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Numerical Model of the Changes in Geothermal Activity in the Rotomahana-Waimangu System Due to the 1886 Eruption of Mt Tarawera

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ABSTRACT

We are modeling the perturbations in the pressure-temperature gradients and the fluid flow paths within the Rotomahana-Waimangu geothermal system caused by the 1886 volcanic eruption of Mt. Tarawera. This short lived eruption destroyed the Pink and White Terraces and led to the subsequent outbreak of geysers and hydrothermal eruptions in the Waimangu Valley. Our conceptual model suggests that most of the changes in surface activity came about as the water table, which lowered about 100 m due to the volcanic eruption, rose over a ~10-year period to near its pre-eruption level by 1895. Geysering and hydrothermal eruptions (1900 to 1917) ensued when hot water rising through narrow vertical conduits had pushed out cold water, which had flooded the shallow subsurface immediately following the volcanic eruption. The changes in surface activity were influenced by effects at relatively shallow depths of <1 km within the geothermal system. Preliminary results suggest that approximately 0.1 km^3 of hot water was removed catastrophically during the 1886 eruption. Pressure-temperature gradients and fluid flow stabilized within ~40 years, indicating a relatively short recovery period after the 1886 eruption.

1. INTRODUCTION

With an approximate thermal power output of 300 to 400 MW (e.g. Bibby et al., 1994; Simmons et al., 1994), the Rotomahana-Waimangu geothermal system would be an attractive resource for exploration drilling, if it were not for the high conservation value placed on the surface thermal activity which has been evolving naturally in the aftermath of the 1886 volcanic eruption of Mt. Tarawera. Apart from the scientific interest in understanding the natural changes in fluid flow, the Rotomahana-Waimangu system provides insight to recovery of surface thermal features that have been damaged, seemingly irreparably, by exploitation of a geothermal resource for electricity generation as has happened, for example, at Wairakei (Glover and Mroczek, 2009). Here we report our preliminary findings of numerical modeling which has been undertaken to assess changes in fluid-flow brought about by the changes in permeability and pressure-temperature gradients resulting from the 1886 eruption of Mt. Tarawera. We start by summarizing the modern state of the system as determined from detailed study of hot springs (Simmons et al., 1994) and then describe a conceptual model for change that has been interpreted from the study of the photographic record of surface thermal features (Simmons et al., 1993). Ultimately, we hope to resolve the permeability structure and fine scale changes in fluid flow and pressure that led to spectacular geysering and hydrothermal eruptions that made the Waimangu valley famous in the early 1900s.

2. ROTOMAHANA-WAIMANGU SYSTEM

The geothermal system is one of approximately 20 known systems in the Taupo Volcanic Zone, North Island, New Zealand (Figure 1). It is located about 20 km south of Rotorua, and it has been a major tourist attraction since the mid-1800s when Europeans came to visit the renowned Pink and White Terraces, which were two of the largest silica sinter terraces known on earth. Maori settlements, however, had been well-established around Lake Rotomahana long before the first European visitor. In the early morning hours of 10 June, 1886, a small, powerful and short-lived eruption of basalt magma occurred, starting on the summit of Mt. Tarawera and then migrating along a fissure southwestward through the Rotomahana-Waimangu geothermal system. The Pink and White Terraces were destroyed during phreato-magmatic explosions that excavated approximately 0.5 km^3 of surrounding rock material, and this crater later became the site of the modern Lake Rotomahana (Nairn, 1979). The vents that formed from the volcanic eruption extend >16 km length, and these conduits likely coalesce at depth to from an en echelon, dike-filled extensional structure (Nairn and Cole, 1981).

