruanui Formation

Oruanui Formation was erupted from Taupo Caldera at approximately 27 ka (Wilson 2001; Lowe *et al.,* 2008). Although it is widespread across the central North Island, only small isolated deposits are found within the greater Lake Tarawera catchment. The Formation includes airfall and ignimbrite components. The ignimbrites are coherent but non-welded and are firm in consistency (Leonard *et al*., 2010).

The Oruanui Formation is generally not jointed or fractured, but is “characterised by a high primary permeability” (Hadfield *et al.*, 2001). Transmissivities for this unit in the Reporoa area are generally in the order of 10^{1} m^{2}/d, although values in the range of 10^{-1} and 10^{2} m^{2}/d have also been estimated (Piper, 2005).

2.2.12 Q1 to Q4 Undifferentiated Pyroclastics

This group includes various pyroclastic deposits sourced from Okataina Volcanic Centre, and younger than Oruanui Formation in age. For example, the Waiohau Pyroclastics erupted at 11 ka (Nairn 2002) are thought to have a thickness of approximately 30 m. Speed *et al*. (2002) characterised the Waiohau Pyroclastics as ash fall deposits and pyroclastic flow deposits including surge deposits, and block and ash flows. The pyroclastics are locally welded (Leonard, 2010) and the included finer grained beds (surge deposits) may act as local aquicludes (White *et al.*, 2003). Waiohau Pyroclastics are overlain by Kaharoa Pyroclastics which erupted from a vent on Mt Tarawera 700 years ago as massive pyroclastic flow deposits, cross-bedded surge deposits, block and ash flows and stratified fall deposits (Nairn, 2002). Based on regional tephra mapping (Pullar and Birrell 1973) the thickness of these pyroclastics in the catchment area is estimated to be 10 to 30 m (White *et al.*, 2003).

Groundwater investigations by Thorstad *et al*. (2011) show Kaharoa pyroclastics as a shallow unconfined aquifer consisting of unconsolidated sand- and gravel-sized pyroclastic debris. White *et al.* (2003) suggest that Kaharoa Pyroclastics are highly permeable due to the lack of streams draining the area covered by these deposits. This indicates that most of the rainfall, net of evaporation, is likely to be directly absorbed into the ground. Two hydraulic conductivity values of 0.12 and 0.51 cm/s (i.e., approximately 100 m/day and 440 m/day, respectively) were estimated by aquifer tests for these pyroclastics by Rose *et al*. (2012). Older pre-Kaharoa pyroclastics had hydraulic conductivity values of approximately 10^{-1} cm/s, (or 100 m/day) estimated from two aquifer tests (Rose *et al*., 2012). However, their stratigraphic classification is uncertain as the only other restriction is provided by the underlying Rangitaiki Ignimbrite. Therefore, it could not be determined exactly in which formation this hydraulic conductivity was measured.

2.2.13 Tauranga Group Alluvium

This group comprises Pliocene to Holocene alluvial sediments (in particular, sands and gravels), as well as non-welded ignimbrite and tephra layers, typically located in valleys and commonly associated with lakes. Tauranga Group deposits are mostly saturated, indicating good opportunities for groundwater supplies, however, most wells in this unit yield low rates of groundwater flow (up to 13 L/s; White, 2005).

2.3 SUMMARY OF THE BOPRC LAKE TARAWERA GROUNDWATER INVESTIGATION PROJECT

Exploratory wells were drilled at 10 different sites throughout the catchment as part of the 2011 – 2012 Lake Tarawera groundwater investigation project (Figure 4; Thorstad *et al.*, 2011; Rose *et al.*, 2012; Lovett *et al.*, 2012). The depths of the drill holes were between 60 and 100 m and lithology was generally logged and sampled for every drilled meter. Aquifer tests (constant rate pumping tests or slug tests) were conducted in the more permeable units (Table 1).

Table 1 Interpretation of drill holes (listed by GNS ID and BOPRC ID) including layer numbers, formation names and hydraulic conductivity estimates from the 2011 – 2012 Lake Tarawera catchment groundwater investigation project (Thorstad *et al*., 2011; Rose *et al*., 2012; Lovett *et al*., 2012). See Figure 4 for the locations of drill holes.

Drill Site	Layer Number	Depth Range (m BGL)	Formation Name (proposed)	Age	Hydraulic conductivity (cm/s)
Site 1 - Dollimore 1000129	1	0 – 1	Fill	present day	
	2	1 – 3	Undifferentiated rhyolitic volcanic clastics	post 7.5 ka	
	3	3 – 10	Lacustrine silty clay	post 7.5 ka	
	4	10 – 13	Reworked Mamaku Formation	post 7.5 ka	
	5	13 – 43	Mamaku Formation	7.5 ka	0.2; 0.3; 3.6
	6	43 – 48	Pre- Mamaku Formation	7.5 – 9 ka	
	7	48 – 54	Rotoma or Waiohau Pyroclastics?	9 ka or 11 ka	
	8	54 – 60	Rotorua Pyroclastics	13.5 ka	
Site 2 - Te Miro 1000131	1	0 – 3	Undifferentiated rhyolitic volcanic clastics	~0 – 22 ka	
	2	3 – 37	Mamaku Plateau Formation	220 ka	0.83
	3	37 – 51	Pokopoko Pyroclastics	~ 225 – 230 ka	0.012; 0.01; 0.02
	4	51 – 59			
	5	59 – 60			

Drill Site	Layer Number	Depth Range (m BGL)	Formation Name (proposed)	Age	Hydraulic conductivity (cm/s)
Site 3 - Lake Tarawera outlet 1000134	1	0 – 5	Redeposited ash and scoria from Tarawera and Rotomahana Pyroclastics	post 1886 AD	
	2	5 – 12	Kaharoa Pumice Alluvium	post 0.7 ka	
	3	12 – 45	Undifferentiated rhyolitic volcanic clastics	post 11 ka	0.07
	4	45 – 51			
	5	51 – 61			
	6	61 – 80			
	7	80 – 87	Okataina Rhyolites-lower Pokuhu Lava	11 ka	
Site 4 - Buried Village 1001051	1	0 – 3	Tarawera Formation	1886 AD	
	2	3 – 5	Undifferentiated pumiceous alluvium	post 0.7 ka	
	3	5 – 14	Kaharoa derived sediments/volcaniclastics	post 0.7 ka	
	4	14 – 37.5	Rotorua eruptive episode	15.4 ka	0.011; 0.031; 0.013; 0.0053
Site 5 - Warmerdam 1001052	1	1 – 11	Kaharoa Pyroclastics	0.7 ka	
	2	11 – 13	Paleosol	pre-0.7 ka	
	3	13 – 17	Undifferentiated pyroclastics	pre-0.7 ka	0.42; 0.65
	4	17 – 22	Undifferentiated pyroclastics	pre-0.7 ka	
	5	22 – 100	Rangitaiki Ignimbrite	0.35 Ma	0.0021; 0.0003; 0.0041; 0.00016
Site 6 - Onuku Trust 1001055	1	0 – 4	Tarawera Formation	1886 AD	
	2	4 – 13	Kaharoa derived pyroclastics/ volcaniclastic debris	post 0.7 ka	0.12; 0.51
	3	13 – 61	Kaharoa Pyroclastics	0.7 ka	
Site 7 - Onuku Trust 1001056	1	0 – 1	Tarawera Formation	1886 AD	
	2	1 – 2	Undifferentiated pyroclastics	pre- 1886 AD	
	3	2 – 11	Onuku Pyroclastics Subgroup	0.23 – 0.32 Ma	
	4	11 – 14			
	5	14 – 64	Matahina Ignimbrite	0.32 Ma	
	6	64 – 72?	Undifferentiated pyroclastics	0.32 – 0.35 Ma	
	7	91.5? – 95	Rangitaiki Ignimbrite	0.35 Ma	

Drill Site	Layer Number	Depth Range (m BGL)	Formation Name (proposed)	Age	Hydraulic conductivity (cm/s)
Site 8 - Woodstock Farms 1001068	1	0 – 29	Earthquake Flat Formation	65	0.22; 0.25; 0.33
	2	29 – 37	Rotoiti Pyroclastics/Onuku Pyroclastics?	>65 ka	
	3	37 – 60	Haparangi Rhyolite	>65 ka	
Site 10 - RDC Reserve 1001069	1	0 – 12	Tauranga Group alluvium		
	2	12 – 60	Undifferentiated pyroclastics		0.21; 2.8; 4.0×10^{-5}
Site 11 - Russell 1001070	1	0 – 2	Tauranga Group alluvium		
	2	2 – 70	Undifferentiated pyroclastics		0.018; ~0.16; 0.00018

2.4 GEOTHERMAL FIELD GEOLOGY

Due to their significant scientific and commercial value, exploratory drilling has often been undertaken in geothermal fields. In many cases, geological logs resulting from these exploration bores have been published or are available through resource consent applications. Geothermal field geology is particularly relevant to the development of the 3D geological model because it is usually the most reliable source of deep sub-surface stratigraphic and structure information. Only the Waimangu-Rotomahana geothermal field is located within the model area boundary. However, useful information can also be sourced from the Waiotapu, Taheke and Tikitere geothermal fields (Figure 2) that are situated adjacent to the study area. Published information on the Waiotapu Geothermal Field includes geology and stratigraphy identified in several drill holes. No exploratory wells have been drilled in Waimangu. Drill hole logs from Taheke/Tikitere are not publically available.

2.4.1 Waiotapu

The Waiotapu Geothermal Field is located at the southwestern boundary of the greater Lake Tarawera catchment. The geothermal field is likely to be stratigraphically and hydrologically connected with both Te Kopia and Reporoa fields (Hunt *et al*., 1994). The Reporoa Caldera and related faults (Paeroa and Ngapouri) are the main structural elements in the area (Grindley *et al*., 1994; Nairn, *et al*., 1994). The Waiotapu Geothermal Field is located in a graben bounded to the west by a rhyolite dome and containing a sequence of ignimbrites (predominantly) and sediments (e.g., Huka Falls Formation) to a known (drilled) depth of 1 km and to an age exceeding 1.4 Ma (Wilson et al. 2010).

