Reconciling Historical and Modern Surveys of the Pink and White Terraces in the Taupō Volcanic Zone: Implications for Geothermal and Geological Reconstruction

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1.0 **Introduction**

The silica sinter *Pink and White Terraces* were an *Eighth Wonder of the World.* In 1886, the Tarawera eruption led to their disappearance. Due to the lack of any survey, it was impossible to state where the Terraces were located and whether they lay buried or destroyed. Controversy followed until World War II.

In 2011, an international oceanographic team announced they'd rediscovered the *Pink and White Terraces* in Lake Rotomahana (GNS Science, 2011a, b). They cited sonar and underwater photography, suggested by old maps and photography. The claims were published in institutional journals (Winner, 2012). In 2016, the team published three articles describing the rediscovery (De Ronde et al., 2016a, b and Keam, 2016).

In 2016 a forgotten survey of the *Pink and White Terraces* was digitally repatriated from Switzerland. It was by the nineteenth-century surveyor and geologist Ferdinand Hochstetter: the *Father of New Zealand Geology*. I noted the survey data might be reverse engineered to plot the *Pink and White Terrace* coordinates. Hochstetter's included maps enabled georeferencing to validate the data. His survey was published in issues 94 and 99 of this journal (Bunn et al., 2018; Bunn, 2019b). These articles concluded the Terrace spring locations lie buried on land around Lake Rotomahana. The Terraces may no longer be considered destroyed.

The marine team's conclusions conflicted with Hochstetter's survey. In this article, I examine their findings, seeking to reconcile the disparate conclusions. The Terraces remain a subject of scientific, economic and cultural fascination. It's important to settle the survey record for the Māori who grieve yet for lost relatives.

2.0 **Findings**

In 2.1 I examine the background provided to the marine team by Prof. Ron Keam (1932-2019). This comprised four pieces of research i.e. his map of old Lake Rotomahana, his altimetry, his

prediction Patiti Island was a pre-eruption feature and his coined *Pinnacle* feature for a geographic datum (Keam, 2016). These provided a framework for the marine team sonar, photography and georeferencing. In 2.2 I review the marine group's findings; explaining the disparity with Hochstetter's survey.

2.1 **Keam's Contributions**

2.1.1 Keam's Lake Rotomahana map

Between 1864 and 2011, one large-scale map was accepted. This was attributed to Hochstetter but produced by August Petermann (1822-1878), (Hochstetter and Petermann, 1864). From 2011, when Hochstetter's 1859 lake maps were published, it is necessary to differentiate these (Johnston and Nolden, 2011). After 2017, when 12 defects in Petermann's map were published: Hochstetter's mapping became the preferred resource (Bunn, 2017).

In 2016, large-scale versions of Keam's map were published. The marine team claimed it showed the *Pink and White Terrace* locations more accurately than Petermann (De Ronde et al., 2016a). Keam's map was drawn in 1959. He referred to it as a draft, *outline map* for he never finished it. It drew on his photograph collection; hence the caveats on photo-interpretation apply (Bunn, 2019a). In 2016, he advised me he'd used trigonometry and *all sorts of extra elements* (R. Keam, pers. commun., March 8, 2016).

In Figure 1, Keam has four landmarks on his map, including a pyramidal feature on the White Terrace embankment; he coined *The Pinnacle*. This *pyramidal feature* appears in pre-eruption photography. It became a landmark for the marine team georeferencing the old lake over the new Lake Rotomahana (see 2.1.3). The marine team later moved this Pinnacle twice during georeferencing; removing any claim of independence for their coordinates.

All of Keam's landmarks were on the northern third of the lake. No photographs apparently survive of/from the southern shore. Thus, two-thirds of his map from Pink Terrace around to Koingo is *mud mapped*. How he oriented it is unknown. There are 14 documented errors in the map (Bunn, 2017; 2020).

Keam recognised the deficiencies: *I felt that the map—even in its outline and incomplete form—could still be usefully employed in conjunction with Hochstetter's published sketch-map* [Petermann's]…(Keam, 2016). By contrast, Hochstetter's surveying and draughting expertise is evident in his books and cartography. He was the only cartographer to visit the lake: I am confident that had Ron Keam the opportunity to consider all of Hochstetter's mapping, he would acquiesce.

A recent analysis of faked Terraces' photography and the pitfalls in applying photogrammetry undermine Keam's photo-interpretative mapping (Bunn, 2019a). Sightlines from composite prints where the skyline is from another negative form poor scientific evidence. We do not know the cameras, lenses or exposure factors. We remain uncertain whether the prints were cropped or enlarged. These are necessary conditions for photogrammetry (Bunn, 2019a).

Therefore it is misleading to claim the Keam map was prepared by photogrammetry or is *the first '…correctly scaled, oriented and positioned outline map of the original Rotomahana…* (De Ronde et al., 2018). Keam never mentioned photogrammetry privately or in Keam, 2016.