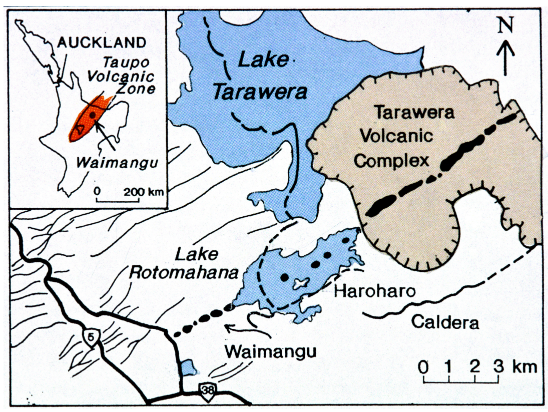

Figure 1: Map showing the main geological features in the vicinity of the Rotomahana-Waimangu geothermal system, including the northeast-southwest trending line of vents (black) that formed during 1886 Tarawera eruption (Nairn, 1989; Simmons et al., 1993)

Geologically, the geothermal system is situated along the southwest boundary of the Okataina volcanic center (Figure 1), which is made up of a sequence of flat-lying pyroclastic deposits and flow domes that have accumulated over the last several hundred thousand years. The Haroharo caldera boundary transects the southwest part of Lake Rotomahana and encompasses the large composite dome complex that makes up Mt. Tarawera. Initial caldera subsidence dates to ~240 to 280 ka, and the present domes developed over the last 18 ka, with the most recent eruption of rhyolite ~900 years ago (Nairn, 1989).

2.1 Modern Hydrological Setting

Surface thermal activity provides the only clues regarding subsurface fluid flow and temperature. The extent of the geothermal system is interpreted from the resistivity boundary (Bibby et al., 1994); and the 10 ohm-m contour encircles an area approximately 16 km^2 (Figure 2). Boiling and sub-boiling hot springs occur along the northwestern edge of this contour, discharging along the bottom of the Waimangu valley and along the western edge of Lake Rotomahana. There is little evidence of steaming ground or fumarolic activity. The two dominant features are Frying Pan Lake and Inferno Crater which occur in the upper part of the Waimangu valley. Both are volcanic vents which formed during the 1886 eruption. Frying Pan Lake occupies the western part of Echo crater, and it is one of the largest thermal features in the Taupo Volcanic Zone, discharging 100 to 120 l/sec. Inferno Crater discharges at a few meters higher elevation and only for 2 to 3 days every 5 weeks (Scott, 1994). In total, there are approximately 20 hot springs (Figure 2), and they discharge chloride water, whose composition is analogous to deeply circulated thermal waters found in geothermal reservoirs at Wairakei and Broadlands-Ohaaki. Stable isotopes indicate the thermal water is largely meteoric in origin, and Na, K, Mg, Ca and SiO_2 concentrations indicate maximum equilibration temperatures of 260° C (Simmons et al., 1994). The deep fluid flow is estimated at 285 kg/s.

2.2 Changes in Surface Activity

Hochstetter (1864) documented the extent and nature of surface thermal activity around Lake Rotomahana before the 1886 Tarawera eruption. Numerous high quality historic photos from the second half of the 1800s onwards provide additional insight regarding the pre-eruption setting and more importantly, of the post-eruption changes in surface thermal activity.

Pre-eruption, Lake Rotomahana was a small shallow lake surrounded by surface thermal activity (Figure 2). The Pink and White Terraces represent two separate features that were both fed by geysering chloride springs. A number of boiling chloride springs also occurred along the eastern shore of the lake as did mud pools and steaming ground associated with acid-sulfate waters. These features represent the characteristic surface expression of an underlying upflow zone where temperature-pressure conditions are close to boiling point for depth down to 1000 m or more. The heights (~25 m above lake level) and areal extents of the Pink and White Terraces suggest that the system had existed in much the same way for several hundred years having reached a steady-state flow condition. Note, there was no documented evidence of surface thermal activity in the Waimangu valley at this time.

