

Relocating the Pink and White Terraces of Lake Rotomahana, New Zealand: resolving the 'battle of the maps'

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ABSTRACT: The disappearance of Lake Rotomahana's Pink and White Terraces in the 1886 Mt Tarawera eruption meant the loss of the 'eighth natural wonder of the world'. The unique geothermal features were either destroyed or left unrecognisable, and other landmarks were eventually submerged. This led to conflicting opinions on the locations and fates of the terraces. In the current decade, the rediscovery of a pre-eruption geological feature led to a photogrammetric map by Ronald Keam predicting that extant terrace features would be submerged in the lake close to the shore (de Ronde *et al.* 2016a), while the discovery of a pre-eruption topographical sketch map by Ferdinand von Hochstetter resulted in a counter-claim that the terraces are buried onshore (Bunn & Nolden 2017). The projection of pre-eruption photographic sight lines onto a topographic map led to a third claim that the terrace sites were further offshore and consequently destroyed (Keir 2017). More recently, confirmation of the accuracy of a published map by Hochstetter led to the conclusion that the terrace locations lie within the confines of the current lake (Lorrey & Woolley 2018).

To resolve this 'battle of the maps', we assembled a pre-eruption lake panorama and used spatial technology to project the current lake level onto the pre-eruption landscape and to determine terrace bearings. When plotted on a topographic map, those bearings intersect terrace bearings derived from another early photograph, confirming the terrace sites are within the current lake, relatively close to the shoreline. Furthermore, comparison of pre- and post-eruption photographs indicates that while some Pink Terrace features might be extant, this is unlikely to be true of the White Terrace.

KEYWORDS: Pink and White Terraces, Tarawera eruption, photogrammetry, forensic cartography, digital spatial technology, sight-line analysis, virtual horizon software, digital elevation model, bathymetric map.

Introduction

Observers familiar with the extraordinary natural wonders that abutted Lake Rotomahana were astonished at the extent to which the landscape had changed as a result of the powerful eruptions that occurred around Mt Tarawera early on 10 June 1886. Those individuals included Māori guides, local settlers, government surveyors, scientists, photographers and artists, some of whom were members of rescue parties that searched for survivors in villages buried under the mud and ash that had rained down on the land. More than 120 people lost their lives in New Zealand's worst recorded volcanic disaster, most of whom were local Māori living or camping on or near the shores of Lake Tarawera and Lake Rotomahana.

Once the rescue effort concluded and survivors were accommodated in Rotorua, where shelter and supplies were available, the attention of the colony and government turned to the issue of what had become of the 'eighth natural wonder of the world' – the Pink and White Terraces – following the volcanic cataclysm (Keam 1988: 335–338). A massive eruption had excavated the lake bed and much of the surrounding shoreline to a considerable depth, forming a huge crater. Surviving landscape features further afield were thickly covered in mud, ash and other volcanic debris.

The pink steps of Otukapuarangi (Fig. 1) and the white steps of Te Tarata (Fig. 2) had developed as amorphous silica (silicon dioxide) precipitated from the hot, mineral-rich spring water to form sinter.[1] The depositional process built up the low frontal ramparts of each terrace. The two terraces delighted all who came from different parts of the world to behold them and bathe in the warm pools.

Lake Rotomahana had been a significant tourist destination since the mid-1860s. A number of artists, such as John Kinder (1819–1903), Charles Barraud (1822–97), William Fox (1812–93) and J.B.C. Hoyte (1835–1913), spent time at the lake, making field sketches and documenting colours before painting romantically inspired landscapes back in the studio. The six weeks that Charles Blomfield (1848–1926) spent early in 1885 camping beside the lake with his easel, canvases, oils and eight-year-old daughter, painting 'direct from nature', arguably gave his reproductions of the terraces (Figs 1 and 2) greater fidelity than those of his contemporaries (Williams 1979: 73).

With the rapid development of photography in the third quarter of the nineteenth century, professional photographers brought large wooden cameras and tripods to the lake in order to expose their glass plate negatives to a wide variety of scenes. Over a period of five days spent at Rotomahana in February 1885 while the Blomfields were still in the vicinity, the Auckland photographer George Valentine (1852–90) amassed what has been described as 'the most… artistically interesting collection' of more than 40 images of Rotomahana (Hall 2004: 37–46). In October 1885, the Dunedin photographer Alfred Burton

Fig. 1 *Pink Terraces*, 1886, oil on canvas, 590 × 945 mm. Artist Charles Blomfield (Te Papa 1943-0009-1). View from the ridge on the southern side of the terrace, looking north-east. The top platform of the Pink Terrace can be seen, but the spring pool is just out of sight. In the middle of the painting, the steps of the White Terrace ascend the northern end of Pinnacle Ridge, behind which towers Mt Tarawera.

Fig. 2 *White Terraces, Rotomahana*, 1897, oil on canvas, 868 × 1483 mm. Artist Charles Blomfield (gift of Mr D.L. Murdoch, Auckland Art Gallery Toi o Tāmaki U/27). View from the northwestern corner of Lake Rotomahana, looking eastward at the northern end of Pinnacle Ridge. The terrace's hot spring pool is at the top of the white steps, within a breached hydrothermal crater. The high point on the left side of the crater rim is the 'Pyramidal feature' labelled on Fig. 4.

(*c.* 1834–1914) camped in front of the White Terrace for eight days (Whybrew 2010: 254), selecting the most promising views and exposing his numerous plates only when atmospheric and lighting conditions were favourable. The Tauranga photographer Charles Spencer (1854–1933) 'built a considerable portfolio of photographs' of the terraces while visiting Lake Rotomahana on a number of occasions (Cocker 2013: 23).

Despite the abundance of pre-eruption painted and photographic imagery, and even the existence of a published map (Hochstetter & Petermann 1864) based on an 1859 scientific survey carried out by a team led by the German-Austrian geologist Ferdinand von Hochstetter (1829–84), the post-eruption fate of the terraces was contested at the time. Guides, local settlers, reporters, photographers, surveyors and scientists reaching the site drew different, sometimes opposing, conclusions, and the matter was never resolved in the nineteenth century, nor in the twentieth. To appreciate why this impasse occurred, further explanation of the events of the eruption is required.

The Tarawera and Rotomahana eruptions

Along the eastern coast of the North Island, a section of the Pacific Plate is being subducted under New Zealand and the Australian Plate (e.g. Reyners *et al.* 2011). The Taupo Volcanic Zone (TVZ) is one manifestation of this regime, where crustal extension in response to steepening and rollback of the subducting slab has resulted in rift formation (Seebeck *et al.* 2014). Basalt sourced from the mantle wedge overlying the descending slab undergoes various degrees of contamination by continental crust to produce eruptive products that range from basalt to rhyolite (Deering *et al.* 2008). Mt Tarawera and Lake Rotomahana are volcanic features within the TVZ. The 1886 Tarawera eruption followed a swarm of earthquakes as basaltic magma made its way towards the surface. Initial magmatic eruptions of ash and scoria along the length of Mt Tarawera were succeeded by interaction between magma and groundwater beneath Lake Rotomahana. The heat of the magma vaporised groundwater, and the resultant extreme pressures caused an

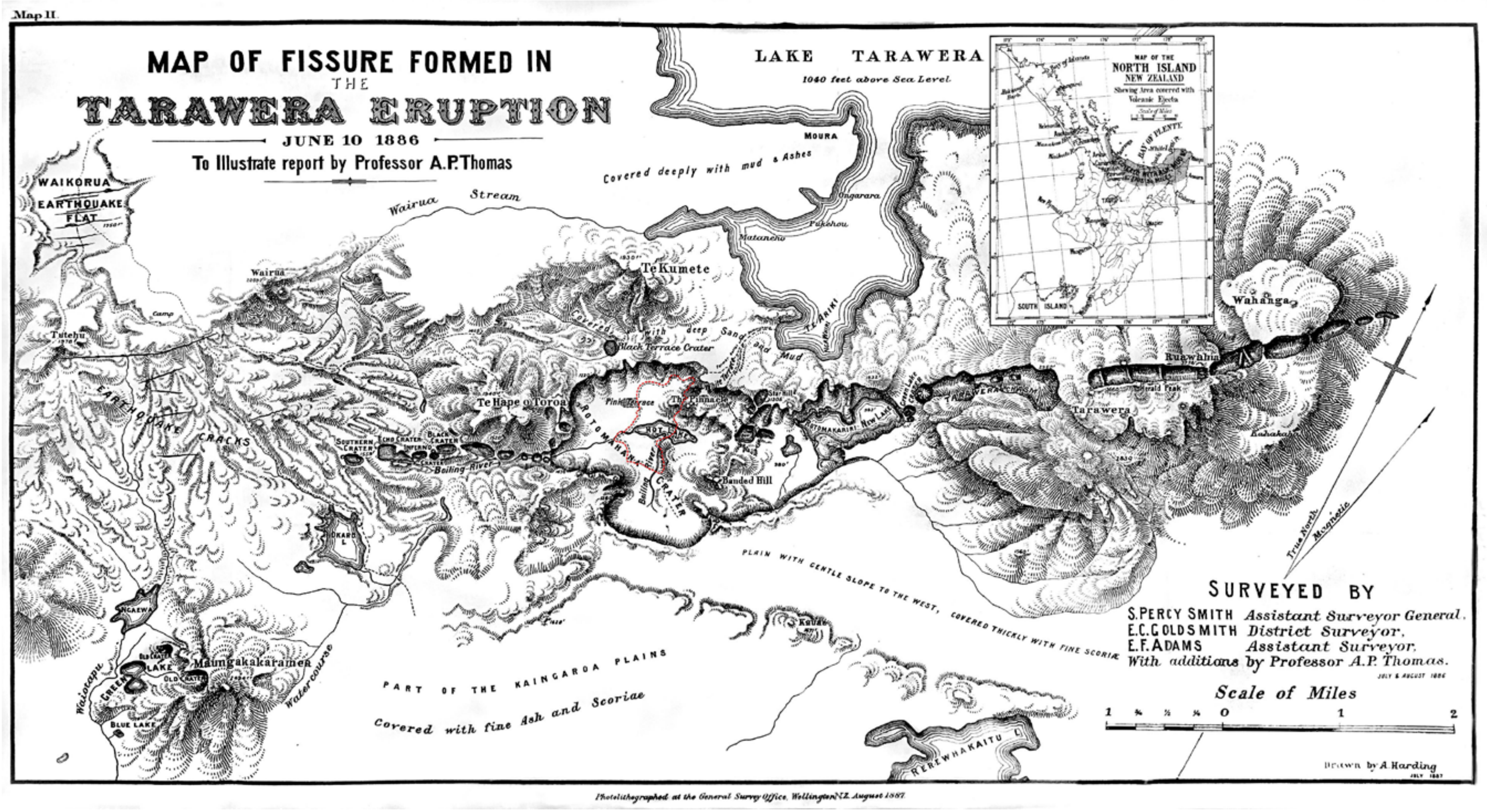

Fig. 3 *Map of Fissure Formed in the Tarawera Eruption, June 10 1886, to illustrate report by Professor A. P. Thomas*. Inset: detail from *Tarawera Eruption Map Shewing the Great Fissure and Points of Eruption*. Cartographer A. Harding. Photolithographs, *in*: Smith (1886). The added dashed red line indicates the extent of pre-eruption Lake Rotomahana as determined by S. Percy Smith.

explosive phreatomagmatic eruption.[2] This event ejected the contents of the lake and excavated the lake floor to a considerable depth to form the Rotomahana Crater.

The extent of the crater is well illustrated on a post-eruption map (Fig. 3) that was based on the July 1886 survey conducted by S. Percy Smith (1840–1922), the Assistant Surveyor General of New Zealand. The map forms part of a report prepared by the Auckland University College geologist Algernon Thomas (1857–1937) that was included in Smith's official report on the eruption to the New Zealand government (Smith 1886). Nearly 0.5 km^3 of sediment was ejected (de Ronde *et al.* 2016b: 74–75), which then fell on the hills, valleys and plateaus surrounding the lake, covering them with a deep layer of mud and sand, metres thick in places. Other phreatomagmatic eruptions southwest of Lake Rotomahana then blasted out a series of smaller craters along the Waimangu Valley. The eruptions that occurred over a six-hour period extended along a 17 km-long feature, the Tarawera Rift, which runs from the Southern Crater, under the current Lake Rotomahana and along the full length of Mt Tarawera.

Following the Rotomahana phreatomagmatic eruption, heat from the intruding basaltic dyke also vaporised water in the hydrothermal plumbing system that supplied the terraces and other smaller geysers and springs, causing less powerful phreatic (hydrothermal) eruptions (de Ronde *et al.*, 2016a: 140),[3] most likely through existing vents. For weeks after the main eruption events, jets of steam intermittently escaped from these vents, or clouds of steam billowed out on a more sustained basis. Such geothermal activity continued for months or even years as Rotomahana Crater gradually filled with water, extinguishing most of the plumes.

Determining the fate of the terraces

In the 133 years since the Tarawera eruption, a significant number of interested parties have used very different methods in the quest to locate the sites of the Pink and White Terraces, and hence determine their fate. Methods include contemporaneous observations, early topographic and geological surveys, photographic and artistic comparisons, manual photogrammetry, remote bathymetric surveying, forensic cartography, sight-line analysis, and the use of ground-penetrating radar and LIDAR (light detection and ranging). The conflicting claims of the current decade have been sparked, however, by two sketch maps prepared exactly 100 years apart, together with the first published map of pre-eruption Lake Rotomahana. These maps have been pitted against each other by various authors to justify claims, counter-claims and rebuttals of claims.

Giving 'familiar' accounts

A number of observers familiar with the pre-eruption landscape visited the site in the days or weeks immediately following the eruption. Some, such as the local tourist guide Alfred Warbrick (1860–1940), claimed the terraces survived under the thick layer of mud and ash that had rained down, while others discounted the possibility that either had survived (Keam 1988: 335–338). That diametrically opposite opinions were expressed was mainly due to the dramatically transformed landscape, both within and surrounding the massive Rotomahana Crater excavated by the eruption beneath the bed of the old lake, which rendered many pre-eruption landmarks unidentifiable. This situation was compounded by the purported absence of a formal survey map (Keam 1988: 335) that could have been used to determine the original location of each terrace by compass bearings, and hence, by direct observation, the fate of each.

