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RESEARCH ARTICLE



Forensic cartography with Hochstetter's 1859 Pink and White Terraces survey: Te Otukapuarangi and Te Tarata

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ABSTRACT

The 1859 field diaries of Ferdinand von Hochstetter (1829–1884) include raw data from a compass survey of Lake Rotomahana. The azimuth array is reverse engineered to identify Hochstetter's survey baseline. Survey iterations are performed to reconstruct the historic Lake Rotomahana over today's topographic map. Hochstetter's papers include a method-of-squares survey map of Lake Rotomahana, providing scale and orientation to the reverse engineered projection. The forensic cartography delivers control points which enabled the authors to georeference Hochstetter's survey map over the new Lake Rotomahana map. Black Terrace Crater and Te Ariki datum are derived. Validation by waterways, valleys and vegetation lines is undertaken, a biological bathymetry completed and three-point resection performed on the key survey station. The cartography shows the Pink, Black and White Terrace spring locations, Te Otukapuarangi, Te Ngāwhā a Te Tuhi and Te Tarata lie buried on land. From novel lake altimetry the plotted terrace spring locations lie buried 10–15 m. A full archaeological site investigation including imaging and core drilling is indicated to examine the three terrace locations. Excavation on one or more of the Pink, Black and White Terrace sites may then be determined.

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Black Terrace Crater; Ferdinand von Hochstetter; Lake Rotomahana; New Zealand; Pink Terrace; Te Otukapuarangi; Te Tarata; White Terrace; Te Tuhi's Spring; survey

Introduction

Forensic cartography is described as part science and part art (Byrd 2000). The forensic approach collects evidence and measurements, developing these for plotting on a map (Gregory 2013). The 2015 International Cartographic Conference proceedings provide a useful introduction to the subject (Sluter et al. 2015). In 2016, the Lake Rotomahana section of Ferdinand von Hochstetter's 1859 field diary was passed to R. Bunn by S. Nolden. Bunn noted the diary contained interval data from a compass survey of the Rotorua district by Hochstetter. These data formed bearings which included Te Otukapuarangi and Te Tarata, the Pink and White Terraces, and Bunn saw the possibility of reverse engineering by resecting these data to plot the terrace locations and resolve their status (Bunn & Nolden 2016, p. 37). For topographical features and place names, please refer to [Figure 1](#).

There was uncertainty over the locations of the Pink and White Terraces following the 1886 eruption of Mount Tarawera. No pre-eruption government survey had been



Figure 1. Features and place names in the Hochstetter survey.

completed of the colony's eighth wonder of the world. Government and university reports failed to quell public uncertainty. In his 1886 eruption report, Stephenson Percy Smith (1840–1922) noted:

[T]he exact position of the [White] terraces cannot be identified, as the ground around where they formerly stood has been blown away; but they evidently were close to, and to the north-west of, the pinnacles [...] The site of the Pink Terraces cannot be identified with more certainty than that of the White Terraces [...] owing to the absence of any proper survey of Rotomahana [...]. (Smith 1886, p. 57)

Sceptics led by Alfred Patchett Warbrick (1860–1940) debated for decades until the eruption survivors passed. Public interest lapsed, but in 2011 again focused on Te Otukapuarangi and Te Tarata, as Cornel de Ronde led a GNS Science and Woods Hole Oceanographic Institute (WHOI) team on three expeditions to Lake Rotomahana. Sonar findings in 2011 and 2012 led him to report the terraces were relocated, in part or entirety, deep in the lake and global media interest ensued (Winner 2012). When the GNS research was published in 2016 the authors resiled from earlier press releases, concluding the terraces were likely destroyed (de Ronde et al. 2016a, p. 27). A prior survey is thus of interest for it might resolve the status of the Pink and White Terraces, while contributing to GNS findings at Lake Rotomahana (Bunn & Nolden 2016, p. 45).

Hochstetter arrived in New Zealand with the Imperial Austrian *Novara* expedition on 22 December 1858 and went on to spend some 9 months in the provinces of Auckland and Nelson. He based his survey on the data produced by the *Pandora* coastal survey of New Zealand (Byrne 2007). This was executed 'by means of the Azimuth-compass, a system of triangulation which I based on Captain Drury's nautical coast-survey' (Hochstetter 1867, p. 20). An azimuth compass is often called a ship's compass and is similar to a surveyor's circumferentor. It was used for surface navigation and could measure the azimuth or arc along the horizon from magnetic north to the

point on the horizon below, for example, the sun. It is equipped with sights for accurate bearings. These would prove useful as many of Hochstetter's bearings were on mountain peaks. The *Novara* carried multiple compasses and the survey instrument may have been one of these. The nineteenth century marine surveying technique is summarised thus:

The first part of the work [...] laying off a suitable base line [...] The next thing to be done is [...] a process called 'triangulation'. Each end of the base line is made a station for observations, and from these stations angles are measured [...] The first point chosen is then plotted off on its true bearings from both ends of the base line [...]. (Brown 1953, pp. 191–192)

Hochstetter followed this approach at Lake Rotomahana over 28–30 April 1859 as he conducted the only survey of the lake and the Pink and White Terraces. When reverse engineering Hochstetter's 1859 survey we adopted the instruction issued by the Admiralty to Drury as *Pandora* set sail:

[T]he topographic portion [...] should contain [...] principal features [...] [and] secondary objects [...]. In short, during the whole progress of a survey it should be steadily borne in mind [...] that it is only a means to an end; and that its real merit will less depend on the science and taste which have been employed in its construction than on the practical utility of its results. (Byrne 2007, p. 84)

Given the irreplaceable survey data, we also noted Hochstetter's caveat on his small scale North Island maps:

It stands to reason, that a map which contains nearly 2,500 miles (10,000 square miles) and embraces more than the fourth part of the Northern Island, executed by the assistance of a compass alone, within the period of three months, can make no pretensions to a trigonometric exactness. It is, however, the first map which gives a correct view of the rivers and mountain systems, and of the lakes in the interior of the Northern Island, and will be useful until some better and more complete map takes its place. (Hochstetter 1867, pp. 49–50)

For Lake Rotomahana and the Pink and White Terraces, his compass survey and method-of-squares map became the only mapping. It is worth noting Drury's 1856 coastline survey remained the mainstream New Zealand survey until 1936, demonstrating the utility of compass survey technology (Byrne 2007).

Hochstetter travelled with a large party including two prominent surveyors, Julius von Haast (1822–1887) and George William Drummond Hay (1827–1881), and the artist and lithographer Augustus Carl Ferdinand Koch (1834–1901), and completed the survey, geology, sketches, cartography, field observations and his field diary in 48 hours at the lake (Hochstetter 1859). His final method-of-squares Lake Rotomahana map was completed after he left New Zealand. His field diary and sketches remained in the Hochstetter family archive where they were rediscovered in 2010 by Nolden while documenting the Hochstetter Collection Basel (Nolden & Nolden 2011, 2012, 2013).

Source survey data

Figure 1 contains the place names of features discussed in this article.

Hochstetter's 1859 field diary

Page 57 of Hochstetter's diary is reproduced in the supplementary Figure S1. The original is found in the Hochstetter Collection Basel. This records the azimuths taken from his Observation Station 21.

Guided by Akutina Rangiheuea, Hochstetter's party walked to Lake Rotomahana on a windy 28 April 1859 from the parsonage of Rev. Seymour Mills Spencer (1812–1898) at Te Mu. They camped on Te Puai Island and canoed and circumnavigated the small lake on foot. Hochstetter surveyed the lake and the Pink and White Terraces, assisted by surveyors Haast and Hay, and Koch. He made three sketch maps of the lake, filling 24 pages of his diary. His photographer Bruno Lancel Hamel took photographs (Hamel 1859). From Bunn's 2014 Pink and White Terraces Limited (PAWTL) Project (Bunn 2016) experience at the new Lake Rotomahana and Nolden's research into Hochstetter's records, he established a survey base line from the southern shore (Observation Station 21). Hochstetter chose a second observation station on Te Puai Island.

Hochstetter, like many surveyors and geologists, was a competent artist and completed the method-of-squares survey map of the lake in [Figure 2](#). This manuscript map was unknown prior to being published in 2011 (Johnston & Nolden 2011). The diary, map and sketches, together with his correspondence, books and lectures in New Zealand provide a range of evidence to fix the lost locations of the Pink and White Terraces.

Analysis

Compiling a 157-year-old survey in nineteenth century handwritten German proved difficult. The surviving survey data were in diary format and not intended for publication as a dataset. Nolden's expertise with Hochstetter and nineteenth century German holographs and idioms overcame these issues. Compounding the difficulty was the destruction of many survey landmarks by the 1886 Tarawera eruption, and its dissection of Lake Rotomahana. These factors restricted the survey landmarks to 10. Ten compass azimuths survive from those taken at Station 21. Three azimuths survive from Te Puai Island station. From so few bearings we could not compile Hochstetter's original survey. However, Bunn saw it was possible to reverse engineer Hochstetter's notes and resect his azimuth data. By computing reciprocal bearings we could plot where he stood to take the bearings from Station 21 and Te Puai Island. From those points it was possible to reconstruct the survey baseline on today's topographic map. Given the baseline, Hochstetter's method-of-squares map could be fitted to it, with the baseline providing orientation and scale. We were then able to establish the latitude and longitude of the Pink and White Terraces, and answer the 130-year-old mystery.

The 10 surviving survey landmarks comprise:

1. Rev. S. M. Spencer's home at Te Mu, Tarawera.
2. Five peaks along Te Kumete ridge.
3. A peak on Makatiti plateau.
4. Three bearings on Mt Tarawera.

model from the National Oceanic and Atmospheric Administration. It is noted this model differs slightly ($\leq 1^\circ$) from period Admiralty declination records in the Bay of Plenty and from Smith's 1886 post-eruption mapping (Smith 1886). Sensitivity testing was then undertaken on the bearing data to account for residual variance. After consulting GNS on local variation, there were no data sources (W. Heise, GNS Science, pers. comm. 2016; T. Hurst, GNS magnetism, pers. comm. 2017). We minimised the 'triangle of error' to account for any local variation, by Lehmann's method. Below are the azimuths from Station 21.