Within a few hours, the 1886 Tarawera eruption destroyed the Pink and White Terraces and excavated a deep large crater that was occupied by Lake Rotomahana. Steam issued from the crater for several months after the eruption, but by the end of 1887, it began to fill with cold water and by the mid 1890s it reached close to its modern lake level. Thermal activity persisted along the western edge of the crater where it still occurs today. The intense hydrothermal activity exhibited by the Waimangu valley craters declined rapidly within a few weeks after the eruption, and these too became cold-water filled depressions. It was not until 1890 that photographic evidence demonstrates the reappearance of surface thermal activity. From then on, hot springs continued to develop in the Waimangu valley.

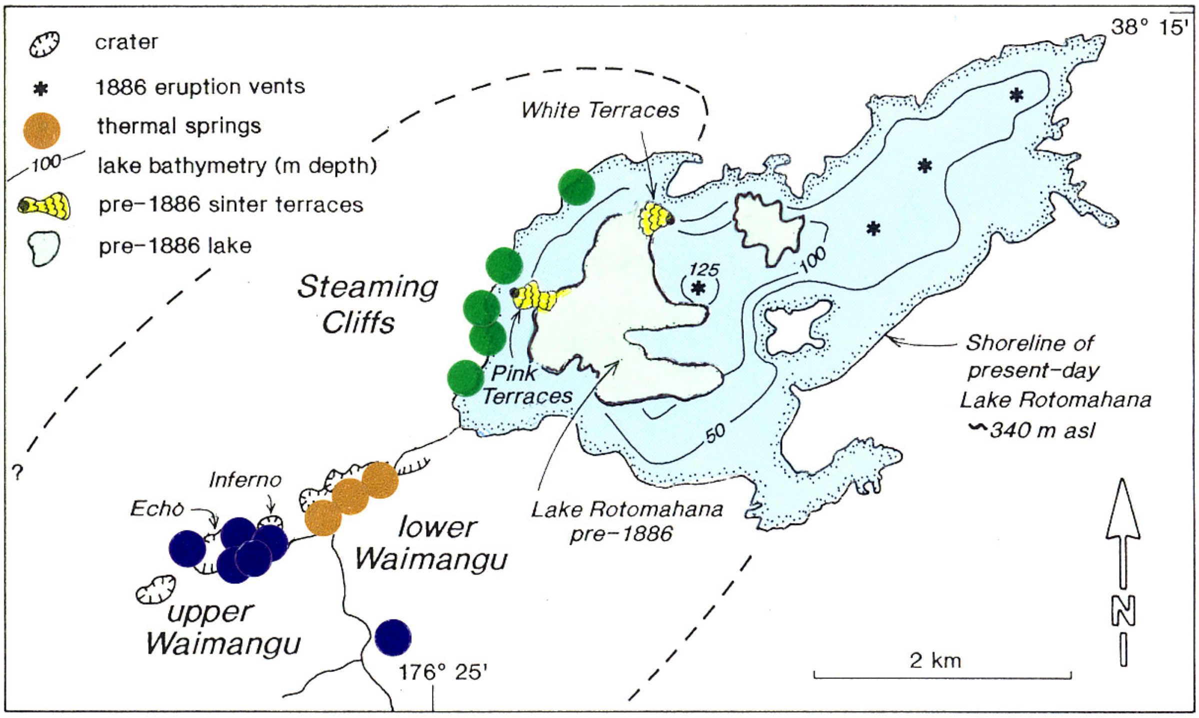

Figure 2: Map showing the relations between the modern and pre-1886 Rotomahana lakes and hot spring activity. Dashed line is the approximate position of the 10 ohm-m resistivity boundary, delimiting the area underlain by hot chloride waters (from Simmons et al., 1993)

Two major events mark the early evolution of the surface activity. The first was the outbreak of the Waimangu geyser in the eastern part of Echo crater (Figure 2). It was active between 1900 and late 1904, and for much of this time the eruption was cyclical; the geyser had a repose period of 30 to 36 hours and then would be active for up to 6 hours. The eruptions were explosive, propelling rock material, water and steam to 450 m height. The second event was the large-scale hydrothermal eruption of Frying Pan flat which occupied the western part of Echo Crater and which occurred on 1 April, 1917. The eruption lasted 3 days, ejecting rock debris and mud up to 750 m distance. Within ~2 weeks, the newly formed crater began filling with hot water to form the modern Frying Pan lake.