Comparing 'before and after' photographs

In February 1887, pre- and post-eruption photographs taken by Valentine of the site of the White Terrace were exhibited in Otago Museum, confirming 'the total destruction of the White Terrace' (*Otago Daily Times* 1887: 2).[4] In an illustration in his report on the Tarawera eruption, Thomas compared engravings based on those two photographs 'taken from the same point of view', and concluded that 'the exact position of the [White] terraces cannot be identified, as the ground around where they formerly stood has been blown away' (Thomas 1886: 52 and 57). That the two photographs were taken from the same vantage point depended on comparing the 'outlines of hills', which, according to another reporter, 'proved tolerably conclusively that a lake now exists on the site of the White Terrace' (*New Zealand Herald* 1886: 4).

Painting the same scene

After the Rotomahana eruption, which Blomfield compared to the loss of a near relative, the painter returned to the site and over a period of three weeks 'went down into the crater day after day, painting and sketching everything of interest about the great rift'. Furthermore, he added that 'some of the sketches I then took were as near as possible from the same position as some of those I took before the eruption and on comparing them afterwards I was more than ever confirmed in my opinion as to the impossibility of the least fragment of the terraces ever being seen again' (Blomfield 1902; Blackley 1987: 15).[5]

Unfortunately, most of these post-eruption oil sketches have either been lost or have not yet made their way into public collections. A small oil sketch entitled *Site of Destroyed Terrace, October 1886* (reproduced in Williams 1979: 93) is clearly meant to be of the site of Otukapuarangi given the shape of the peak protruding above the ridgeline, but as the equivalent pre-eruption painting has not been located, it cannot be used to illuminate the fate of the Pink Terrace.

Treating cameras as 'recording theodolites'

Given the abundance of high-quality pre-eruption photographs, particularly those by Burton, Valentine and Spencer, the physicist Ronald Keam created an outline map (Fig. 4) of pre-eruption Lake Rotomahana in 1959 by treating the cameras that had taken the images as 'recording theodolites' (Keam 2016: 25 and 27). Using a form of pre-digital photogrammetry, he estimated relative bearings to important landscape features from three key pre-eruption photographic vantage points (Panorama Point, C. Spencer No. 9 and Koingo). This required deducing the approximate angular measure of the field of view of each glass plate negative. Keam then adjusted the relative positions of the three vantage points and the orientation of the views from each, either mathematically or graphically, until the three bearings to each of the more significant features intersected on a sketch map.[6] Knowing the approximate sizes of the terraces and the distances between some landscape features from earlier accounts, he estimated a scale for the map. How he determined the geographical orientation of the map is unclear.

Although Keam's 1959 pre-eruption outline map of Lake Rotomahana provides a geographical bearing from one terrace spring to the other, and their approximate distance apart, it could not be used at that time to locate the terraces geographically as there was no feature on that map that could be aligned with any known landmark on a modern topographic or bathymetric map and therefore function as an anchor point.

Making an incidental discovery while scanning the lake bed

In 2012, a Geological and Nuclear Sciences (GNS) team led by the volcanologist Cornel de Ronde collaborated with oceanographers from Woods Hole Oceanographic Institution in the United States to conduct a bathymetric survey of Lake Rotomahana using sonar scanners in state-of-the-art autonomous underwater vehicles, which resulted in a highly accurate bathymetric map (Fig. 14). One of the more surprising visual discoveries was a rocky underwater promontory located at ~38°15'38" S, 176°26'8" E (de Ronde *et al.* 2016a: 130, fig. 5B), which bears a strong resemblance to a distinctive rock formation (Fig. 11) visible in a number of post-eruption photographs and paintings (de Ronde *et al.* 2016b: 65, fig. 6). The location of this feature, labelled 'The Pinnacle', is marked on the 1886 post-eruption map (Fig. 3). The Pinnacle is considered to be the remnant of a volcanic dyke belonging to an earlier intrusion of rhyolitic magma, which cooled *in situ* to form a highly resistant structure (de Ronde *et al.* 2016a: 138–139).

The research team acknowledged the difficulty of ascertaining the location of The Pinnacle relative to the terraces before the eruption, which constrained their 'ability to directly tie present-day bathymetry back to the pre-eruption landscape' (de Ronde *et al.* 2016a: 138). However, Keam fixed its location on a revised version of his outline map ~150 m northeast of the vent of Te Tarata spring (Fig. 4, black ✱ symbol), deep within the ridge that originally housed the White Terrace (de Ronde *et al.* 2016a: 128, fig. 3). Keam argued that it had to be located somewhere in the northern part of Pinnacle Ridge, because the southern part was too low given the overall mass of material removed from the ridge during the Rotomahana eruption. The location within the northern end was specified on the basis of a 'careful analysis of numerous photographs that pre-date the eruption' (de Ronde *et al.* 2016a: 138). This is puzzling, because if The Pinnacle was deep within Pinnacle Ridge, then it would not be visible in any pre-eruption photograph.[7]

On the basis of the assumed accuracy of Keam's revised pre-eruption outline map and his placement of The Pinnacle on that map, de Ronde *et al.* (2016a: 139) proposed that Te Tarata spring would have been located about 150 m from the known geographical coordinates of The Pinnacle along a bearing of ~240°, and that Otukapuarangi spring would be located approximately 1150 m away along a bearing of ~245°. These locations would place the sites of both terraces within the current lake, but relatively close to the shore.

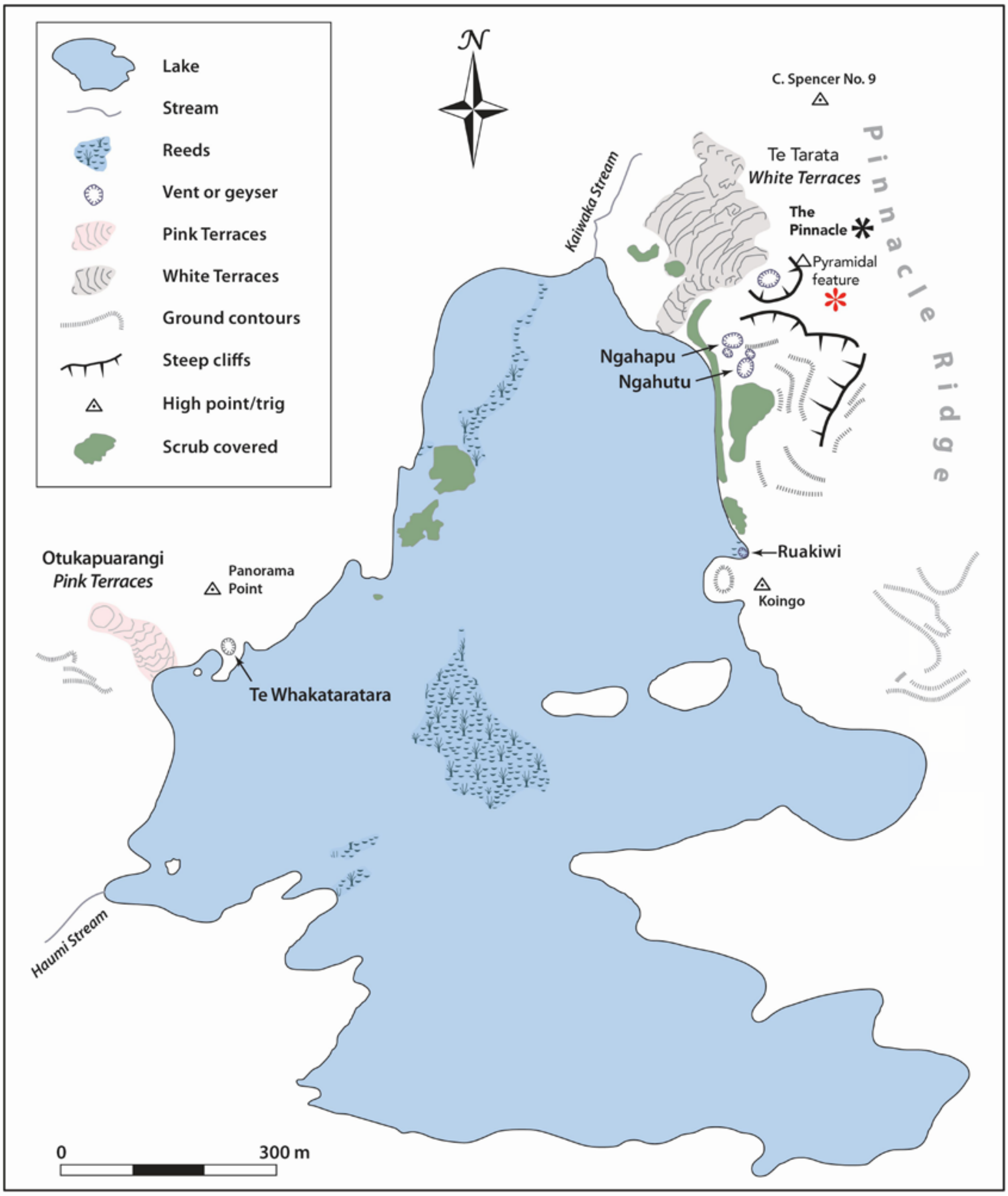

Fig. 4 *Map of Lake Rotomahana pre-1886 eruption, as determined by photogrammetry*. Reprinted from de Ronde, C.E.J., Fornari, D.J., Ferrini, V.L., Walker, S.L., Davy, B.W., LeBlanc, C., Caratori Tontini, F., Kukulya, A.L. and Littlefield, R.H. (2016a) The Pink and White Terraces of Lake Rotomahana: what was their fate after the 1886 Tarawera Rift eruption? *Journal of Volcanology and Geothermal Research* 314: 126–141, copyright (2016), with permission from Elsevier. Reproduced by Tony Mander. The three triangles with a dot mark the vantage points of the key pre-eruption photographic views that Keam analysed using photogrammetric methods in order to generate the map. Keam inserted the location of The Pinnacle (black ✱ symbol) after its rediscovery in 2012. De Ronde *et al.* (2018) shifted its location to southeast of the 'Pyramidal feature' (added red ✱ symbol).

Comparing modern views with early photographs

The amateur investigator Herbert Fitzgerald compared photographs he had taken on and around the modern lake with pre- and post-eruption photographs to support his claim that the terraces had survived with only 'some superficial damage' and could be re-exposed by lowering the lake level (Fitzgerald 2014: 79). This seems a somewhat optimistic conclusion given the strength of the phreatomagmatic and phreatic eruptions that occurred in the vicinity of the terraces.

'Reverse engineering' a rediscovered sketch map

In 2010, in a private collection in Basel, Switzerland, the research librarian Sascha Nolden rediscovered the field diary in which Hochstetter recorded observations made and bearings taken at Lake Rotomahana, as well as two sketch maps of the lake (Nolden & Nolden 2013). One of the maps is a 'topographical sketch', most likely completed by Hochstetter immediately after his Rotomahana visit (Hochstetter 1867: 420). The other is a gridded copy (Fig. 5), originally thought to have been prepared after he had returned to Europe for the cartographer August Peterman (Bunn & Nolden 2016: 38), but now considered more likely to have been drawn in New Zealand during 1859 (S. Nolden, pers. comm., 2018). Nolden translated sections of the field diary pertaining to the Rotomahana survey measurements, and in 2016 collaborated with the independent researcher Rex Bunn, who reversed bearings in order to establish the geographical coordinates of Hochstetter's two observation stations (Bunn & Nolden 2017). A partially transparent copy of the gridded map was overlain on a Google Maps view of Lake Rotomahana, and then scaled and rotated until the two observational stations on the sketch map sat over their respective geographical coordinates in Google Maps. The two terrace springs were then deemed to be at those locations on the modern map beneath those marked on the sketch map, which happen to be under land not far from the lakeshore rather than within the current lake (see de Ronde *et al.* 2018: 9, fig. 1A).

In their rebuttal of de Ronde *et al.*'s (2016a) findings, Bunn and Nolden (2017) argue that Keam's revised outline map was not a reliable tool for georeferencing the terraces because his placement of the recently rediscovered 'Pinnacle' was speculative and unsupported by evidence (Bunn & Nolden 2017: 16). Regardless of whether this allegation is true or not, the lack of clarity in the de Ronde *et al.* article about how Keam determined the location of The Pinnacle within the northern end of Pinnacle Ridge did not help matters. There is, however, also an issue with Bunn and Nolden's methodology. As one of the observation stations was on Puai Island in Lake Rotomahana and the other near the southern lakeshore, Hochstetter had no way of measuring the distance between them. Therefore, he had no measured baseline with which to construct an accurate 'topographic sketch' with a reliable scale. Consequently, there is likely to be a considerable margin of error in where he placed the springs on his sketch map. Moreover, even though the bearings for Te Tarata and Otukapuarangi springs from the southern observation station are likely to be accurate, the fact that Hochstetter never completed his obvious intention of taking similar bearings from the Puai Island station (Hochstetter 1859: 53) means that the location of each spring cannot be determined from the intersection of two bearings.

Using sight lines to pin down locations

In a further attempt to locate the terraces, the freelance researcher Bill Keir projected sight lines derived from pre-eruption photographs onto the current topographic map in order to determine the original locations of the two terraces (Keir 2017). Such sight lines are based on one identifiable extant feature, such as a hilltop, lying directly in front of a more distant extant feature, such as a mountain peak. When a pair of such sight lines derived from a single photo are projected onto the topographic map, their intersection marks the vantage point of the photographer.

After applying this method to a number of pre-eruption photographs, Keir asserts that the geographical locations of the terraces would have been well within the confines of the current lake. Furthermore, for the terraces still to exist at those loci, given their original altitudes and the current elevation and depth of the lake, they would have to be floating in the lake – clearly a physical impossibility. Keir's conclusion, therefore, is that they no longer exist (Keir 2017: 5).