Azimuth 1: Rev. S. M. Spencer's parsonage at Te Mu (bearing 306°30')

Spencer's parsonage appeared the hardest bearing. The house no longer stands at Te Mu and the old Lake Rotomahana has vanished. We knew Hochstetter stayed at the parsonage before and after his Rotomahana survey, hence was familiar with the surroundings. Hamel photographed the residence. The Te Mu block subdivision plans survive and show the parsonage, high on a ridge at an elevation of 450–460 m. This was c. 150 m higher than Station 21 which Bunn calculated stood at c. 310–320 m above sea level (MASL). However, the intervening country rises to c. 500 MASL and the parsonage could not have presented in a line of sight. The parsonage stood at the head of a small valley under Hill 505 and it was considered Hochstetter used this hill as a surrogate. The initial reciprocal crossing Wairere Falls reproduced his azimuth. After visiting the Buried Village, the excavated Rotomahana Hotel offered more precise coordinates for the parsonage. The bearing and distance from the hotel porch gave a more accurate location for this fourth iteration.

Azimuths 2–6: five peaks along Te Kumete ridge

Five azimuths are given along this ridge, one exposed to the force of the Rotomahana eruption. Peaks one to four, by their proximate bearings were clustered.

- Bearing two—peak on the track 314°40'
- Bearing three—peak 322°40'
- Bearing four—highest point, 326°0' (azimuth 4)
- Bearing five—peak 334°20'
- Bearing six—point on Tarawera 355°0'

The Te Kumete ridge lies within the 36 inch depth ashfall area and within range of the 'high speed blasts of hot rock, water and steam [sweeping] horizontally outwards for 5–10 km from Rotomahana' (Nairn & Houghton 1986, p. 204). The main blast direction lay west of the section surveyed by Hochstetter. It was possible to locate two of the five landmarks used by Hochstetter (azimuths 4 and 6) and to interpolate the remaining three. Azimuth 4 was clearly Te Kumete (trigs 3058 Station 7691 and ALQC Te Kumete) and we know from Smith's post-eruption map that Te Kumete remained identifiable after the eruption (Smith 1886, p. 42). Azimuth 6 is Mataneho Point on Lake Tarawera, also identifiable after the eruption. The point may not have been on the skyline from Station 21, but was from Station 20 where Hochstetter took sightings. His sketch map in supplementary Figure S1 also shows this as an escarpment. Lake Tarawera is now c. 7 m higher than before the eruption (from c. 291 to 298 MASL) and following it

the lake rose c. 13 m after the outlet blocked with eruption debris. In 1904 this dam burst and the level dropped towards its present 298 MASL. The Mataneho bearing is thus from a point close offshore from the northwest nose of today's point.

Azimuths 3 and 5 were interpolated and matched with peaks and high ground. Azimuth 2 was located after studying Hochstetter's sketch map of Te Kumete Ridge in supplementary Figure S1. This shows peak a) as an escarpment and one is found on this azimuth, west of Te Kumete plateau. This trial bearing was checked against Hochstetter's path from Te Mu to Lake Rotomahana along the Tūhourangi track between the two lakes, for he specified the peak was 'on the track'. This track is shown in the map included in Hochstetter's book *New Zealand, Its Physical Geography, Geology and Natural History* (Hochstetter 1867). It joins the village of Kakerangi where Hochstetter's Station 20 was located. From there it heads south, close to today's Tarawera Trail (implemented by descendants of Te Tūhourangi who guided Hochstetter). It bends west around the head of the old Wairua Inlet, then heads south to strike the southwest corner of old Lake Rotomahana where it ran by Oruakorako Hill. The crossing point on the Wairua stream is c. 1100 m from today's stream exit versus the Tarawera Trail crossing at c. 550 m above the exit. This upstream shift reflected the Wairua Inlet running further inland before the eruption. After the eruption it infilled with eroding mud. If we follow this course we cross Te Kumete Ridge via a saddle close under the escarpment on Hochstetter's bearing. This evidence supports the location of azimuth 2. Azimuth 3 was tangential to the leading left edge of the Te Kumete plateau where there is a peak of > 500 m. Azimuth 5 crossed the left end of a high plateau labelled Hill 515. The ground rises to the left of this plateau to meet the bearing. These five azimuths comprise a mutually supporting array for Station 21 and Te Puai Island Observation Stations.

Azimuth 7: a peak on Makatiti plateau

This azimuth did not fit with today's trig on Makatiti. Nor did it fit with the nearby Peak 934. The azimuth lay to the west. The solution lay in a Hochstetter field map showing the Makatiti plateau. There is only one peak marked, at the western end and Hill 873 was the bearing. Alfred Warbrick witnessed Tarawera erupt from this plateau and reported the hut was buried in ash, forcing his party to escape through the roof. Trees there retain volcanic ash in their branches (Waddell 2014).

Azimuths 8–10: three bearings on Mount Tarawera

This group of azimuths was taken on a mountain which erupted in 1886. Could we rediscover Hochstetter's bearings after the eruption? This proved straightforward for the upper mountain plateau of Mount Tarawera was largely unchanged after the eruption, save for cratering. Ruawahia remained the highest point and the southeastern and southwestern edges remained defined, as did Koa trig. Dr Ian Nairn reported: 'In general, the mountain did not look greatly different prior to the 1886 eruption, except that there were no craters on the summit' (Nairn & Houghton 1986, p. 202). The plateau edges Hochstetter used proved viable as Nairn noted: 'The 1886 basalt deposits [...] rapidly thin to c. 1 m only a few hundred meters away from the fissure' (Nairn & Houghton 1986, p. 204). Smith, in his 1886 eruption report, provided pre- and post-eruption skyline views: the pre-eruption high points remained in relative position (Smith 1886, p. 42).