The deepest Waiotapu drill hole, to a depth of 761 m, does not intersect greywacke (Wood, 1994). However, the elevation of greywacke basement at Waiotapu is estimated at between -500 and -1300 m RL (Modriniak and Studt, 1959; Rogan, 1982). Waiotapu Ignimbrite is a major unit at Waiotapu, with a thickness up to 360 m. The unit is densely welded through most of the formation, and therefore unlikely to have significant diffuse permeability. However, the formation has abundant sub-horizontal joints that may allow fluid flow. Whakamaru Group ignimbrites (Rangitaiki Ignimbrite) overlie Waiotapu Ignimbrite. Pyroclastic flow and fall deposits above Whakamaru Group ignimbrites include Matahina and Kaingaroa formations, and Onuku Pyroclastics. Lake sediments of the Huka Falls Formation (siltstone and muddy sandstone) provide the impermeable cap-rock of the Waiotapu Geothermal Field (Wood, 1994).

3.0 METHODOLOGY

A 3D geological model is generally composed of a series of units (layers), that are assembled with respect to their chronology and structural relationships. These units are defined by a set of regularly gridded boundary surfaces and the boundary surfaces are developed from source data points. Source data sets include topographic data, geological maps and cross-sections, and well logs.

A combination of GIS (ESRI ArcGIS 10) and 2D and 3D modelling software (EarthVision 8.1, Dynamic Graphics Inc.) is used to construct the 3D geological model of the greater Lake Tarawera catchment. The modelling process starts with the grouping of formations that are mapped at the ground surface within the study area into hydrogeological units, and the assembling of QMAP polygons for each unit. These QMAP polygons are then used to identify topographic data points for the areas where units that belong to a hydrogeologic grouping are mapped at the ground surface. This surface exposure data is then combined with sub-surface data points that are derived from other model data sources, resulting in an irregular scattered data set for each unit. EarthVision uses a minimum tension (minimum curvature) gridding technique to produce 2D and 3D grids from scattered data. The minimum tension technique is a bicubic spline algorithm, which seeks to honour the input data when calculating an evenly-spaced grid.

The surfaces of these geological unit groupings are modelled to construct the 3D geological model. Each geologic horizon is built sequentially as 2D grids representing the top surface of each horizon. All the grids are then assembled in stratigraphic sequence to produce a stratigraphic 3D model.

3.1 MODEL DATA SOURCES

3.1.1 Topographic Data

A LiDAR DTM provided by BOPRC is used to represent the ground surface elevation in the study area. This DTM is also used to identify the top surface of geological units in all areas where the unit is exposed at the surface as identified by geological maps (Section 3.1.2).

Elevations of lake beds are calculated as lake surface elevation (Table 2) minus lake bathymetry. Lake bathymetry data has been provided by BOPRC for all eight lakes within the catchment.

Table 2 Lake water levels for the greater Lake Tarawera catchment (BOPRC, 2013).

Lake	Surface elevation (m RL)
Lake Okataina	311
Lake Okareka	355
Lake Tikitapu	415
Lake Rotokakahi	394
Lake Tarawera	298
Lake Rotomahana	339
Lake Okaro	419
Lake Rerewhakaaitu	435

3.1.2 Geological Maps

Surface geology in the greater Lake Tarawera catchment has been compiled from the 1:250,000 scale Rotorua QMAP (Leonard *et al*., 2010). This map has 44 distinct map units covering the study area and these are aggregated into hydrogeological units in the model (Section 3.2).

3.1.3 Cross-sections

Published geological cross-sections provide the most useful information about the subsurface distribution of geological formations in the three-dimensional model. Principally, a cross-section dissecting the northern to northeastern part of the greater Lake Tarawera catchment (Nairn, 2002) was one of the main sources of information for the model construction in that area.

3.1.4 Consulting of Volcanic Geologists

Graham Leonard, a Volcanic Geologist who specialises in mapping of volcanic rocks and is one of the editors of the Q-map Rotorua (Leonard *et al*., 2010), was consulted regularly and had major input into the model construction. Brad Scott, a Volcanologist who has worked in the study area for many years, was also consulted.

3.1.5 Well Log Data

Well log data sources include: the BOPRC data base (Figure 4), the Lake Tarawera groundwater investigation project (Section 2.3) and the Waiotapu Geothermal Field.

Unfortunately, the quality of many well log descriptions in the BOPRC database is questionable, as the lithologies were logged by drillers and not by qualified geologists. Lithological descriptions in the BOPRC well database vary with the driller and drilling method, and are not subjected to any quality control. To well drillers, the lithological characteristics of many formations in volcanic terrains are probably similar. For example, ‘welded ignimbrite’ is often described as ‘rhyolite’ (White *et al*., 2007) which can make the distinction between rhyolite lava and ignimbrite flows very difficult. Non-welded ignimbrite is often logged as ‘pumice gravel’ or ‘sand’ which does not allow any differentiation from volcanogenic sediments. Most of the BOPRC wells have been drilled within the surface extent of pyroclastics (Onuku, Pokopoko, Kaharoa) as identified by the geological map (Leonard *et al.,* 2010). Wells drilled in rhyolite outcrops are rare.

Geological interpretations of well logs from the Lake Tarawera groundwater investigation project (Section 2.3) were very useful in determining model formation boundaries. Published well log data from the Waiotapu Geothermal Field was used to ascertain the occurrence and thickness of geological formations in the southwest of the study area. Core logs from the Kaituna River Hydro scheme within, and outside, the study area could not be used for the modelling: these core logs only include lithological descriptions and no deduced geological interpretations. Classification of the geological units of these cores would be difficult and would go beyond the scope of this project.

3.1.6 Location of Faults and Caldera Boundaries

A large number of faults dissect the study area because of the Taupo Rift passing through the OVC. Of these, five major faults were selected to be represented in the model (Figure 5). Information about fault locations was obtained from Nairn (2002) and Leonard *et al*., (2010).

Fault offsets and dip angles were set following Nairn (2002) and Leonard (2013). Boundaries of the two calderas associated with the Matahina and Rotoiti eruptions were defined by Leonard *et al.,* (2010). These two calderas intersect, and this overlap was also built into the model.

3.2 GROUPING OF FORMATIONS RELEVANT TO GROUNDWATER FLOW

Shallow formations are most relevant to groundwater flow in the greater Lake Tarawera catchment. However, to characterise the entire groundwater system for this area, important deeper aquifers like the Whakamaru Group ignimbrites are included in the model. Therefore, the greater Lake Tarawera catchment geological model was developed to represent all formations between the ground surface and the base of the Whakamaru Group ignimbrites.

For the study area, 44 geological units have been mapped in the QMAP (Leonard *et al*., 2010). However, it is not preferable to represent this many distinct geological layers within a 3D model of the size of the greater Lake Tarawera catchment. Therefore, geological formations mapped at the ground surface were aggregated into 13 hydrogeological groups relevant to groundwater flow with regard to formation age, lithological features and hydrogeological properties (Table 3). The Geographic Information System ArcGIS 10 was used to identify all geological units in the study area from the Rotorua QMAP (Leonard *et al*., 2010) and to assemble them in hydrogeological groups (Figure 5; Section 3.2 and Table 3). The hydrogeological units are cross-referenced to geological unit codes and stratigraphic names used in the GIS version of the geological map (Figure 5; Leonard *et al*., 2010).

Table 3 Grouping of geological map units (QMAP Rotorua, Leonard *et al*., 2010) into hydrogeological units used for the modelling.

Hydrogeological unit	QMAP code	QMAP unit	QMAP stratigraphic unit name	QMAP sequence
Hydrogeological unit 1: Tauranga Group sediments	Q1al	Holocene alluvium		Tauranga Group
	Q1as	Holocene swamp deposits and peat		Tauranga Group
	Q1af	Holocene alluvial fan deposits		Tauranga Group
	Q3ah		Hinuera Formation	Tauranga Group
	lQal	alluvial terrace deposits	(undifferentiated)	Tauranga Group
Hydrogeological unit 2: Q1 to Q4 undifferentiated pyroclastics	Q1atw	Scoria alluvium	Tarawera alluvium	Tauranga Group
	Q1kap		Kaharoa Formation	Okataina Group
	Q1mkp		Mamaku Formation	Okataina Group
	Q1rmp		Rotoma Formation	Okataina Group
	Q1twp	Rotomahana mud and Tarawera scoria	Tarawera Formation	Okataina Group
	Q1vop		(undifferentiated)	Okataina Group
	Q1wkp		Whakatane Formation	Okataina Group
	Q2rep		Rerewhakaaitu Formation	Okataina Group
	Q2rop		Rotorua Formation	Okataina Group
	Q3op		(undifferentiated)	Okataina Group
Hydrogeological unit 3:	Q2okr		Okareka Formation	Okataina Group