However, Keir's dependence on sight lines with one or other of the two determining features being a poorly defined aspect of a distant hill or mountain, the lack of cross bearings approaching perpendicularity in the analysed collection of photographs, and the absence of measured distances from the intersection of projected bearings to conjectured terrace locations tend to undermine confidence in his conclusion.

Fig. 5 Hochstetter's gridded field map prepared for the cartographer August Peterman (detail), watercolour, ink and pencil on paper (Hochstetter collection Basel, HCB 3.5.10). The southern observation station is marked by a cross within a circle, labelled 'Beob.pkt' (*Beobachtungspunkt*, or 'observational point'). The dashed red line between the two terrace springs has been added.

Hunting for the terraces using radar

In September 2017, Bunn and others used ground-penetrating radar to survey areas above the lake shoreline where he believed remnants of the terraces would be found. Six months later, in a Radio New Zealand interview, Bunn reported that the survey was unsuccessful as the radar had not been able to penetrate the ground far enough for imaging to confirm the presence or absence of terracing at those locations (Bunn 2018).

Revising bearings and relocating the terraces

Early in 2018, Bunn revised the geographical locations of Hochstetter's two observation stations based on a more accurate interpretation of what the bearings were pointing to in the field diary. This nearly doubled the distance between them (Bunn *et al.* 2018: 11). The effect of this is to relocate the terraces when Hochstetter's map is overlain on a Google Earth view, but they remain on land close to the shoreline (Fig. 10; triangle symbols indicate the locations on the topographical map). Furthermore, Bunn asserted that the locations of the terraces had now been established, but that the only way to confirm his 'on-land' locations would be to drill (Bunn 2018).

Tangata whenua express doubts

Such was the contested state of affairs in late March 2018 when Alan Skipwith, chairman of the Tuhourangi Tribal Authority, which holds trusteeship for much of the land on the western side of the lake, responded to Bunn's announcement. Skipworth stated that 'there have been numerous attempts and similar statements made in the past as to possible locations for the terraces with assurances that those conclusions have withstood scientific scrutiny and peer review. Unfortunately, none of those investigations have proven fruitful' ('Iwi speaks out' 2018).

Rebutting a rebuttal and relocating the Pink Terrace

In August 2018, de Ronde *et al.* published an additional paper rebutting Bunn and Nolden's 2017 rebuttal of their earlier paper and challenging the claim that the terrace remnants would be found on land rather than under the lake. The researchers used sight lines derived from a pre-eruption photograph by Charles Spencer (Fig. 9) to show that the White Terrace could not have been above the modern shoreline as Bunn and Nolden claimed,[8] and the location of a magnetic anomaly to demonstrate that the Pink Terrace had to be situated within the boundary of today's lake.

A further revision of Keam's pre-eruption outline map (de Ronde *et al.* 2018: 15–16) placed the Pink Terrace where sonar had located terrace remnants on the lake floor (Fig. 10, magenta cross), and enabled the western shoreline to align more closely with distinctive bathymetric features. That the conjectured location of The Pinnacle relative to Te Tarata was shifted on the outline map in order to facilitate the above alignments means that the final placement of that structure is no longer based solely on an '*independently* ascribed' location (italics in original) as was initially determined (de Ronde *et al.* 2018: 14).

Using Hochstetter's published map and LIDAR

Following these conflicting accounts of the original locations of the terraces, the Tuhourangi Tribal Authority asked climate research scientists Andrew Lorrey and John-Mark Woolley at the National Institute of Water and Atmospheric Research (NIWA) to review Hochstetter's survey notes and maps. The scientists evaluated an extensive set of Hochstetter's field data in order to reconstruct his survey site and stations (Lorrey & Woolley 2018). This reconstruction was supported by digital elevation models generated from site data produced by a remote sensing system known as LIDAR, which measures distance and topography by timing reflected light pulses. Their methodology confirmed that Hochstetter's published map (Fig. 6), which is a projection relative to magnetic north, is far more geographically reliable than the topographical sketch map used by Bunn *et al.* (Fig. 5).[9] Using freshly determined locations of Hochstetter's two observation stations as anchor points, the NIWA scientists oriented and scaled a semi-transparent version of the published map over the current topographical map. They found that the terrace locations are entirely within the confines of the modern Lake Rotomahana, close to where the GNS research team had determined them to be.

Our research journey

Intrigued by the fact that such a wide variety of approaches had failed to produce consensus on the original location and status of each terrace, but had rather led to often opposing claims regarding the location and status of both Te Tarata and Otukapuarangi, we investigated whether the use of virtual horizon software to identify the vantage points of pre-eruption imagery, as well as further visual comparisons of pre- and post-eruption photographs, might contribute to resolving the 'battle of the maps'.

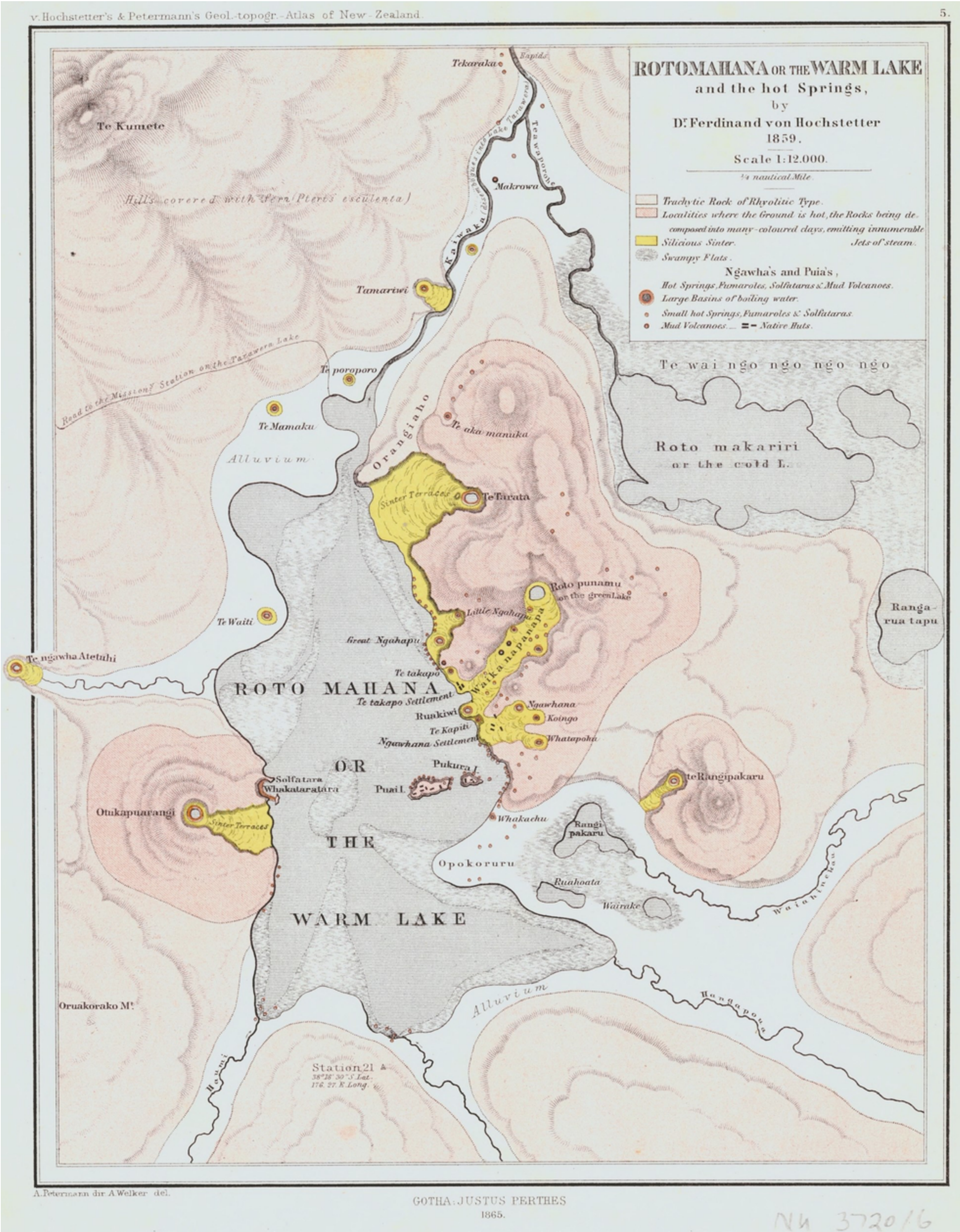

Fig. 6 The English version of Hochstetter's published map of Lake Rotomahana (Hochstetter & Petermann 1864). Lorrey and Woolley (2018) determined that the map is oriented to magnetic north.

Contemplating landscape paintings

As a co-author of this article, George Hook, had previously located unknown sites of wilderness and alpine paintings by the antipodean artist Eugene von Guérard (1811–1901) by applying spatial technology to the accurate field sketches on which his artworks are based (Hook 2018), we initially contemplated analysing Charles Blomfield's 'direct from nature' Rotomahana paintings. Promisingly, one particular subset of three paintings encompassed most of the background landscape surrounding the lake. Despite the photographically confirmed fidelity of Blomfield's terrace depictions, it was scientifically (if not from an art history perspective) disappointing to find that the artist heightened background mountains and hills to dramatise the view, and foreshortened middle grounds to bring features closer to the viewer. Through such artistic devices Blomfield sought to create sublime landscapes, but in doing so he rendered them unsuitable for spatial analysis. We therefore shifted our research focus to analysing early photographs.

Assembling a pre-eruption panorama

Given the inconclusive results of comparing single-plate 'before and after' photographs (Thomas 1886), and of intersecting sight lines derived from pre-eruption images (Keir 2017), it occurred to us that if panoramic images could be located or assembled out of adjacent or overlapping photographs, these would provide a more reliable indication of the original locations and possibly the fates of the terraces. The much wider field of view of panoramas would encompass more horizon landmarks and generate cross-bearings approaching perpendicularity, thereby resulting in the determination of accurate vantage points and bearings using spatial technology.

An impressive double-plate pre-eruption panorama of each terrace by Charles Spencer was located in the online collection of the Museum of New Zealand Te Papa Tongarewa (Te Papa).[10] Unfortunately, neither panorama encompassed enough widely spaced extant horizon features to enable the vantage point and field of view to be established accurately by the use of spatial technology, as in each case the horizon is largely dominated by the now missing terrace and enclosing crater, as well as the ridge(s) that housed the terrace.

Further trawls through scans of glass plate negatives and sepia-coloured photographs held in the pictorial collections of Te Papa and the Alexander Turnbull Library (ATL) in Wellington revealed that Alfred Burton was by far the most prolific photographer of Lake Rotomahana.[11] Visual comparison of numerous photographs led to the identification of five 6 × 8 inch glass plate negatives, likely taken in October 1885, that were undoubtedly meant to form a single, very wide panorama encompassing the whole of Lake Rotomahana and its environs.[12] An attempt to use the Photomerge function of Adobe Photoshop to stitch the scans together failed as there was insufficient overlap between adjacent images, so two highly competent Photoshop users were separately asked to merge them manually. After dehazing the high-resolution scans and adjusting a range of settings to give the clearest and most tonally consistent images, as well as dealing with some of the distortions created by the camera lens, such as vignetting, the images were integrated into a coherent, seamless panorama (Fig. 7).[13] The fact that marginal features of adjacent images could be merged so smoothly confirms that the legs of the tripod on which Burton's large wooden camera was mounted were not moved as the series of exposures was recorded, although the far right image was not taken in quite the same horizontal plane as the camera had been tilted upwards by about 1°, most likely accidentally.

Starting from the left side of the panorama, the multiple peaks of Mt Tarawera tower behind what is now known as Pinnacle Ridge, with its numerous geysers, basins of boiling water and fumaroles. The white steps of Te Tarata ascend the left (northern) end of that ridge to the crater that partially encloses the spring pool from which steam is wafting, and from which a geyser would intermittently erupt. Adjacent to the base of the other end of the ridge are two small islands, Puai and Pukura, behind which sits the more elevated dome of Te Rangipakaru. In the foreground of the middle section of the panorama, the small Whakataratara crater emits sulphurous fumes and steam, next to which is a small circular bay open to the lake. Across the lake from that feature sits Rotomahana hill, with the more distant peaks of Maungakākaramea (Mt Kākaramea or Rainbow Mountain) jutting over the far right end of the ridge. In the middle ground of the far right section, the terraced pools of Otukapuarangi step upwards from the lake to the top platform, with its spring pool partially obscured. Above that terrace lies Oruakorako hill, with the summits of Hapeotoroa dome spread out behind it.

Clearly, Burton's panoramic vantage point was significantly higher than the top platform of Otukapuarangi, which is estimated to have been about 25 m above the pre-eruption lake level (Keam 2016: 25). This gave some hope that, despite the ~48 m rise in the lake's elevation estimated by recent research (de Ronde *et al.* 2016a: 138), Burton's vantage point might have been on land above the current shoreline or, if out on the lake, at least not under the modern water level.

Fig. 7 *Panorama of Lake Rotomahana*, assembled by Andrew Thomas from scans of five gelatin dry plate negatives, all 150 × 200 mm. Photographer Alfred Burton. Plates (all Te Papa): [untitled] (C.010659); *Rotomahana* (C.010654); *Rotomahana* (C.010655); *Rotomahana* (C.010656); *Rotomahana (Pink Terrace)* (C.010594). These plates were most likely exposed during October 1885.

Applying spatial technology

An alternative approach to determining the vantage point of a photograph by intersecting sight lines is to use 'virtual horizon' software. Such an application is typically used in the field to identify surrounding peaks once the location has been determined from signals received from the Global Positioning System and the bearing is fixed by the tablet's or mobile phone's compass. However, the software can also be used to determine the vantage point from which a photograph was taken if the virtual horizon can be aligned with the photographed horizon, although this can be a time-consuming process. In this approach, the position of the virtual observer is moved about on a Google Earth or Google Map view of the landscape until the profile of the virtual horizon comes to resemble that of the photograph. When the shape, location and elevation of the virtual peaks – as well as those of any other distinctive features of the horizon, such as the gap between peaks – align with equivalent features in the photograph, then the geographical coordinates and elevation of the virtual viewer will be close to the vantage point of the photographer. Moreover, the vantage point of a panoramic photograph can be accurately determined because there are more features to align, and those features are often further apart, allowing more reliable comparisons to be made.