These three azimuths provided right-angled crossing with Te Kumete azimuths which optimised accuracy of the locus. They comprise:

Mount Tarawera, highest point, $43^{\circ}30'$

Northwestern corner of the upper mountain plateau, NW $46^{\circ}10'$

Southeastern corner of the upper mountain plateau, SW $33^{\circ}0'$

These azimuths contained two errors and a correction. The first and second azimuths were transposed, (the highest point must be south of the northwest plateau). Bunn restored the data and the array fitted the landmarks. Hochstetter overwrote 'SO' over 'SW'. In German SO is southeast, so the third azimuth was the southeastern edge of the plateau. This must be greater than the other azimuths for it is southernmost. The 33° appeared a typographic error for 53° which indeed fitted the plateau edge below Koa trig and the locus on a reciprocal.

In earlier iterations Bunn plotted the central point of the 10 azimuth locus, to derive the coordinates for Station 21. For the fourth iteration, on consulting surveyor advice, a subset of three Hochstetter azimuths was plotted (Mount Tarawera peak, Te Mu and Te Kumete). The complex algorithm of earlier iterations was simplified by plotting reciprocal bearings onto Google Maps and obtaining more accurate coordinates. These azimuths are shown intersecting in supplementary Figure S2, along with the locus coordinates.

Having established one end of Hochstetter's survey baseline, Bunn calculated the locus of three reciprocal bearings from Te Puai Island. These were as above, from Te Kumete, the peak on the track and the highest point on Mount Tarawera. The same approach was taken in computing and plotting reciprocals and the estimated location of Te Puai Station is shown by the locus and coordinates in supplementary Figure S3. In view of the importance of Te Puai Station to the cartography, a three-point resection was undertaken with pleasing results.

From the Station 21 and Te Puai Island Station coordinates, the survey baseline was reconstructed of c. 558 m and aligned at 25° . The fourth iteration methodology was applied to the method-of-squares map in Figure 2 and the published version of the map prepared by August Heinrich Petermann (1822–1878), with the title 'Rotomahana or the Warm Lake and the hot Springs' (Hochstetter & Petermann 1864).

The two projections of Hochstetter's mapping differ, and in the March 2017 digital mapping analysis significant drafting errata were detected in the Hochstetter & Petermann (1864) map and it was relegated. This paper next examines Hochstetter's original undated (circa 1861) method-of-squares map, which is now considered the only reliable map for georeferencing of the four old lake maps available (i.e. Smith 1857; Hochstetter, Figure 2; Hochstetter & Petermann 1864; Keam 2016). After digital mapping assessment, the scale of the method-of-squares map was determined to be 1:6000. Standard map navigation technique was used to orient the map to the survey baseline (i.e. the Hochstetter map was oriented to true north by $+14.04^{\circ}$). Bearings were taken from true north in an anti-clockwise sequence, moving from Te Puai to Te Tarata and thence to the other features in the schematic map in Figure 3.

In Figure 3 the old lake is c. 1380 m on the long Haumi–Te Proporo axis (c. 1200 m to the Kaiwaka entry). The Pink and White Terraces and Tamariwi are shown approximately to scale (with Hochstetter's artwork). The Te Tarata location lies northwest of the Pinnacle as Smith indicated. The Pink Terrace spring location lies along the coast above Te Otukapuarangi Bay. The Pink Terrace distal (i.e. southeast corner) projects into the new lake

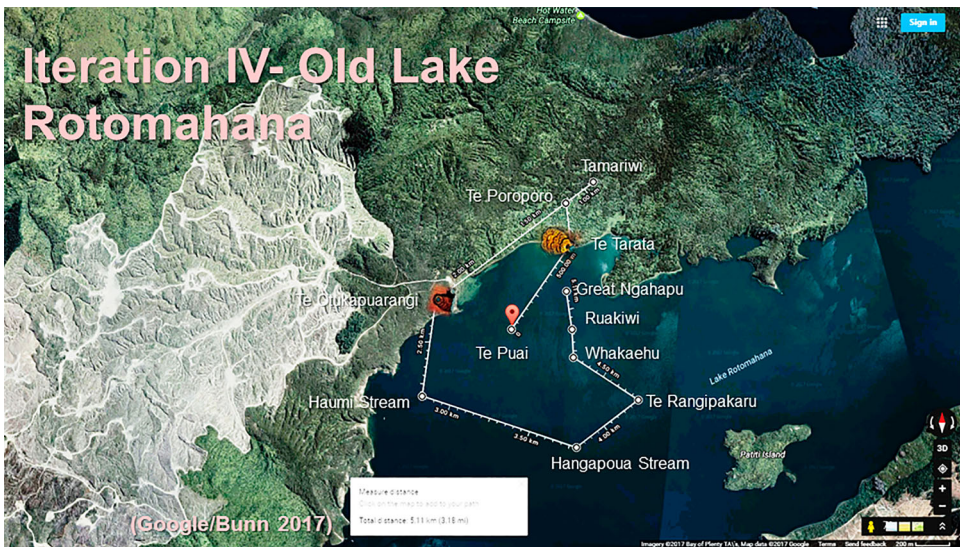


Figure 3. Iteration IV outline of Hochstetter’s method-of-squares map (Hochstetter 1861) plotted over the new Lake Rotomahana (Google Maps/Bunn).

