BLACK TERRACE, ROTOMAHANA

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Keywords: *Black Terrace, Rotomahana, sinter, GPR, passive seismic tomography.*

ABSTRACT

Prior to 1886 there was widespread thermal activity around Lake Rotomahana. In addition to the Pink and White terraces, there were smaller sinter terraces, including one known as Black Terrace, or Te Ngawha a Te Tuhi. All of those features were either ruined or buried during the 1886 Tarawera eruption. The former locations of the Pink and White terraces are now beneath the enlarged Lake Rotomahana, but the Black Terrace site to the northwest is outside the former and current lake.

About two months after the Tarawera eruption, a hydrothermal eruption at the location of Black Terrace threw out rocks and mud, and the crater grew to ~180 m in diameter over two days before activity gradually waned over the next few weeks. Being surrounded by hills covered in unconsolidated eruption debris, this crater was rapidly infilled over subsequent years. It is no longer obvious on maps, aerial photos, or in the field.

Through a combination of geological and geophysical techniques, we believe that we have relocated the buried Black Terrace Crater, although it remains to be seen whether any sinter is preserved at depth.

Proximity to the crater is indicated by boulders (up to 1.5m diameter) that overlie Rotomahana Mud near the site. Those boulders are mostly rhyolite, but include several fragments of silica sinter.

There are indications from LIDAR of a partially preserved crater rim deposit around the inferred southern edge of the crater.

Ground Penetrating Radar (GPR) revealed possible normal fault features close to where the western crater rim was inferred to lie, and features that might represent a buried, partial ejecta apron to the west of the buried crater rim.

Passive seismic tomography data revealed a lateral east-west change, with hard reflectors located 35-50m below the ground surface within the bounds of where the crater floor is inferred to lie.

1. INTRODUCTION

1.1 19th Century History

Prior to 1886, there were several boiling springs, geysers and areas of silica sinter at Rotomahana. The two largest, the Pink and White Terraces (Otukapuarangi and Te Tarata) were major tourist attractions, but in addition there were at least three smaller springs with silica sinters on the west, north and east sides of the lake. These were not included on the organised tours, as they were not as impressive or accessible as the Pink and White Terraces, but all were mapped by Hochstetter in 1859. The westernmost spring and sinter were known as Te Ngāwhā a Te Tuhi, or Black Terrace (reportedly from the colour of some of the sinter there). Hochstetter (1867) wrote "*A little beyond the lake, in a small side-valley, lies the Atetuhi …*".

On 10 June 1886, the basaltic eruption of Mt. Tarawera and phreatomagmatic eruption of Rotomahana buried and/or destroyed all of the silica sinters at Rotomahana. About 7 weeks after that eruption (on 31 July 1886), there was an eruption near the site of Black Terrace. Smith (1887) wrote "*Early in July this crater-lake was ejecting a little steam. On the 31st of July the survey party, in their camp some three miles away, was startled by some smart earthquake-shocks, and a considerable increase in the roar from the crater. This denoted the birth of another crater on this site of the Black Terrace …*". The crater grew to about 200 yards (180 m) in diameter and became known as Black Terrace Crater (Figure 1).

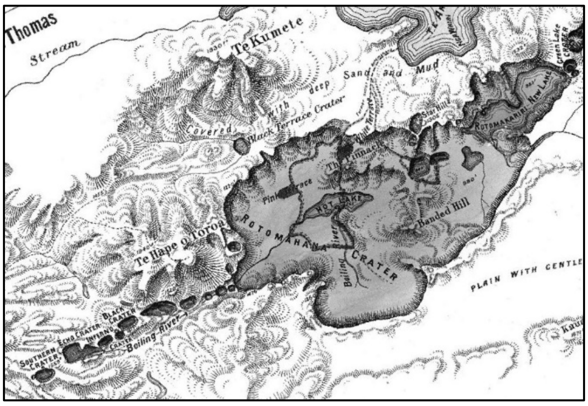

Figure 1: Part of a map of Rotomahana showing Black Terrace Crater (Thomas 1888).

