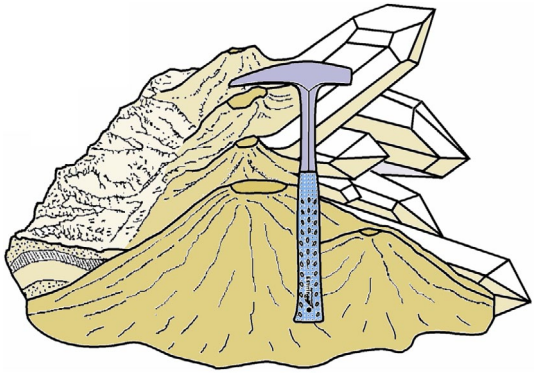


Geocene

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CONTENTS

Instructions on use of hyperlinks and hyperlinks	*last page*	25
MATUKUTŪRURU / WIRI VOLCANO INSIDE AND OUT	Bruce W. Hayward, David Fraser	1 – 11
INTERPRETATION OF A MID-SLOPE LANDFORM ON MT HOBSON (ŌHINERAU): QUARRY OR PALEO-LANDSLIDE?	Beatrice Bertelli, Martin Brook	12 – 15
RISE AND DEMISE OF MUSHROOM ROCKS AT TI POINT, LEIGH, NORTH OF AUCKLAND	Bruce W. Hayward	16 – 18
CAN WE REDUCE GREENHOUSE GASES FROM CEMENT PRODUCTION IN NEW ZEALAND BY PARTIAL SUBSTITUTION OF NATURAL POZZOLANS?	Ian Simpson	19 – 21
IDENTIFICATION OF A “NEW” TUFF RING AT TE APUNGA-O-TAINUI/MCLENNAN HILLS VOLCANO	Dougal Townsend, Graham Leonard	22 – 24
Corresponding authors’ contact information		25

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Contributions about the geology of New Zealand (particularly northern New Zealand) from members are welcome. Articles are lightly edited but not refereed.

Please contact Jill Kenny jill.kenny@xtra.co.nz

MATUKUTŪRURU / WIRI VOLCANO INSIDE AND OUT

Bruce W. Hayward, David Fraser

Early in 2025, we received information that the Basalt Business Park being constructed inside the former NZ Railways Wiri Volcano quarry (Fig. 1) was nearing completion and that soon all the lower parts of the quarry cuttings might be hidden by buildings and concrete walls. We also knew that most of the old quarry cuttings had recently been cut back slightly further by the developers and these cuttings currently provided fresh faces for examining the volcanic rocks. On the first visit it became apparent that there were roads and driveways open to the public that provided reasonably good views of many of these cuttings and so a Geoclub field trip was organised for two weekends later, before the last of the large industrial buildings were erected in front of them. These fresh faces revealed insights into the formerly hidden inside of Wiri Volcano, not all of which had been seen previously.

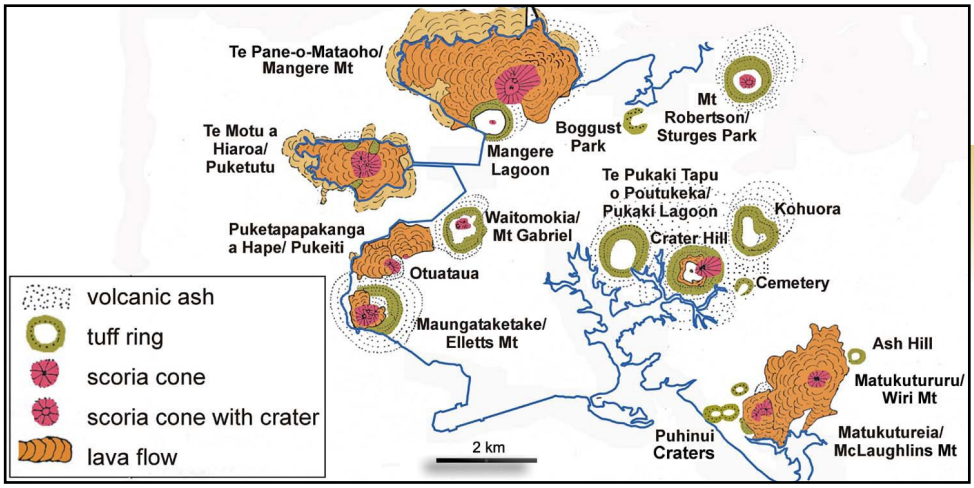


Fig. 1. Location of Matukutūruru/ Wiri Volcano (lower right) in the southern part of the Auckland Volcanic Field. From Hayward (2019).

