INVESTIGATING CONTROLS ON GEOTHERMAL UPFLOW BENEATH THE ROTORUA LAKES

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ABSTRACT

Seven of the 11 largest lakes in the Rotorua region have geothermal manifestations. All seven are associated with collapse caldera features, while the other four which do not have any identified geothermal manifestations are situated some distance from any caldera structures. Six of the geothermally influenced lakes are close to the boundaries of the Okataina Volcanic Centre (OVC), which is a composite caldera collapse feature partly filled with lava domes. Lake Rotorua, the seventh, sits to the west and fills the centre of a single volcanic caldera. In this project, we use heat and fluid flow models to explore the role the OVC might play in determining the locations of upflow beneath the Rotorua lakes.

We created highly simplified TOUGH2 models to identify individual processes that could affect upflow locations. The model area encompasses the six lakes that lie close to the OVC boundary and the four cold lakes to the west and south. The base of the model is a uniform hot plate with 700 mW/m^2 heat input. The top of the model follows water table elevation, which is a slightly muted reflection of topography. The model initially had uniform rock properties, with permeability variations added later to replicate an OVC boundary that acts as a barrier or conduit to flow.

Model results show that topography alone can drive convection so that geothermal upflows occur beneath Lakes Tarawera, Rotomahana and Okataina, along the western edge of the OVC boundary. Upflows were too far to the north for Lakes Rotoiti, Rotoehu and Rotoma, but if a barrier to horizontal flow was included at the inferred location of the OVC boundary, model upflows occurred in approximately the right places. It therefore appears that geothermal manifestations beneath the Rotorua Lakes are influenced by a combination of topographically-driven convection and structural controls related to the OVC boundary.

1. INTRODUCTION

The Rotorua region, in the central North Island of New Zealand, hosts a number of lakes of varying sizes. Seven of these lakes have geothermal springs and seeps or chemical evidence of geothermal fluid input (Bioresearches, 2003). They are fed from underlying geothermal systems that are classified according to their potential use, ranging from protected (Waimangu-Rotomahana-Tarawera Geothermal Field), to limited development (Rotorua and Rotomā-Tikorangi Geothermal Fields), to development (Rotoiti Geothermal Field), to other (Lakes Okataina and Tarawera; Figure 1). Geothermal resources in the area provide electricity, tourist attractions, direct use and cultural value (Daysh et al., 2020; White & Chambefort, 2016). It is therefore important to understand why the geothermal systems have developed where they are and how stable they are on both field and regional scales.

Geological structures are thought to be major influences on geothermal system locations, as fluids flow through fractures particularly in low-permeability basement rocks (Rowland & Sibson, 2004). In the Taupo Volcanic Zone, where most of the high-enthalpy geothermal activity in New Zealand is found, only a few of the 23 geothermal systems appear to be associated with major faults (e.g. Waiotapu, Te Kopia, and Orakei Korako) (Villamor et al., 2017). However, the locations of six of the geothermally-influenced lakes in the Rotorua region coincide with the structural boundaries of the Okataina Volcanic Centre (OVC). The four cold lakes in the area

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are between 0.6 and 9 km from the OVC (Figure 2). Numerical modelling allows us to simplify geological complexities and ignore localised magmatic heat sources to explore whether structural variations associated with the OVC are a control on geothermal upflows beneath the Rotorua Lakes.