Since the 1920s, thermal activity has stabilized reaching a new condition of near steady-state flow. However, unique cyclic activity exists between Inferno crater and Frying Pan lake, lasting approximately 38 days (Scott, 1994). During the cycle, Inferno crater water level rises approximately 10 m to an overflow condition which last 3 days and then falls, while the discharge from Frying Pan lake decreases from 120 to 100 l/sec and then increases again.

2.3 Hydrologic Effects

The main changes in surface thermal activity are summarized in Figure 3. The geothermal system had attained a long-lived steady state flow condition prior to the 1886 Mt. Tarawera eruption. Because of the relatively small size of the eruption, its main effect was to excavate the shallow part of the upflow zone and enhance permeability in the volume of rock surrounding and underlying the former Lake Rotomahana. In addition, new fluid conduits formed in Waimangu valley in the vicinity of and within the volcanic craters. The hydrostatic head dropped >100 m in the vicinity of Lake Rotomahana, and then rose to close to its former level over the next 10 years. The high surface permeability created by the volcanic eruption thus allowed cold-water ingress into the shallow parts of the system. Near boiling conditions were temporarily quenched and thermal gradients were likely sharpened at some depth where descending cold water encountered rising hot water. Because these two fluids were probably confined to near vertical conduits, time dependent variation in pressure-temperature gradients led to instabilities that manifest as the geysering and hydrothermal eruptions between 1900 and 1920. Since then, the shallow part of the system has attained a new steady state flow condition. The new Lake Rotomahana forms a cold hydrostatic cap over the eastern part of the system, which was once the focus of shallow boiling fluid upflow. It seems likely that rising hot water is diverted around the lake bottom and discharges along the western shore.

The total amount of hot water catastrophically removed during the 1886 Tarawera eruption is estimated by us to be approximately 0.1 km^3. Taking the volume of rock (0.5 km^3) excavated from beneath Lake Rotomahana, this equates to 20% porosity, which is a reasonable estimate for shallow volcanic deposits in the Taupo Volcanic Zone. Also, this volume of water is attained in about 10 years with a modern natural flow of 285 kg/s, consistent with the period it took to refill Lake Rotomahana to its modern level and the outbreak of new hot springs in the Waimangu valley. We think the water volume is conservative, but if it is reasonable, it represents about 5% of the total volume of water produced in the 50 years of production at Wairakei.

3. MODELING

The effects of the 1886 Tarawera eruption on fluid flow were modeled using TOUGH2. We started by computing a steady state condition representing the pre-eruption state during which time the Pink and White Terraces formed. Two temporal changes were then introduced. The first was the significant enhancement in vertical permeability through a narrow slot (25 m wide) which formed during the volcanic eruption of 3 to 4 hours. The second involves the excavation of a large crater 100 m depth within the site occupied by the Pink and White Terraces, followed by lake infilling over the next 10 years.