Previous observations and history

This article reports on what we saw in these exposed quarry faces before they are hidden, overgrown by weeds or the tuff weathers to clay. We have also taken the opportunity to try and interpret the eruption history of Wiri Volcano and the surface landforms this produced. First off, we caution that we have found no photographs taken from on land or in the air, of the volcano prior to 1949, by which time almost all the eastern half of the cone had been quarried away (Fig. 2).

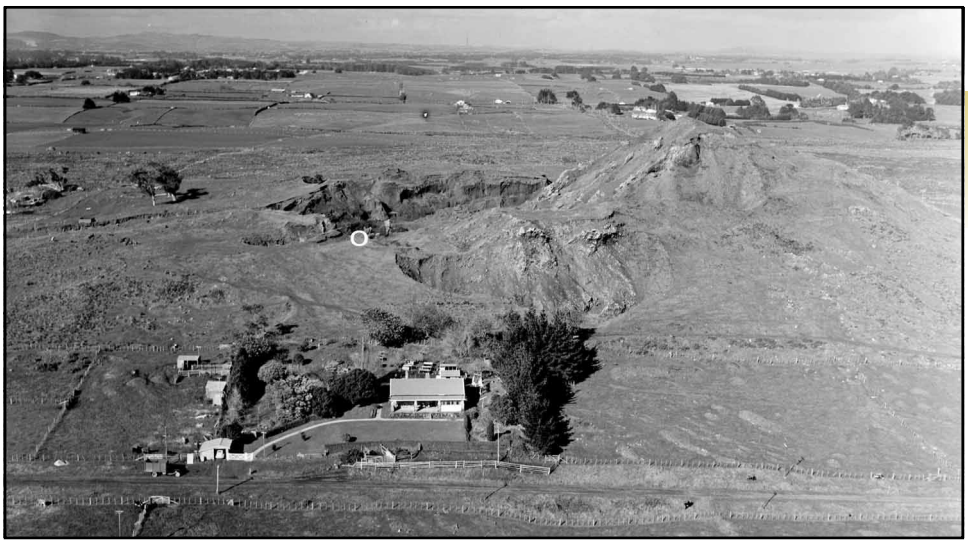


Fig. 2. The earliest known aerial photograph of Wiri Volcano, taken in 1949 looking south, by which time most of the eastern half of the cone had been quarried away. Wiri Station Rd runs across the bottom of the image and Rumney Cottage is in middle foreground. White circle is entrance to Wiri Lava Cave as a reference point. Whites Aviation.

Wiri Volcano appears on the earliest published geological maps of Auckland by Heaphy (1860) and Hochstetter (1864), although neither provide any detail of its landform. Hochstetter (1864) did state, however, that the "scoria cones supply the road metal for Great South Rd." Hochstetter only saw the volcano in the distance, whereas Heaphy clearly visited the area, as he painted Wiri and the adjacent Matukutūreia/McLaughlins Volcano in February 1859 (Fig. 3). He may have painted them from earlier individual sketches, because they appear to have been swapped in position. Heaphy submitted this painting to the Geological Society of London to accompany his manuscript published in 1860, but the painting was not published.

Most of the quarrying of Wiri Volcano was undertaken by NZ Railways Dept to supply scoria ballast for beneath the tracks. NZR quarrying is reported to have started in 1915 (Fig. 4) and continued apace until the 1990s (Kermode *et al*. 1992).