If a virtual panorama could be aligned with Burton's photographic panorama, then the virtual view could also be used to infer bearings to significant hydrothermal features visible in the photographic panorama, such as a terrace spring, or define an arc between two bearings for a whole terrace. A further bonus is the possibility of projecting the current lake level onto the pre-1886 panorama, which would clarify whether the visible hydrothermal features, if extant, might be buried on land or submerged in the lake.

For this process we used the PeakFinder application, whose digital elevation model is based on Shuttle Radar Topography Mission (SRTM) elevational data (F. Soldati, pers. comm., 2018).[14] The position of the virtual observer is given to the nearest arc second (symbol "), which at all longitudes is ~31 m in the north–south direction, and at Lake Rotomahana's 38° S latitude is ~24 m in the east–west direction. Thus, the virtual observer is located somewhere within a ~750 m^2 rectangle, which is equivalent to 0.075 ha. Given that the two terrace springs were only about 1 km

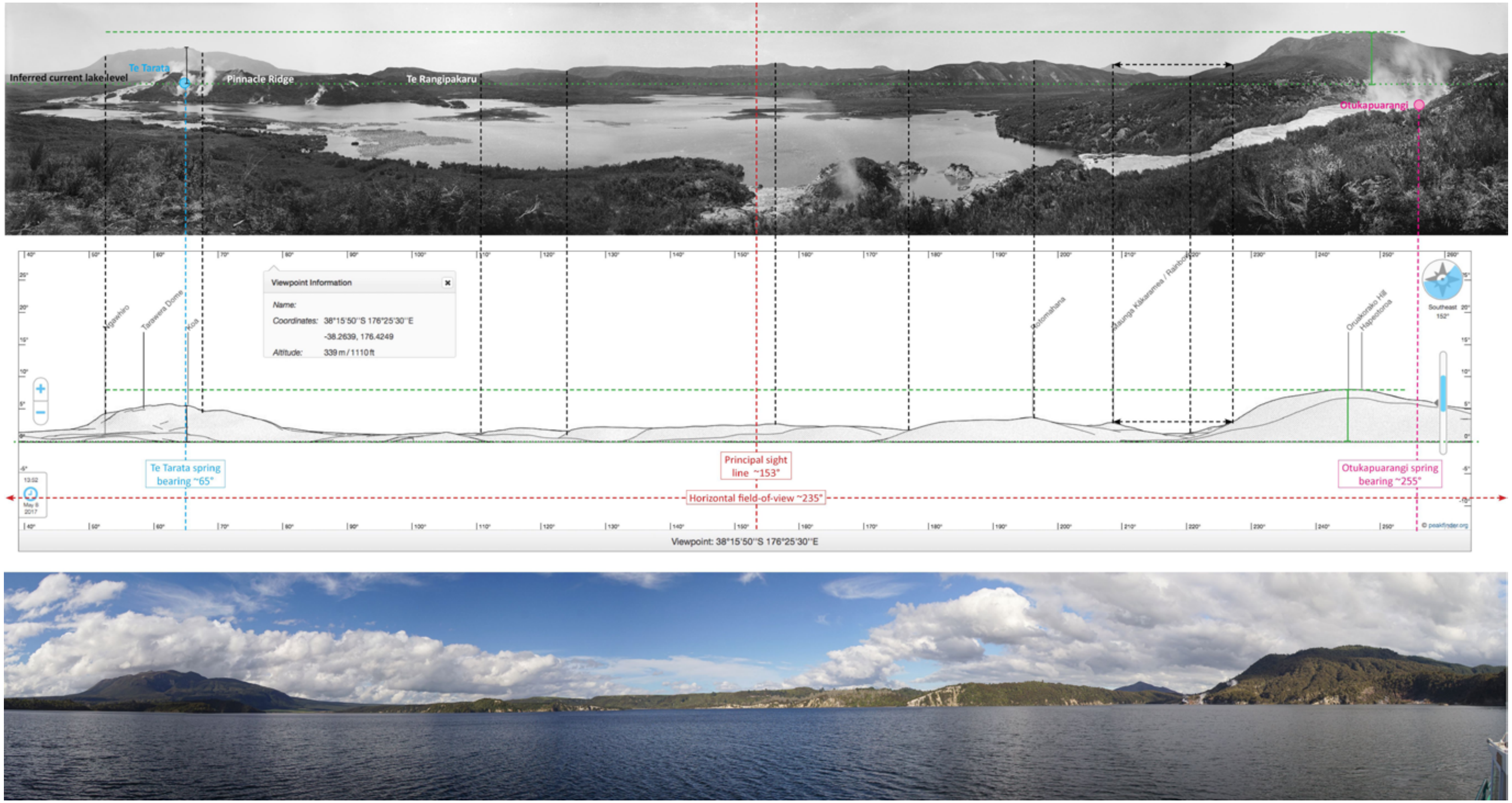

Fig. 8 Comparing virtual and photographic panoramas. Top: panorama of Lake Rotomahana (see Fig. 7). Middle: PeakFinder's virtual view from the same locus as Burton (© peakfinder.org). Bottom: *Panorama of Lake Rotomahana Taken from Aboard the Launch Ariki Moana*. Photographer Andrew Thomas. Dashed magenta lines relate to the Pink Terrace and cyan lines to the White Terrace. The dashed green lines indicate the elevation of Hapeotoroa and the dotted green lines the projected current lake level.

apart according to the scale on both Hochstetter's and Keam's published maps (Figs 4 and 6), and that the White Terrace was nearly 250 m in length and the Pink Terrace was at least 150 m long (Keam 2016: 25), then a projected bearing to the middle of each terrace taken from a vantage point located to the nearest arc second would be sufficient to intersect the original location of that terrace, even though Burton was obviously positioned much further away from the White Terrace than the Pink Terrace. However, in our photographic analysis we used bearings to the approximate locations of the spring pools, which act as more constrained visual reference points than the terraces. The spring pool of Te Tarata covered an area of ~350 m^2, and that of Otukapuarangi ~150 m^2 (Hochstetter 1867: 410 and 418).

An initial location on the northwest shore of the current Lake Rotomahana was selected, and the virtual vantage point systematically moved horizontally on land and on the lake, as well as vertically above the land or water, until most of the more distinctive distant virtual landscape features came into alignment with equivalent features on Burton's panorama. The closest fit occurs out on the lake at the geographical coordinates 38°15'50" S, 176°25'30" E at an elevation of ~339 m (Fig. 8). Although the degree to which a virtual view matches a photographed view is a subjective visual judgement, when a cluster of closely spaced virtual views are compared, the one that produces the best fit with the photographed horizon is usually readily identifiable (see below). According to the bathymetric map (Fig. 14), the current lake is ~80 m deep at that location, but given the steeply sloping lake floor and the ±0.5" locational accuracy of PeakFinder, there is a considerable margin of error. Nevertheless, even at a shallower depth, a significant amount of the ground beneath Burton's feet must have been removed in one of the hydrothermal eruptions that occurred in the vicinity (de Ronde *et al.* 2018: 8).

To test the extent to which the virtual horizon might still match the photographic horizon at locations slightly further afield, a 5" × 5" grid was used with the above coordinates as the central point. Locations at the eight compass rose points 1" away resulted in minor misalignments with Burton's panorama, but those 2" away resulted in significant dislocations. We also elevated the virtual observer at the optimal geographical location, but just a 10 m gain in altitude revealed significantly more of distant Maungakākaramea above the far right flank of Rotomahana hill (along bearing 208° on Fig. 8).[15] As PeakFinder's virtual observer cannot descend below the lake's surface, we were unable to check whether the relative heights of distant features in the virtual panorama might form an even better fit with the photographic panorama at a lower elevation. Thus, the locus of the virtual viewer would be within ±1" horizontally and between +5 m and −15 m vertically of Burton's vantage point (Fig. 10, red flag), the latter allowing for the possibility of a better alignment underwater.

As the photographic panorama did not need to be rotated for the virtual horizon to align, Burton's camera was well levelled in the horizontal plane, although the long axis of his camera lens was angled downward by somewhere between 5° and 10° in order to record more landscape and less sky on each plate as the camera was rotated. While the profiles of distant features in the virtual view match the shapes, heights and locations of most equivalent features in the panorama, there are some discrepancies. Nearly all of Pinnacle Ridge and much of Te Rangipakaru dome are no longer apparent, but that is because most of their mass was removed in the phreatomagmatic eruption that created Rotomahana Crater. More problematic is the ill-matching profile of Hapeotoroa dome, but this appears to be the result of poor SRTM data for its slopes and summits, as the shape of the dome in current photographs still closely matches that illustrated in Burton's 1885 panorama (Fig. 8, top and bottom).

According to the equivalent virtual panorama, the five-plate panorama encompasses a horizontal field of view of ~235°.[16] One way of visualising the perspective of this panorama is to imagine it as a partial cylinder encircling a little less than three-quarters of one's head. From Burton's locus at ~38°15'50" S, 176°25'30" E, the whole of the more distant Te Tarata fits within an arc of ~24° between bearings 43° and 67°, with its obscured spring lying on a bearing of ~65°. The much closer Otukapuarangi occupies a ~55° arc between bearings 205° and 260°, with its spring judged to lie on a bearing of ~255°.[17] Therefore, whenever Burton looked towards one spring, the other would be almost directly behind him.

While those spring bearings can be projected onto a topographical map from the now known vantage point, the locus of each spring along those bearings cannot be determined on the basis of Burton's panorama alone. However, as the current lake's surface sits on the 0° altitude line of the vertical field of view in the virtual panorama, that line can be projected onto the photographic panorama (Fig. 8, top and middle, dotted green lines) to indicate whether any extant terrace features would be beneath the lake's surface or above the current shoreline. It should be borne in mind, though, that Burton's vantage point could well have been up to 10 m or so below the surface of the current lake, in which case the inferred lake level would be too low. When compared with the ~25 m height difference (Martin 1888: 15) between the foot and top platform of the Pink Terrace visible in the photographic panorama, the projected current lake level appears to be somewhere between 5 m and 10 m above the top platform. Regardless of whether the inferred lake level is correct or ought to be higher because Burton was in fact lower, any features of Otukapuarangi that survived the eruption would lie beneath the lake's surface buried under ejected mud as well as more recently deposited sediment.

The inferred current lake level also sits just above the top platform of the White Terrace on the far left of the panorama, but as Te Tarata is significantly further away from Burton's vantage point than Otukapuarangi, an assertion that any extant features must also be underwater rather than on land cannot be made confidently on the basis of this image alone.

Acquiring further bearings

In order to obtain a second bearing to each terrace spring that would intersect the bearing derived from Burton's panorama when projected onto a topographic map, thus determining the approximate location of each spring, we analysed a single-plate photograph by Charles Spencer, entitled *Foot of White Terrace. No. 9* (Fig. 9). This image had the additional benefit of its vantage point being close to Te Tarata, thus enabling a more reliable assessment of whether any extant features would be underwater or not. Spencer's pre-eruption photograph is the first image analysed by Keir in his sight-line projections (Keir 2017: 4–6), and is also one of the three key photographic images used by Keam to derive his sketch map of the original Lake Rotomahana (de Ronde *et al*. 2016a: 128, fig. 3).[18] Spencer's photograph has been used repeatedly because it shows features of relatively close extant hills in front of distant known peaks, Te Tarata occupies the full width of the middle ground, and Spencer took it from a hilltop that was slightly higher than the top platform of Te Tarata.[19]

To locate Spencer's vantage point, elevation and field of view, we used the same approach taken in our investigation of Burton's panorama, even though such a limited field of view would not generate the widely separated bearings required to fix his locus as accurately as Burton's. Following Keam's lead (de Ronde *et al*. 2018: 17), we explored the view from the surface of the lake in the area northwest of the small dogleg-shaped Te Tarata Peninsula on the northern shore (Fig. 10). The virtual PeakFinder observer was moved about until horizon features began to align and then shifted a few arc seconds in the north–south or east–west direction, as well as some metres above the lake, until the virtual horizon was optimally aligned with the photographic horizon (Fig. 9, top and bottom). Again, it was not possible to know whether an even better alignment with the photographed view existed at a locus beneath the lake's surface. The very good match between the shapes, locations and heights of features in the middle section of the horizon gives us confidence that the virtual vantage point at 38°15'28" S, 176°26'04" E and at an elevation of 339 m is close to where Spencer placed his tripod (Fig. 10, blue flag). Although this spot is within the boundary of the current lake, it is in relatively shallow waters at a depth of about 25 m. If Spencer's camera was at the same elevation as the surface of today's lake, then much of the hilltop on which he stood must have been removed during the eruption. Even though it is more likely that Spencer's vertical locus is beneath the surface of the lake, as is Burton's, the fact that the relative heights of distant peaks above closer hills in the lake-level virtual view are close to those shown in Spencer's photograph implies that his locus would not have been far beneath the surface of the current lake.

In this instance, the field of view captured by the glass plate negative in Spencer's camera encompasses an arc of ~63° between bearings 187° and 250°, with the Te Tarata spring lying on a bearing of ~190°. Unfortunately, no steam was wafting from the concealed location of Otukapuarangi spring when Spencer exposed his negative. However, the approximate location of the Pink Terrace spring is flagged by rising steam (Fig. 9, inset) in another, albeit poorly exposed, Burton photograph taken from close to Spencer's principal sight line but from the lower steps of the White Terrace. The equivalent bearing on the PeakFinder digital elevation model is ~235°.