According to Thomas (1888), the crater "*… was throwing out stones and mud with great vigour … for two days, and, with a smaller degree of energy, for some weeks longer*". The NZ Herald (8 January 1887) reported "*… there is nothing black about it … numerous boulders and stones of all colours and descriptions lie scattered about in all directions. We picked up some fine specimens here, amongst which were lumps of petrified wood and charcoal.*"

Within a few years, Black Terrace Crater was infilled and the location of this feature was lost. The crater was marked on a map of the area from 1893, but not in 1895, just 9 years after the eruption. Since the surrounding hills were covered in several tens of metres of loose eruption debris (the "Rotomahana Mud") and the crater was located in a valley close to lake level, it is hardly surprising that it was infilled so rapidly.

1.2 Recent Work

Following the discovery of unpublished diaries of Hochstetter, there has been a resurgence of interest in the silica terraces at Rotomahana. Those diaries contain additional survey information that was not shown on his published maps.

Using that data, several authors have recently attempted to reconstruct the present locations of the Pink and White Terraces, and other associated features including Black Terrace (*e.g*. Bunn and Nolden 2017, Lorrey and Woolley 2018). This has not been straightforward, since many landmarks in the area were destroyed or buried by the 1886 eruption and the subsequent rise in the level of Lake Rotomahana. While the general location of Black Terrace is known, the precise location was unclear.

2. GEOLOGICAL INVESTIGATIONS

During field work in the area of Black Terrace in 2017, boulders up to 40 cm in diameter were discovered strewn over the surface on gently sloping broad ridges. These boulders appeared to be in situ, and were larger than the largest clasts in the underlying Rotomahana Mud (which are generally <100 mm). The discovery of sinter fragments among the boulders increased the likelihood that those boulders had been erupted from Black Terrace Crater, which must have been located nearby.

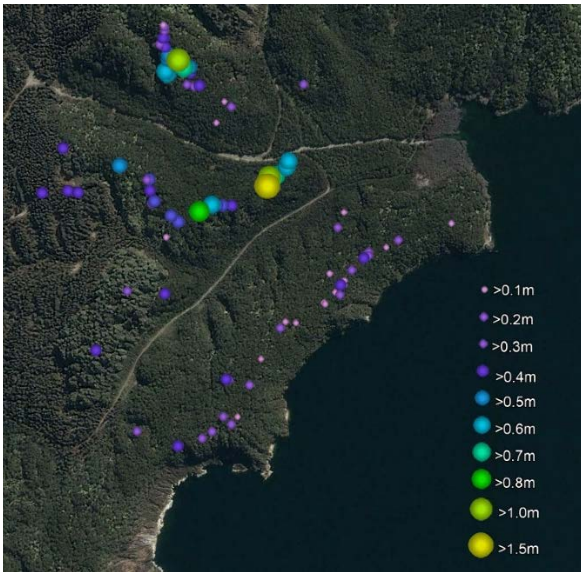

Figure 2: Map showing the size distribution of boulders found at the surface near the location of Black Terrace Crater, using a Google Earth base map.

On a second visit to the site in 2018, the size distribution of the boulders was mapped out using a GPS and tape measure. On this occasion, boulders were found up to 1.5 m in length, with boulders more than 1 m in length occurring on either side of a valley that drains east to Lake Rotomahana (Figure 2). This gave strong evidence that Black Terrace Crater was located in that valley close to where the largest boulders are now found. This is approximately 450 m west of the present shore of Lake Rotomahana. Smaller boulders up to 30-40 cm in diameter were found as far as 500 m south of the inferred crater location. Most of those boulders comprise rhyolite, but several more sinter fragments were found. The crater itself has been completely infilled by post-1886 alluvial deposits, and is no longer evident at the surface.

3. REMOTE SENSING AND GEOPHYSICAL INVESTIGATIONS

3.1 LIDAR

A high-resolution digital elevation model (DEM) was produced from LIDAR data provided by the Bay of Plenty Regional Council (see Lorrey and Woolley 2018 for more details). This DEM was used to produce a topographic map of the field area with 1 metre contour intervals. It shows a possible remnant crater rim as a partial semi-circular feature at the base of a slope flanking the southern margin of the former Black Terrace Crater site (Figure 3). In addition, this DEM was used to topographically correct geophysical data gathered for this study.