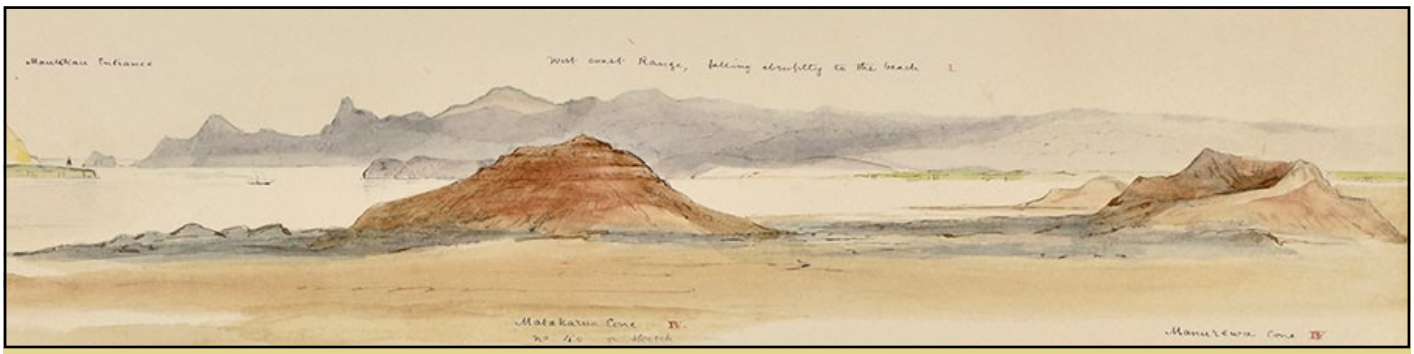


Fig. 3. Watercolour painting from southeast of Matukutūreia/McLaughlins and Matukutūruru/Wiri volcanoes by Heaphy, February 1859. The position of the two seems to have been switched, because McLaughlins was characterised by its wide breached crater and was also 30 m lower than Wiri, as depicted in the volcano on the right. The cone on the left has the extensively terraced profile of Wiri and even the lava flow pedestal on the lower west slope (left).

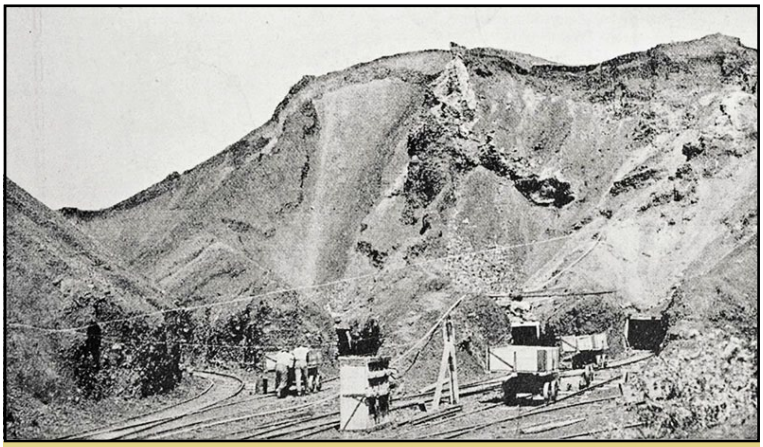


Fig. 4. NZ Railways built a short side track into their Wiri Quarry, which removed scoria from 1915 for use as ballast beneath the rail tracks. The depression on top may be the remains of the crater. Photo: Auckland Public Library, 1922.



Fig. 5. Two subvertical, basalt dikes (one thick, one thin) intruding the Wiri scoria cone. These dikes were visible in 2005 in the disused quarry face beneath the entrance to Wiri Lava Cave but have since been removed. Photo: BW Hayward.

Firth (1930) was the first geologist to specifically write about Wiri Volcano, noting that "the remnant of a small crater is still to be seen at the head of the main quarry. This quarry also reveals irregular masses of highly scoriaceous basalt traversing the scoria in the vicinity of the old vent."

Searle (1961) described Wiri as a scoria cone surrounded by an extensive lava flow field. He noted that Wiri was the middle of three volcanoes in a line – McLaughlins, Wiri and Ash Hill (Fig. 1). Searle (1961) inferred that the cone was built by "fire fountaining from a number of vents". Even by 1961, Searle noted that "Extensive quarrying for railway ballast has so reduced the cone, approximately 300 ft high, that it is now very difficult to recognise the original form. Apparently, it was rather a squat mound of scoria with a single summit crater. The sites of active vents are indicated by several plug-like masses of lava-welded scoria and by bodies of scoriaceous basalt. The beds of scoria are at times cut by small irregular dikes" (e.g., Fig. 5) … "some of them are associated with small flows interbedded with the layers of scoria and, in some instances extend out from the foot of the cone to build up a massive lava platform above the level of the main lava field."

Searle (1961) was able to make these valuable observations of the structure inside the scoria cone because quarrying had only removed about half the cone by this time (Fig. 6). They are all the more important because today no trace of the scoria cone remains. Searle saw no trace of the underlying tuff ring that is now clearly visible in the old quarry walls. Indeed, it would seem that his "lava platform above the level of main lava field" is underlain by the tuff ring and composed of thin lava flows overtopping it (see later).