As the geographical coordinates and the elevation of PeakFinder's virtual observer are close to the spot where Spencer took his photograph, the 0° elevation line in the virtual view, which also happens to be at the lake's current elevation, can be projected onto the photograph to give the inferred lake level (Fig. 9, dotted green line). With Spencer's vantage point being much closer to Te Tarata, more notice can be taken of this projection, which indicates that the current lake level would cover the top platform of that terrace by several metres if it were still in existence, just as it does when the current lake level is projected onto Burton's

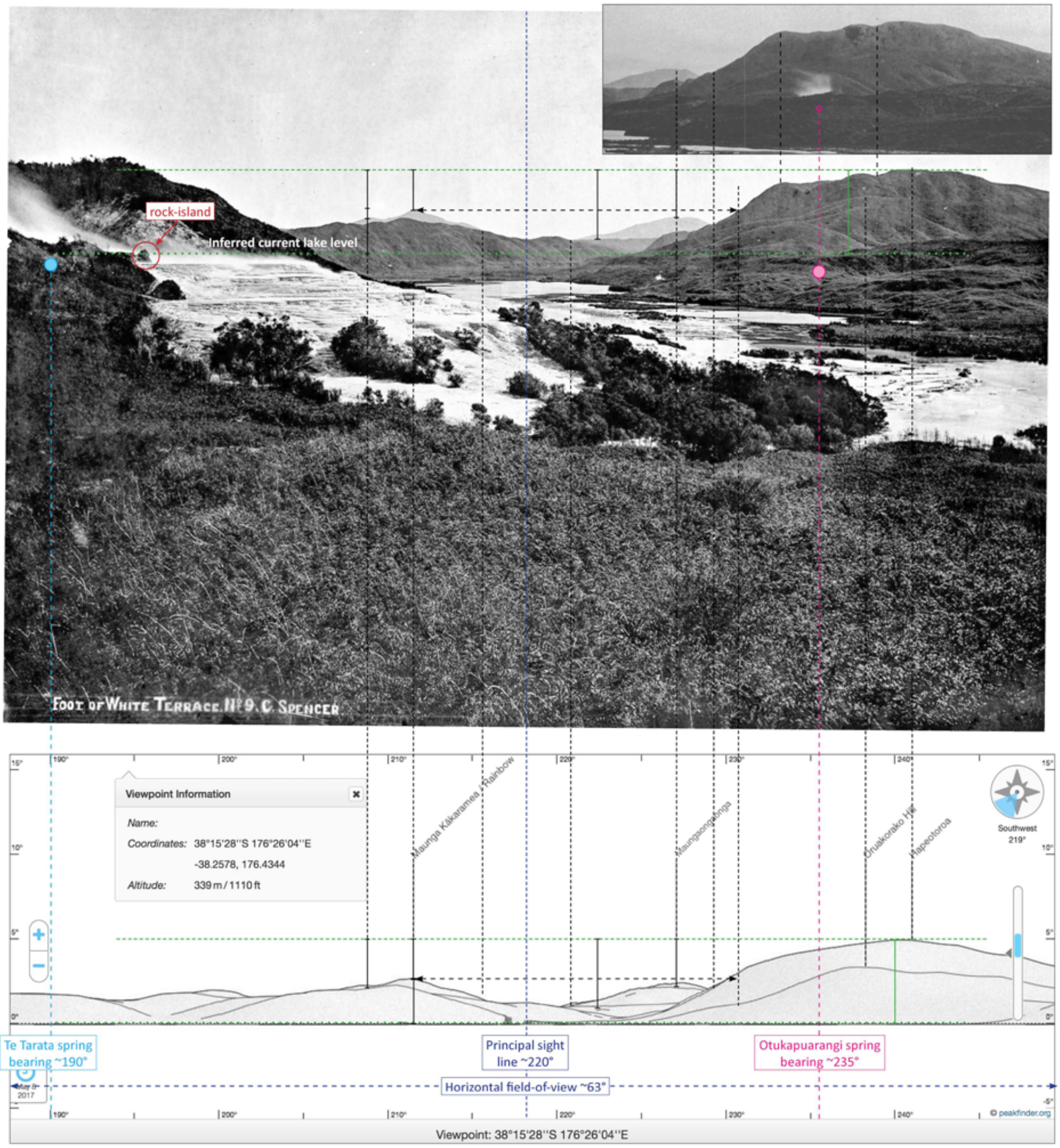

Fig. 9 Comparing the virtual view with Spencer's photograph. Top: *Foot of White Terrace, No. 9*, *c.* 1881. Photographer Charles Spencer (Rotorua Museum Te Whare Taonga o Te Arawa, OP-792). Inset: [Lake Rotomahana viewed from the lower steps of the White Terraces], detail. Photographer Alfred Burton (Hocken Collections Uare Taoka o Hākena). Bottom: PeakFinder's virtual view from the same locus as Spencer's vantage point (© peakfinder.org.). Dashed magenta lines relate to the Pink Terrace, and dashed cyan lines to the White Terrace. The dashed green lines indicate the elevation of Hapeotoroa dome, while the dotted green lines indicate the projected current lake level. The rising steam in the inset photograph indicates the approximate location of Otukapuarangi spring. The 'rock-island' is a resistant rock formation found right on the edge of Te Tarata spring.

panorama (Fig. 8). This does, however, raise an issue with regard to the actual elevation of the top platform of Te Tarata. PeakFinder's measure of the altitude of the current lake level is ~339 m, so the top platform would have been a couple of metres lower at, say, ~336 m, but Keam estimated the platform had an elevation of ~322 m (= 292 m estimated lake level prior to eruption + 30 m measured terrace height). The cause of this ~14 m discrepancy is difficult to resolve. As the GNS bathymetric survey determined that the lake's elevation was 339.885 m in 2012, PeakFinder's 339 m altitude for the lake's surface stands, so either Spencer's locus was in fact some metres underwater, or Keam's estimate of a 292 m elevation for the original lake comes into question.[20] However, whether one considers the inferred lake level relative to the position of the top platform in the photograph, or the current lake level relative to Keam's estimate of the elevation of the top platform of Te Tarata, the three-dimensional space originally occupied by the whole of that terrace would now be beneath the surface of the lake.

Intersecting the terrace spring bearings

In order to plot the loci and bearings associated with Burton's panorama and Spencer's photograph, two 1:50 000 topographic maps were downloaded from the Land Information New Zealand website, as Lake Rotomahana straddles both (Land Information New Zealand 2015). The relevant sections of the two maps were merged in Photoshop. As can be seen on the resulting topographic map (Fig. 10), the locations in which both nineteenth-century photographers stood are within the modern boundary of the lake, with Burton's vantage point (red flag) being close to the western shore, about 500 m west of the semicircular Otukapuarangi Bay, and Spencer's (blue flag) near the northern shore, about 100 m west of Te Tarata Peninsula.

Before bearings were plotted on the topographical map, a convergence-angle correction of +2° was applied to each.[21] When the corrected bearing to the approximate centre of Otukapuarangi spring is plotted from each vantage point, the spot where the two bearings intersect at ~38°15'52" S, 176°25'20" E (~1290 m from Spencer's vantage point and ~240 m from Burton's) indicates the locus of the hydrothermal crater that partially enclosed Otukapuarangi spring, placing it well within the modern lake's boundary.[22] Similarly, when the corrected bearing to the approximate centre of Te Tarata spring is plotted from each vantage point, the intersection of the two bearings at ~38°15'38" S, 176°26'02" E (~850 m from Burton's vantage point and ~325 m from Spencer's) identifies the location of the hydrothermal crater that partially enclosed Te Tarata spring, which is also within the lake's boundary. Bearing in mind that, over a distance of 1 km the ±2° margin of error for the spring bearing would result in a 70 m-wide arc (~2"), and the ±1" margin of error for the location of each photographer's vantage point would add to this, the locus of a spring at the intersection of two bearings would be subject to an aggregated margin of error of ±2".

As Burton was higher than the top platform of Otukapuarangi, and Spencer was higher than the top platform of Te Tarata, any extant features of the two terraces, other than perhaps their crater rims, would be underwater. According to the bathymetric map (Fig. 14), the lake is ~40 m deep at the coordinates of both the Pink Terrace and the White Terrace, although it should be noted that the lake bed is steeply sloping at both locations. Given that the crater wall of Te Tarata spring was between 9 m and 12 m high (Hochstetter 1867: 410), and that of Otukapuarangi appears to have been lower when photographs are compared, any extant part of the crater rims would be underwater as well.

According to our projections, the terrace springs are ~1090 m apart, with Te Tarata spring lying on a ~67° true bearing from Otukapuarangi spring, and conversely with Otukapuarangi spring lying on a ~247° true bearing from Te Tarata spring. Even though those locations are subject to significant margins of error, the terraces created by the geothermal springs were relatively large, with the 'silicon apron' of Te Tarata occupying ~2.8 ha and that of Otukapuarangi ~2 ha (de Ronde *et al.* 2016a: 127). We are confident, therefore, that the fan-shaped White Terrace would have been located immediately to the northwest of the postulated locus of Te Tarata spring, and that the rectangular-shaped Pink Terrace would have been located immediately to the southeast of the conjectured locus of Otukapuarangi spring.

Looking for comparable pre- and post-eruption panoramas

Having located the terrace springs on the current topographical map and established that any extant features would be beneath the lake surface rather than the land, our attention focused on whether we could locate and compare pre- and post-eruption photographs taken from close to the same spot, encompassing a similar, preferably panoramic, field of view. The aim of this was to shed some light on the state of the terraces in the days and months immediately following the eruption.

An extensive search through collections holding post-eruption images taken from around the vast, still steaming Rotomahana Crater located only two contiguous photographs taken from the same vantage point. When merged, these strongly overlapping images, taken by Valentine, form a '1½-plate'-wide incidental panorama (Fig. 11, middle). Disappointingly, this view was not comparable to either of Spencer's two-plate panoramas, nor to any section of Burton's five-plate vista that included a terrace. We were, however, able to locate several pre-eruption photographs of Te Tarata whose skylines aligned closely with Valentine's post-eruption mini-panorama.

Comparing pre- and post-eruption Te Tarata photographs

One pre-eruption Te Tarata image, entitled *White Terraces, Rotomahana*, was taken by Napier photographer William Collie (c. 1826–c. 1900) in 1874 (Fig. 11, bottom; see also Keam 2016: 37, fig. 32). This pre-eruption view of the northern end of Pinnacle Ridge, taken from the north, just captures the full extent of the steps of the White Terrace and looks directly into the crater that partially enclosed the 'boiling cauldron' of the hot spring. Collie would have exposed his glass plate on a hilltop just north of Kaiwaka Creek, the original outlet of the lake (Fig. 6), which flows out to the left from the pool in the middle ground.

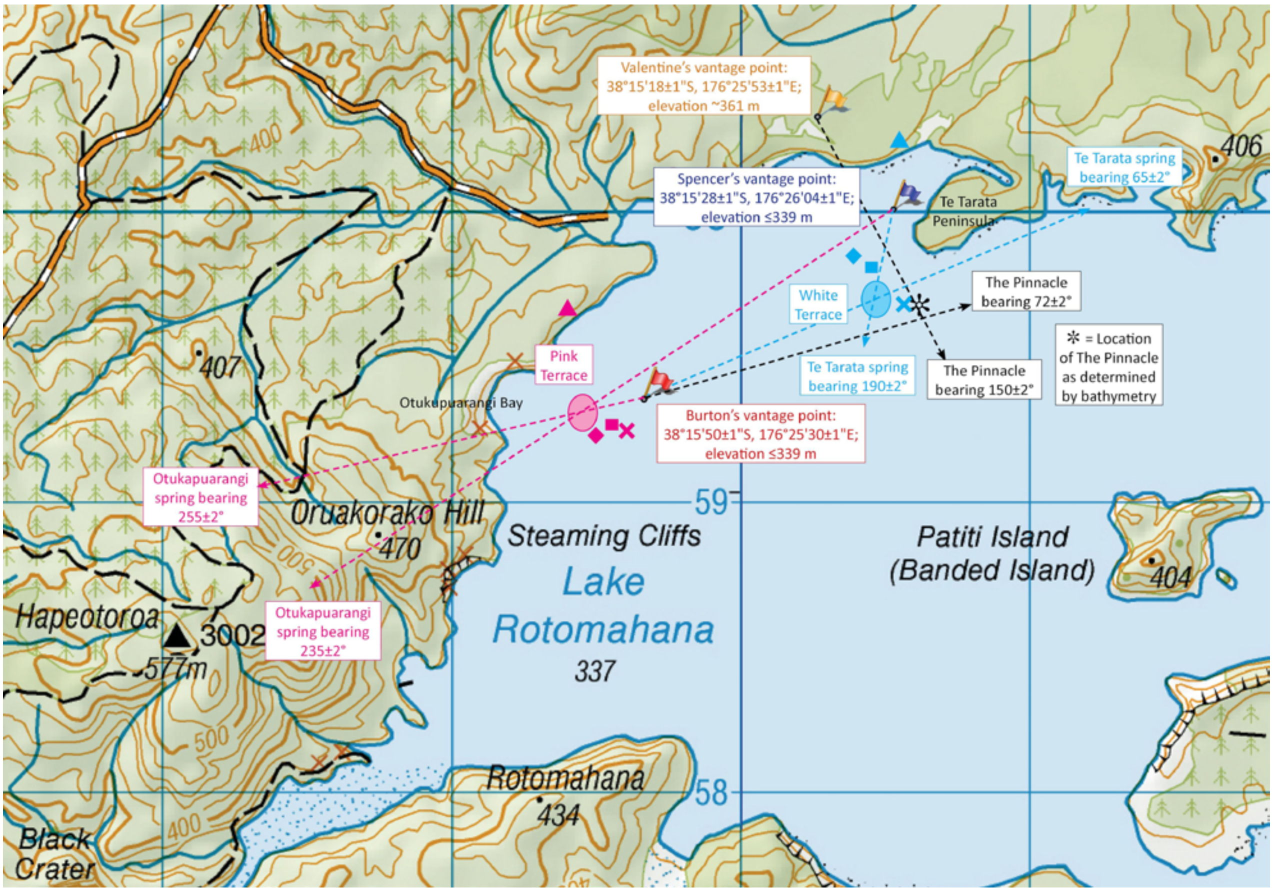

Fig. 10 Locating the Pink and White Terraces on the topographical map. Sourced from joined sections of Topo50 Map BF37 *Waiotapu* and Topo50 Map BF38 *Kaingaroa Forest*. Crown copyright reserved. The maps are projected on a New Zealand Transverse Mercator 2000 grid. A grid convergence correction of +2° was applied to each of the true bearings generated by PeakFinder before these were plotted. The red flag indicates Burton's vantage point, the blue flag Spencer's, and the gold flag Valentine's. Cyan arrows, symbols and shapes relate to the conjectured loci of the White Terrace, and magenta ones relate to the Pink Terrace. The crosses indicate de Ronde *et al.*'s (2018) postulated locations of the terraces, the triangles indicate Bunn *et al.*'s (2018), the diamonds indicate Keir's (2017), and the squares indicate Lorrey and Woolley's (2018). The two ellipses indicate the ±2" margin of error for our proposed loci. Black arrows and symbols relate to the actual location of The Pinnacle.