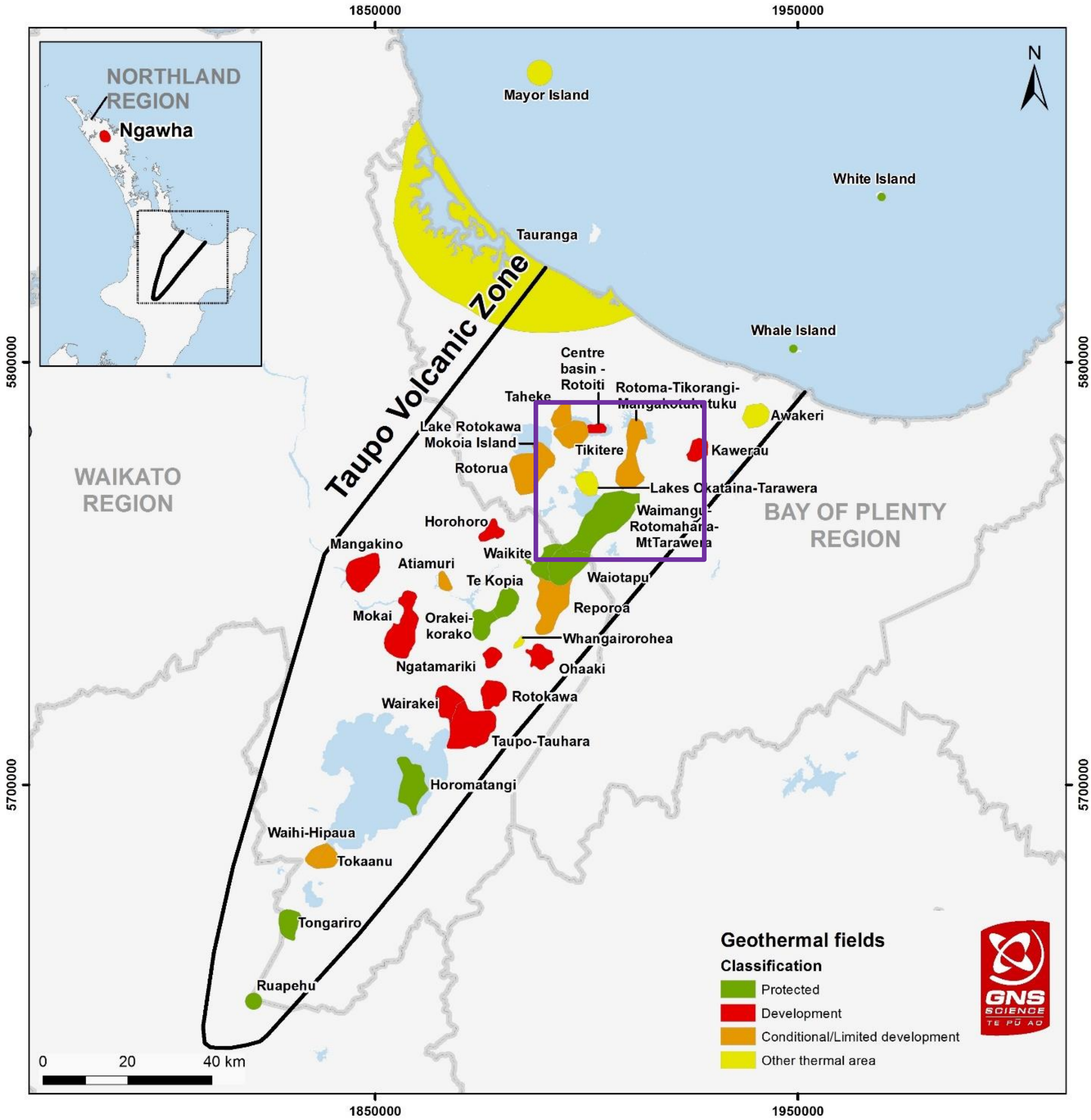

Figure 1: Map of study area (purple box) in the centre of the North Island with lakes and geothermal fields (NZGA, 2018).

2. STUDY AREA

Our study area is centred on the OVC and covers approximately 40 km by 40 km. The OVC is a composite caldera collapse feature partly filled with lava domes. It is sited mainly within the central active corridor of the Taupo Rift and contains the northeastern-most caldera complex in the onshore Taupo Volcanic Zone (Cole et al., 2010). The southern part of the OVC was formed by caldera collapse resulting from the eruption producing the Matahina Formation ignimbrite at c.322 ka (Deering et al., 2010). The eruption of the Rotoiti Formation pyroclastics at c.54 ka (Barker et al., 2020) was accompanied by caldera collapse on the northern side of the OVC. Volcanic eruptions between these caldera-forming episodes and since have resulted in formation of lava and pyroclastic massifs within the OVC (Cole et al., 2010). The structural boundaries of the OVC calderas are therefore complex and primarily buried by later eruptions. The outer boundary of the OVC is often hidden and different authors have proposed different outlines (Nairn, 2002; Rowland & Sibson, 2004; Villamor et al., 2017). We follow an approximation of the outer limit of structural collapse from the geologically defined topographic margin (Leonard et al., 2010), where it is consistent with gravity data and thus excluding the apparently erosional Puhipuhi basin. There is little control geologically on the southeastern third of the structural margin and this should be considered less accurate than the other two thirds.