Hydrogeological unit	QMAP code	QMAP unit	QMAP stratigraphic unit name	QMAP sequence
Youngest Okataina rhyolites	Q3trr		Te Rere Formation	Okataina Group
	Q1mkr		Mamaku Formation	Okataina Group
	Q2rer		Rerewhakaaitu Formation	Okataina Group
	Q1wkr		Whakatane Formation	Okataina Group
	Q2wir		Waiohau Formation	Okataina Group
	Q1kar		Kaharoa Formation	Okataina Group
	Q7vor		(undifferentiated)	Okataina Group
	Q2ror		Rotorua Formation	Okataina Group
Hydrogeological unit 4: Earthquake flat formation	Q3or		Oruanui Formation	Taupo Group
	Q4ro		Rotoiti Formation	Okataina Group
	Q4eq		Earthquake Flat Formation	Okataina Group
Hydrogeological unit 5: Rainbow Mountain dacite	mQvd	Includes four peaks	(undifferentiated)	Okataina Group
Hydrogeological unit 6: Mamaku Plateau Fm.	Q7mk		Mamaku Plateau Formation	Ohakuri-Kapenga-Rotorua-Reporoa
Hydrogeological unit 7: Kaingaroa Fm.	Q7kiu	Q7ki	Kaingaroa Formation	Reporoa group
Hydrogeological unit 8: mQ to Q7 undifferentiated pyroclastics	Q7vp		Onuku Pyroclastics	Okataina Group
	mQvop		(undifferentiated)	Okataina Group
Hydrogeological unit 9: Pokopoko Pyroclastics	Q8pp		Pokopoko Formation	Okataina Group
	Q8mr	Millar Road ignimbrite	Millar Road formation	Okataina Group
Hydrogeological unit 10: Okataina and other rhyolites (middle rhyolites)	Q14vor		Q1-Q4 (undifferentiated)	Okataina Group
	Q11vor		(undifferentiated)	Okataina Group
Hydrogeological unit 11: Matahina Formation	Q8ma		Matahina Formation	Okataina Group
Hydrogeological unit 12: Whakamaru Group	Q9w		(undifferentiated)	Whakamaru Group
Hydrogeological unit 13: Oldest rhyolites, pre-Whakamaru	mQvur		(undifferentiated)	
	lQvor		(undifferentiated)	Okataina Group
	mQvor		(undifferentiated)	Okataina Group

In short, these hydrogeological units were derived as follows:

The main ignimbrite sheets (e.g., Whakamaru Group, Matahina Formation and Mamaku Plateau Formation), in general, were kept as distinct units. However, sediments, pyroclastics, rhyolites and minor ignimbrites were grouped into hydrogeological units according to their hydrogeological properties, if applicable. For example, all rhyolites within the model area are likely to have similar hydrogeological properties. However, due to their prominent age differences it was not feasible to group all rhyolites into one unit. The EarthVision model-building process used in this report follows stratigraphy and so expects that model units were deposited in a chronological order. Therefore, the rhyolites were split into three single hydrogeological groups with different stratigraphic positions within the model. Hydrogeological groups consisting of undifferentiated pyroclastics were aggregated because of the similarity of the deposits and assumed similar hydrogeological characteristics, taking into account that there is no hydrogeological information available for most of these units. Earthquake Flat Formation, Rotoiti Formation and Oruanui Formation were grouped into one hydrogeological group due to their similar lithology, stratigraphic age and assumed similar hydrogeology.

3.3 DEFINITION OF BOUNDARY SURFACES

A 3D geological model is generally a series of units, which are assembled with respect to their chronology and structural relationships. The model developed in this report is constructed in a similar way, but instead of individual units, it is built from a sequence of formation groups (layers) that are aggregated from individual formations and units (Section 3.2). The horizontal extent of each group is defined by boundary surfaces. Therefore, a key step in the modelling process is determining the number of layers and boundary surfaces in the model. Generally only the top surface is defined for each layer, as the bottom surface of each group is automatically represented by the top surface of the layer underneath it.

For example, the greater Lake Tarawera catchment 3D model includes a layer for the Whakamaru Group ignimbrites, one of the main aquifers in this catchment. The top surface of this layer was constructed from a variety of sources including: QMAP Rotorua (Leonard *et al*., 2010); a cross-section published by Nairn (2002); additional information from Leonard (2013); and well logs from the Waiotapu Geothermal Field (Wood, 1994), and the BOPRC Lake Tarawera groundwater investigation project (Thorstad *et al.,* 2011; Rose *et al.,* 2012; Lovett *et al.,* 2012.)

The amount of information available for a layer provides constraints on the possible ranges of the layer location and elevation. A layer can be well constrained if, for example, a high density of wells are available that penetrate this layer and underlying units, or poorly constrained due to lack of wells or other information.

Faults and caldera boundaries are represented as boundary surfaces that dissect layers vertically. Fault surfaces are constructed by digitizing a fault trace on the geological map, transferring the trace onto the DTM and using a dip angle to generate the surface. The approximate caldera boundaries were delineated by Leonard (2013) and their surfaces were generated in the same way as the fault surfaces.

3.4 BOUNDARY SURFACES OF MAJOR HYDROGEOLOGICAL UNITS

3.4.1 Base of the Model

The base of the model is assumed to be the base of Whakamaru Group ignimbrites. It has been constructed primarily following a cross-section published by Nairn (2002) and discussions with Leonard (2013). Additional information was gained from drill holes in the Waiotapu and Rotorua geothermal fields. BOPRC bore data could not be used as the bores did not penetrate the base of Whakamaru Group.

3.4.2 Okataina Rhyolites pre-Whakamaru

QMAP Rotorua has been used to specify the surface extent of these old rhyolites. The subsurface shape has been adjusted to steep flanks not unsimilar to the youngest rhyolite domes e.g., Mt Tarawera. Rhyolite has also been drilled and described by Lovett *et al.,* (2012) south of Lake Rotokakahi, but further delineation of the subsurface extent of these lava domes and flows is speculative. BOPRC driller's logs are sparse in this area and only give ambiguous information (Section 3.1.5). Additionally, it is not possible to identify if the drilled rhyolite belongs to these old rhyolites as younger rhyolites also crop out nearby.

3.4.3 Whakamaru Group

The top surface of this unit has been constructed primarily following a cross-section published by Nairn (2002) and discussions with Leonard (2013). Whakamaru Group has been logged in drill holes in Waiotapu Geothermal Field and in drill holes west and east of Lake Rerewhakaaitu in the southern part of the study area, which were logged by Thorstad *et al*., (2011) as part of the BOPRC Lake Tarawera groundwater investigation project. Whakamaru Group ignimbrites crop out in the southern part of the greater Lake Tarawera catchment, but they are assumed to cover the entire model area below the surface (Nairn, 2002; Leonard, 2013). BOPRC driller's logs do not allow a clear differentiation between some units, e.g., Kaingaroa Formation, Matahina Formation, and Whakamaru Group ignimbrite. In the southern part of the study area, bores in areas where these different ignimbrites crop out often have similar lithological descriptions (e.g., rhyolite, sandy ignimbrite, etc.). Therefore, in this area the driller's logs could only be used as an indication of the thickness of overlying units.

3.4.4 Matahina Formation

The top surface of this unit has been constructed primarily following a cross-section published by Nairn (2002) and discussions with Leonard (2013). It is assumed to have a thickness of up to 750 m within the caldera boundary and covers wide areas east and northeast of the study area. However, outcrops in the model area are only of limited extent. The ignimbrite has been drilled in one bore west of Lake Rerewhakaaitu by Thorstad *et al*., (2011), but was not encountered in other drill holes of the Lake Tarawera Groundwater Investigation Programme (Section 2.3) At its deposition, Matahina Formation ignimbrite likely covered the southern part of the model area like a sheet, but has possibly been eroded widely before it was buried by younger pyroclastics. BOPRC driller's logs do not allow a clear differentiation between ignimbrite units (Section 3.1.5). In the southern part of the study area, bores in areas where these different ignimbrites crop out, often have similar lithological descriptions (e.g., rhyolite, sandy ignimbrite, etc.). Therefore, in this area the driller's logs could only be used as an indication of the thickness of overlying units.

3.4.5 Okataina and other Rhyolites

The surface extent of these rhyolites was determined from the QMAP Rotorua with steep flanks in the subsurface, not unsimilar to the youngest rhyolite domes (e.g., Tarawera). Rhyolite has also been drilled and described by Lovett *et al.,* (2012) south of Lake Rotokakahi, but further delineation of the subsurface extent of these lava domes and flows is speculative. BOPRC driller’s logs are sparse in this area and only give ambiguous information (Section 3.1.5). Therefore, driller’s logs were, in this case, only used to give an indication of the thickness of overlying sediments.

3.4.6 Pokopoko Pyroclastics and Millar Road Ignimbrite

Pokopoko Pyroclastics underlie Mamaku Plateau Formation in the northwestern part of the study area. There is no indication that it also exists underneath the block of Mamaku Plateau Formation at the southern extension of Lake Tarawera. Thus, it is not clear how far it extends to the south. Pokopoko Pyroclastics have been identified in one drill hole of the Lake Tarawera catchment investigation programme (Section 2.3). BOPRC driller’s logs within the areas, where Pokopoko Pyroclastics have been mapped at the ground surface, describe the pyroclastics in general as pumice sands, possibly with silts and or gravels. The logs show a thickness of these deposits of at least 52 m north of Lake Okareka (well ID: 11535) and a thickness of 2 – 20 m (e.g., in wells 3728, 3729, 1276, etc.) west of Lake Okareka. Here, the ‘pumice sands’ occur above ‘ignimbrite’ or ‘rhyolite’. However, there is no indication if ‘ignimbrite’ or ‘rhyolite’ refer to actual underlying ignimbrite sheets, rhyolite lavas that are associated with the Okataina domes in the vicinity, or to welded parts of the pyroclastics itself. The driller’s log of the deepest of these wells, Well 220, records ‘rhyolite’ from a depth of 2 to 92 m, which is the bottom of the well. It is assumed that this is not a pyroclastic that is only ‘moderately compacted’ with ‘welded flow units’ within Pokopoko Pyroclastics (Section 2.2.4). Therefore, these logs describe the boundary between Pokopoko Pyroclastics and an underlying ignimbrite or rhyolite.

3.4.7 Lake Sediments

Lake sediments were deposited in palaeolakes within the calderas and subsequently downfaulted (Nairn, 2002; Leonard, 2013). Their extent is approximated by caldera boundaries and their thickness is an estimated 200 m, following a cross-section of Nairn (2002). Although they are depicted as one layer, multiple layers are likely because the lakes existed at different stratigraphic positions within the caldera depressions.