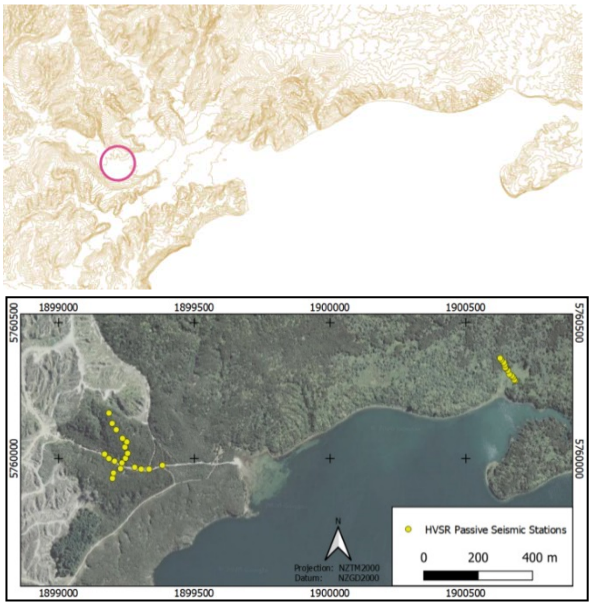

Figure 3: (Top) LIDAR DEM contours of the northwest corner of Lake Rotomahana including the inferred location of the Black Terrace Crater (pink circle); (bottom) aerial photo showing locations of HVSR passive seismic stations. Black Terrace Crater is covered by two HVSR survey lines. Ground penetrating radar coverage was collected over a much wider area, and includes the area covered by HVSR passive seismic stations.

3.2 GROUND PENETRATING RADAR

A MALA GroundExplorer system was deployed along gridded transects covering the Lake Rotomahana access road in an area that blanketed the inferred location of the Black Terrace Crater (identified in Lorrey and Woolley 2018). For data collection, an 80MHz antenna was used to send and receive radar signals that produce radargrams which can define sub-surface layering and structures. The antenna was dragged across the ground manually, and electromagnetic radar data from the receiver was viewed in a base control unit in near-real time. Acquisition rates of sub-surface data signal were set to 0.1 second, with a soil velocity of 0.7 um/s. The GPR's internal Global Positioning System (GPS) unit was utilised for horizontal control, and all radar profiles were topographically corrected using the LIDAR DEM dataset (see Lorrey and Woolley 2018 for details). All GPR data were imported to GPR-SLICE v7.MT for quality control, adjustment of the signal-to-noise ratio, and for combination into a 3-D stratigraphic model. Interpretations of the subsurface stratigraphy and features detected beneath the ground surface were made based on 2-D cross sections and 3-D models (see Figure 5).

3.3 HVSR PASSIVE SEISMIC TOMOGRAPHY

The Horizontal-to-Vertical Spectral Ratio (HVSR) seismic method relies on small ambient ground vibrations (hence 'passive') for its signal. Passive seismic vibrations are recorded typically for 20 minutes in discrete time windows in all three dimensions. The time series data are then converted into the frequency domain via Fourier processing, resulting in power spectrums of the horizontal and vertical frequency responses over the 20-minute recording time. The ratio between horizontal to frequency responses highlights resonances above seismic layers as peaks, which are caused by acoustic impedance changes in the ground (*e.g.* soft sediment on bedrock). The self-contained Tromino seismometer was used to collect the HVSR data (see Figure 4), and each measurement site corresponds to one "sounding". Typical of seismic methods in general, the technique assumes each deeper layer has a greater seismic velocity than the one above, but velocity inversions are observed when the HVSR drops below a value of 1.

Figure 4: left: MALA GroundExplorer GPR 80MHz antenna; right: Tromino HVSR passive seismic device in use on site.

The cleaned and filtered HVSR passive seismic data acquired at the site generally displayed a mid-to-high frequency 'acoustic bedrock' frequency response peak at ~2-5Hz, and a secondary high frequency HVSR peak response caused by an acoustic impedance contrast at a shallower depth in an alluvium sequence. To convert the HVSR frequency peaks ($f0$) to depths, shear wave velocities of the strata must be measured or estimated. Here, an estimated average shear wave velocity (Vs) of 400 m/s was applied (see Equation 1 below) to calculate interface depth (h). Independent depth measurements (such as drill hole data) are generally used to refine the Vs estimate.

$$\boldsymbol{f0} = \frac{\boldsymbol{Vs}}{\boldsymbol{4h}} \quad \text{(Equation 1)}$$

4. GEOPHYSICAL INTERPRETATION

For this presentation, we have focused on one transect down the Lake Rotomahana access road (Figure 3) that includes both continuous GPR and passive seismic tomography measurements (spaced every 50 m, with 25 m supplementary data) spanning the suspected Black Terrace Crater site identified by Lorrey and Woolley (2018).