Hot springs have been mapped within and around the OVC (GNS Science, 2005; Figure 2). Three geothermal fields have been identified from DC resistivity surveys: Waimangu-Rotomahana-Mt Tarawera, Rotoiti and Rotomā (Figure 1; Bibby et al., 1995). More detailed near-surface geothermal areas have been delineated by heat flow and gas flux mapping (Hughes et al., 2019; Mazot et al., 2014; Tivey et al., 2016). Our study area contains 10 major lakes, with Lake Rotorua to the west (Figure 2). Lakes Rotomahana, Tarawera, Okataina, Rotoiti, Rotoehu and Rotomā have evidence of geothermal inputs; Lakes Okareka, Tikitapu, Rotokakahi and Rerewhakaaitu do not or it is ambiguous (Bioresearches, 2003). The apparent proximity of the geothermally-influenced lakes to the OVC boundary structure makes this an ideal area to explore whether faults influence the locations of geothermal systems in the Rotorua region.

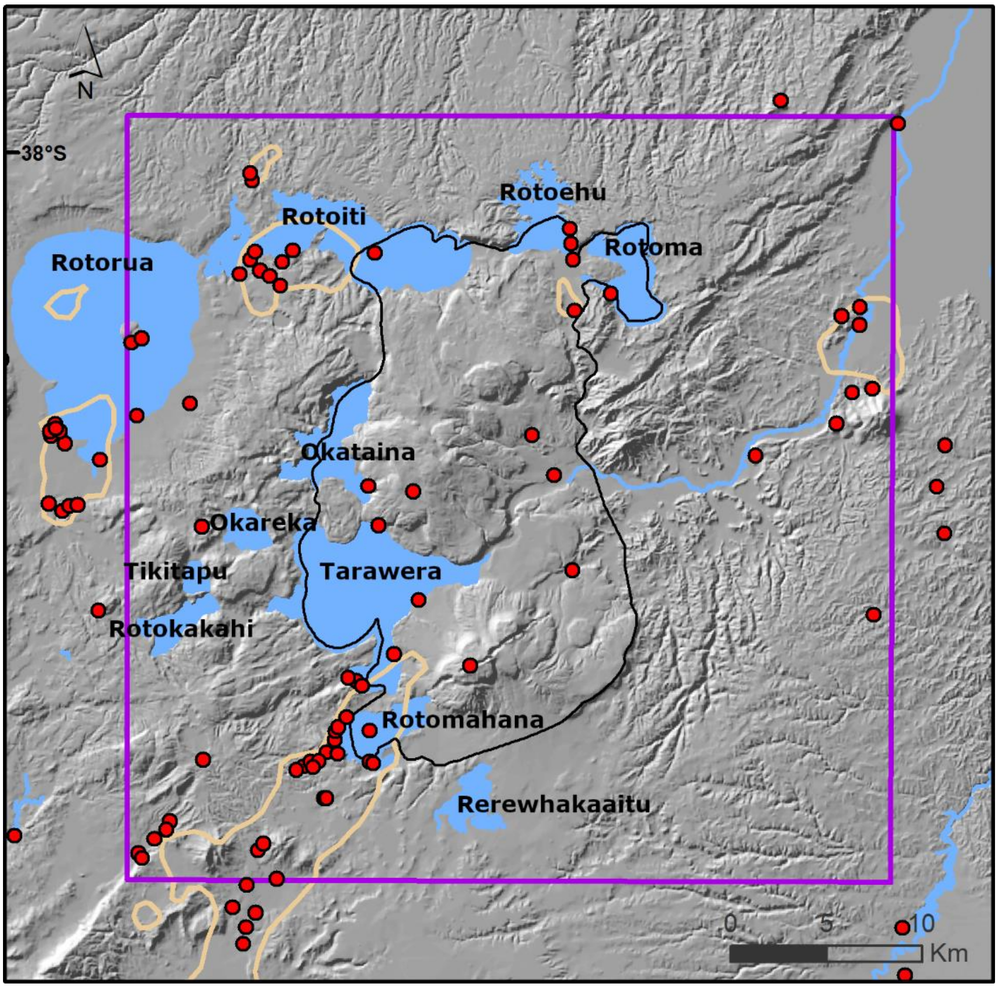

Figure 2: Aerial map of the study area. Lakes are in blue and labelled. Red circles correspond to mapped geothermal surface features (GNS Science, 2005). Tan outlines correspond to geothermal upflow zones identified from 30 Ωm DC resistivity anomalies (Bibby et al., 1995). The black outline is the inferred outer eroded boundary of the Okataina calderas' collapse area (Cole et al., 2010) and the purple box is the model area.