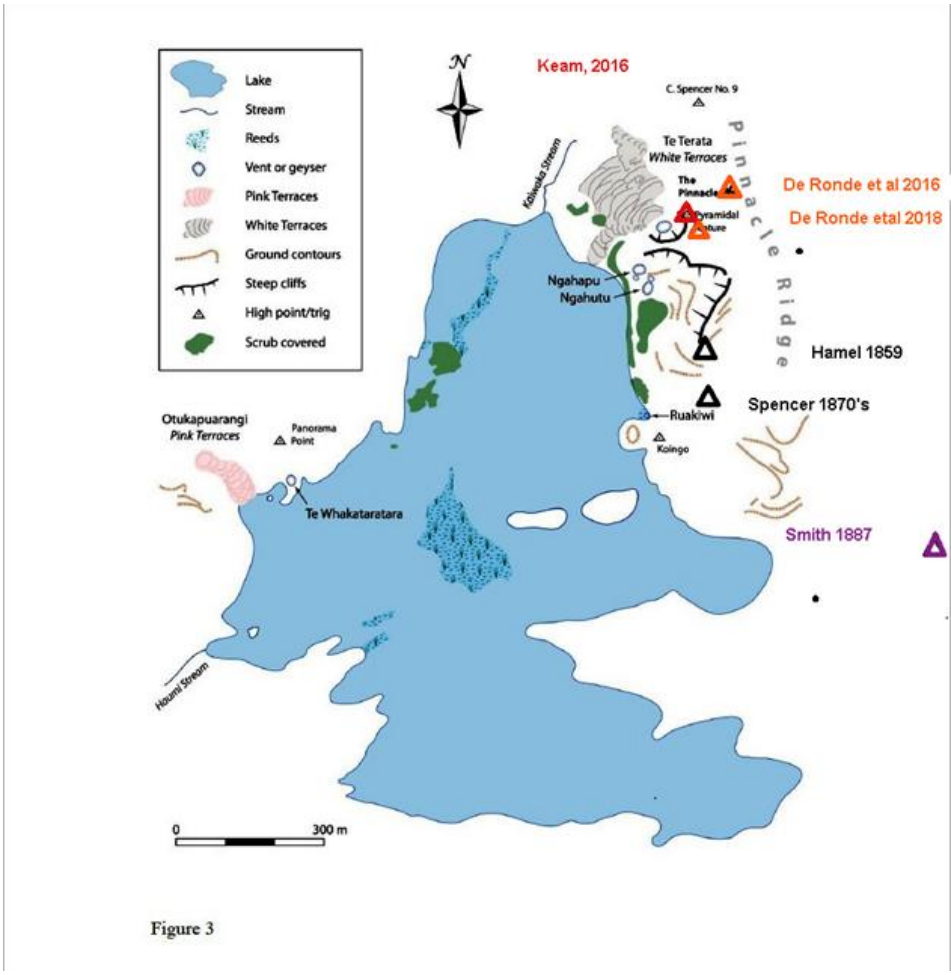

Figure 1- Keam's draft map.
(© Copyright R. Keam, 1959; Bunn, 2016a reproduced with permission, annotated.)

In Figure 1, Keam's coined *Pinnacle* or *pyramidal feature* is the left red triangle. The marine team's first relocation is shown to the NE in a red triangle, labelled *The Pinnacle.* They later moved this SW below Keam's location to the third red triangle. The remaining triangles show other documented pinnacle features (see Figures 4 and 5).

To reconcile the Keam and Hochstetter mapping, I georeferenced Keam's map over Hochstetter's observation stations in Figure 2 (Bunn, 2019b).