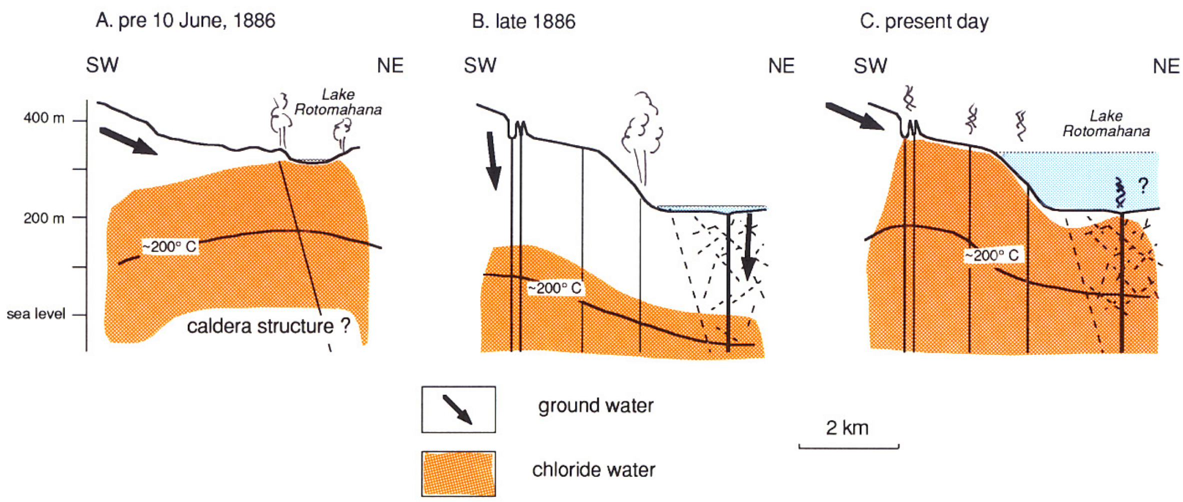

Figure 3: Schematic cross sections showing the evolution of the shallow hydrology of the Rotomahana-Waimangu geothermal system in response to the eruption of Mt Tarawera (Simmons et al., 1993). The main changes involve the ingress of cold ground water into the shallow zone where vertical permeability is enhanced around the volcanic vents (black vertical lines) and in the newly fractured rocks beneath Lake Rotomahana. In the present day panel (C), thermal discharge on the floor of Lake Rotomahana is suggested but the only evidence comes from lake bottom temperature surveys having a maximum value of 38°C (Whiteford and Graham, 1994)

3.1 Conditions & Model Parameters

The grid mesh covers an area of 19x15 km^2 and extends to 3 km depth, encompassing the most of the rock volume hosting the geothermal system as reflected by the resistivity anomaly (Figure 1). Most of the cells are 1000x1000x500 m^3, except in the top 1 km and within the vicinity of the vertical slot, where the cell dimensions are shortened to assess changes in pressure due to rise and fall in water level and the sharp increase in vertical permeability caused by the eruption of magma. We assume that the deep mass flow of ~285 kg/s of 260°C water remained constant based on a comparison of modern estimates and pre-eruption surface thermal activity.

As there has been no drilling, we have had to make assumptions about the permeability structure based on what is known from other nearby geothermal systems that have been drilled and also from the changes in surface thermal activity.

In the pre-eruption model, the porosity decreases with depth from 10 % in the top kilometer layer to 1% in the bottom kilometer layer, and the permeability is highest (100 mD) in the blocks underlying the Pink and White Terraces while the surrounding blocks have low and uniform permeability (3 mD). In the post-eruption model, the permeability through the slot is increased to 300 mD and surface blocks are removed to represent the excavation of the crater that becomes lake-filled over the next 10 years. In this period, the water level rises incrementally ~10 m/year to assess the effect of pressure increase on temperature and fluid flow.

3.2 Preliminary Results

In the pre-eruption model, steady state thermal fluid flow is attained over an arbitrary period of several tens of thousands of years. It is distributed over the area represented by the resistivity boundary, with localized boiling conditions in the blocks beneath the then existing, Lake Rotomahana.

Since the model only assesses the effects associated with formation of new vertical permeability and change in hydrostatic head within Lake Rotomahana, it is not surprising that the thermal structure at >500 m depth in the post-eruption phase is very similar to that found in the pre-eruption phase (Figure 4). In fact the cooling effects associated with lake filling are restricted to <100 m beneath the new lake floor.