GPR reveals many subsurface features along the Lake Rotomahana access road based on alternations in the intensity of radar signals that change at depth. The radar signal is completely attenuated at 20m depth across the site, likely due to presence of primary and reworked Rotomahana mud. There are three main components to the GPR radargram along the access road: 1) a western section located to the west of the inferred Black Terrace Crater margin that contains shallow graded beds dipping from west-to-east with shallow, superimposed pond-like features that collectively drape strong reflectors that step upward toward the western crater rim margin, 2) a central section containing a suite of steep, eastward-dipping clinoforms and flat-lying reflectors astride the inferred location of the western boundary of the Black Terrace Crater, which are directly adjacent to structures that indicate progressive shallowing of a deep basin (with abundant superimposed hyperbolic interference features), and 3) an eastern section showing a palaeodeltaic facies, including basin infill (bottomset beds), clinoform bedding dipping to the east at the angle of repose (foreset beds) and stratigraphy with a shallow slope that prograded over the foreset sequence (interpreted as topset beds and alluvium). The eastern section of the radargram is separated from the central section by subtle mound features seen in the subsurface stratigraphy. While there are fewer hyperbolic attenuation signatures in the eastern area of coverage, some co-occur with the eastern margin of where the crater rim was estimated to occur while others are concentrated within the deltaic sediments.

The vertically exaggerated and amplitude normalised HVSR cross section shown in Figure 6 highlights areas of high amplitude acoustic impedance contrast as "hot" colours, with areas of little to no acoustic impedance contrast shown by "cooler" colours. Interpreted depths to the acoustic bedrock and shallower, significant acoustic interfaces are plotted on the cross sections as dashed black lines. The strongest local 'acoustic basement' signal on this transect is interpreted to represent the bottom of the former Black Terrace Crater. Overlying shallower acoustic interfaces are likely lithological and clast-size contrasts that represent primary sedimentary cover sequence (inferred to be crater infill not long after the crater was formed). The lateral extent of the lower acoustic bedrock response on the western margin closely aligns to the extent of the former crater boundary.

The acoustic contrasts in the upper half of the sequence that overlie the bottom of the crater may represent alternating lithological changes from different in-fill sources and mass wasting processes. These features, and those observed in the GPR, suggest an episodic and punctuated refill history, where there were oscillations between quiet lacustrine mud and detritus settling through a water column with intervening (rapid) fluvial deposition related to storm or secondary eruption events.

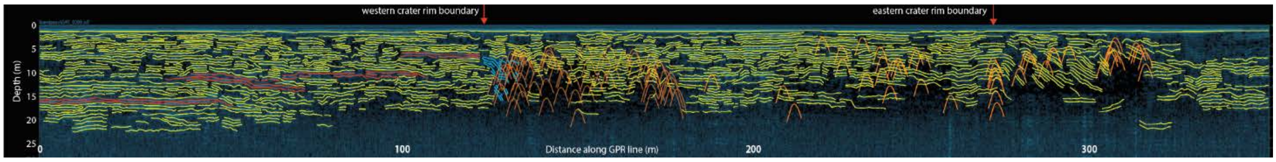

Figure 5. Cyan-enhanced radargram showing the stratigraphy underneath the Lake Rotomahana access road acquired using a MALA GroundExplorer GPR system coupled with an 80MHz antenna. The cross-section view is looking to the north, and left to right is proceeding along the trackline from west to east. The maximum depth estimation for GPR penetration here is estimated at 20m using a field-tested velocity verified at the site. Red lines in the eastern side of the radargram highlight strong reflectors, packages of blue eastward-dipping and flat lines align to the inferred location of the western crater boundary and orange hyperbolic signatures suggest the presence of gas at depth. Yellow lines in all three diagrams are interpreted as sedimentary infill, deltaic sediments and alluvium layers.