3.4.8 MQ to Q7 Undifferentiated Pyroclastics

The top surface of this unit has been constructed primarily following the Rotorua QMAP (Leonard *et al*., 2010), a cross-section published by Nairn (2002) and discussions with Leonard (2013). These pyroclastics have been logged in geothermal wells at Waiotapu Geothermal Field. BOPRC driller’s logs commonly describe these pyroclastics as sandy or gravelly pumice. From these logs, the pyroclastics in the southern part of the model have a thickness between 30–60 m. In this area they are underlain directly by either Whakamaru Group or Matahina Formation ignimbrites that are both often described as ignimbrite, rhyolite or hard rock.

3.4.9 Kaingaroa Formation

Kaingaroa Formation ignimbrite has been mapped at the ground surface in the southern part of the greater Lake Tarawera catchment (Leonard *et al.*, 2010). The subsurface extent was constructed primarily following a cross-section published by Nairn (2002) and discussions with Leonard (2013). Kaingaroa Formation is distributed mostly to the south of the model area. It has been drilled in Waiotapu Geothermal Field drill holes, but it is not clear how far north the unit extends in the subsurface, and BOPRC driller's logs do not allow a clear differentiation between ignimbrite units (Section 3.1.5). In the southern part of the study area, bores in areas where these different ignimbrites crop out often have similar lithological descriptions (e.g., rhyolite, sandy ignimbrite, etc.). Therefore, in this area the driller's logs could only be used as an indication of the thickness of overlying units.

3.4.10 Mamaku Plateau Formation

This unit has been mapped mostly in the northwestern part of the model area (Leonard *et al.*, 2010). Its southernmost outcrop is located south of Lake Rotomahana and its subsurface extent is assumed to be limited to the area north of the Rotomahana West Fault. Mamaku Plateau Formation is assumed to cover that entire area like a sheet and is presumably found within the caldera boundaries (Nairn, 2002; Leonard, 2013). It has been drilled northwest of Lake Tarawera at a depth of 3 m and with a thickness of 34 m (Thorstad *et al.*, 2011). BOPRC driller's logs show that only two other wells have been drilled within the surface extent of this formation (Leonard *et al.*, 2010). One of these wells does not list any lithological information (well ID: 4031) and the other well (well ID: 10421) reports 'cemented pumice' to a depth of 37 m. These wells do not allow the identification of the boundary between Mamaku Plateau Formation and the underlying Pokopoko Pyroclastics.

3.4.11 Rainbow Mountain Dacite

The surface extent of Rainbow Mountain has been identified from the QMAP geological map. The slope angles are assumed for the dacite dome below the ground surface, similar to the slopes of the exposed dome at the surface.

3.4.12 Earthquake Flat Formation and Rotoiti Pyroclastics

Earthquake Flat Formation has been mapped on the surface in the western part of the study area. Its subsurface extent is assumed to be closely limited to areas of surface exposure. Nairn (1971) and Scott (2013) suggest a maximum thickness of 120 m using the depth of valley incursions into the pyroclastics, as these are likely to have been controlled by an underlying harder, more erosion-resistant formation, as well as the elevation of underlying units.

Rotoiti Pyroclastics are exposed at the surface primarily in areas north of the study area. Nairn (2002) and Leonard (2013) assume a thickness of up to 470 m within the Rotoiti Caldera. Rotoiti Pyroclastics could not be positively identified in driller's logs from within the catchment.

3.4.13 Youngest Okataina Rhyolites

Most of the actual shape and extent of these young rhyolites can be followed and mapped on the surface (Leonard *et al.*, 2010). Only the areas covered by lakes, younger pyroclastics and sediments have to be interpolated. This was done by projecting the shape and slope of the exposed rhyolite domes to the subsurface.

3.4.14 Q1 to Q4 Undifferentiated Pyroclastics

The youngest pyroclastics are not overlain by other deposits, so their entire surface extent can be obtained from the geological map (Leonard *et al*., 2010). These pyroclastics have a thickness of at least 61 m at a distance of approximately 4.5 km from the Tarawera vent system (Rose *et al.*, 2012) and BOPRC driller's logs record a thickness of 53 m of 'loose grey pumice with organics' in Well 10606 located approximately 7 km south of the vents.

3.4.15 Tauranga Group Alluvium

Tauranga Group sediments are not overlain by other deposits, so their entire surface extent can be obtained from the geological map (Leonard *et al*., 2010). BOPRC driller's logs in the southern part of the model provide a thickness of between 20 and 50 m for Tauranga Group sediments.

3.5 ASSEMBLY OF THE 3D SIMPLIFIED GEOLOGICAL MODEL

Following the construction of layer and fault boundary surfaces the final geological model is assembled as a chronological sequence of layers with defined types of contact between them (e.g., depositional contact or unconformity). Fault surfaces and caldera boundary surfaces provide the structural component and layers are offset by these surfaces as appropriate.

4.0 RESULTS

4.1 MODEL DESCRIPTION

The greater Lake Tarawera 3D geological model consists of 16 layers, including:

- One model layer representing all eight lakes;
- Thirteen layers representing hydrogeological units that are groupings of formations that are exposed at the ground surface within the model area (Leonard et al., 2010) (Table 3; Section 3.2);
- Two layers that are not exposed at the ground surface within the model area: 'lake sediments' and the 'undifferentiated base of the model' layer (i.e., all geological formations that are older than Whakamaru Group and don't crop out within the model area).

The geological model of the greater Lake Tarawera catchment in chronological order from the oldest stratigraphic unit to the youngest is shown in Figure 6 and Figure 7. The model is split into fault blocks defined by the caldera faults of Rotoiti and Matahina calderas, as well as the rift faults of the Ongahoro, Tumunui and Ngapouri fault systems. The model extends over an area of 386 km^2, and a gridding resolution of 80 by 80 m has been chosen in correspondence to the resolution of models developed for BOPRC prior to this project. The vertical extent of the model is between -2600 m RL and 1100 m RL, which allows representation of the caldera fill as estimated by Nairn (2002).

The base of the model (i.e. the base of Whakamaru Group ignimbrites) is simplified as a flat surface in all areas where no other information is available. In the southern part of the study area it has an undulating surface as represented in Waiotapu drill holes. The Whakamaru Group ignimbrites cover the entire model area as a sheet. They are buried by younger pyroclastics and rhyolites over most of the study area, but they crop out in the southern part where they have a thickness of up to 350 m. Here, they are partly eroded and buried by younger deposits.

Matahina Ignimbrite is the thickest unit, up to 750 m, within the combined Rotoiti/Matahina Caldera depression. Outside of the calderas the unit is partly eroded. Pokopoko Pyroclastics are limited to the northern model area. Here, they directly underlie Mamaku Plateau Formation with a thickness of up to 200 m and are laterally bounded in the northeast and southwest by remnants of older lava domes. Old lake sediments are approximated within the caldera boundaries with a thickness of 200 m. Although they are depicted as one layer, it is likely that lakes existed at different stratigraphic positions within the caldera depressions. MQ to Q7 undifferentiated pyroclastics are exposed at the surface in the northern and southern parts of the model with a thickness of up to 150 m. They also fill the caldera depressions and are modelled as far north as Lake Rotomahana.

These undifferentiated pyroclastics are overlain by Kaingaroa Formation ignimbrite. This ignimbrite has a thickness of up to 200 m in the southern part of the model, where it is exposed at the surface. Its thickness decreases to less than 50 m in the overlapping Rotoiti/Matahina calderas. Mamaku Plateau Formation ignimbrite exists over large parts of the model area north of Ngapouri Fault. It is exposed at the ground surface mostly in the northern part of the study area, but also crops out north of Lake Rotomahana. The subsurface distribution of the ignimbrite shows that it flowed around the older rhyolite domes until it stopped north of the Ngapouri Fault scarp.

Earthquake Flat Formation was deposited only in the west of the model area with a thickness of up to 150 m. Rotoiti Pyroclastics, which belong into the same hydrogeological group, were deposited in large thicknesses, up to 400 m, in the Rotoiti Caldera depression. The youngest pyroclastics (Q1 to Q4) have a thickness of up to 70 m proximal to their vents at Mt Tarawera and thin out farther away from the source vents. The young rhyolite domes within the caldera boundaries have a thickness of up to 800 m thinning out to the flanks.

Offsets on the Tumunui and Ongahoro faults all increase with the age of the stratigraphic unit that they dissect. For example, the Earthquake Flat Formation is offset by 40 m, but the Whakamaru Group ignimbrites are offset by 90 m at each of these faults. The offset at the Ngapouri Fault is 500 m, which results in older ignimbrite sheets (e.g., Whakamaru Group, Matahina Ignimbrite) being exposed at the ground surface in the southern model area. Younger ignimbrites and other pyroclastics (Pokopoko Pyroclastics to Earthquake Flat Formation) are exposed at the ground surface north of this fault and only in areas that are outside of the caldera boundaries.

4.2 MODEL DATASETS

This section provides a record of the study area boundary used for the modelling, as well as the developed 3D datasets for the final version of the greater Lake Tarawera geological model (Table 4).

Table 4 2D and 3D model datasets of the final model version. The file formats are proprietary to EarthVision (Dynamic Graphics, Inc., 2013).

File name	Description
Tarawera_model_boundary_B.ply	Study area boundary used to clip the model
T19.seq	Sequence file used to define the stratigraphic and structural relationships between geological layers.
T19_clip.unsliced.faces	3D volume file built using the sequence file

4.3 MODEL UNCERTAINTIES

Geological models are, by definition, a simplification of the Earth’s stratigraphy and structure. These models are subject to uncertainty with regard to input data and model construction.

Model input data has varying degrees of uncertainty. There are some data types whose uncertainty is solely linked to measurable resolution, for example ground elevation data (Section 4.3.1.1), whereas some data sets are heavily influenced by unquantifiable personal interpretation and human error, such as well log data. For example, well logs are a construct of a driller’s interpretation of the drilled materials, and some drillers record only very general descriptions of geological units.