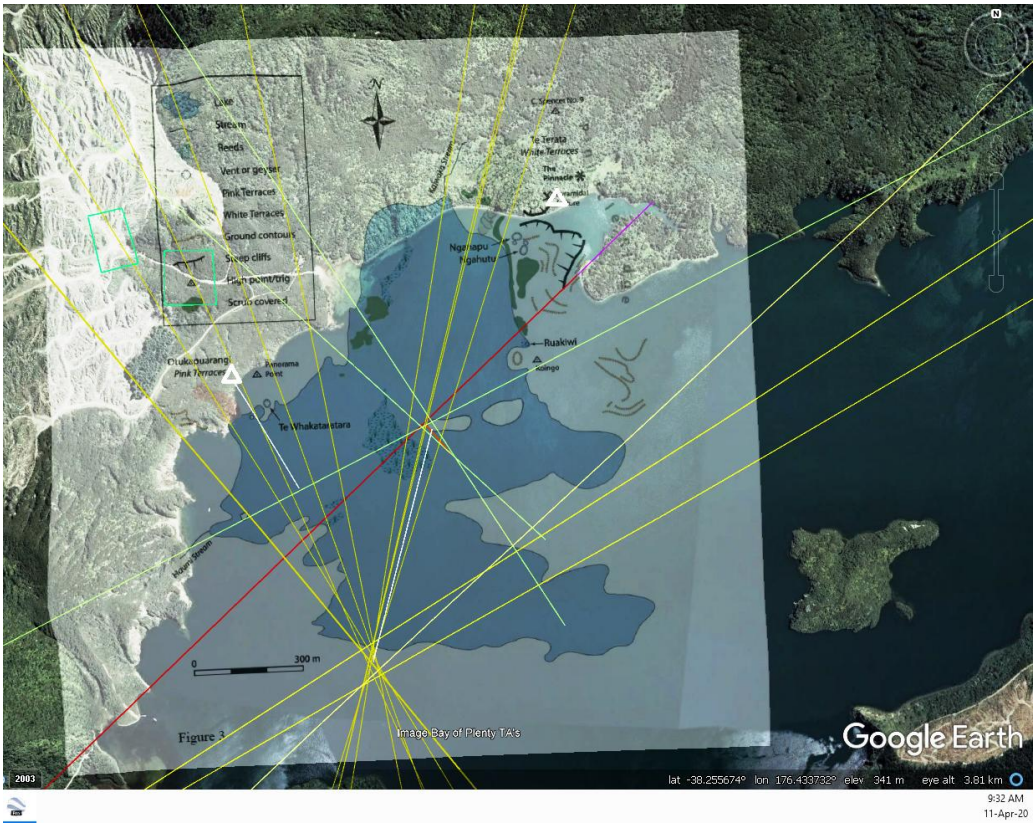

Figure 2- Keam's map georeferenced on Hochstetter's Stations 21 and Puai. (© Copyright Google Earth™ and Keam, used with permission; Bunn, 2019b. White triangles show adjacent Hochstetter survey *Pink and White Terrace* locations

In Figure 2, Keam's Pink and White Terrace locations abut Hochstetter's (Bunn, 2019b). Both Keam's spring sites lie on land, as do Hochstetter's. The georeferencing of Keam's and Hochstetter's mapping agrees. In 2012, American marine team members georeferenced Keam's map and published findings. Their spring locations also abut the Figure 2 locations (Winner, 2012). Despite errata in Keam's map, his Terrace locations are consistent with Hochstetter's. The marine team disparity does not derive from this map.

2.1.2 Keam's Altimetry

Given landform changes, establishing the altitude of old Lake Rotomahana is mandatory when the geospatial analysis is attempted of Terrace locations. Keam provided the marine team with his guessed altitude of ~2 m above Lake Tarawera level i.e. ~292 MASL (Keam, 2016). This conflicts with evidence-based altimetry (Bunn, 2017; Bunn et al., 2018; Bunn, 2019b). The 1858-1886 lake altitude of 303 m ± 1-2 m derives from borehole evidence and 15 published eyewitnesses. It confirms the altimetry by James Healy OBE (1910-1994) of ~301 MASL (Healy, 1975a and 1975b). Healy's meta-analysis of Healy, Smith, Malfroy and Warbrick agrees at ~303 MASL (Healy, 1975b). Keam and the marine team ignore their distinguished predecessor in favour of a guess.

2.1.3 Keam's Pinnacle

After the 1886 eruption, two sets of rocky outcrops north and south of the Rotomahana crater rift were christened *the pinnacles* in Figure 3. The high point of the northern set was christened the *Pinnacle*. Keam asserted this had been a minor pyramid-shaped summit on the pre-eruption White Terrace embankment in Figure 4. To him, it *seems sufficiently 'pinnacle-like' to justify the name's use in the pre-eruption era also* (Keam, 2016). This provided the marine team with a landmark; enabling georeferencing of old-lake features over the new Lake Rotomahana.

Figure 3- Burton photograph of Pinnacles on either side of the rift, 1886 (Te Papa MA_1323002).

Figure 4 shows the pre-eruption feature Keam termed … *the Pinnacle*.

Figure 4: White Terrace showing pyramidal feature. (Spencer c. 1880, Te Papa, O.027194).

To photo-historians there were similar features in the landscape. Figure 5 shows another *pyramidal feature* ~500 m S of Keam's pinnacle.

Figure 5: The Pinnacle feature above Tekapo ~0.5 km south along Steaming Ranges. (Hamel, 1859, Hochstetter Collection Basel, 2.7.31-copy1).

Apart from Figure 4, there is no supporting photographic, survey, cartographic or historical evidence for Keam's pinnacle on this pyramidal summit. I sent Figures 4 and 5 to Keam and he did not challenge Figure 4 as his *Pinnacle* (R. Keam, pers. commun., July 11, 2016). In Figure 1, the Pinnacle lies on the northern rim of the White Terrace embankment, at ~355 MASL. De Ronde et al., 2016a include Keam's map with the *Pinnacle* relabeled *Pyramidal feature* and a second point labelled *The Pinnacle* to the northeast. We now have two pre-eruption Pinnacles.