From quarry exposures of Wiri's lava flows, both near the centre and also to the east and south, Searle (1961) concluded that the cone was surrounded by lava flows, the earliest of which were quite thick (~8 m), becoming thinner later. The



Fig. 6. View from southeast over quarried remains of Wiri Mt in 1958 showing the extensive exposures of the inside of the scoria cone that were able to be studied by Searle (1961). White circle is entrance to Wiri Lava Cave as a reference point. Whites Aviation.

youngest flows (up to 8 on the eastern flank) formed a pedestal surrounding the base of the scoria cone and were all significantly thinner (1–4 m). Searle (1961) also infers that present day Puhinui Stream was displaced around the edge of the lava flow field to the north. Kermode (1992) produced a detailed map of the extent of the lava flows as part of his 1:50,000 geological map of Auckland.

Following agitation from the Geological Society of New Zealand and the Historic Places Trust, a strip of the lower northeastern slopes of Wiri Volcano containing Wiri Lava Cave was set aside from quarrying in the 1960s–1990s. It was not until 1998 that this land was transferred to the Department of Conservation and gazetted a Scientific Reserve (Hayward & Crossley 2014). Adjacent to this strip of land alongside Wiri Station Rd, and containing the old farmhouse, Rumney Cottage, is another larger section that formed the lower northern slopes of Wiri Volcano (Hayward 2019). It is largely underlain by tuff and was of little value for quarrying, and therefore survived. Beneath the present long grass, it contains remnants of prehistoric gardening. It was transferred to the Tūpuna Maunga Authority from the Crown in 2014.

Quarrying in the 1990s lowered the floor of the quarry to up to 5 m lower than the surrounding land (Fig. 7) and the hole filled with water to become a lake (Hayward *et al*. 2011). Through the period 2000–2012, the lake prevented close access to the quarry cuttings as they became overgrown by scrub. In preparation for industrial development, the lake was progressively filled and the former quarry walls on the north side, where remnants of the lower volcano slopes remained (Fig. 8), were slowly cleared of vegetation and cut back, exposing sections of tuff ring (Hayward 2019).

It was partway through this process that Macquarie University PhD student, April Foote, studied some of the recently accessible and cleaned exposures (Foote *et al*. 2022). Since her field studies, the lower portions of some of these



Fig. 7. View from northeast over the deeply quarried Wiri Volcano in 1994. The lowered portion later became a lake for several decades. White circle is entrance to Wiri Lava Cave as a reference point. Photo: BW Hayward.



Fig. 8. View west over Wiri Volcano quarry in 2009. Wiri Station Rd is on the right. Note the vegetation-covered quarry faces around the sides of the lake in the quarry floor. White circle is entrance to Wiri Lava Cave as a reference point. Photo: BW Hayward.

exposures have been buried and other portions of faces hidden at the time by vegetation have been cleared. Foote *et al*. (2022) documented in great detail the strata in two portions of the tuff ring newly exposed in the quarry face and interpreted them in terms of eruption styles. They also documented the scoria overlain by lava flows exposed in the face beneath the entrance to Wiri Lava Cave on the northeast slopes of the volcano. They also reaffirmed the well-established sequence of eruption styles of most Auckland volcanoes, starting with wet phreatomagmatic eruptions building a tuff ring, followed by a switch to dry strombolian fountaining producing a scoria cone, with late-stage effusion of voluminous lava flows. In an unusual departure, they inferred that a major break in the tuff ring on its western side was a result of the eruption of a previously unrecognised tuff ring through the existing main tuff ring (Foote *et al*. 2022). This same feature had previously been inferred to have been produced by part of the tuff ring slumping into the crater (Hayward 2019, p. 301), a common occurrence in many of the exposed tuff rings in Auckland volcanoes.

The eruption of Wiri Volcano has been dated at 30,500 years by a combination of radiocarbon, paleomagnetic and Ar–Ar methods (Hopkins *et al*. 2021). Within error this is the same as the date on the adjacent small explosion crater and tuff ring, Ash Hill (Hayward 2008).