The complexity of model generation is linked to the geological complexity being represented. Invariably, the model generation process is sufficiently complex to require both the skills of a geologist as well as an expert model builder. However, uncertainty analysis is not commonly used with geologic models (Lelliot *et al.*, 2009). Key issues that require expert judgment include correlation of strata identified in well logs and interpretations of structure based on geological maps. The use of expert judgement can reduce, but not eliminate, uncertainty in geological models.

The following sections aim to outline some of the uncertainties in the Tarawera geological model. However, a full assessment of model uncertainty is complex and beyond the scope of this project.

4.3.1 Uncertainty in Model Input Data

4.3.1.1 Topographic data

Topographic data was sourced from BOPRC LiDAR measurements and digital terrain maps derived from 1:50,000 maps published by Land Information New Zealand (LINZ). Processed LiDAR data was provided by BOPRC as a 50 by 50 m horizontal resolution grid, down-sampled from the 2 m Rotorua District DEM. Unprocessed LiDAR data has a higher horizontal resolution and, therefore, a lower uncertainty. However, unprocessed LiDAR data also results in very large file sizes and for the geological modelling it is not practical to use such computationally intensive datasets.

DTMs are commonly generated as a 10 m grid calculated from 20 m contours developed for 1:50,000 maps by LINZ. The uncertainty in these gridded elevation estimates, assessed in comparison with LIDAR measurements on a 2 m grid (Table 5), may be approximately +/- 2 m for relatively flat terrain and +/- 30 m for mountainous terrain. Uncertainties in elevation estimates by LIDAR are approximately 15 cm (Levick, 2011).

Table 5 Comparison of the difference between elevations estimated with 20 m contours and LIDAR elevation estimates gridded at a 2 m interval (Levick, 2011).

Location	Topography	Number of points of elevation difference calculation	Mean elevation difference (m)	Standard deviation of elevation difference (m)
Hawkes Bay	Flat	100	-2.8	32.5
Palmerston North	Flat	100	-1.4	6.7
Alpine fault	Mountainous	100	-26.2	44.5
Christchurch	Flat	100	-2.2	18.7

4.3.1.2 Geological map boundaries

Digital geological maps express map units as polygons and uncertainty is associated with these boundaries. The QMAP 1:250,000 Geological map of Rotorua (Leonard *et al.*, 2010) is the best data source for information on the geological conditions at the ground surface in the model area. The spatial accuracy of this map is estimated to be no better than +/- 100 m for ‘accurately’ located geological features and in some places may exceed 250 m. Geological data attributed as ‘approximately’ located will have a spatial accuracy no better than 250 m and in some places is expected to be significantly less accurate.

Additionally, geologic units might not be shown in a map if their thickness is below a certain value. QMAP, for instance, generally will not display a unit unless it is at least 10 m thick or very important. This can result in unit boundaries that are quite different than the actual boundary (Begg, 2011).

4.3.1.3 Subsurface geological data

Well logs provided by BOPRC are the main source of subsurface data for the construction of the 3D greater Tarawera geological model. Section 3.1.5 describes some of the limitations of this dataset. Generally, uncertainties associated with well log data include data collection, storage and/or spatial sampling uncertainties.

The uncertainties in well log data collection can include:

- location and well depth estimates may be poorly identified;
- logging by drillers is of variable quality with some drillers recording only very general descriptions of geologic units;
- drilling methods are variable and some are better than others for identifying geology. For example cable tool drilling provides more reliable geologic logging results than air rotary in unconsolidated sediments;
- commonly, wells are not logged by a geologist or hydrogeologist and so descriptions of formations are typically highly variable. For example ignimbrite may be variously named as ‘rhyolite’, ‘volcanic rock’, ‘rock’, or ‘ignimbrite’ by drillers. In addition, formation names are not often recorded by drillers and are generally unknown to them. The names may even be imperfectly identified by field geologists or hydrogeologists until corroborated by more experienced professionals in the office or examined in the laboratory.

Data storage uncertainties associated with well logs include incorrect data entries (e.g., typographic mistakes, incorrect decimal points in well depth or logged interval fields, etc.) or wells that have been entered more than once. Any obvious errors have been manually corrected. However, minor errors in the stored well data can be particularly problematic during the 3D model development as they often remain undetected and therefore poor quality data can be used to constrain layer surfaces.

Whereas storage uncertainties of well data sets often remain undiscovered, spatial sampling uncertainties are obvious by nature. Spatial sampling uncertainties consist of all uncertainties introduced due to limitations in the availability of information throughout the model area, or lack thereof. Usually, this constitutes well log density, distribution and depth. In general, the denser the population of well logs within a part of the model area is, the greater the certainty in model development for this area. The pattern of distribution of well logs throughout the model area is another important factor. For example, models in areas without any well logs, or with very few well logs, have a far higher uncertainty than models in areas with evenly distributed well logs. The uncertainty in geological layer location increases with depth. This is because wells are generally shallow (typically less than 100 m deep in the greater Tarawera model area) and geophysical methods produce less certain results as the depth of the target (e.g., a geological layer) increases.

There are 88 wells with lithological logs located within the study area, which corresponds to approximately 1 well per 4 km^2 (Figure 4) if the wells were evenly distributed. However, the highest densities of these wells are in the southern part of the model area, near to Lake Rerewhakaaitu and Rerewhakaaitu township, and in the east near to Lake Okareka. No well logs are recorded throughout large parts of the model area. About 80% of all well logs recorded by BOPRC in the model area are less than 100 m deep. The maximum well depth in the model area is 244 m. The vertical extent of the model, however, is 2600 m below sea level, resulting in high uncertainties in deeper units.

4.3.2 Uncertainty in the Model Construction

4.3.2.1 Modelling software

The greater Lake Tarawera catchment model was developed using EarthVision geological modelling software version 8.1 (Dynamic Graphics, Inc., 2013). The surfaces were interpolated using EarthVision's ‘Minimum Tension Gridding’ method at a horizontal resolution of 80 x 80 m. This gridding method uses an iterative approach to calculate a smooth, evenly distributed grid while seeking to honour the input data.

4.3.2.2 Model structures

Uncertainties are associated with the location of faults and other large-scale geological features such as fault blocks. Faults and caldera boundaries in the greater Tarawera model are mapped at the ground surface (Leonard *et al.*, 2010). However, the distribution of these features at depth can be quite speculative. In addition, the estimates of the location of these features are not verifiable with current data. Therefore estimates of the uncertainties in greater Tarawera model structures are not made.

4.3.2.3 Layer surfaces

Additional uncertainty may be introduced through the gridding algorithm used to interpolate the layer surfaces and the gridding resolution chosen for the model grids. Gridding is the process of interpolating a regular grid based on irregular data points in a 3D space (e.g., interpreted well log data). A surface that is created through one gridding method can differ immensely if another gridding method is used. The more data points that are available, the lower the uncertainty resulting from the gridding method. However, the uncertainty can only be quantified if ground-truthing data is available.

4.3.2.4 Layer distribution

Interpolation of input data to create layer surfaces subsequently generates a model of subsurface layer distribution. Uncertainty in layer distribution for layers below the ground surface is relatively high compared to units exposed at the ground surface. Uncertainty in the vertical location of layer boundaries (i.e. layer tops and bottoms), may be near zero for layers exposed at the ground surface. However, uncertainties in observations and interpretation will lead to larger uncertainties for layers below the ground surface.

5.0 CONCLUSIONS

Understanding the groundwater system in the greater Lake Tarawera catchment is important for the assessment of the effects of land use on lake water quality. The Lake Tarawera groundwater investigation project, part of the Rotorua Te Arawa Lakes Programme, was initiated in 2011 to gain a thorough understanding of the geological and hydrogeological conditions throughout the catchment. The project involved exploratory drilling with geological logging, sampling and testing of wells and aquifers at ten different sites in the catchment to address data gaps. The development of a simplified geological model for the greater Lake Tarawera catchment, as described in this report, is the first phase of a three-phase investigation to develop and apply groundwater models in the Lake Tarawera catchment for assessment of land use impacts and nitrogen discharge to surface water.

Primary sources of information to develop the simplified geological model were the Rotorua QMAP geological map, published geological logs (including those from the exploratory drilling project) and cross-sections, as well as discussions with volcanic geologists and experts on the geology of the wider Tarawera area. Information from BOPRC driller’s logs were of limited utility, and were only used where the data was available and verifiable. The study area is located in an active volcanic centre and the local geology is predominantly a heterogeneous mixture of a variety of volcanic rocks that are often not accurately described in these logs. As a result, well log information can be misleading and therefore is not a highly reliable source of data for the model build. Nevertheless, the logs were useful to tentatively identify boundaries between heterogeneous formations with stark contrasts, for example, to determine the thickness of Tauranga Group alluvium overlying ignimbrites.

For the development of the simplified geological model, the geological map units were grouped into 13 hydrogeological units based on their hydrogeological similarities. These 13 units comprise:

- Ignimbrite sheets (4 model units);
- Other pyroclastics (4 model units);
- Rhyolite and dacite lava or domes (4 model units);
- Alluvial sediments (1 model unit).

Additionally, a geological layer was added for the lake sediments that do not crop out within the model area. The base of the model is delineated by the base of Whakamaru Group, while the top layer of the model is not a geological unit, but represents the lakes.

The model extends over an area of 386 m^2 and has a grid resolution of 80 by 80 m. The vertical extent of the model is between -2600 m RL and 1100 m RL.

The geology in the model area consists mainly of ignimbrite sheets, other pyroclastics and rhyolite and dacite lava or domes. Alluvial sediments are mainly limited to valleys eroded into the volcanic deposits. Rift faults of three northeast-southwest striking fault zones dissect the model area: the two Ongahoro Faults in the north, the two Tumunui Faults and the Ngapouri Fault in the south. The old ignimbrite sheets (Whakamaru Group, Matahina Ignimbrite) are expected to cover most of the model area, but only crop out south of the Ngapouri Fault.