The marine team later admitted their 2016 Pinnacle relocation was mistaken (De Ronde et al., 2018). In Figure 1, after moving the Pinnacle ~100 m NE in 2016, they moved it ~105 m SW in 2018 (De Ronde et al., 2018). The marine team now had three pre-eruption Pinnacles against one post-eruption Pinnacle. Let's term them Pinnacle I by Keam (Figure 1), marine team Pinnacles II and III (Figure 1), with Pinnacle IV lying at ~323 MASL in the new lake (Figure 3). The pyramidal summit in Figure 5 we may term Pinnacle V and the southern outcrop, Pinnacle VI (Figure 3). There is a surfeit of pinnacles contributing to the disparity.

The new lake took years to fill. The crater floor was ~222 MASL. The Pinnacle was ~100 m above it in 1886. The area surrounding the Pinnacles was in elevated view for years. During that time, three government survey and mapping teams worked around the crater as did three university teams and Māori teams. Records exist from tourists and guides. None report any terrace-like feature on the crater floor or walls, in the marine group locations. While the lake

slowly filled (the Pinnacle was dry in 1893); erosion progressed and any terrace adjacent to the Pinnacle would be exposed. Keam's Pinnacle, if it existed before the eruption (other than Figure 3), lay ~35 m underground. This is the crux- there is no pre-eruption photographic, artwork, survey, historical or map evidence for Pinnacles II, III, IV or VI.

Had Keam or the marine team selected the Figure 5 pinnacle, then their georeferencing agrees with Hochstetter's survey. Both then concur with Keam's suggestion the Rotomahana *climactic base surge* broke out on land and *centred somewhere in or close to the Waikanapanapa Valley* (Keam, 2016). This pinnacle construct explains much of the disparity between the surveys.

2.1.4 Keam's Rangipakaru Hill and Patiti Island Prediction

Te Rangipakaru was a hill on the southeast side of the lake. Hochstetter described it: *…in the rear there rises an isolated hill, Te Rangipakaru (broken sky) on the west side of which, from a crater-shaped excavation, a powerful solfatara steams forth, depositing great quantities of sulphur…(*Hochstetter, 1867). In the crater lay a hill the colonists named *Banded Hill*. When the lake filled it became *Patiti Island*.

Ron Keam claimed this island was conterminous with Te Rangipakaru Hill (pers. commun., June 6, 2016). In 2018-2019, our final survey iterations showed Patiti Island indeed overlaps Rangipakaru Hill in Figure 6 (Bunn, 2019b). Hochstetter's Rangipakaru bearing corroborates Keam's claim, for it bisects the island (Bunn, 2019b). Rangipakaru Hill (Broken Sky) survives as Patiti Island and at a credible altitude (Bunn, 2019b). Other proximal landmarks may now be determined by triangulation and trilateration.

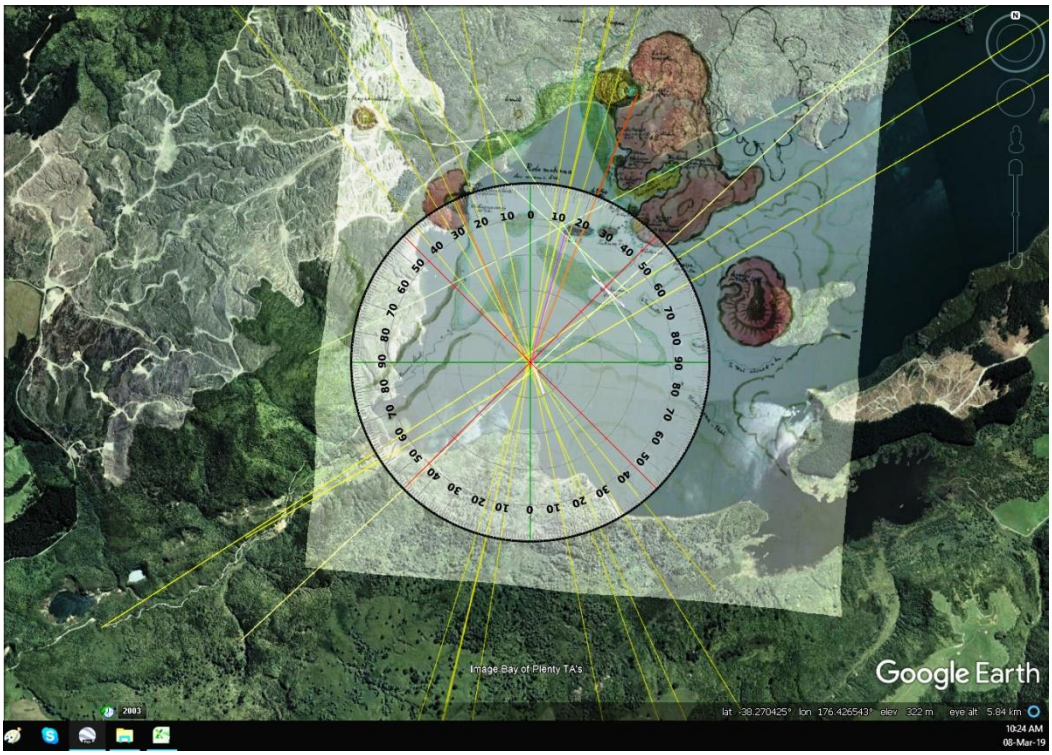

Figure 6- Rangipakaru Hill overlapping Patiti Island. (© Copyright Google Earth™/*Surveying+Spatial* used with permission/ Bunn 2019b).