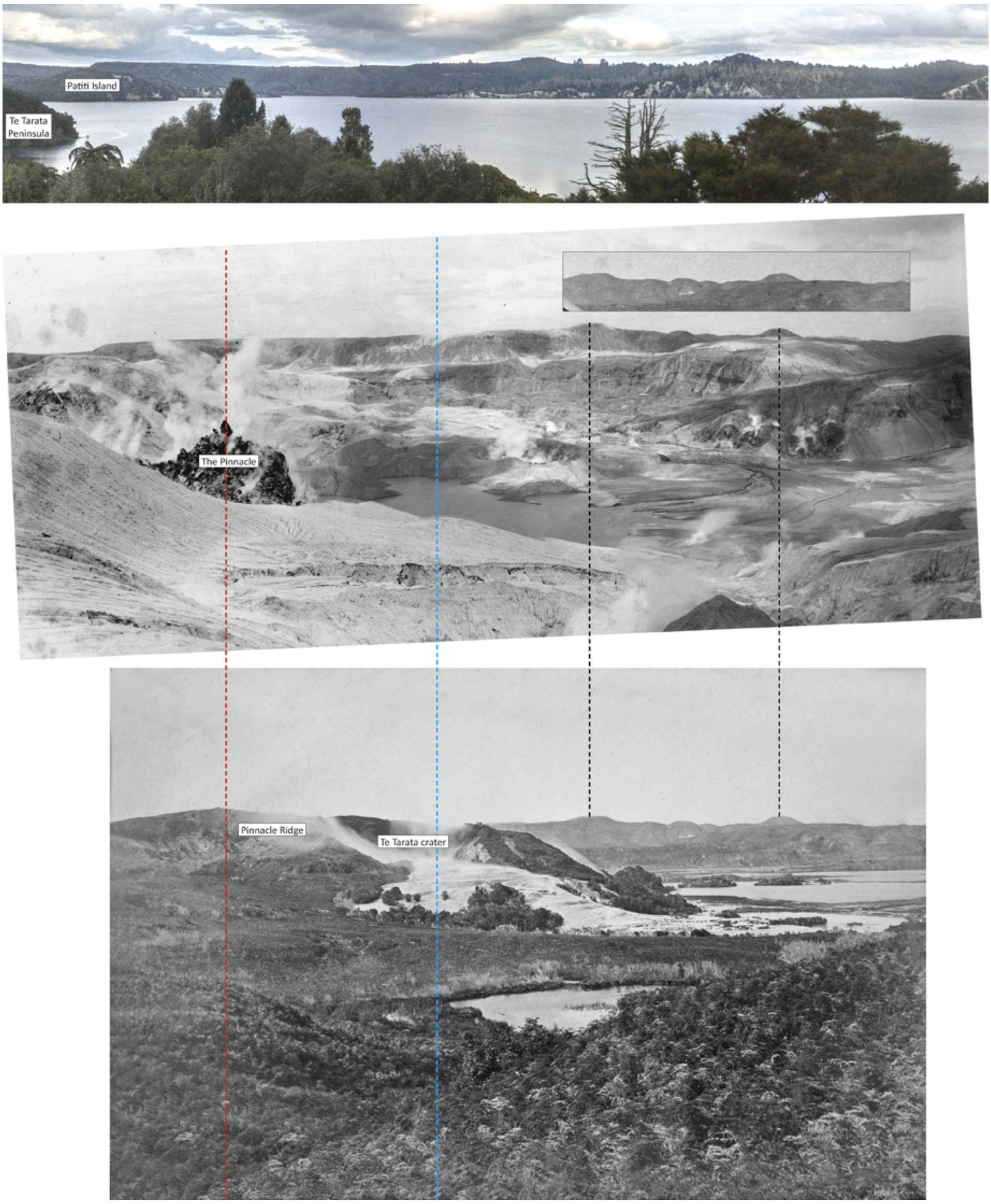

Fig. 11 Comparing the current landscape with pre- and post-eruption views. Top: southeast to south-southwest view from the plateau northwest of Te Tarata Peninsula (see Fig. 10). Photographer Andrew Thomas. Middle: post-eruption panorama of Rotomahana Crater, assembled by Tony Mander from two photographs by George Valentine: *Fumarole Peaks and Site of White Terrace, Rotomahana* and *Rotomahana Showing the Site of the White Terraces*, both 1886, albumen prints, 190 × 290 mm. (Alexander Turnbull Library PA7-54-13 and PA1-q-138-008). Bottom: *White Terraces, Rotomahana*, 1874, albumen print, 155 × 245 mm. Photographer William Collie (Te Papa PA7-40-19). The middle image needed to be rotated 2.5° anticlockwise for its horizon to parallel that of the well-levelled pre-eruption photograph. The dashed blue line indicates the sight line for the original location of Te Tarata crater, and the dashed red line that of The Pinnacle.

Valentine's dystopian image (Fig. 11, middle) reveals a newly blasted volcanic landscape. The irregular contours of the freshly excavated and slightly flooded Rotomahana Crater are visible in the middle ground, and a furrowed hillside and flat occupy the foreground, between which a glistening, dark rocky structure dominates the scene. That formation is the aforementioned The Pinnacle, which either 'materialised' in the eruption or was a pre-existing structure excavated or exposed by the eruption.[23]

At first glance it may appear that the two images have little in common, but the shapes and relative positions of the hilltops forming the right horizon of Valentine's post-eruption panorama match aspects of equivalent features on the more distant horizon in the pre-eruption photograph (Fig. 11, middle and inset). Furthermore, the flat-topped hill immediately in front of the right trapezoidal hilltop has the same shape and position relative to the horizon in both photographs. As that trapezoidal hilltop (38°17'38" S, 176°25'51" E) is about 1.5 km further away than the flat-topped hill (38°16'57" S, 176°25'47" E), those similarities are strong indicators that Valentine was positioned very close to Collies's principal sight line. Although the left and right trapezoidal hilltops are slightly further apart in the photograph on which the right half of the panorama is based than in the pre-eruption image, this does not necessarily mean that Valentine was closer to the view, as he may have used a slightly wider-angle lens. He would, however, have been at a somewhat higher elevation, as distant peaks adjacent to the right trapezoidal hilltop can be seen that are not visible in the pre-eruption photograph. This is because the land on which Valentine was standing was 'covered with deep sand and mud' ejected during the eruptions (Fig. 3).

PeakFinder was used to determine that Valentine was standing on a plateau northwest of Te Tarata Peninsula, close to the locus 38°15'18" S, 176°25'53" E and at an elevation of ~361 m (Fig. 10, gold flag). The application also gave a true bearing of ~150° for The Pinnacle, which intersects its bathymetrically determined location within the ±2° margin of error, thus confirming the accuracy of our estimation of Valentine's locus. As the view from that locus is now obscured by bush, we used a drone-mounted camera to photograph the horizon from about 15 m above ground level.[24] The resulting panoramic photograph exhibits comparable skyline features (Fig. 11, top), confirming that the drone was close to Valentine's geographical coordinates, albeit a couple of arc seconds northeast.

Close inspection of the photographs reveals that Patiti Island, which was originally part of Te Rangipakaru dome (de Ronde *et al.* 2018: 28, fig. 3 caption), and the plateau behind it on the right, as seen in the drone panorama, are also identifiable in the post-eruption image. However, Te Rangipakaru dome is not visible in the pre-eruption landscape because Pinnacle Ridge intervenes. Furthermore, the furrowed foreground of the post-eruption image appears to be too close to the viewer to have been part of Pinnacle Ridge. If, as we contend, the pre- and post-eruption images were taken from close loci, it is difficult to avoid the conclusion, based purely on comparative visual evidence, that most of Pinnacle Ridge was removed in the eruption, except for the glistening black rocky structure confronting us just beyond the foreground of Valentine's photograph. If this is correct, little hope can be held for the survival of significant sections of Te Tarata after the phreatomagmatic eruption that blasted away most of Pinnacle Ridge. Clearly, the crater that enclosed Te Tarata spring, the extensive top platform and most of the steps are no longer in existence, although some parts of the lowest steps may survive, buried beneath the mud in the foreground.

As will also be noted when comparing the drone and post-eruption images (Fig. 11, top and middle), Te Tarata Peninsula is actually the upper part of the furrowed foreground hillside, with the rest of the foreground now being underwater, along with the entirety of The Pinnacle just behind it. Nevertheless, The Pinnacle's position with respect to the original location of Te Tarata spring becomes clearer when comparing the post-eruption panorama with the pre-eruption photograph. As we are looking from the north at the northern end of Pinnacle Ridge, which according to both Hochstetter's and Keam's maps ran in a north–south direction, The Pinnacle lay somewhere along a sight line to the south that passes ~150 m east of Te Tarata crater (Fig. 11, dashed red line), with which Keam's initial placement accords (Fig. 4, black ✱ symbol). How far into the ridge the rocky promontory was embedded cannot, however, be determined from this comparison alone.

Comparing pre- and post-eruption Otukapuarangi photographs

Only one pair of pre- and post-eruption views looking towards the vicinity of Otukapuarangi with somewhat similar skylines could be located. We compared a post-eruption photograph by Valentine, entitled *Rotomahana, Looking to Site of Pink Terrace* (Fig. 12, top), taken from the same vantage point as his 1½-plate panorama, with a section of the right half of Burton's pre-eruption panorama that originally straddled two plates (Fig. 12, bottom). Although Valentine was about 1100 m further away from the Pink Terrace than Burton (Fig. 10), his higher elevation meant that he could see more of Maungakākaramea jutting out above the right flank of Rotomahana hill, and his more northerly position meant the summit of Oruakorako hill was in front of the left summit of Hapeotoroa dome rather than the middle summit.

Despite these differences, the comparison does provide an indication of the fate of the Pink Terrace. In the vicinity where the cascade of pools could previously be seen sitting between bush-covered ridges, there are a number of vents billowing steam dispersed among mud-encrusted hillocks and slips. The two lower ridgelines highlighted in the post-eruption landscape appear to be part of the original ridge and crater wall that enclosed Otukapuarangi. Given that Valentine had extensive pre-eruption experience of this location, his unambiguous identification of the location deserves respect.

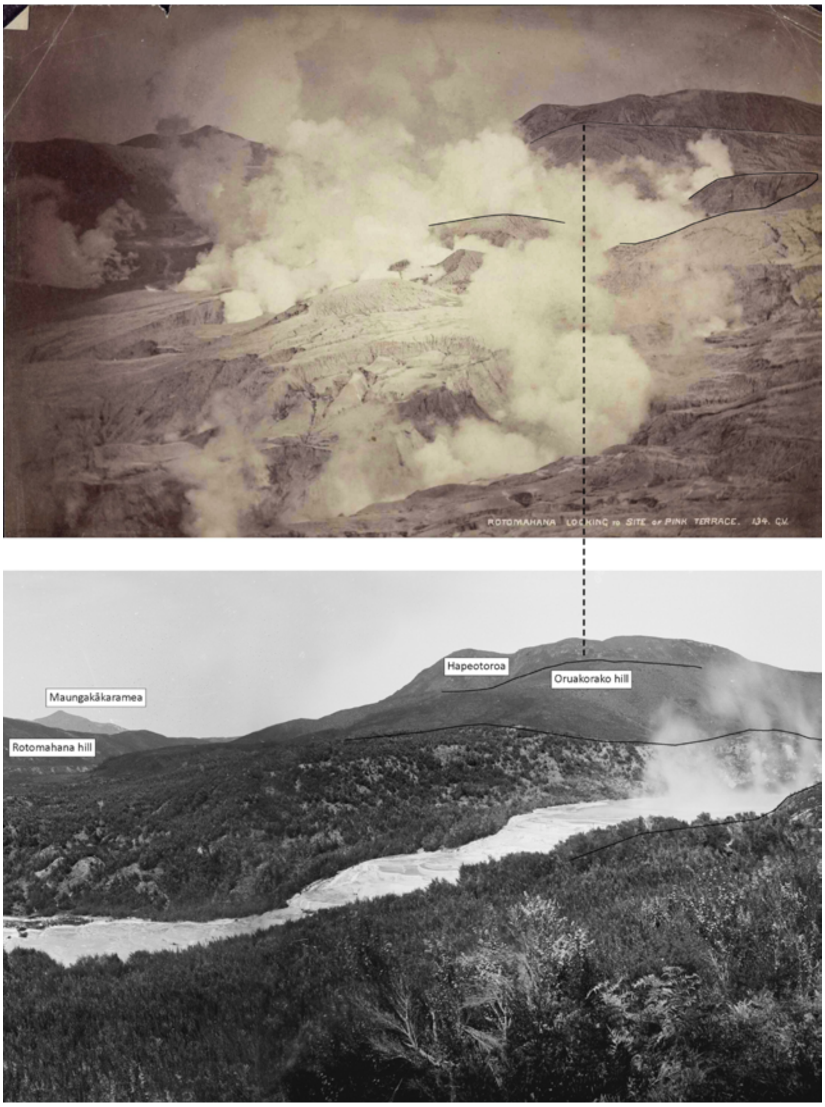

Fig. 12 Comparing pre- and post-eruption views of the site of the Pink Terrace. Top: *Rotomahana, Looking to Site of Pink Terrace*, 1886, albumen print, 190 × 290 mm. Photographer George Valentine (Alexander Turnbull Library PA7-54-14). Bottom: section of *Panorama of Lake Rotomahana* (Fig. 7). Added solid black lines on both images indicate contours of the ridge bordering the terrace, the crater rim encompassing the hot spring pool, and Oruakorako hill.