The more interesting aspects of the model deal with quantifying the changes in direction and flow of fluid as represented in Figure 5. In the pre-eruption profile, flow is distributed beneath Lake Rotomahana. In the post-eruption profiles, upflow increases in the same region, while shallow cells to the southwest are dominated by down flowing cold water as Lake Rotomahana refills. These down flow zones extend a maximum of ~750 m depth, and they only last for a few years, as by year 9 (not shown) they are completely eliminated. Overall, the patterns are consistent with historic photographs which indicate hot spring recovery was well advanced by the mid 1890s (Simmons et al., 1993).

CONCLUSIONS & FUTURE DIRECTIONS

The main conclusion drawn from the results is confirmation of the conceptual model shown in Figure 3. However, the results are preliminary, and we are running new models to learn how variations in permeability and porosity affect the temperature and flow profiles and the distribution of two-phase boiling conditions. Once a reasonable range of possibilities are known, we will explore the finer scale permeability structure in the vicinity of Echo and Inferno Craters to see if we can determine how pressure and temperature gradients evolved in the lead up to the outbreak of the Waimangu Geyser and subsequent hydrothermal eruptions.

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REFERENCES

Bibby, H. M., Bennie, S. L., Stagpoole, V. M. and Caldwell, T. G.: Resistivity structure of the Waimangu, Waiotapu, Waikite and Reporoa geothermal areas, New Zealand, *Geothermics*, **23**, (1994), 445-471.

Glover, R. B. and Mroczek, E. K.: Chemical changes in natural features and well discharges in response to production at Wairakei, New Zealand, *Geothermics*, **38**, (2009), 117-133.

Hochstetter, F., von: Geologie von Neu Seeland:Beiträge zur Geologie der Provinzen Auckland und Nelson: Novara-Expedition, Geologisches Teil volume 1 (translated byC. A. Fleming, 1959, Wellington, New Zealand Governtment Printer, 320 p.)

Nairn, I. A.: Geological map of New Zealand: Mount Tarawera: Wellington, New Zealand, DSIR sheet V16 AC, (1989) scale 1:50,000.

Nairn, I. A.: Rotomahana-Waimangu eruption, 1886: Base surge and basalt magma, *NZ Journal Geology & Geophysics*, **22**, (1979), 363-378.

Nairn, I. A.., and Cole, J. W.: Basalt dikes in the 1886 Tarawera Rift, *NZ Journal Geology & Geophysics*, **24**, (1981), 585-592.

Scott, B.J.: Cyclic activity in the crater lakes of the Waimangu hydrothermal system, New Zealand, *Geothermics*, **23**, (1994), 555-572.

Simmons, S. F., Keywood, M., Scott, B.J., and Keam, R.L.: Irreversible change of the Rotomahana-Waimangu hydrothermal system (New Zealand) as a consequence of a volcanic eruption, *Geology*, **21**, (1993), 643-646.

Simmons, S. F., Stewart, M. K., Robinson, B.W., and Glover, R.B: The chemical and isotopic compositions of thermal waters at Waimangu, New Zealand, *Geothermics*, **23**, (1994), 539-553.

Whiteford, P. C., and Graham, D. J: Conductive heat flow through sediments in Lake Rotomahana, New Zealand, *Geothermics*, **23**, (1994), 527-538.