Younger ignimbrites and other pyroclastics, such as Mamaku Plateau Formation or Earthquake Flat Formation, are exposed at the surface north of the Ngapouri Fault and only outside of the caldera depressions. Mamaku Plateau Formation is assumed to cover most of the area north of this fault. Inside the caldera boundaries, only the youngest pyroclastics and rhyolites are exposed at the ground surface. Greywacke basement is not exposed or drilled in the greater Lake Tarawera catchment and as a result is not represented in the model.

The degree of fracturing, and the interconnectivity of fractures, control groundwater flow in welded ignimbrites, and rhyolite lavas and domes. High hydraulic conductivity values that correspond to the upper range for fractured rock in the literature were measured, for example, in Okataina rhyolites and Matahina Formation ignimbrite. However, fractured rocks are highly heterogeneous, and hydraulic conductivity may vary over several orders of magnitude throughout the same geological unit.

The groundwater flow in unconsolidated sediments, unwelded ignimbrites and other pyroclastic units is controlled by the grain size of the material. Coarser deposits, for example sands and gravels of the Tauranga Group, permit higher permeability. However, fine-grained basal tephra layers of ignimbrites and other pyroclastic units (e.g., Onuku Pyroclastics) or thick, well developed paleosols between formations, may act as aquitards.

The developed three-dimensional geological model described in this report provides a simplification of a complex system based on hydrogeological characteristics. This model will be used as input for the catchment-scale groundwater flow model that will be developed in the next phase of this project.

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8.0 FIGURES

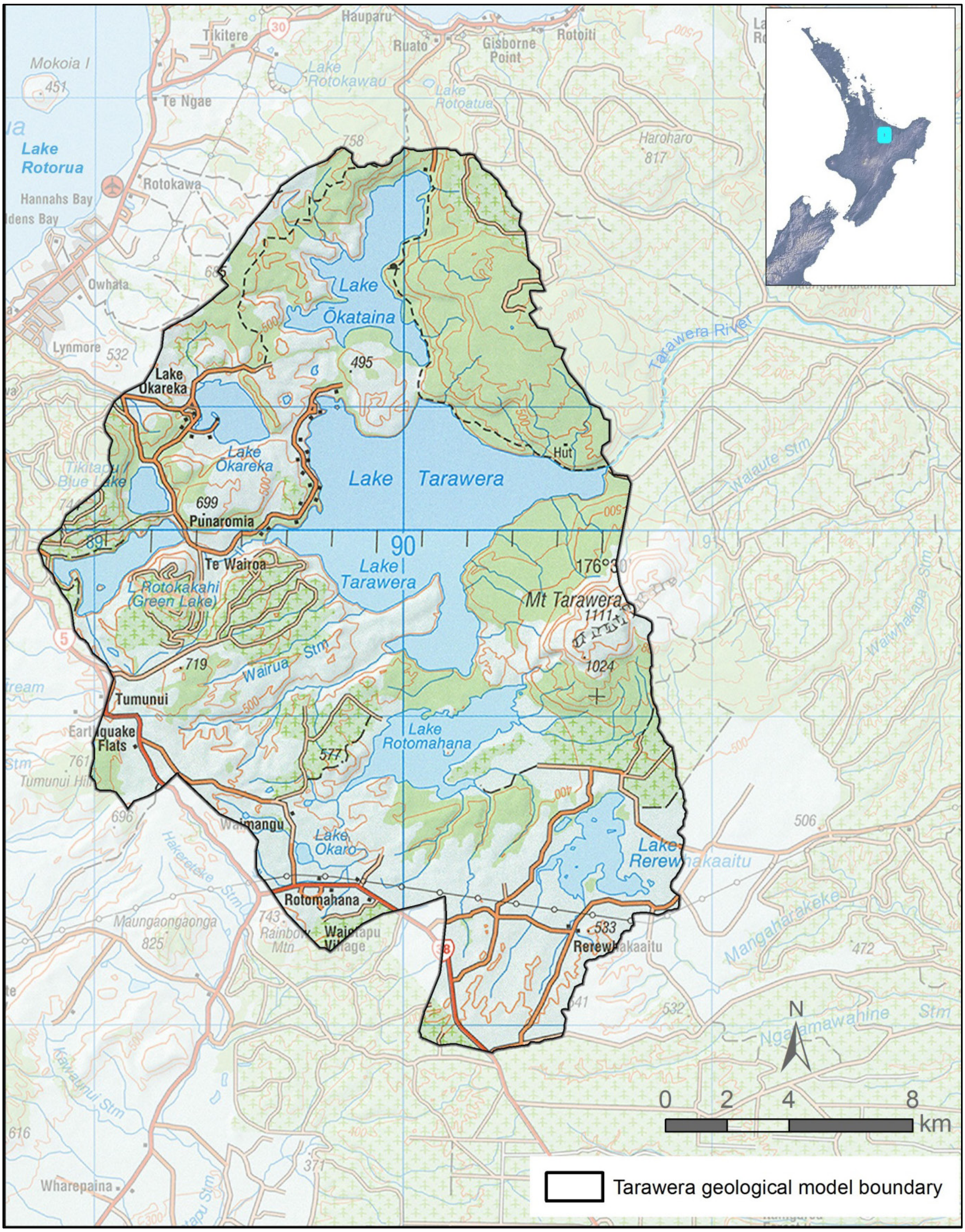

Figure 1: Location of the greater Lake Tarawera catchment study area and the Tarawera River.

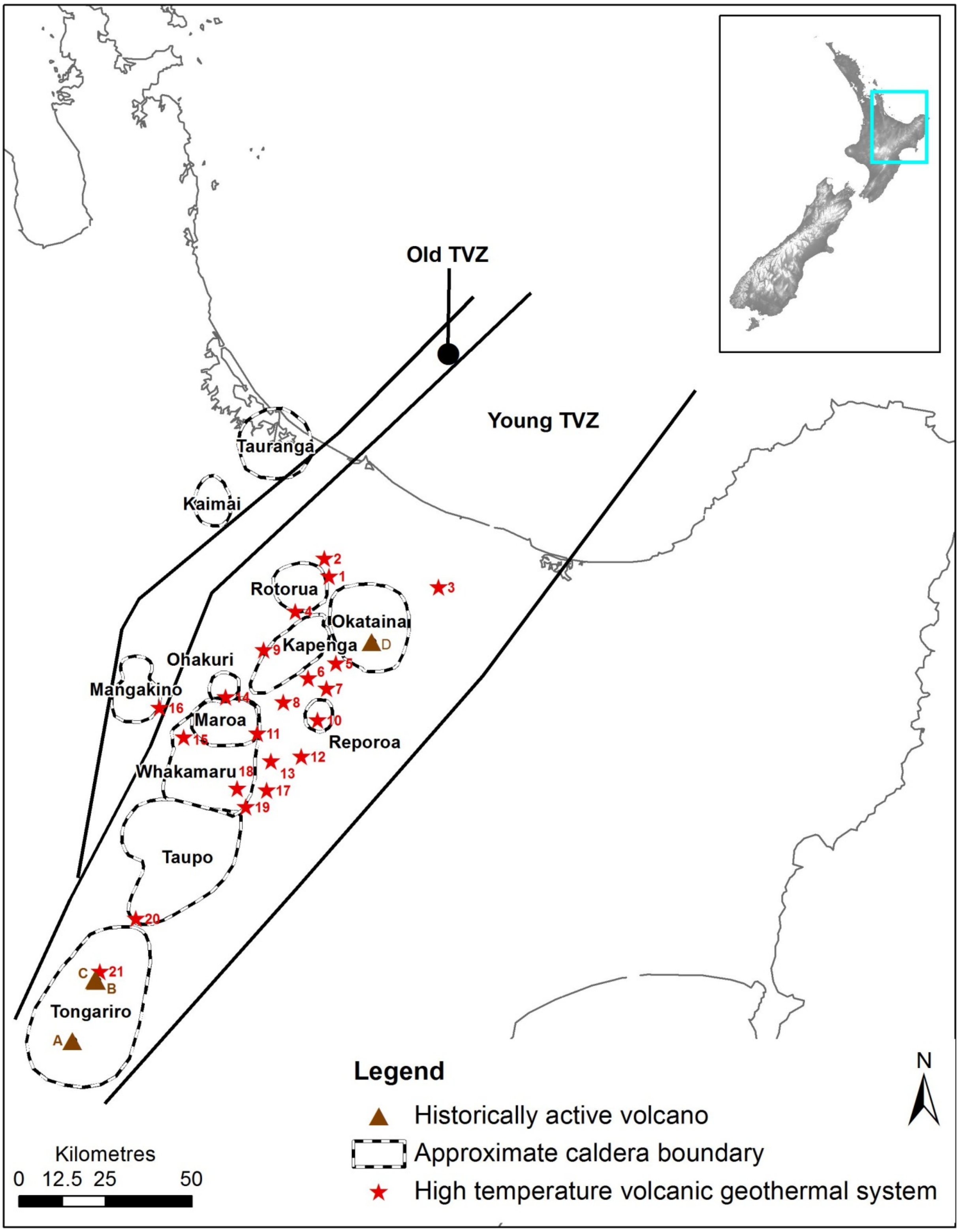

Figure 2: Calderas, historically active volcanoes and geothermal systems in the Taupo Volcanic Zone. Volcanoes: A: Ruapehu, B: Ngauruhoe, C:Tongariro, D: Tarawera; Geothermal systems: 1: Tikitere, 2: Taheke, 3: Kawerau, 4: Rotorua, 5: Waimangu, 6: Waikite, 7: Waiotapu, 8: Te Kopia, 9: Horohoro, 10: Reporoa, 11: Orakei Korako, 12: Ohaaki, 13: Ngatamariki, 14: Atiamuri, 15: Mokai, 16: Mangakino, 17: Rotokawa, 18: Wairakei, 19: Tauhara, 20: Tokaanu-Waihi, 21: Ketetahi Springs.