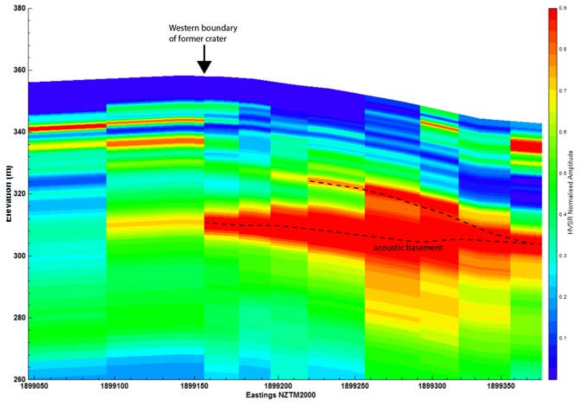

Figure 6: Normalised amplitude-depth HVSR cross section from survey Line 01 down the Lake Rotomahana access road, which highlights a strong acoustic basement interpreted as the bottom of the Black Terrace Crater, and a secondary flat lying acoustic impedance contrast just above the acoustic bedrock. It is possible that silica deposited from geothermal fluids flowing through the vent breccia or coarse slump deposits has amplified the signal within the crater. Numerous shallow interfaces are observed, and some of these features are presented in more detail using the GPR radargram in Figure 5.

3. GEOPHYSICAL DATA SUMMARY

The geophysical methods used along the Lake Rotomahana access road were deployed in a way that used map-based evidence of the former Black Terrace Crater location (Lorrey and Woolley 2018). They complement the wider boulder survey that sought to find coarse end members of a hydrothermal eruption. Collectively, the GPR and HVSR passive seismic evidence, coupled with historic details from maps and LIDAR, suggest there is an infilled crater beneath the Lake Rotomahana access road. The HVSR passive seismic technique provides greater depth penetration than the GPR and it suggests the bottom of the Black Terrace Crater ranges from 35-50m below the present ground surface. The GPR results provide finer detail for subsurface structures within and outside the relic crater. The radar results suggest part of an ejecta apron may be preserved along the western crater boundary at depths 5-15 m below the present ground surface, that the lake once penetrated the valley up to the eastern margin of the crater rim (and probably overtopped it), and that gas is still being emitted from the buried Black Terrace Crater site. Additional high-resolution passive seismic transects over Black Terrace Crater and the surrounding area may help resolve the exact geometry of the crater features and let us ascertain whether any remnants of the Black Terrace silica sinters exist at depth.

5. DISCUSSION

Through mapping out the size distribution of boulders and identifying sinter fragments among those boulders, supported by geophysical techniques, we believe that we have relocated the site of the (now buried) Black Terrace Crater. It remains to be seen whether any sinter is preserved at depth, or if it was completely destroyed by the eruption at this site.

Our work here provides unequivocal evidence that the Black Terrace Crater is positioned along what is now the Lake Rotomahana access road, in a spot where the alignment of an 1893 survey map (Smith 1894) and modern maps indicated it was located (Lorrey and Woolley 2018).

None of the sinter boulders found to date near this site are black; most are typical white siliceous sinters, and many of them contain silicified plant and tree fragments. One sample has a grey appearance, but this could be due to weathering. It is unclear why parts of the Black Terrace sinter might have been black, unless perhaps there was unsilicified carbonaceous material incorporated within it. Such carbonaceous layers have been observed in other sinter deposits.

6. CONCLUSION

Black Terrace Crater is buried beneath alluvial deposits in a valley some 450 m west of Lake Rotomahana. This site corresponds to the location that was provided by positioning old historic maps into modern cartographic space that originally showed the crater when it could still be seen during the late 1800s. It unknown whether some of the original Black Terrace sinter is still preserved beneath the Rotomahana Mud and post-1886 alluvial material at this site. The location of Black Terrace Crater can now also be used as an independent vector to guide exploration for the former Pink and White Terrace sites.

ACKNOWLEDGEMENTS

Tuhourangi are the tangata whenua of the Rotomahana-Waimangu area, and the events of 1886 were devastating on their tangata, their whenua, and their taonga. The generous assistance of Tuhourangi in facilitating and supporting fieldwork and allowing publication of this paper are gratefully acknowledged. We would also like to thank Resource Potentials of Perth for donating their time, expertise and Tromino HVSR equipment for this project, and Nigel Veale and Johanna Fischi for assistance in the field.

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