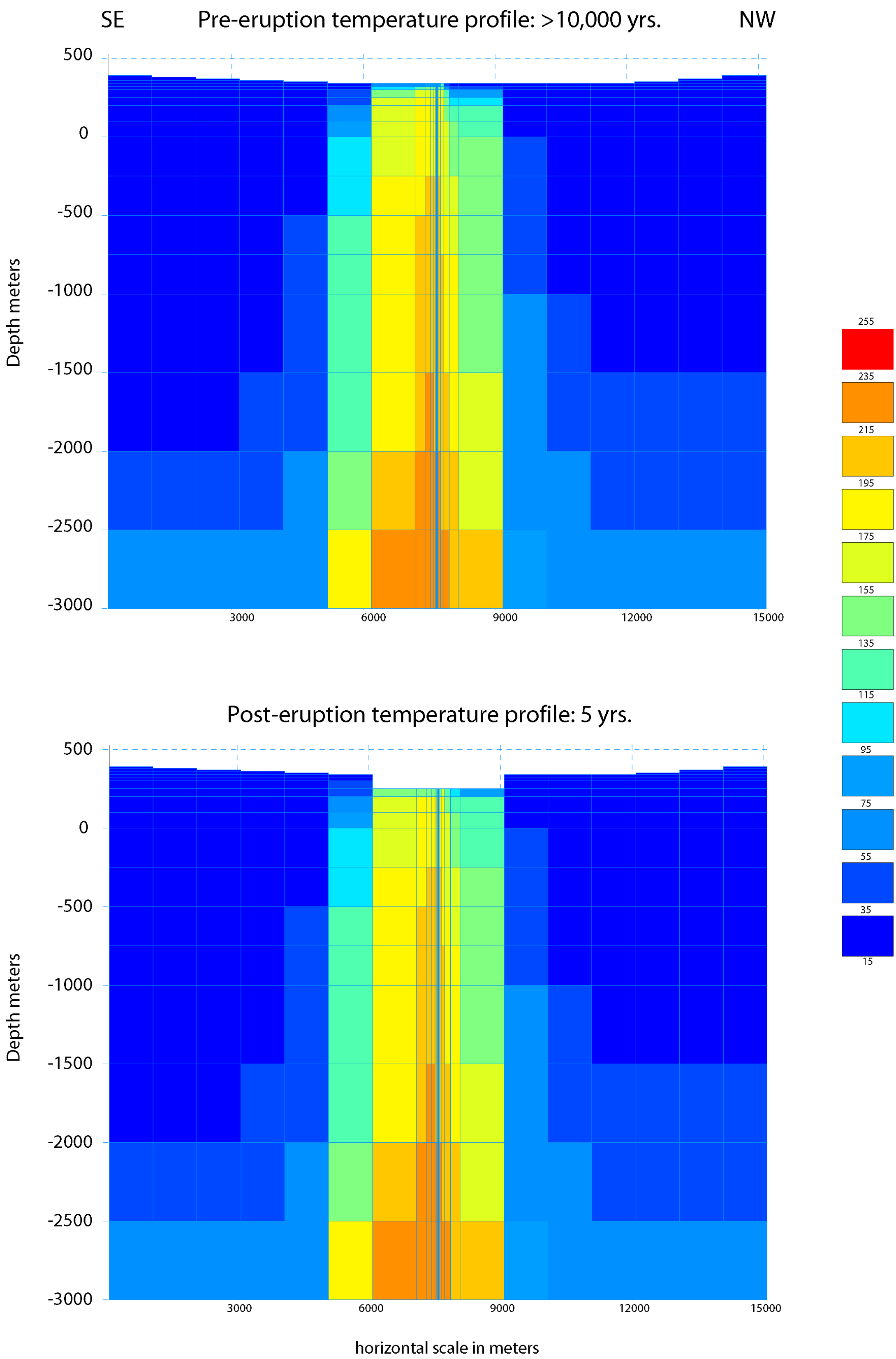

Figure 4: Modeling results (pre-eruption and 5 years after the eruption) as represented by a northwest-southeast profile across the line of vents formed by the 1886 Tarawera eruption. The temperature distribution is the same for both profiles; temperature scale shown right. Note the modification to the topography at the top of the lower profile representing the excavation of the modern Lake Rotomahana basin