north of Warbrick’s Bay. The location is somewhat consistent with the 2011–2012 claim by Cornel de Ronde of GNS Science to have located a Pink Terrace fragment off the coastline south of this location. It is inconsistent with the 2016 GNS-reported location of a Pink Terrace fragment. While both terrace spring locations lie near the shore (and near the Rotomahana crater edge), neither spring location is near local eruption cratering. There is a magnetic anomaly enclosing the Pink Terrace location and both terrace locations about shallows not accessible to GNS submersibles (de Ronde et al. 2016b, figures 16A, 9B, 9C). ‘An active hydrothermal discharge zone [lies] along the north shore between the historic Pink and White sites’ (Walker et al. 2016, p. 149). This lies immediately south west of Te Tarata location.

The White Terrace spring location (Te Tarata) lies west of Te Tarata Point, on land with its distal section reaching toward Te Poroporo. The elevations mean both terrace spring locations are c. 10–15 m underground. All old lake features save Te Poroporo, Te Waiti, Te Mamaku, Tamariwi and the shoreline between the terrace springs, lie over the new lake eruption crater and must be considered lost. Nearly all the Pink Terrace location and the northern half of the White Terrace location lie on land (i.e. are underground). Some features shown inshore may lie beneath the new lake floor; given the new lake surface is now c. 35 m above the old lake and the new lake floor c. 75 m below the floor of the old lake. Given the eruption and ash-fall sequence, it is possible that distal sections of terrace were quickly buried and the new lake later rose over them.

Validation

While the locus of the azimuths was sound, it would strengthen the survey if we validated the findings. This was difficult given the absence of another survey. However, eight techniques were developed to challenge and validate the survey. In Smith’s

report *The Eruption of Tarawera, a Report to the Surveyor-General* (Smith 1886) he gives one bearing only of 62° , from the pre-eruption trig along the centre-line of the eruption fissure: ‘The old station [...] position was right in the centre of the fissure, and just to the east of the point lately determined, at a distance of about 250 yards’ (Smith 1886, p. 46). This latter point is now known as the Ruawahia trig station. Smith went on to report: ‘From the [...] old station, a line drawn on a true bearing 62 degrees for rather more than a mile, will follow along the center of the fissure [...]’ (Smith 1886, p. 46). He adds: ‘[...] along this portion, the width of which averages 250 yards [...]’ (Smith 1886, p. 47). After referring to the Topo50 map, Bunn drew up the positions of the old and new trigs following Smith’s directions (i.e. moving 250 yards eastward from today’s Ruawahia trig).

Given his description, the rift angle of 57° and the trig moving east; Smith’s trig station now lies in the centre of the rift to the east. The rift opens up here and bears to the north. The net effect is that the Hochstetter bearing from Station 21 goes past today’s Ruawahia trig and on through the pre-eruption trig location as measured by Smith. Smith’s 62° bearing thus validates the nearby Hochstetter bearing of 58.147° through the highest point on Mount Tarawera. Station 21 is coincidentally along the line of the southern part of the eruption fissure along Ruawahia and Tarawera. This was welcome confirmation of the calculated Hochstetter reciprocal bearings. Smith’s report also comments on the post-eruption mountain plateau. Compared to the chaos at Lake Rotomahana there was little change on the plateau, apart from 12–15 m of ejecta lying near the fissure. This diminished towards the edges of the plateau where Hochstetter made two of his three Tarawera bearings. While the plateau elevation increased by volcanic fallout (by 12–15 m according to Smith 1886, and more by Nairn & Houghton 1986), the relative heights of the pre-eruption high points remained. Along those areas of the tops used by Hochstetter, the Ruawahia peak was, and remains, the highest point on the three mountains, and the edges of Tarawera remain in situ.

Tienstra resection

The Te Puai Island Observation Station is now recognised as the most important station, as it is where the Hochstetter survey azimuths intersect with his method-of-squares map. Accordingly, we performed a three-point resection on the Hochstetter azimuths using Bryan Farrar’s Knightwood and Westfall’s software, designed for archaeologists and geologists. The result is shown in supplementary Figure S3 where the resection confirmed the graphical plots from Hochstetter’s azimuths.

Watercourses, valleys and vegetation lines

In supplementary Figure S6 there are two vegetation lines along valleys bearing northeast from the northern lake shore. The right vegetation line was considered the course of the old Kaiwaka Channel. A pipe was installed there in 1974. The Tamariwi location lies close to the left vegetation line. Tamariwi was (see Figure 1) a silica terrace forming on the true left bank of Kaiwaka Channel, above the junction between the Kaiwaka Channel and Awaporohe Stream. The Tamariwi location lies close to the left vegetation arc connecting with today’s watercourse draining the isthmus northeast along the old/new Kaiwaka Channel