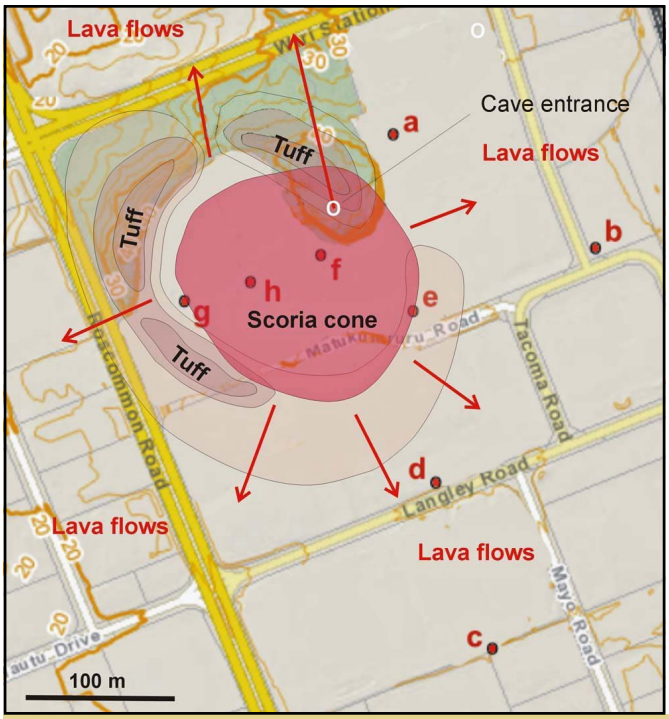
Borehole record

In the New Zealand Geotechnical Database, there are logs of 8 boreholes (a–h, Fig. 8) that provide useful information on the internal structure and eruption history of Wiri Volcano (see Appendix for summary). The borehole data indicates that the original land surface (Tauranga Group) beneath Wiri Volcano was somewhat variable, being higher in the south and west (up to 21 m asl) and lowest in the northeast (10–11 m asl), possibly approaching the pre-lava flow route of Puhinui Stream. Any explosion crater formed during the early phreatomagmatic phase of eruption must have been rather small (no wider than 200 m) as it was not detected in the boreholes, except in borehole h, which was entirely through 36 m of massive basalt lava down to 20 m below sea level. This borehole is inferred to have drilled down part of the lava-filled throat of the volcano.

The 4–6 m of tuff in boreholes e and f (Fig. 9) is massive tuff breccia with numerous clasts of country rock – the same lithology as the oldest unit exposed in the tuff ring in the quarry face. The lava flow field surrounding the cone has all been quarried for aggregate. Borehole a, beyond the northeast base of the cone, had 20 m of lava flows prior to quarrying. The other location with significant basalt (3 flows, 7.5 m thick) was borehole g, in the shallow moat between the tuff ring and the scoria cone (Fig. 9). No scoria was encountered in any of these boreholes, as the entire scoria cone, except the lava cave scientific reserve, has been removed by quarrying.

2025 observations in cut faces

The entire volcanic edifice around its southern half has been quarried away and there are no quarry faces remaining on this side. Four cut faces that still exist in the remaining lower northern slopes of the volcano (Fig. 10) are briefly described:



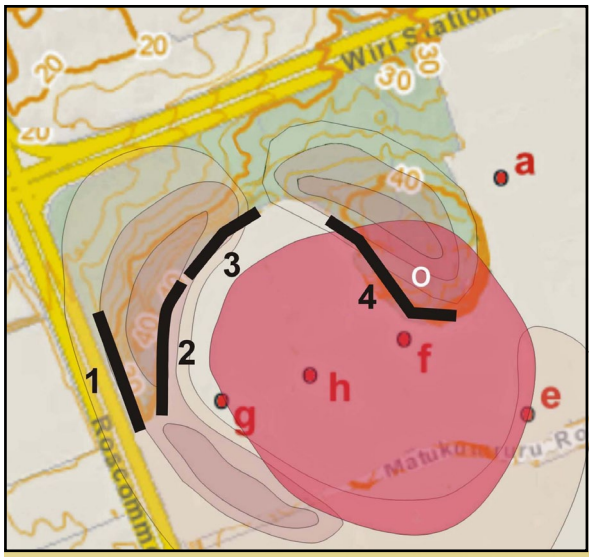


Fig. 10. Location of numbered cut faces (black lines) in the remnant of the lower northern slopes of Wiri (green shades) described in this note.

Fig. 9. Map of Wiri Volcano footprint with respect to present day roads and the remaining lower northern slopes now in reserves (green). The reconstructed, contoured extent of the tuff ring (browns) and extent of the scoria cone (red) are shown, based on boreholes (a–h), quarry faces and historic data. Main lava flow directions are inferred.

1. Roscommon Rd cutting

This 5–10 m high cutting (Fig. 10, [1]) consists of 6–8 m of bedded tuff overlain by several thin basalt flows. The tuff must be on the outer slopes of the tuff ring as it dips gently west throughout the cutting (Fig. 11). At the southern end of the cutting, the strike of the tuff swings towards the southeast and a greater thickness and number of flows are visible overlying the dipping tuff slope (Fig. 12).