Fig. 13 *Mt Tarawera from Rotomahana, After Eruption 10 June 1886*, gelatin dry plate negative. Photographer Alfred Burton (Te Papa C.010715).The field of view is similar to that of Blomfield's painting looking towards Mt Tarawera (Fig. 1). Added solid black lines indicate the contours of the ridge that bordered the southern side of the Pink Terrace steps, and of the crater that partially enclosed the semicircular bay between the foot of the terrace and Whakataratara solfatara (see Fig. 8, between bearings 175° and 190°).

A post-eruption photograph taken by Burton from Hapeotoroa dome (Fig. 13), looking towards Mt Tarawera and with Oruakorako hill forming the foreground, provides the reverse view of Valentine's image (Fig. 12 top). In this photograph, the rims of three unusually steep-sided, cup-shaped depressions can be seen cutting into the left plateau. When their shape is compared with other slopes visible in the photograph, it is clear that the trio are not the result of slips but are in fact craters. In the basin in the middle ground, the ridgelines visible in Valentine's photo can be seen among the steam vents. The angled ridge immediately in front of the midpoint of Oruakorako hill in the foreground appears to be part of the ridge that originally bordered the southern side of the Pink Terrace steps (Fig. 12, bottom), while the jagged ridgeline just behind it resembles the rim of the crater that partially enclosed the semicircular bay between the foot of the terrace and Whakataratara solfatara (Fig. 8, between bearings 175° and 190°).

Those three steeply sloping craters, as well as the intact ridgelines in the basin, suggest that hydrothermal eruptions occurred in this vicinity on 10 June 1886 (de Ronde *et al.* 2018: 8), most likely through outlets of the original plumbing system that supplied Otukapuarangi spring and other nearby hot springs such as Te Ngawha Atehui and Te Waiti (Fig. 6). Given these hydrothermal eruptions would have been significantly less violent than the phreatomagmatic eruption that created the Rotomahana Crater (de Ronde *et al.* 2016b: 68; Keam 2016: 21–22), significant sections of the Pink Terrace may have survived intact but lie buried beneath layers of mud and sediment. However, the close resemblance of the semicircular rims of the trio of craters to three adjacent curved bays on the northwestern shore of the bathymetric map of Lake Rotomahana (Fig. 14) implies that any extant features associated with the Pink Terrace would be under the sediment of the lake bed, albeit not far from the shoreline.

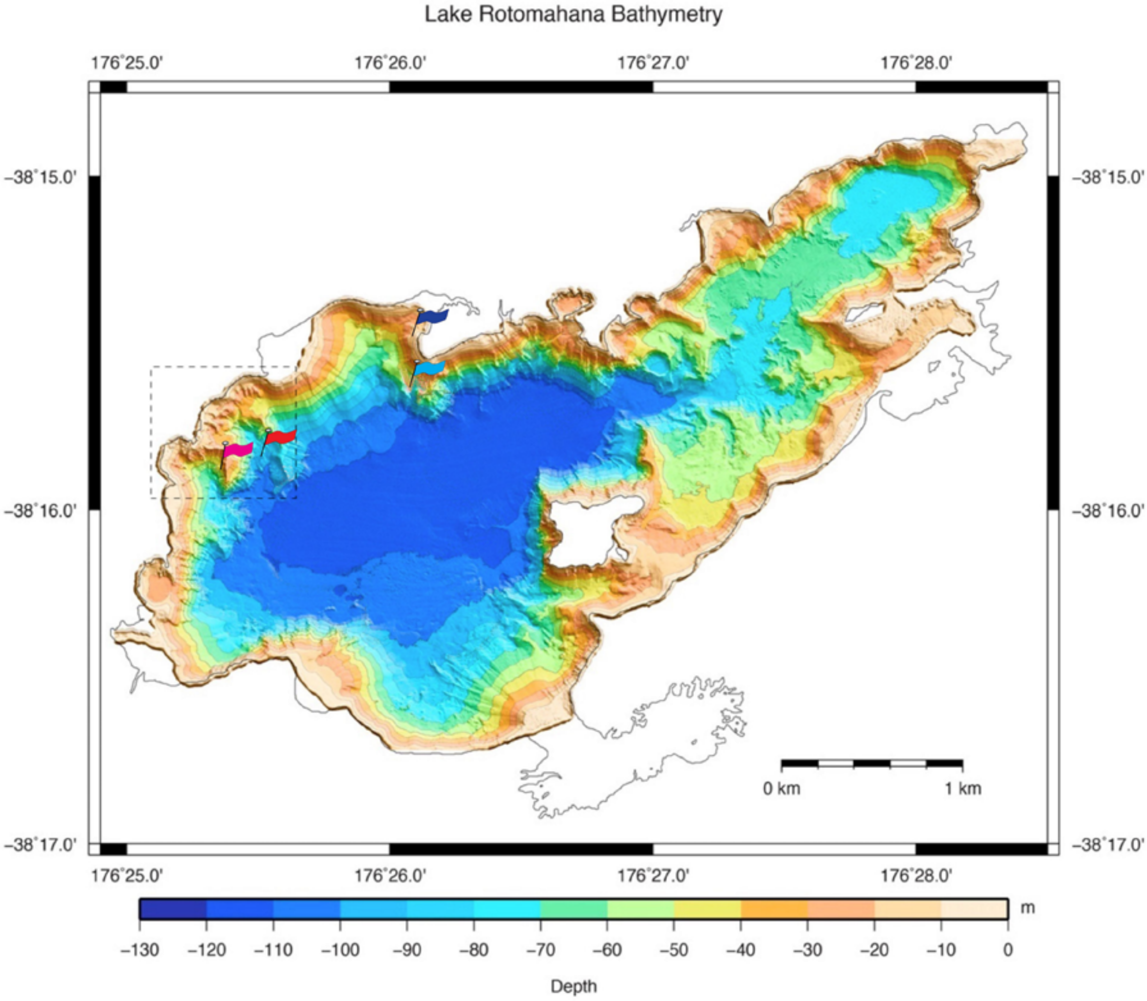

Fig. 14 *Bathymetry map of Lake Rotomahana, New Zealand*. Reprinted from Tivey, M.A., de Ronde, C.E.J., Tontini, F.C., Walker, S.L. and Fornari, D.J. (2016) A novel heat flux study of a geothermally active lake – Lake Rotomahana, New Zealand. *Journal of Volcanology and Geothermal Research* 314: 95–109, copyright (2016), with permission from Elsevier. The contour interval is 10 m. The dashed lines that indicated the conjectured locations of Lake Rotomahana and Lake Rotomakariri have been removed, as have the symbols that marked the authors' presumed locations of the Pink and White Terraces. Burton's vantage point (red flag) has been added at ~38°15.8' S, 176°25.5' E, where the depth of the lake is ~80 m deep. Spencer's vantage point (blue flag) has been added at ~38°15.5' S, 176°26.1' E, in shallow water about 25 m in depth. Our methodology located the spring of Te Tarata (cyan flag) at 38°15.6' S, 176°26.0' E, where the depth of the lake is ~40 m, and the spring of Otukapuarangi (magenta flag) at 38°15.9' S, 176°25.3' E, where the depth of the lake is also ~40 m. However, as the lake bed is steeply sloping at the last three locations, the depth involved may not be very accurate. The dashed-line rectangle encloses the three adjacent curved bays that bear a close resemblance to the semicircular rims of the trio of hydrothermal craters visible in Fig. 13.

Resolving the 'battle of the maps'

Based on the projected current lake level when the virtual view coincides with Burton's pre-eruption panorama (Fig. 8), as well as the determination of the loci of the two springs by intersecting bearings derived from analysing photographs taken from different vantage points (Fig. 10), any extant features of Te Tarata or Otukapuarangi would be located beneath the surface of the current lake.

Our findings challenge Bunn and Nolden's 2017 assertion, repeated by Bunn in 2018, that the terraces lie underground just beyond the shoreline of the current lake, which is based on overlaying Hochstetter's field map (Fig. 5) on a Google Earth image of the Rotomahana landscape (Bunn *et al.* 2018: 11, fig. 8) after reversing the geologist's bearings to determine the loci of his two observation stations. We question the accuracy of the outline of the lake on the topographical sketch, given our spatial analysis of Burton's panorama of the whole lake. From the photographer's vantage point (Fig. 8), the bearings to the two springs differ by ~192° (255° to Otukapuarangi, less 63° to Te Tarata), so Burton would have been standing east of a straight line drawn between the two terrace springs (Fig. 5, dashed red line). According to Hochstetter's sketch map, Burton would therefore have been taking the photographs for his panorama from out on the lake, a conclusion that is clearly mistaken. Thus, either the outline of the lake is inaccurate or one or other of the terraces is incorrectly positioned on the map. Regardless of that conundrum, the specified bearings to the terrace springs from Bunn's revised locus for Hochstetter's southern observation station (Bunn *et al.* 2018: 11, fig. 8, red lines) pass within 2–3° of where our method positions the springs, and would certainly intersect the original spaces occupied by the terrace cascades, given their size and orientation relative to the springs.

The locations that Keir proposes for the two terraces are in deeper water than ours (Fig. 10, diamond symbols), but the unavoidable limitations of the sight-line method he uses raise doubts as to whether the terraces would necessarily be located within the elliptic stars on his topographic map (Keir 2017: 5, fig. 2). Consequently, his claim that neither terrace survives intact because at those locations they would be floating impossibly above the lake bed in the 50–80 m-deep zone of the bathymetric map (Fig. 14) is open to question. Furthermore, it is at odds with some of the geological and bathymetrical evidence assembled by de Ronde *et al.* (2016a, 2018).

The latest relocation of the terraces by de Ronde *et al.* (2018), in their recent rebuttal of Bunn and Nolden's 2017 claims, is based on superimposing an appropriately scaled, updated version of Keam's geographically oriented, pre-eruption outline map on the GNS bathymetric map (de Ronde *et al.* 2018: 9, fig. 1 composite map). The position of The Pinnacle relative to Te Tarata crater on the outline map functions as the sole anchor point, which is situated over its known bathymetric location. The update to Keam's map involved shifting the location of The Pinnacle about 100 m along a bearing of 217° (de Ronde *et al.* 2018: 15–16), so that the conjectured location of The Pinnacle (Fig. 4, added red ✱ symbol) is now ~50 m southeast of the 'Pyramidal feature' on Te Tarata crater rim. This was done so that the suggested position of Otukapuarangi sits over possible remnants of the Pink Terrace located by side-scan sonar imaging (de Ronde *et al.* 2018: 9, fig. 1, 15–16).

This move compromises the value of Keam's map as independent evidence of the locations of the terraces, as the location of The Pinnacle on his map is no longer 'independently ascribed'. In an effort to ascertain the validity of this move, we compared highly detailed pre- and post-eruption photographs of Mt Tarawera as viewed from the southwest (Fig. 15). The pre-eruption photograph is the far right plate of the Alfred Burton five-plate panorama (Fig. 7), while the dramatic post-eruption image with the nonchalant pipe-smoker gazing into the abyss was exposed in August 1886 by Frederick Muir (*c.* 1852–1945), a photographer contracted by the Burton Brothers (Whybrew 2010: 271). The comparison confirms that The Pinnacle was located further south along the north–south-oriented Pinnacle Ridge than Te Tarata crater (Fig. 15, dashed red arrow). Based on our earlier photographic analysis of Burton's panorama (Fig. 8), the bearing to the postulated location of The Pinnacle would be ~72° which, when plotted on the topographic map (Fig. 10, dashed black arrow), intersects the bathymetrically determined location of The Pinnacle just within the margin of error. Moreover, when the southward-facing view of the northern end of Pinnacle Ridge in Fig. 11 is considered in conjunction with the northeastern-facing view of the same end of that ridge in Fig. 15, it is abundantly clear that The Pinnacle was indeed located southeast of Te Tarata crater. This restores the 'independently ascribed' location status of The Pinnacle on the latest iteration of Keam's outline map. Nevertheless, based on Keam's estimate of ~244 m for the length of the White Terrace (de Ronde *et al.* 2016a: 127), the 'before-and-after' comparison in Fig. 15 suggests that The Pinnacle is likely to have been about 125 m southeast of the 'Pyramidal feature' on the rim of Te Tarata crater, rather than just 50 m.