3. METHOD

We used TOUGH2 to create heat and fluid flow models as it is the default industry standard in New Zealand. Leapfrog Geothermal was used to turn a simple geological model (Alcaraz et al., 2012) into a block model that could be used in TOUGH2. The model covered 40 km by 40 km and extended to 5 km depth below sea level. Grid blocks were 500 m by 500 m horizontally (Figure 3), and 250 m vertically. The model was fully saturated, and its top boundary followed the water table. The water table was calculated from the topography, with a model height of between 100 and 1000 metres above sea level (Westerhoff et al., 2018). A uniform heat source at the base of the model of 700 mW/m² was used as a representative average of the TVZ for simplicity (Bibby et al., 1995). We ran the model for 100,000 years, by which time an approximate steady state was achieved.

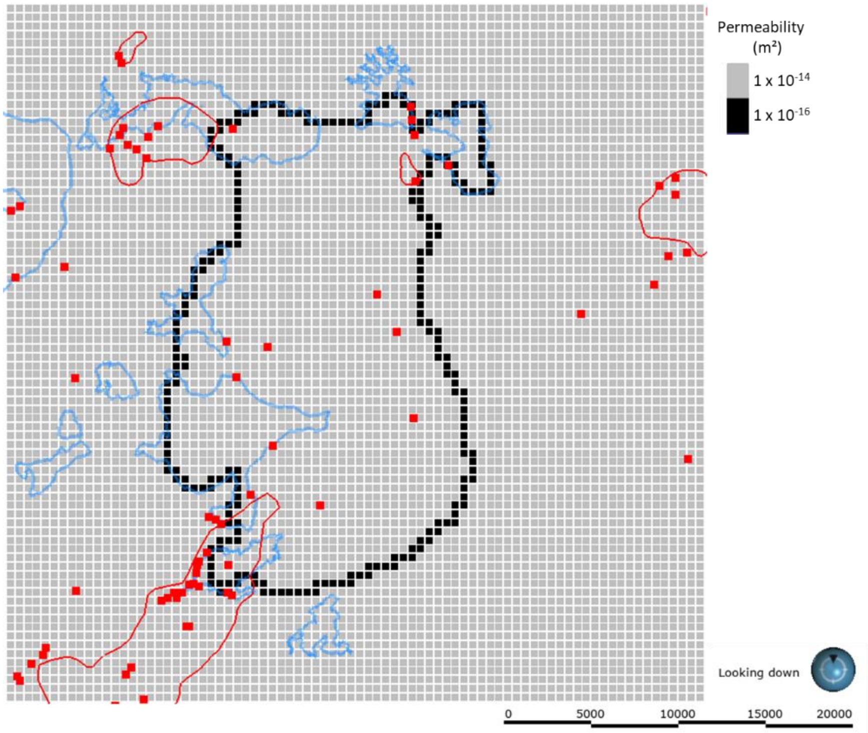

Figure 3: TOUGH2 model grid. Black is the lower-permeability OVC boundary, grey is the higher-permeability surrounding rock. Lakes (blue outlines), geothermal surface features (red squares) and geothermal upflow zones (red outlines) are also shown.