In marine group georeferencing with Keam's map, Patiti Island is distant from Rangipakaru Hill, indicating an error. Their distance from Opokoruru Flat to Rangipakaru is ~1,200 m. On Hochstetter's and Petermann's maps it is ~720 m and ~670 m. The marine team georeferencing has a serious error of ~0.5 km, explaining more disparity (De Ronde et al., 2018).

2.2 **Oceanographic Group Findings and Errata**

In 2.1, Keam's map errata were insufficient to explain the disparity between the marine group Terrace locations and those from Hochstetter's survey. Both surveys rely on georeferencing pre-eruption geospatial data over today's topography. In this section, we examine the geospatial measures used by the marine group.

2.2.1 Arcuate Ridges

On 2.2.2011 the marine team institutions began media claims: *we are now 95 percent certain we are seeing the bottom two tiers of the Pink Terraces* (GNS, 2011).

The team based their claim on identifying an underwater ridge in the new lake and associating it with one on Keam's map and in Figure 7. Navigating from the sonar of this ridge, they took sonar and photographic imagery of their estimated Pink Terrace location and in three days published their Pink Terrace claim (GNS, 2011).

Figure 7: Spencer photo cited by the marine team over 2011-2016 (Charles Spencer. Te Papa (O.030702).

Figure 8- General view of the Hot Lakes, Rotomahana. (Mundy, c.1870. Te Papa, MA_136306).

Error entered when they assumed there was one ridge and their sonar image showed it. They were mistaken. In photography and Hochstetter's and Keam's mapping there were two adjacent ridges over the old lake. Today there are two ridges in the new lake in Figure 9; but are they the same ridges? It is conceivable they were created during the eruptions.

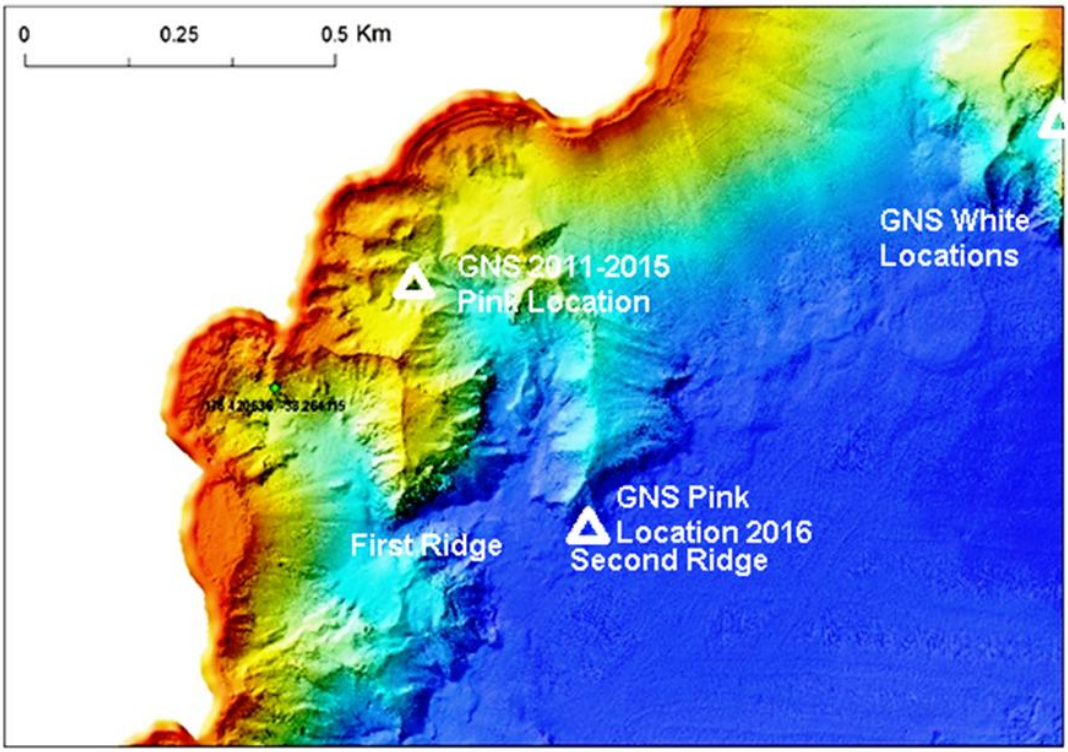

Figure 9- Bathymetry in the *Pink and White Terrace* areas. The green dot is our 2016 dive location in Pink Terrace Bay. (© Copyright de Ronde, 2016 used with permission and reproduced from Bunn, 2016a with annotation).

Figures 7-8 show the Pink Terrace lay below the first ridge, yet in Figure 9 their vehicle is in the next bay (De Ronde et al., 2016a; GNS, 2012). In Figures 7 and 8, the Pink Terrace is in the left foreground and the first ridge is in the midground. The second ridge is obscured by steaming-fog and is better shown in Figure 8.