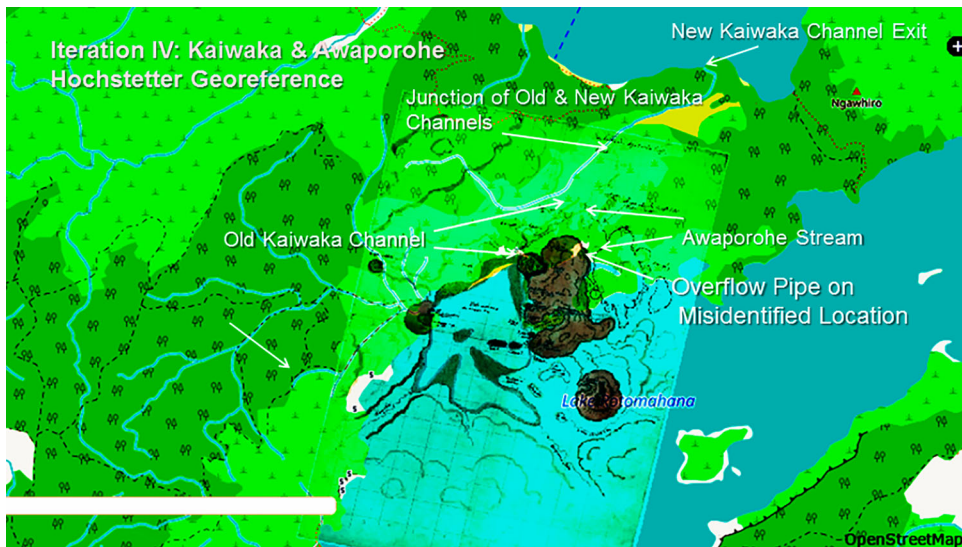


Figure 4. Hochstetter's method-of-squares (1861) map warped over Topographic Map (Bunn/Harvard).

course into Te Rata Bay. In Bunn's 2016 book (Bunn 2016, ch. 5), it was posited that the right watercourse lay over the Awaporohe Stream. The fourth iteration strengthens that conclusion as Te Poroporo marked the entry to the Kaiwaka Channel and was used as a surrogate by Hochstetter. Tamariwi should lie well downstream from the Kaiwaka Channel entry, as in Figure 3. On the old lake the Kaiwaka Channel and Awaporohe Stream entries were c. 500 m apart and merged below Tamariwi. The Kaiwaka Channel descended c. 12 m. The vegetation lines are consistent with such stream lines and the entries to the Kaiwaka Channel and Awaporohe Stream in Figure 4 and supplementary Figure S6. The watercourses can also be seen in the first aerial photography from 1923 (Rotorua District Council 1986, p. 209). This coincidence supports the location and orientation of the overlay in Figure 3.

Georeferencing

To elaborate the Hochstetter survey findings, map warping (georeferencing) technology was employed to orient the old lake projection over the new. Map warping is described thus: 'to register an image with a reference grid such as a map, or to align two or more images' (Brown 1992, p. 325). Harvard University developed a specialised map warper tool for 'digitally aligning (geo-rectifying) scanned historical maps to match today's precise maps' (<http://warp.worldmap.harvard.edu/>). This is ideally suited to the forensic cartography in this article. In Figure 4, the Hochstetter method-of-squares map is warped over a topographic map using four control points—Te Tarata, Te Otukapuarangi, Te Poroporo and Tamariwi. The warp indicates the Pink Terrace spring location is onshore and Te Tarata spring location is also onshore west of Te Tarata Point. Te Poroporo is superimposed on the left vegetation arc and the Awaporohe Stream lies beside the assumed course of the Kaiwaka Channel. The vegetation lines, valleys and junction about the Kaiwaka and Awaporohe streams. This array overlays the stream draining the isthmus today (i.e. the new Kaiwaka Channel).



Figure 5. Hochstetter’s method-of-squares map warped over Google Maps, showing Te Tuhi’s Spring (Bunn/Google Maps/Hochstetter).

These topographic relationships are shown in close-up in [Figure 5](#). Also in this figure we note the proximity of the Waikanapanapa Valley (marked in yellow in the layer) to Te Tarata Point, below which lies the Pinnacle, a rocky column considered by Keam and de Ronde to be a ‘remnant volcanic neck thought to mark a volcanic feeder zone’ (de Ronde et al. 2016a, p. 21). Keam avers the climactic base surge of the Rotomahana eruption occurred on land, on Pinnacle Ridge, and ‘more specifically that it was centred somewhere in or close to the Waikanapanapa Valley’ (Keam 2016, p. 28). The georeferenced Hochstetter map places the eastern end of Waikanapanapa Valley adjacent to Te Tarata Point and the Pinnacle. This points to the Pinnacle perhaps marking ground zero for Keam’s climactic base surge of the Rotomahana eruption, in [Figure 5](#).

Te Ngāwhā a Te Tuhi (Te Tuhi’s Spring) or Black Terrace Crater

Of special interest in [Figure 5](#) is the location of Te Tuhi’s Spring inside the cleared tongue of forestry land at 10 o’clock. From nineteenth century reports, this spring and terrace feature was the only mapped, close-in, pre-eruption geothermal spring to survive the eruption and to play afterwards. It was the final stage of the Rotomahana eruption and renamed Black Terrace Crater. It is shown on both Hochstetter’s maps and on both Smith’s 1886 eruption report maps.