Initially we created a model with homogeneous permeability to explore the effects of the varying water table, which has been shown to localize and stabilize geothermal upflow within the wider Taupo Volcanic Zone (Pearson-Grant & Bertrand, 2021). We then created a new rock type to represent the outer boundary of the OVC (Figure 3). We varied the permeability to represent different relationships between the rock types, with a more or less permeable OVC boundary compared to the surrounding rock. Results were compared qualitatively to upflow zones, surface features and locations of lakes that show geothermal influx (Bibby et al., 1995; Bioresearches, 2003; GNS Science, 2005).

4. RESULTS

Model results show that with a completely uniform model, where the top boundary is flat and geology is homogeneous, warmer temperatures corresponding to geothermal upflows occur all over the model area and continuously change location (Figure 4). When water table variations are included, upflows become localized and relatively stable (Figure 5). Observed upflows under Lakes Rotomahana, Tarawera and Okataina to the west of the OVC occur in this latter model. However, to the north of the OVC, model upflows do not appear to be as stable and are too far to the north compared to Lakes Rotoiti, Rotoehu and Rotomā.

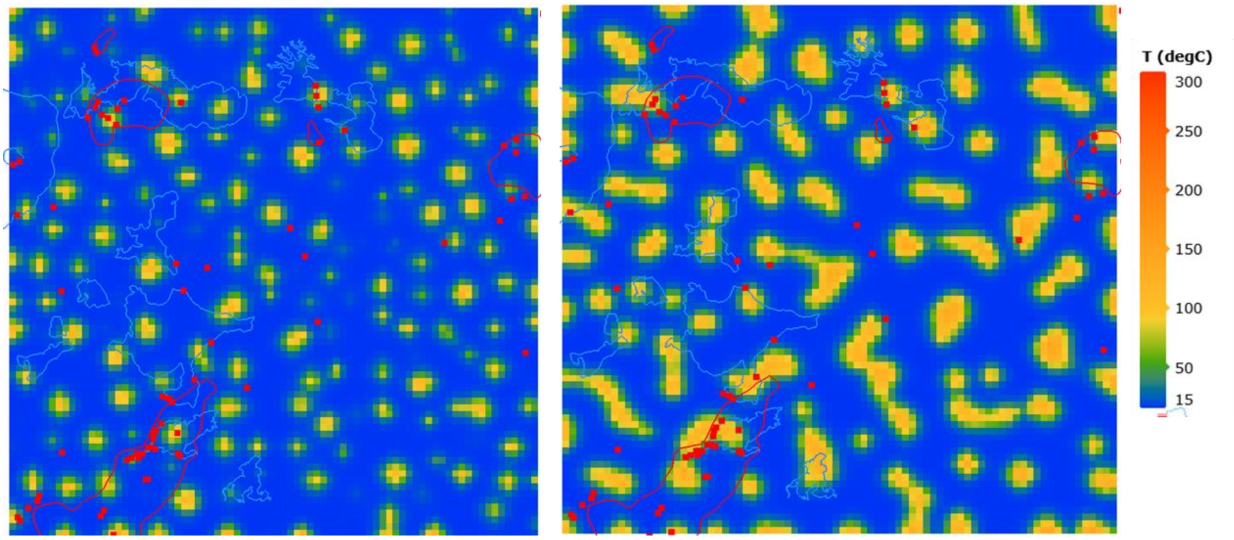

Figure 4: Temperatures resulting from a model with uniform basal heat flow, a flat top surface and homogeneous geology after 50 ky (left) and 100 ky (right).