The fog behind the first ridge marks the bay where the marine team stated they found the Pink Terrace in 2011-2012 (GNS, 2011; 2012): ergo they were in the wrong bay. In Figures 7-8, the first ridge is silhouetted against fog and the fog is silhouetted against the second ridge. This mistake explains more of the disparity.

2.2.2 Note on Pinnacles

In 2016, the marine team altered their Pink Terrace location to lie below the second ridge in Figure 9 (Tivey et al., 2016). I enquired and was advised it had been moved after comparing angles and distances from Keam's map Pinnacle against the sonar of a second location (De Ronde, pers. commun. February 18, 2016). It follows that the sonar, photography, bathymetry and cartography claimed as evidence over 2011-2015 for the marine team's Pink Terrace claim, cannot apply to this new location.

Later in 2016, I noted the Pinnacle location also differed on the Keam maps and enquired about this apparent error (R. Keam, pers. commun. July 20, 2016). I was advised the new location better fitted the distance and angle to the sonar of the new Pink Terrace location (Keam and de Ronde, pers. commun. July 20, 2016). From 2.1.3 it appears the revised Pink Terrace and Pinnacle locations were attempts to reconcile Keam's map, sonar, photo-interpretation and underwater photography.

2.2.3 Altimetry and bathymetry errors

In 2.1.2 I outlined the disparity with the marine team altimetry. Keam's ~292 MASL old-lake level disagrees with their sonar depths: there is a ~30-50 m variance in the revised Pink Terrace sonar locations (Tivey et al., 2016). This increases to ~40-60 m on our altimetry. No matching sonar data for the new White Terrace location were given.

This altimetry error led the marine team to estimate the old lake was ~31 m deep (De Ronde et al., 2016a). There is published evidence the lake was <10 m deep and the modal depth was 1-2 m (Bunn and Nolden, 2018; Bunn, 2020). This mistake biases their bathymetry and restricts their analysis to 2D. Latitude and longitude are inadequate for georeferencing. Accurate altimetry is also required for buried Terrace locations (Bunn and Nolden, 2018; Bunn, 2020).

2.2.4 Sonar interpretation

The marine team claims from 2011- first relied on sonar imagery which was interpreted as terrace basins. We are the only investigators to scuba-dive Lake Rotomahana, and their sonar imagery better resembles the basin-shaped vents and wave-terraces we filmed. These basin-vents emitted gas and could not be terrace basins; for the latter had imperforate bases. The wave-terraces formed on rocky shelf features as the new lake filled over decades. These basin-vents and wave-terraces were videoed in Bunn, 2016b and in Figure 10.

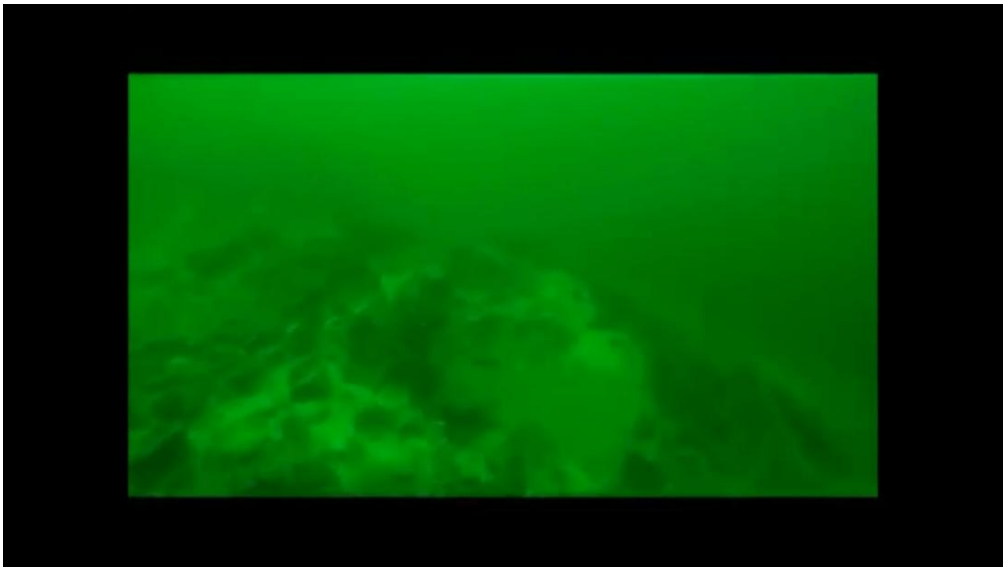

Figure 10- One of many large basin-shaped gas-vents in Lake Rotomahana.
(Frame-capture © Copyright B. Fisher, Bunn, 2016b).

For example, sonar from the Pinnacle area will naturally return strong signals. The marine team reported bubble-plumes here, indicating vents like those in Figure 10 (Bunn, 2016b). On sonar, these can misleadingly resemble Terrace basins. We found such exposed rocky lake-floor at each dive location; something unsurprising in a crater lake.