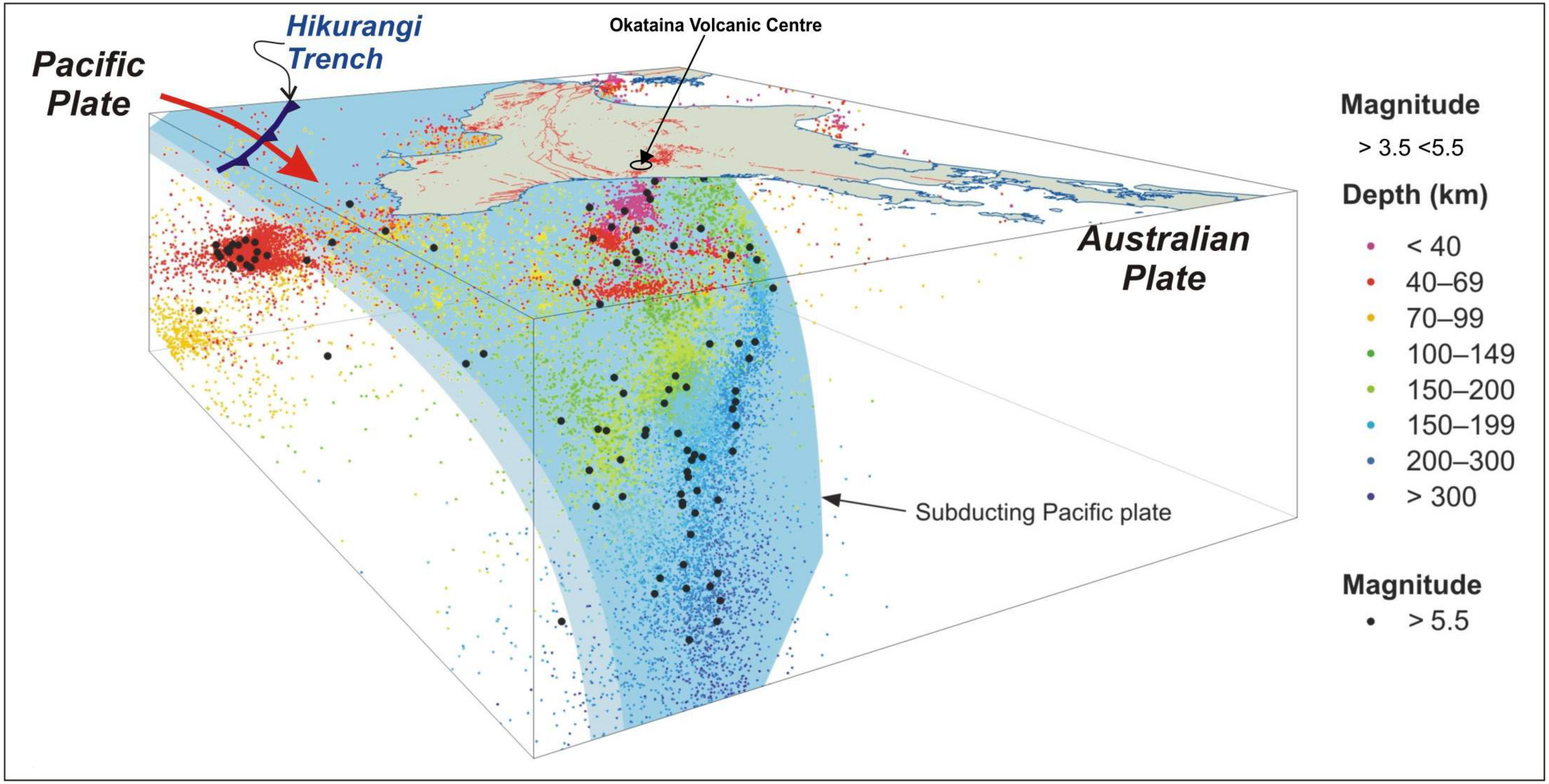

Figure 3: A cross-section through the Hikurangi Margin showing the Pacific Plate dipping beneath the Australian Plate, with the North Island, as well as the epicentres of all earthquakes recorded between 1990 and 2009. The approximate location of the Okataina Volcanic Centre is indicated (adapted from Leonard *et al.,* 2010).

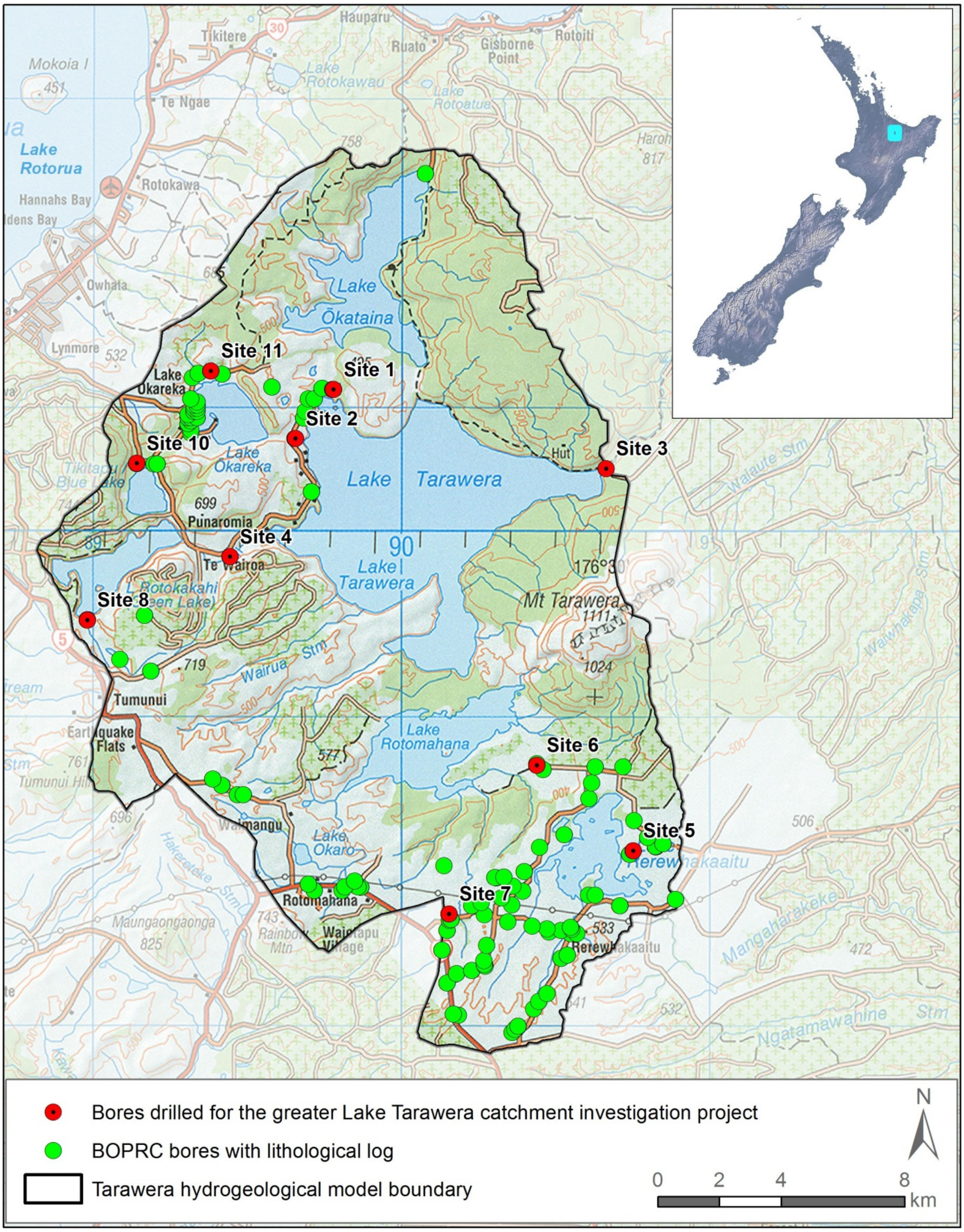

Figure 4: Bores with lithological logs (Section 2.3; Section 3.1.5).