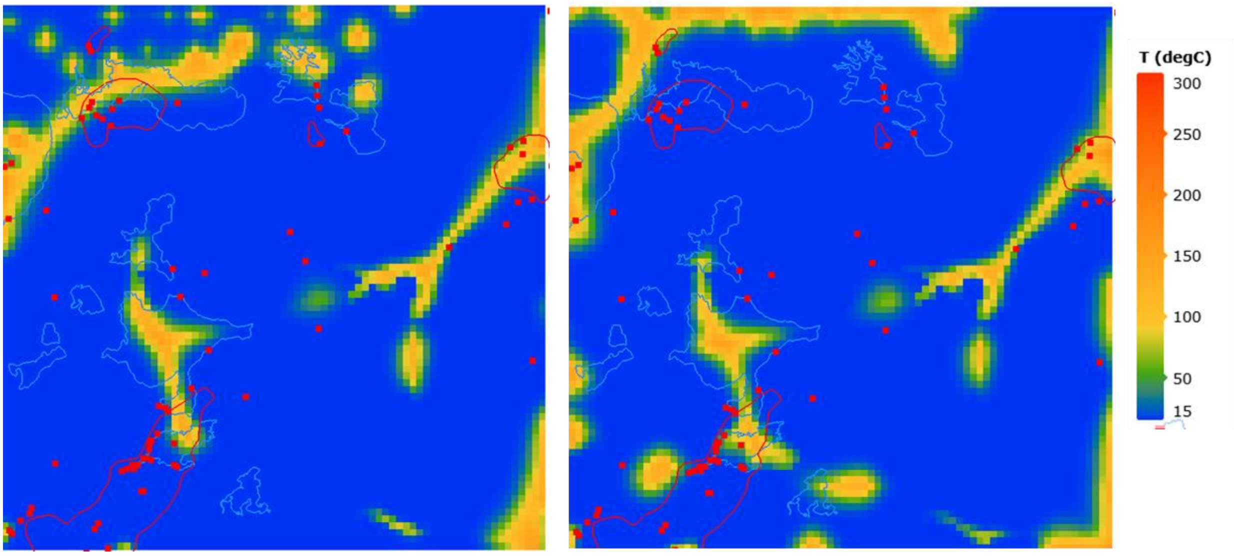

Figure 5: Temperatures resulting from a model with uniform basal heat flow and homogeneous geology but the top surface following the water table, after 50 ky (left) and 100 ky (right).

When a low-permeability zone corresponding to the assumed location of the OVC boundary is introduced (Figure 3), upflows become localised over time. If the model has a flat top surface, upflows occur around most of the OVC boundary by 100,000 years (Figure 6). However, they have not occurred by 50,000 years and include areas to the northwest and southeast where we do not observe any surface manifestations. When a variable water table and a low-permeability zone are included, upflows occur under all six of the lakes where geothermal inputs have been detected (Figure 7). Only Lake Rerewhakaaitu to the south shows an upflow where none has been observed.