2.2.5 Keam cartography compiled

Keam's map scale and lake size transformed with marine group georeferencing. As the scale enlarged, the lake length shrank from ~1,474 m to ~1,100 m in 2016-2018. Their Keam map is now too small against the historical record. Eyewitnesses report the old lake was nearer 1,600 m than 1,100 m (Bunn et al., 2018). The marine team length error is ~0.5 km. Keam published his large-scale map in 2016; 57 years after drawing it (Keam 2016). He advised it was *essentially unaltered* (R. Keam, pers. commun. March 8, 2016).

2.2.6 Photography Interpretation

The 2011 marine team Pink Terrace claims were based on sonar, cartography and photography. The White Terrace claim was based on sonar. No georeferencing was published until 2016.

Of the 5,123 photographs the marine group took, 14 were published and two were foremost.

(a) Photograph *2011_01_30_23_53_55-enhanced.*

From 2.2.2011 the marine team promoted their Pink Terrace claim with this photograph across institutional and online media:

Photograph *2011_01_30_23_53_55-enhanced* was described as:

"… the strong reflectors of the Pink Terraces … show the vertical edge of a terrace head on." http://juliansrockandiceblog.blogspot.com/2011/02/

It was published as slide 55 at https://www.slideshare.net/petergnz01/pink-white-terraces-cornel-de-ronde and in de Ronde et al., 2016a Figure 12c.

In 2012, the *Woods Hole Oceanographic Institution's* official journal *Oceanus* published a cropped version, captioned:

"… the rosy, bumpy buttress of one tier of Pink Terraces that was found near the bottom of Lake Rotomahana in 2011. (Photo by Dan Fornari, WHOI)" (Winner, 2012). The same article claimed: *'The Terraces were never destroyed', he 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'* [emphasis in original] (Winner, 2012).

In 2016 this photograph was again published, but now as the White Terrace [sic]:

Photograph taken … immediately west of The Pinnacle … where the ridge shallows to ~40 m …. The pronounced runnel texture seen on the face of the outcrop is remarkably similar to the textures seen on the outward facing buttresses to the White Terraces (De Ronde et al., 2016a).

The feature cannot exist in two locations and its provenance must be established before it becomes evidence.

(b) Photograph 2011_01_30_23_54_05.

On 2.2.2011 a second photograph was published by the marine team. Figure 11 was also claimed to show the Pink Terrace. It is slide 57 at: https://www.slideshare.net/petergnz01/pink-white-terraces-cornel-de-ronde It is not associated with sonar and no location coordinates were given.

Figure 11- Image 2011_01_30_23_54_05- An image of the Pink Terraces under water with kaumatua Anaru Rangiheuea. (Used with permission Stuff / Dominion Post, 2.2.2011).

Caption- *On the right, the dark shadow is one of the terrace steps, whilst further to the left, across the sloping muddy lake floor there are some smaller exposed vertical sections of rock. These shapes are typical of hydrothermal silica deposits*. 2/2/2011 http://juliansrockandiceblog.blogspot.co.nz/2011/02/final.html

On enlarging and brightening the image, the *dark shadow* is not a terrace step but an artifact. On brightening the photograph, this surface feature extends back out of the shot. On this surface, there is no sign of any smooth shelf, terrace basin, regular surface or e.g. stalactites … only irregular mud-covered rock.

By 2016, the marine team photography except for image *2011_01_30_23_53_5* makes no specific claim to be of a Terrace tier. While image *2011_01_30_23_53_55-enhanced* and to a lesser extent image 2011_01_30_23_54_05 might resemble silica sinter, this does not prove they are attached to a terrace. Sinter existed around old Lake Rotomahana in many places. Sinter findings on land by our 2017 *PAWTL2 Project* and our 2016 scuba team couldn't enable claims they were from a Terrace. The marine team did not produce evidentiary samples.

The marine team's photographic misinterpretation adds to the survey disparity.

2.2.7 Validation of marine team georeferencing.

From 2011-2015 the marine team claims relied on sonar and photography. The imagery was specific to the stated lake-floor locations. Coordinates of claimed terrace locations cannot be established beyond their large markers on small illustrations.

In 2016, the marine team introduced georeferencing, using their Pinnacle construct as a surveying landmark:

Keam … top of the Pink Terraces would be located ~1160 m bearing ~245° from The Pinnacle. If we then project a line from the present-day position of The Pinnacle in Figure 5B towards 245°, remarkably we intersect the terrace-like features seen in Figure 10 after ~1085 m … (De Ronde et al., 2016a)

From the 2016 correspondence cited, the 245º azimuth did not strike the team's Pink location. There was another sonar signal ~0.5 km south, close to the azimuth. In 2016, the Pink Terrace moved to this in Figure 9 (Tivey et al., 2016).