Black Terrace Crater is visible in the aerial amalgam of Smith’s and Hochstetter’s maps in [Figure 6](#). It lies inside the tongue of land where there is a feature of the expected diameter. There is aerial evidence of altered ground at this location, within the area disturbed by forestry operations. This site lies at c. $-38.2562, 176.4201$ and is c. 500 m northwest of Te Otukapuarangi, consistent with nineteenth century reports from Smith who mapped it as lying c. 1463 m from the Pinnacle in this location and draining southeast into today’s



Figure 6. Smith and Hochstetter arcs marking Black Terrace Crater (Bunn/Google Maps/Smith).

boat-launching bay. The colonists reported the crater lay c. 400 m from the crater edge. The pre-eruption maps agree, showing the spring lay 460–480 m from Te Otukapuarangi or 420–440 m from the old lake shore. In this area, the new lake shore follows the old crater line (Healy 1975b, p. 79). The agreement of the Hochstetter warps and Smith survey supports the lake positioning in Figure 3.

Te Ariki datum

A second pre-eruption landmark has been recovered, the exit of the Kaiwaka Channel at Te Ariki landing on Lake Tarawera. There are photos, maps and first-hand reports identifying the channel exit at the village of Te Ariki. These are incorrect for there was no Te Ariki village per se. The name referred to the southern arm of the lake. According to a Hochstetter sketch (Nolden & Nolden 2013, p. 74), confirmed by Mr Rangitihī Pene of Te Tūhourangi Tribal Authority, around this arm lay six village and Pā locations: Moura (Ngāti Rangitihī); Te Koutu (Ngāti Rangitihī); and four Tūhourangi villages (Kokotaia, Piripai, Pukekiore and Otuapane). Kokotaia Pā was abandoned in favour of Pukekiore (Rat Hill) around 1854. Smith also documented Kokotaia (Smith 1857–1858). In a 1923 aerial photograph the hill resembles a rat crouching in water with the Kaiwaka Channel its tail (Rotorua District Council 1986, p. 209).

After comparing early photographs and maps with today's topography, the village of Te Ariki is Kokotaia. This Tūhourangi centre with an 1886 population of about 25 persons lay near today's Rapatu Bay jetty and nearly a kilometre from the channel which exited under Pukekiore (Rat Hill) at Te Ariki landing. After aerial, photographic and topographic analysis, the channel exit is located on the line of today's Kaiwaka Stream under Pukekiore Hill in Figure 7. From here (allowing for lake rise and fall), reputable eye-witnesses record it was 1 mile up the Kaiwaka to the channel entrance beside the White Terrace with a 40'



Figure 7. Te Arika location and the 1609 m arc on which the Kaiwaka Channel entry lay (Bunn/Google Maps/Hochstetter).

increase in elevation (Bunn 2017). The country was open with a line of sight down the channel course. There was no landmark at the channel entry, it being a reedy place with a meandering waterway beside the terrace. Hochstetter used Te Poroporo as a surrogate, as do we. The Kaiwaka Channel with entry and exit landmarks, as the crow flies a mile over a c. 12 m descent, with its fairly steep rapid section and Awaporohe junction, provides a datum for terrace navigation. In Figure 7, we describe an arc at 1609 m radius from the Kaiwaka exit. A correctly oriented pre-eruption map should deliver its channel entry close to that arc.

The Hochstetter map channel exit and entry are shown in Figure 7. The yellow trapezoid marks Te Poroporo and the arrow marks the actual channel entry beside Te Tarata. The map location is close to the Kaiwaka entry arc, (allowing for the meandering waterway versus the line of sight plot); further indicating the schematic in Figure 3 is correctly located.

Kaiwaka altimetry

The Arika datum also allowed us to overcome the chronic inability of investigators to fix the elevation of the old lake surface and floor; both being necessary to establish the latitude, longitude and altitude coordinates of the terraces. By returning to eyewitness accounts of the (overlooked) Kaiwaka Channel and with a gap analysis of its entry and exit altitudes at c. 12 m, together with Healy's borehole evidence, we may fix the old lake surface elevation at c. 303 m \pm 1–2 m for the 1857–1886 period (Bunn 2017). This is consistent with Healy's 1975 estimate of 301 m (Healy 1975a, p. 83). The mean of the four altitudes given in his 1975 Royal Society paper (by Malfroy, Smith, Healy and Warbrick) is almost identical to our altitude i.e. 303.17 MASL versus 303 MASL (Healy, 1975a, p. 83).

Biological bathymetry

De Ronde in his 2016 papers estimated the lake altitude at 292 MASL and its depth at c. 31 m. There is depth sounding evidence for the maximum depth being 10 m (Warbrick 1936, p. 3). Much of the lake was < 10 m deep, judging by abundant reed beds in old lake maps and photos. In the absence of the lake, these reed beds provide a surrogate bathymetry of the old lake. The authors identified *Eleocharis sphacelata* (kuta) and/or *Schoenoplectus validus* (kāpūngāwhā), later renamed as *Schoenoplectus tabernaemontani*, in old lake photos and these reeds continue to grow in Rotorua lakes. They grow in North Island freshwater lakes in up to 2 m and 1 m depths, respectively (Coffey & Clayton 1988, pp. 49, 55). Thus we can deduce the lake depths over the large areas of reed beds occupying much of the southern and central lake and nearly all the littoral zone. At the time of the eruption, the authors estimate the modal lake depth was likely 2–3 m. These two species are shown growing today in Lake Tikitapu in supplementary Figure S5.

Data quality

Spatial error analysis was completed for the Hochstetter survey following the method of Foote & Huebner (1995). LINZ confirmed the Topo50 map at defined points around Lake Rotomahana may be accurate to ± 22 m. Our analysis, including all likely sources of error and a Topo50 versus Google Earth audit, concluded the likely additional plotting error is some 17 m, giving a total likely error of ± 35 m. This may seem significant until we consider the terraces search is for structures the size of a city block, where an error of ± 35 m is practically insignificant.