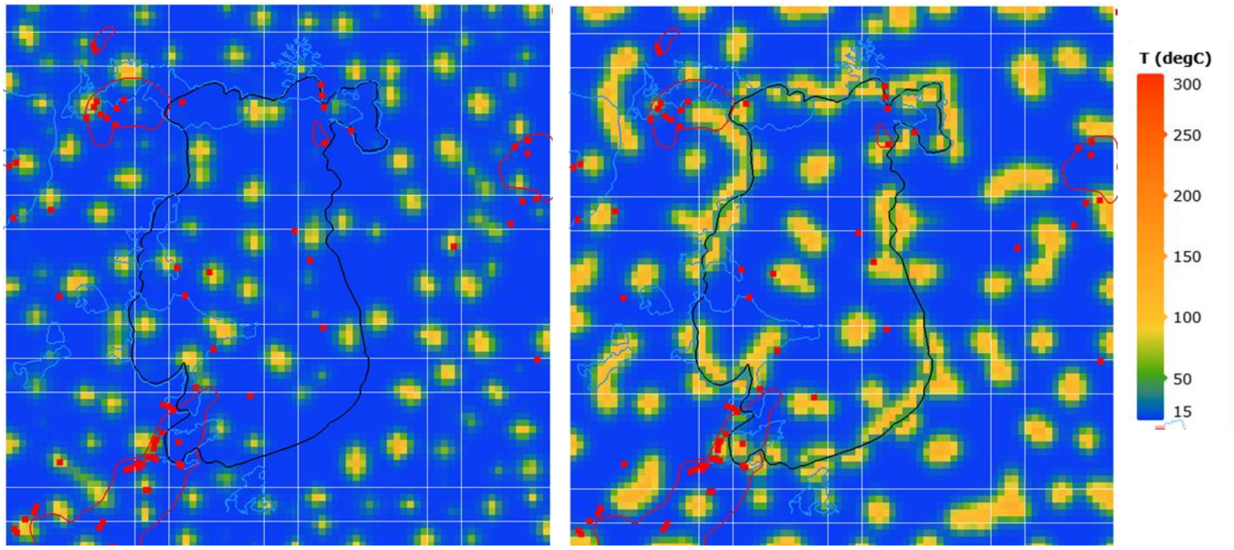

Figure 6: Temperatures resulting from a model with uniform basal heat flow and a flat top surface but a low-permeability zone corresponding to the outer boundaries of the OVC after 50 ky (left) and 100 ky (right).

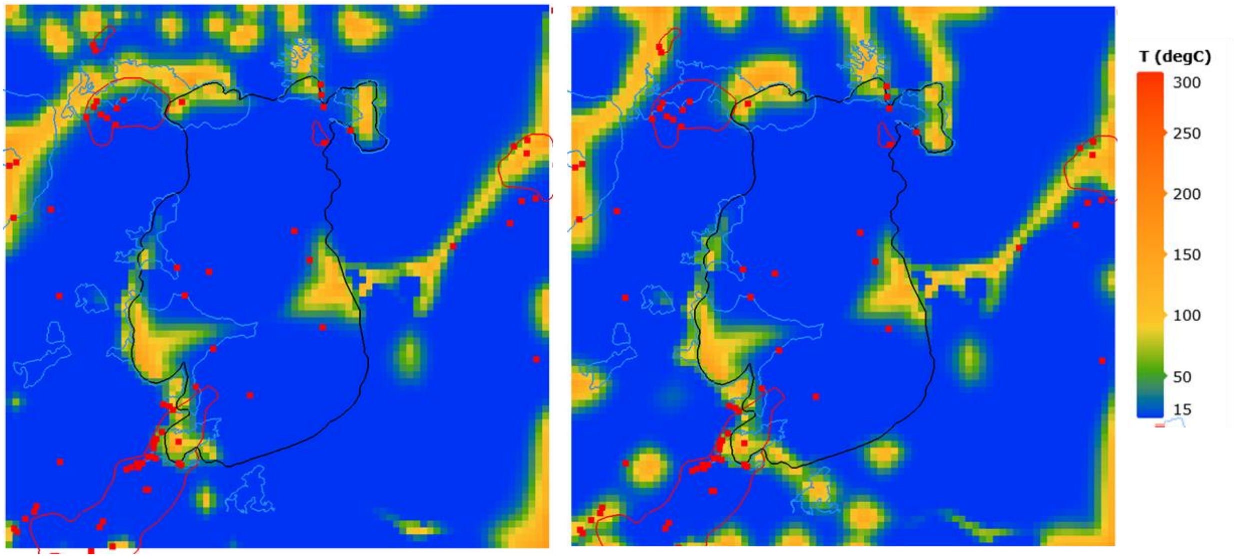

Figure 7: Temperatures resulting from a model with uniform basal heat flow, a top surface that represents the water table and a low-permeability zone corresponding to the outer boundaries of the OVC after 50 ky (left) and 100 ky (right).

If the OVC boundary is a high-permeability zone rather than low-permeability, small upflows occur under Lakes Rotomahana, Rotoiti and Rotoma, with a more substantive one under Lake Tarawera (Figure 8). The other two geothermally-influenced lakes do not show upflow in the modelled results.