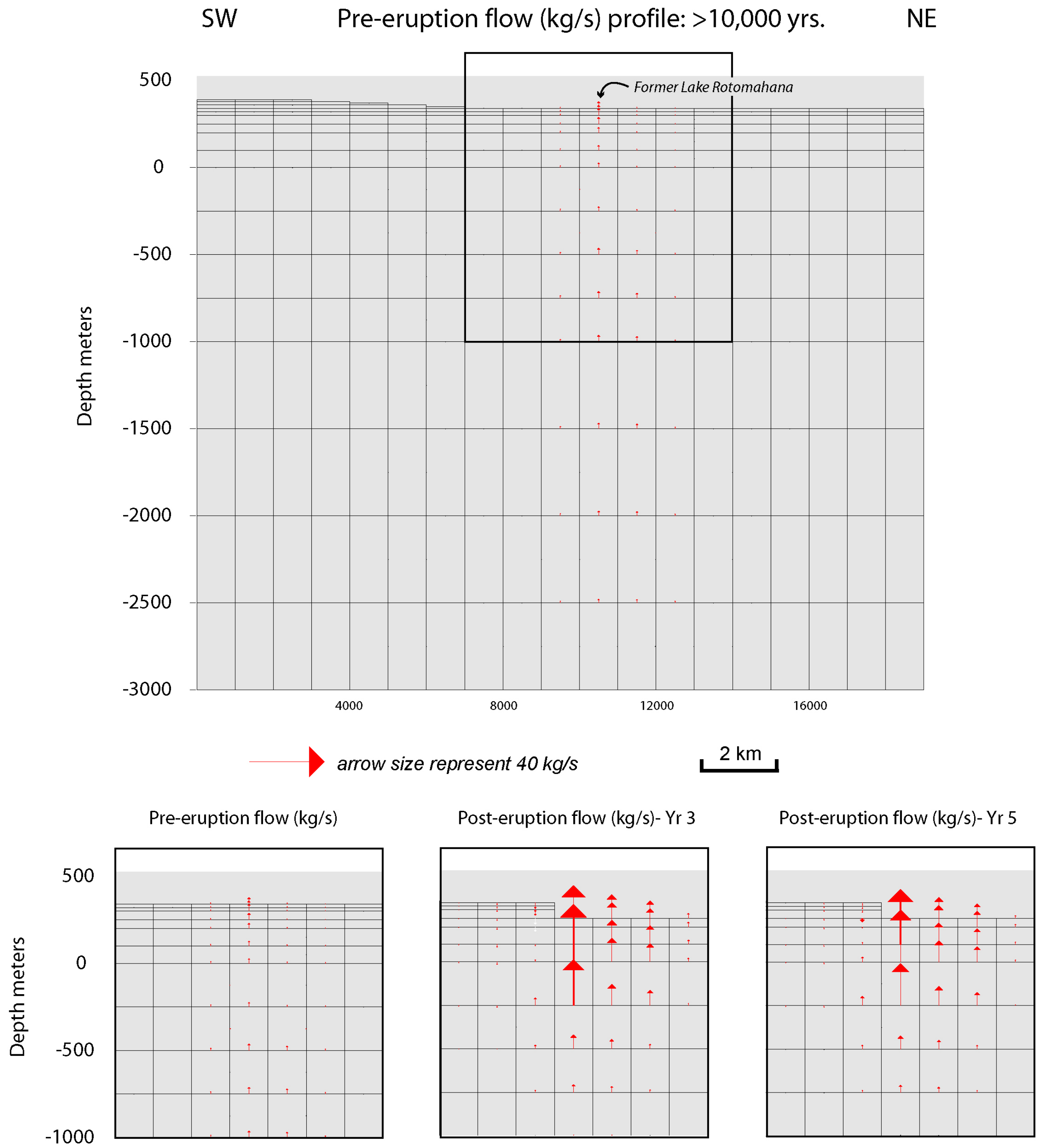

Figure 5: Modeling results (pre-eruption and post-eruption) showing flows in a southwest-northeast profile along the line of vents formed by the 1886 Tarawera eruption. The rectangle in the top profile is magnified in the lower three profiles to illustrate the changes in flow (magnitude and direction). Horizontal and vertical scales are the same in all profiles