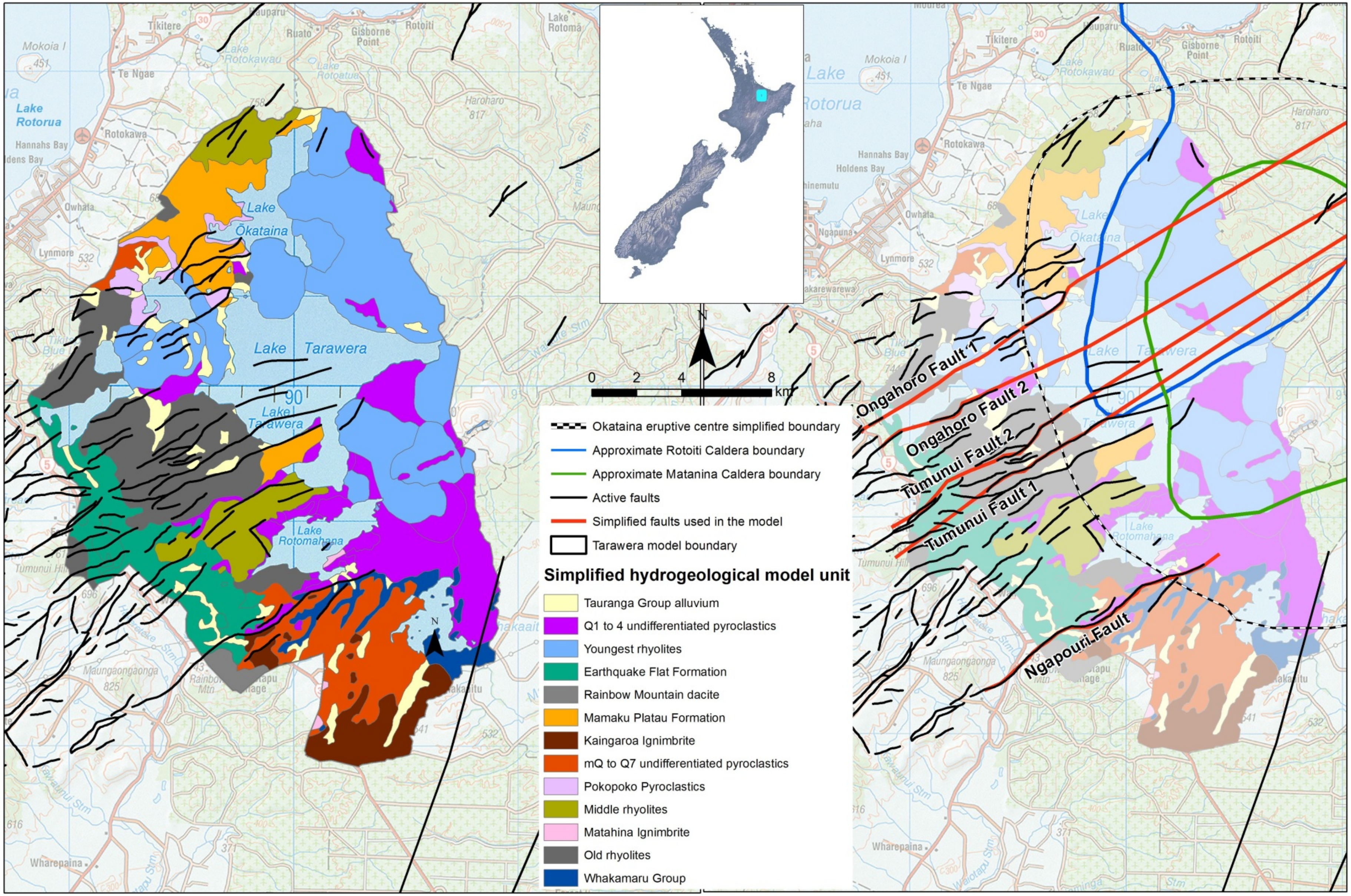

Figure 5: Simplified geological map (left) and simplified structural components (right) used for the model build (Leonard *et al.*, 2010).

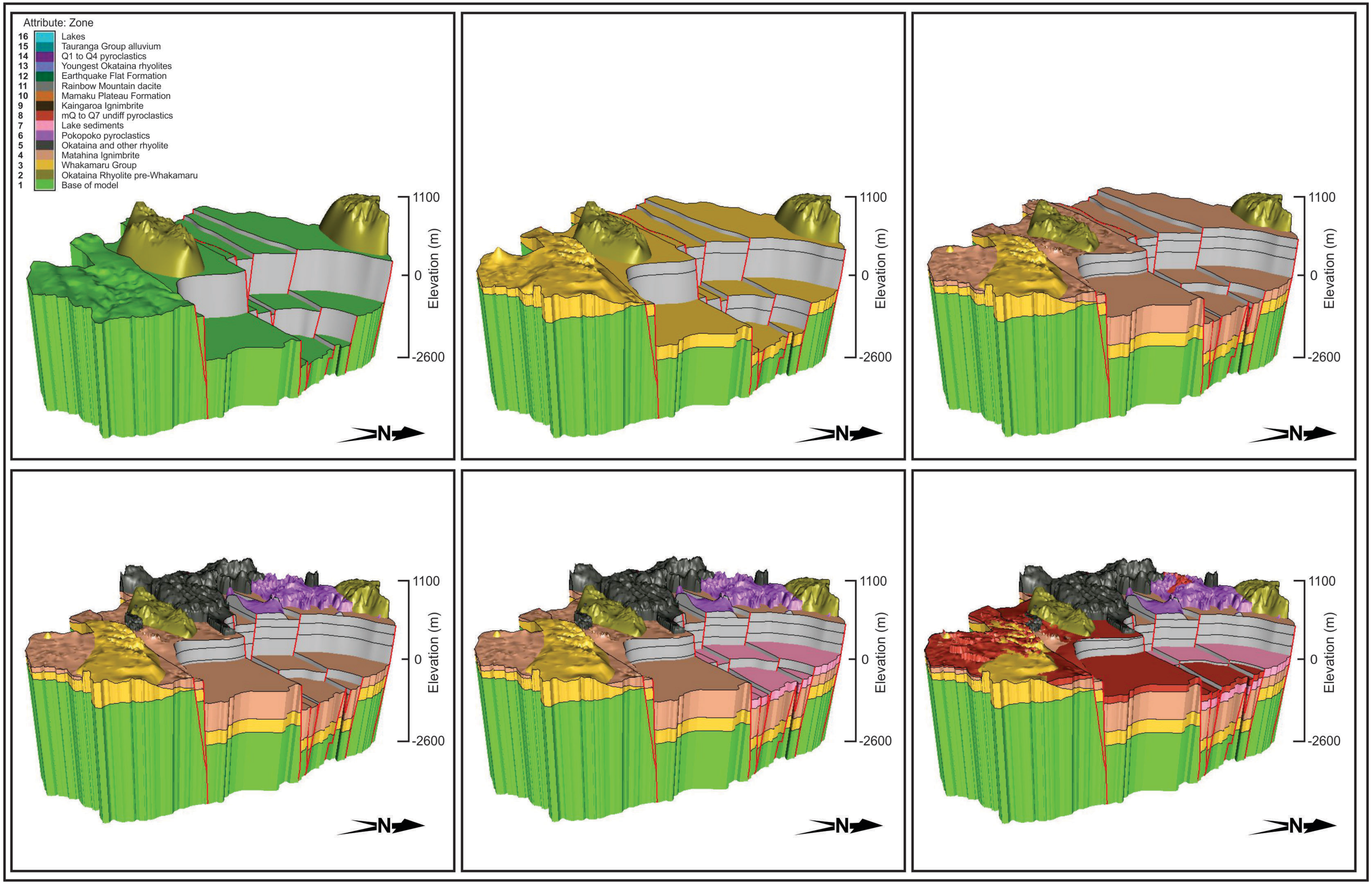

Figure 6: Views of the model showing older units.

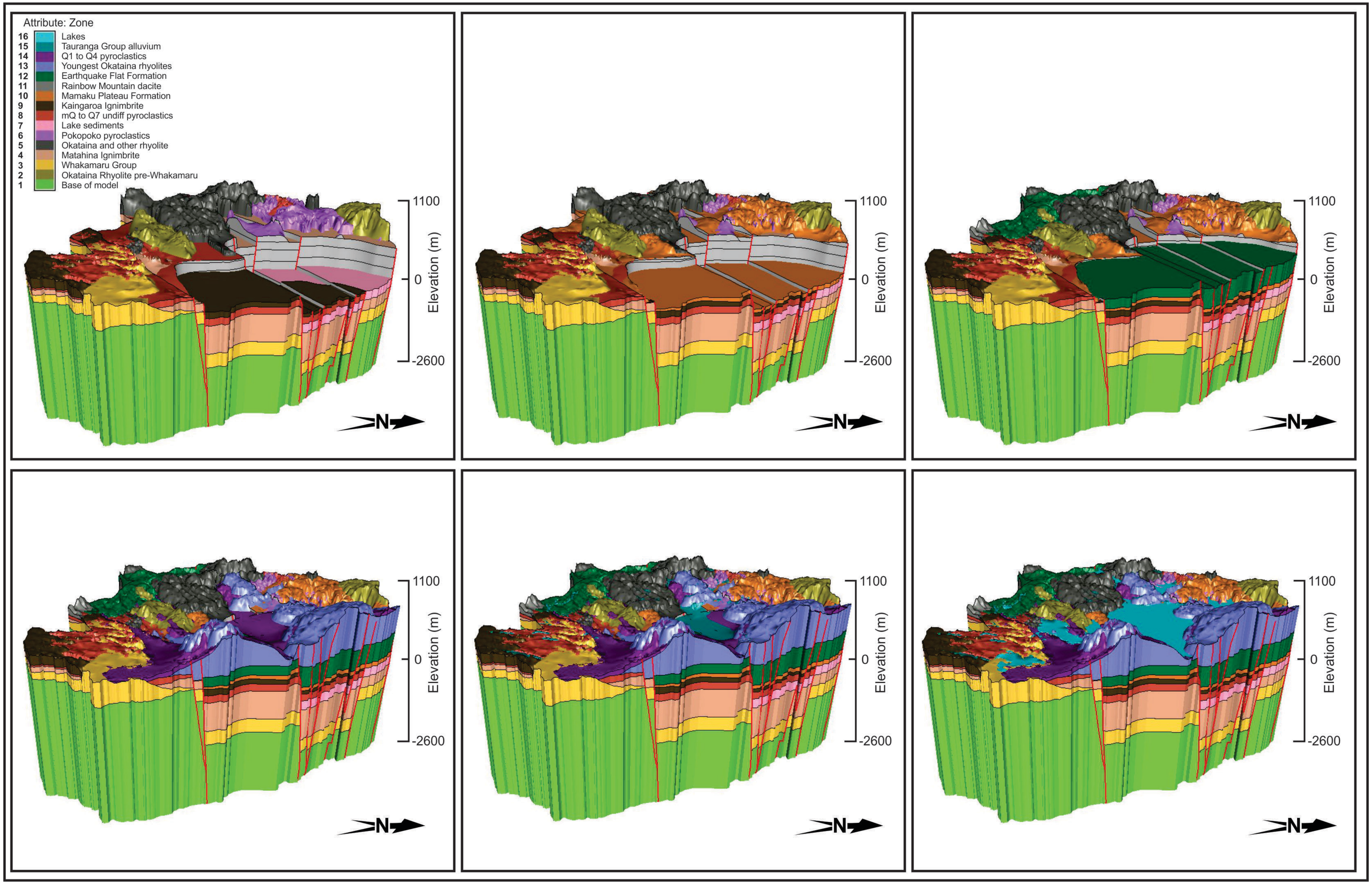

Figure 7: Views of the model showing younger units and the lakes.

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