The marine team was handicapped by having only one landmark i.e. the Pinnacle. In survey resection three are required. Keam's map could accommodate terrace locations off their 245º azimuth in two ways:

a) If Keam's map was moved along the 245º azimuth, one or both Terrace locations might luckily align with the lake-floor returning a sonar signal.

b) If Keam's map was anchored at the Pink end, the map could be shrunk or enlarged to shift the White Terrace location along the azimuth. A range of White locations could become available.

There is a problem however: the new Pink sonar location is ~1,200 m from the Pinnacle versus ~1,100 m on Keam's 2016 map (Keam, 2016).

This could be solved by shifting Keam's Pinnacle ~100 m NE along the 245º azimuth, to reconcile the relative positions of sonar and Pinnacle coordinates in today's lake; with the relative locations of both terraces and Keam's Pinnacle on his map (de Ronde, pers. commun., July 11, 2016). This was apparently done.

With Keam's map, I replicated the marine team georeferencing under b). To align Terrace locations, the new Pink sonar site and the lake Pinnacle along the 245º azimuth; Keam's map must be reduced to ~1,100 m in length. Coincidentally, this became the length of Keam's lake map in de Ronde et al., 2016 and 2018. A length of 1,100 m conflicts with Hochstetter's survey and historical records of ~1,600 m. It conflicts with earlier publications of Keam's map where his length was ~1,475 m (Keam, 1988 and 2004).

The marine team mapping solution also uncouples the 2011-2015 sonar and photography used to justify the Pink Terrace claim. These locations are not along the 245º azimuth. From 2016, the Pink and White locations moved south to fit the revised narrative. The photography was from 2011 and 2014, hence no new sonar or photography exists of these revised Terrace locations. The authors were restricted in claiming their sonar and photography were from nearby locations.

The inter-survey horizontal interspaces between Terrace spring locations are ~0.5 km. The perpendicular interspaces between spring locations are ~50 m (Tivey et al., 2016: de Ronde et al., 2018).

2.2.8 Bubble Plumes and Magnetic Anomalies

The marine team's focus on a transverse lake axis and the pinnacles is unfortunate for a perpendicular axis is more illustrative, following the Steaming Ranges south to Patiti Island. The Steaming Ranges lie north-south in Figure 6. Keam divided the ranges into northern and southern sections, adding the base surge initiated near their meeting in/on the Waikanapanapa Valley. Hochstetter's survey agrees with him and this valley abuts the lake pinnacle in Figure 6.

The marine team charted magnetic anomalies consistent with an 1886 basalt dike here (Tontini et al., 2016). Hydrothermal bubble plumes in this area agree (Walker et al., 2016). The Rangipakaru-Patiti datum also agrees as discussed. These place the *base surge* site near the northern lake pinnacle and the Figure 5 pinnacle above Tekapo is a prime candidate for such a dike.

These marine team findings are consistent with Hochstetter's survey.

3.0 **Discussion**

This reconciliation focuses on the 2016-2018 marine team's claims the Terraces were destroyed against their 2011-2015 claims they were discovered *in situ* (Winner, 2012). Their 2016-2018 georeferencing of the *Pink and White Terraces* was replicated.

The flawed Keam map proved reliable in georeferencing the Terrace locations against Hochstetter's survey. Keam's successful map orientation was remarkable, with a 2º error. However, his flawed map and mistaken altimetry led to errata which were avoidable had he followed his predecessor Healy. His Pinnacle invention was adopted by the marine team who lacked a means of georeferencing their sonar and photography. Keam was aware of multiple Pinnacles in 2016 and I listed six: which question marine team reliance on it.

Providing one bearing, the Pinnacle was inadequate for resection or triangulation. It required adjustments that disconnected earlier sonar and photography, damaging the validity of Terrace claims. The marine team compiled Keam's map but omitted Rangipakaru; the one proximal feature correctly claimed by Keam to exist in the pre and post-eruption landscape. This forms a better survey datum than arcuate ridges or pinnacles.

The marine team altimetry and bathymetry contradict the historical record. Their shrinkage of Keam's map to accommodate their 2016 Terrace locations, conflicts with historical records and Hochstetter's survey. Their best photography is compromised by confusion over which Terrace location it represents. An authority on photo-manipulation confirms the versions cited are the same photograph (Elisabeth Bik, pers. commun. May 16, 2020).

The marine team employed surveying and georeferencing methodology but without formal discussion of survey error. No latitude or longitude coordinates were provided. A bearing error

of ≤1-2 degrees is required (McFadgen, 1999). Of the inter-survey spatial differences, the elevations are more significant i.e. for drilling and excavation.

The marine team claims from 2011 appear based on cartographic, photographic and sonar misinterpretation. Subsequent efforts to strengthen their findings by georeferencing Keam's map were unhelpful. Keam's evidence appears more consistent with Hochstetter's survey than with the marine team iterations. On balance, their 2016-2018 iterations are inadequate to establish where the *Pink and White Terrace* locations exist today. Hochstetter's survey remains the only primary, pre-eruption survey evidence of the Pink, Black and White terrace locations.

Acknowledgements

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