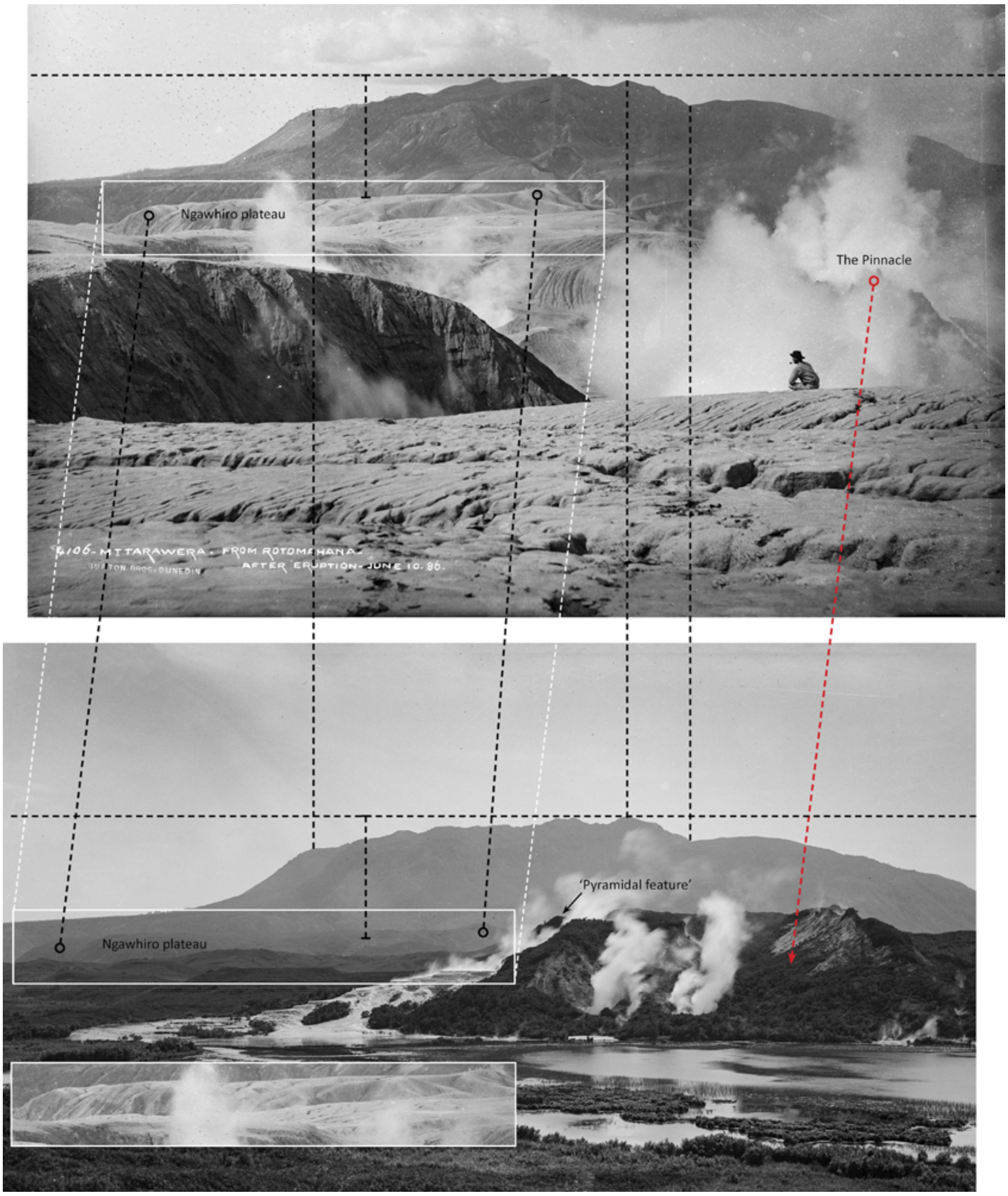

Fig. 15 Comparing pre- and post-eruption views of Pinnacle Ridge. Top: *Mt Tarawera from Rotomahana After Eruption, 10 June 1886*, gelatin dry plate negative. Photographer Frederick Muir (Te Papa C.010716). Bottom: [View of Mt Tarawera and the White Terrace], gelatin dry plate negative (detail). Photographer Alfred Burton (Te Papa C.010659). The Ngawhiro plateau at the foot of Mt Tarawera is clearly visible in the post-eruption photograph, even though further to the right than in the equivalent but fainter section of the pre-eruption image. The two photographs must, therefore, have been taken from close, but not identical, vantage points. The Pinnacle can just be made out through the steam in the post-eruption image. The dotted red line points to its likely original location within Pinnacle Ridge. As the view is looking to the northeast, The Pinnacle must have been further south than Te Tarata crater.

Given the importance of Keam's map to de Ronde *et al.*'s schema (2016a, 2018), it is disappointing that no margin of error for the map bearings or distances is specified in that article.[25] Regardless, the loci we propose for the two springs are close to the inferred geographical coordinates (Fig. 10, crosses) of those features on their composite bathymetric map (de Ronde *et al.* 2018: 9, fig. 1), either within or just outside of the likely margins of error implicit in both approaches. Our method places Te Tarata at the same latitude but 4" further west (38°15'38" S, 176°26'02" E, cf. 38°15'38" S, 176°26'06" E). Our locus for Otukapuarangi spring is 1" further north and 8" further west than de Ronde *et al.*'s (38°15'52" S, 176°25'20" E, cf. 38°15'53" S, 176°25'28" E), which is a significant difference of ~200 m. This may be due to the difficulty of determining the exact location of the spring in both Burton's panorama and Spencer's photograph. According to our determination, Te Tarata spring lies ~1090 m from Otukapuarangi along a ~67±2° bearing, which compares reasonably well with the ~1000 m distance along a ~64° bearing on the composite bathymetric map.

According to the NIWA scientists, their determination of the former locations of Pink and White Terraces using Hochstetter's published map is 'congruent with [geological] evidence from recent Rotomahana investigations' undertaken by the GNS scientists. Furthermore, the NIWA-determined terrace locations (Fig. 10, square symbols) overlap with the GNS ones (Lorrey & Woolley 2018: 30 and 27, fig. 12). As the locations proposed by de Ronde *et al.* (2018) are close to our projected locations, the findings of three studies using quite different methodologies concur on the most probable locations of Te Tarata and Otukapuarangi springs.

Conclusion

After intense arguments over the fate of the Pink and White Terraces in the last decade of the nineteenth century, and intermittent debates during the twentieth century, the issue came to a head in the current decade in what we have termed the 'battle of the maps'. The incidental rediscovery of a highly distinctive underwater promontory in Lake Rotomahana, and the chance rediscovery of historical documents in Basel, led to sometimes contradictory, map-based claims regarding the original location and, consequently, the ultimate fate of each terrace (de Ronde *et al.* 2016a; Bunn & Nolden 2017; Keir 2017; de Ronde *et al.* 2018; Lorrey & Woolley 2018). Despite the availability of extensive photographic archives, early maps, historical records and scientific accounts, forensic cartography and photogrammetry, as well as a highly sophisticated bathymetric survey of the entire lake and radar and LIDAR surveys, articles relocating the terraces, rebutting those relocations, and even rebutting the rebuttals, continue to be published. This is largely testament to the destructive power of the phreatomagmatic eruption that excavated Rotomahana Crater, obliterating all recognisable pre-eruption landmarks in the vicinity of old Lake Rotomahana, before ultimately drowning them in a lake that is much larger and with a much higher surface level. Although contradictory claims have generated passionate arguments, the debate can perhaps be seen more usefully in terms of a journey towards knowledge. Competing views have all contributed to clarifying the issues relating to the original location and ultimate fate of the terraces.

Given the divergent claims, the challenge for researchers has been not only to advance a proposition that takes into account different sources of evidence, but also to argue convincingly why alternative scenarios are not viable. In this context, our research findings support some contentions and undermine others. The outcomes of de Ronde *et al.*'s 2018 research are confirmed by the conclusions of Lorrey & Woolley's 2018 investigation, and are largely substantiated by our findings as well. These consistent findings differ significantly from those of Bunn and Nolden (2017), who argue that the terrace spring locations are beyond the shores of the current lake.

Our interest focused on whether the application of spatial technology to pre-eruption photographs, as well as a comparison of pre- and post-eruption photographs, could provide an independent inference of the terrace locations, and therefore their likely fates. While we had no prior opinion on where the terraces were located or their current status, our research leads us to conclude that any extant terrace features would be under the lake bed rather than under land beyond the lake boundary, and they would be in shallower water close to the current shoreline and therefore potentially accessible. Furthermore, although some features of Otukapuarangi may survive buried under metres of mud and lake sediment, we doubt that any significant features of Te Tarata would be extant.

We appreciate that drilling and/or archaeological excavation would be necessary to confirm unequivocally the original location and current state of each terrace, but based on the photographic analysis and virtual evidence presented above, such activity ought to be conducted offshore.

Acknowledgements

For the warm welcome and very generous assistance received during our fieldwork at Lake Rotomahana, we would particularly like to thank Alan Skipwith, chairman of the Tuhourangi Tribal Authority (TTA); Kapu Waretini, general manager, TTA; and Rangitihi Pene, board member, TTA. We would also like to express our appreciation for the support and engagement of David Blackmore, manager of Waimangu Volcanic Valley, and Allan Marshall, skipper of *Ariki Moana*. The significant contributions made by Tony Mander, Michael McBain and Andrew Thomas have also been much appreciated. We thank Roger Blackley, Clare Gervasoni, the late Ronald Keam, Steven Linane, Cornel de Ronde and Fabio Soldati for responding to our queries. We acknowledge Federation University's funding of our field trip to Lake Rotomahana. Finally, we thank the journal's editor, Mark Stocker, for his interest and encouragement; reviewers Sascha Nolden and Pascal Sirguey for their constructive responses; and Susi Bailey for her thorough copy-editing.

Notes

1 The sinter stalactites of the terraces were so hard that an axe was needed to break off specimens (Mundy & Hochstetter 1875: XI).

2 A magmatic eruption is where all the products of the eruption, as preserved in the rock record, are derived from molten rock (magma). In contrast, a phreatomagmatic eruption is one in which heat sourced from molten rock interacts with groundwater to produce an eruption, and the products of the eruption, as preserved in the rock record, are derived from both molten rock and the country rock (host rock).

3 An eruption is described as phreatic or hydrothermal if heat sourced from molten rock interacts with groundwater to produce an eruption, and all the products of the eruption, as preserved in the rock record, are derived from the country rock.

4 The pre-eruption photograph is *White Terrace and Lake Rotomahana*, 15, ref. no. PA1-q-138-009 https://natlib.govt.nz/records/22888541?search%5Bpath%5D=items&search5Btext%5D=White+Terrace+and+Lake+Rotomahana%2C+15, and the post-eruption image is *Rotomahana Showing the Site of the White Terrace*, 135, ref. no. PA1-q-138-008 https://natlib.govt.nz/records/23107989?search%5Bpath%5D=items&searc%5Btext%5D=Rotomahana+showing+the+site+of+the+White+Terrace%2C+135, both Alexander Turnbull Library, Wellington.

5 One framed painting was even given the lengthy title *Site of the Destroyed Terraces After the Eruption, Taken from Very Nearly the Same Position. Oct. 6th 1886*

6 This was confirmed in an email response from Ronald Keam on 6 September 2018.

7 We wrote to Keam asking if he could clarify how he had fixed the location of The Pinnacle at a specific spot within the northern end of Pinnacle Ridge but had not received a response to that particular query before he died on 6 February 2019.

8 It is unfortunate that Bunn's latest relocations, published in March 2018, are not used in de Ronde *et al.*'s rebuttal, published in August 2018.

9 De Ronde *et al.* (2018: 22) also claimed that the published map is a more geographically accurate instrument than the topographical sketch on the basis that it is essentially the same as Keam's map.

10 Charles Spencer, *The White Terrace, Rotomahana*, 1880s, 383 × 161 mm, reg. no. O.000767 https://collections.tepapa.govt.nz/object/193010, and *Pink Terrace*, 1880s, 387 × 160 mm, reg. no. O.000768 https://collections.tepapa.govt.nz/object/193011, both albumen prints, Te Papa, Wellington, gifts of Nancy Adam.

11 Although the negatives are labelled 'Burton Bros. Dunedin', they were taken by Alfred Burton.

12 An 1886 newspaper report states that, very shortly after the eruption, a 'five-plate panorama' was on display in the street-front window of the Dunedin studio of the Burton Brothers (Whybrew 2010: 255).

13 Keam must also have assembled the panorama as it is one of the key views on which he based his 1959 outline map (Keam 2016: 27). A low-resolution image of the assembled panorama is reproduced in a recently published book (Fitzgerald 2014: 60).

14 According to the current consensus, for steeply sloping terrain, Shuttle Radar Topography Mission (SRTM) data are accurate to ±16 m at a 90% confidence interval (Mukul *et al.* 2017: 1–2), but would be significantly more accurate for the more gently sloping terrain found around the current Lake Rotomahana.

15 Rotomahana hill was covered in fine ash and scoria by the eruption (Fig. 3), but much of this unconsolidated material would have been removed during the intervening 133 years, offsetting any gain in altitude.

16 As each plate covers a field of view of about 47°, Burton's lens was approximately equivalent to a 'normal lens' of 50 mm focal length in 35 mm film format.

17 As it is difficult to judge the often partially obscured locations of the terrace springs in the relevant photographs accurately, the margin of error for spring bearings is ±2°.

18 The other two images were both by Burton, one being his panorama and the other taken next to a fumarole called Koingo on Hochstetter's published map (Fig. 6), which was located about 30 m above the lake along the eastern shoreline. The view in that photograph is to the southwest. See *Rotomahana. 3933*, reg. no. C.010598 https://collections.tepapa.govt.nz/object/21522, gelatin dry plate negative, Te Papa, Wellington.

19 We know that Spencer's camera was at a higher elevation than the top platform of Te Tarata because all of the exposed portion of the 'rock-island', which was located on the edge of the spring pool, is visible.

20 Keam's estimated pre-eruption elevation for Lake Rotomahana of 292 m (Keam 2016: 30) is based on Nairn's estimation of the pre-eruption elevation of Lake Tarawera (Hodgson & Nairn 2005: 504) and an apparently untested assumption that Lake Rotomahana could not have been more than 2 m higher than Lake Tarawera, otherwise empty transport canoes could not have been dragged or poled upstream for the ~1.5 km length of Kaiwaka Stream from Lake Tarawera to Lake Rotomahana.

21 The convergence-angle correction is the difference between 'grid north' and 'true north'. A specific correction must be applied to a 'true north' bearing before it can be plotted on a particular topographic map.

22 The intersection of pairs of spring bearings, as well as the distance between the springs and the bearing from one to the other, were confirmed using the application Geocaching Toolkit iGCT.

23 The highly distinctive rock formation starred in numerous early post-eruption photographs, although never at close quarters, perhaps due to the risks associated with the instability of newly formed slopes.

24 The drone was flown on land belonging to the Tuhourangi Tribal Authority, with its kind permission.

25 De Ronde indicated that Keam considered that distances were within ±10% (C. de Ronde, pers. comm., 2018).

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