Comparison with de Ronde et al. findings 2011–2016

Following positive media releases over 2011–2012 by the WHOI/GNS consortium, a public expectation was created that the terraces survived the 1886 eruption viz: ‘The terraces were never destroyed’, he [de Ronde] said. ‘They never went *anywhere*. What happened to them is that they got completely and utterly covered in up to 10 meters of thick mud, which was all excavated out of the old lake. And then, when the waters rose, they and their muddy cloak disappeared from view entirely’ (Winner 2012, p. 46, emphasis in original).

In 2016, when the research was published in a refereed journal, this expectation was dashed by the de Ronde conclusion: ‘We believe that the majority of both sets of terraces were destroyed during the eruption. However, some tantalizing evidence exists for remnants from both sites to exist to this day’ (de Ronde et al. 2016a, p. 27).

The 2011 de Ronde et al. claims for the Pink Terrace appear based on inadequate pre-eruption photographic research leading to a misinterpreted Spencer photo (Te Papa O.030702), and an image from malfunctioning sonar equipment which led to the *Remus* submersible being sent to image an area different to the one the researchers intended. Our later research places Te Otukapuarangi location two bays north of the de Ronde et al. site and on land.

The 2016 de Ronde and Keam papers derive the locations for both terraces differently to their 2011–2012 method. The White Terrace appears southwest of its reported 2011–

2012 location, but the Pink Terrace (marked by a large *P*) is relocated 300–350 m south and east of its 2011–2012 location (Tontini et al. 2016, p. 22). It is shown further out in water 80–100 m deep, below the tip of North Point. The relative positioning is similar, with the terraces c. 900 m apart. Their 2011–2012 Te Tarata location is somewhat closer to the latest Hochstetter survey location, whereas their 2016 relocation is distant.

The Keam and de Ronde lake surface elevation of 292 MASL is based on an assumption by Keam (Keam 2016, p. 21). Their estimated lake depth of c. 31 m is interpolated from the Keam surface assumption and overlooks the 1885 depth sounding (de Ronde et al. 2016b, p. 20). They deliver an old lake altimetry and bathymetry at variance with both the historical record and with the altimetry and ‘biological bathymetry’ prepared for this article.

The 2016 de Ronde/Keam argument for georeferencing the terraces relies on speculation about a new lake feature (the Pinnacle) and its possible location on or under the Steaming Ranges/Pinnacle Ridge above the old lake. The authors equate this feature with a pyramid-shaped peak (one of several similar peaks) above the old lake, where it can justify their revised terrace locations, providing coordinates linking the old and new lakes. The papers (Keam 2016; de Ronde et al. 2016a) cross-cite to establish the pre-eruption photo with the post-eruption Pinnacle. The resulting latitude, longitude and altitude coordinates do not agree with their 2011–2012 terrace locations and these have been revised to fit into this ‘pyramidal peak-Pinnacle’ hypothesis: unfortunately without evidence beyond an assertion by Keam, cited by de Ronde to justify his revised terrace locations. In summary, there is little consensus between the de Ronde et al. and this article’s research findings.

Conclusions

Much in this forensic cartography with Hochstetter’s survey data challenges our inherited views about the locations and reported destruction of the Pink and White Terraces, as well as the ascription of new Lake Rotomahana features to lost features of the old Lake Rotomahana. For example, the cartography indicates Patiti Island cannot be associated with Te Rangipakaru as recently asserted by Keam (2016, p. 19). The reverse engineered Hochstetter survey provides an evidence-based mapping using primary field survey data, forensic cartography and validation techniques to replace nineteenth, twentieth and twenty-first century conjecture about Lake Rotomahana, Te Otukapuarangi, Te Ngāwhā a Te Tuhi and Te Tarata.

Based on this research, the coordinates for Te Otukapuarangi spring location are $-38.2593, 176.4238$, for Black Terrace Crater centre location $-38.2562, 176.4201$ and for Te Tarata spring location $-38.2563, 176.4329$.

Georeferencing and aerial photography enable us to assess the topography of old Lake Rotomahana as surveyed by Hochstetter and that of the new lake. Waterways, valleys and vegetation lines can now be plotted to connect the old and new lakes. In qualifying Te Puai datum, Te Ariki datum and Black Terrace Crater location together with altimetry and a biological bathymetry; we provide further layers of sensitivity testing for the Hochstetter survey and for other research into the Pink and White Terrace locations.

The forensic cartography delivers a new view of the old lake and terraces, one which seems consistent with what we see in the landscape and with the area’s history and cartography. Given we have established the locations for the Pink, Black and White Terraces and old Lake Rotomahana, we recommend these locations enter the New Zealand

Heritage List. In particular, the 750 m shoreline linking the terrace locations is the only surviving section of the old lake. This follows the alignment of the new lake shore and the 1886 eruption crater. It is a unique New Zealand cultural and heritage site.

From our latest altimetry, the Pink and White Terrace spring platforms are located 10–15 m underground, providing they survive. A full archaeological site investigation including imaging and core drilling is indicated to examine the three terrace locations. Excavation on one or more of the Pink, Black and White Terrace sites may then be determined.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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