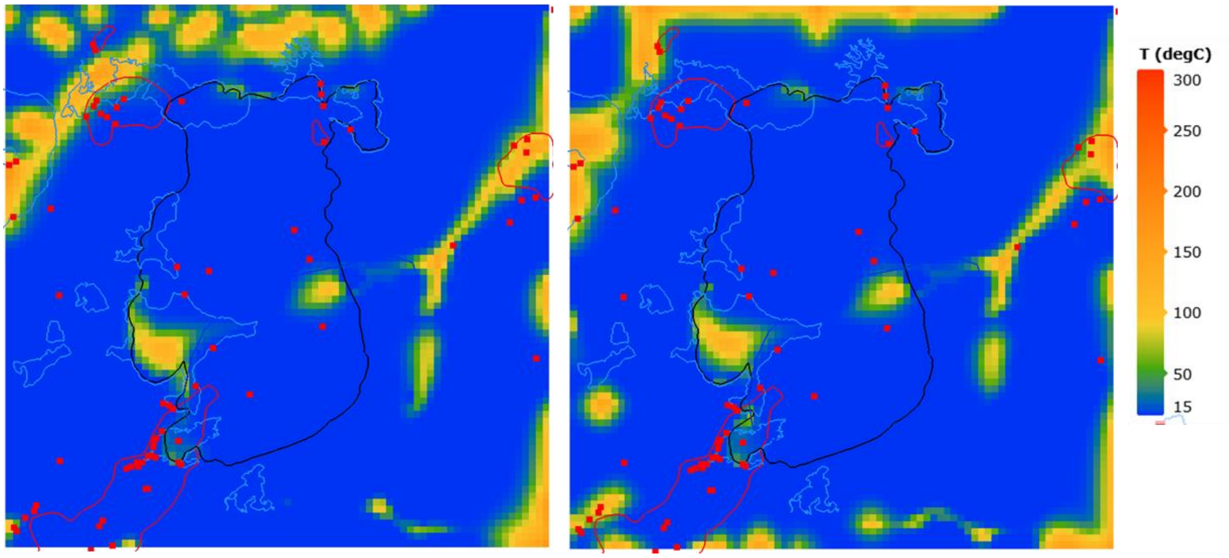

Figure 8: Temperatures resulting from a model with uniform basal heat flow, a top surface that represents the water table and a high-permeability zone corresponding to the outer boundaries of the OVC after 50 ky (left) and 100 ky (right).

4. DISCUSSION AND CONCLUSION

Model results show that geothermal upflows beneath the Rotorua Lakes can be explained by a combination of topographically-influenced convection and geological structures. Upflows occur consistently to the west of the OVC as long as the top surface of the model follows the water table (Figure 5,7,8). This suggests that permeability contrasts relating to the OVC modify rather than drive upflow under Lakes Rotomahana, Tarawera and Okataina. In contrast, warmer model temperatures to the north of the OVC only occur when a permeability contrast is introduced in this area. Interestingly, the strongest upflows are observed when the OVC boundary is a low-permeability barrier to flow. It is often assumed that geological structures are permeable conduits to flow, but this results in much weaker and smaller upflow zones.

There are four lakes that are not close to the OVC boundary and do not have evidence for geothermal inputs. When water table variations are included, upflows do not occur under the three lakes to the west. However, a modelled upflow occurs under Lake Rerewhakaaitu after 100,000 years irrespective of the permeability of the OVC boundary. It is not present after 50,000 years.

Modelled upflows occur under the western side of Lake Tarawera, to the north of the northern lakes, and to the east of the OVC where there are very sparse or no observed geothermal surface features. The northernmost anomalies may be edge effects that are spurious, but the other anomalies suggest that there are other processes occurring in those areas such as variable heat input at depth or geological variations. This is something that we will explore in future work.

These models are extremely simple and neglect factors such as variable heat input at depth, permeability variations due to hydrothermal alteration, geological heterogeneity, and changes in topography due to intracaldera dome formation in the last 25 kyr. However, these factors are poorly constrained, while the water table is based on high-resolution digital elevation models of surface topography, and the boundaries of the OVC have been mapped at the surface at several locations. With just these two factors, we can explain upflows beneath all of the Rotorua lakes where upflows are observed. We may even be able to use more detailed model results to help refine the locations of the OVC boundary where it is not known.

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