Fig. 11. Roscommon Rd cutting through the outer slopes of the Wiri Mt tuff ring that has been overtopped by basalt flows. Photo: BW Hayward 2025.



Fig. 12. Geoclubbers examine the southern end of the Roscommon Rd cutting where two flows overlie the west-dipping tuff ring slopes. Photo: BW Hayward 2025.

2. Northwestern quarry face

The northern half of this face (Fig. 10 [2]) consists of 15 m of tuff overtopped by a 1–2 m-thick basalt flow (Fig. 13). The lower 5 m of the tuff consists of massive tuff breccia (Fig. 14), probably thrown out by one of the first wet phreatomagmatic blasts at the start of the Wiri Volcano eruption. This is overlain by thinner base surge beds of tuff (Foote *et al*. 2022). In the southern half of the face, the tuff ring is replaced by a 50 m-wide sequence of 6–7 basalt flows with rubbly breccia and scoria between flows (Fig. 15). The contact is an unconformity with a 30º slope that is draped by 2 m of dark basaltic

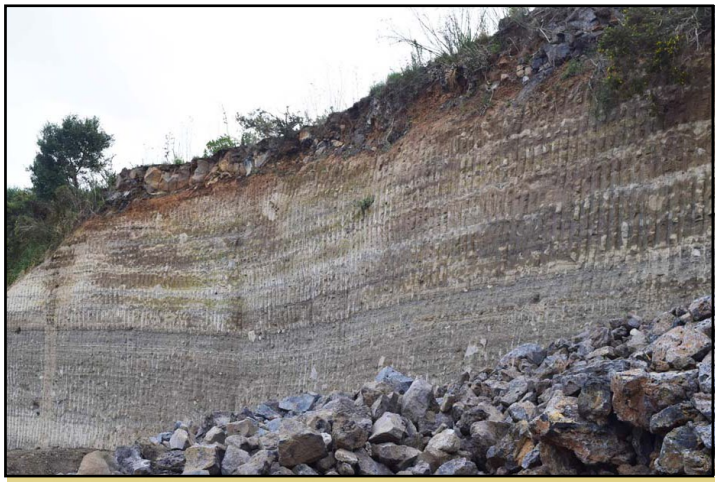


Fig. 13. Much of the northwestern quarry face [2] cuts through the thickest part (15–18 m) of the Wiri Mt tuff ring. The lower part of the tuff consists of a 7 m-thick massive tuff breccia deposit (Fig. 14). Photo: Ilmars Gravis 2025.



Fig. 14. Close-up of the tuff breccia forming the base of the Wiri tuff ring (Fig. 13) consisting of angular clasts of country rock (Waitemata Sandstone) and fewer basalt in an ash matrix. Width of image 1.5 m. Photo: BW Hayward, 2025.



Fig. 15. Southern half of the northwestern face [2] showing a 50-m-wide depression in the tuff ring filled with a sequence of lava flows. The low-angle unconformities between the lava flows and underlying tuff ring can be seen on both sides. Photo: Katherine de Courcy 2017.



Fig. 16. Close-up view of the right end (north) of the northwestern face (Fig. 15) showing the 30º unconformity cutting across the tuff (right), mantled by dark lithic tuff, baked red by the basalt lava flows that fill the overlying depression. Photo: Katherine de Courcy 2017.



Fig. 17. Close-up view of the left end (south) of the northwestern face (Fig. 15) showing the rubbly base of lava flows irregularly overlying red-baked tuff of the tuff ring. Photo: Katherine de Courcy 2017.

tuff, baked red near the top (Fig. 16). The tuff ring reappears at the south end of the face where the unconformable contact is more irregular and gentler, with the upper tuff baked red by the overlying basalt flows (Fig. 17). Foote *et al.* (2022) interpreted this lava-filled hole in the tuff ring to be a small secondary tuff ring (crater). There is no evidence of this hole in the Roscommon Rd cutting (30 m away on the other side of the remaining ridge) and we infer it is more likely a depression created by a slump of wet tuff back into the crater immediately prior to the switch from a wet to dry eruption style.

3. Northern quarry face

The northern face [3] is a continuation of the tuff ring overlain by 1–2 thin lava flows forming the northern half of the northwestern face (Fig. 13). Where the two faces meet there is a well-exposed high-angle unconformity within the tuff ring (Fig. 18). This is inferred to be the side of a slump scarp formed during the course of the phreatomagmatic eruptions. The depression created by the slump has been filled (repaired) with more bedded base surge deposits that initially mantled the steep scarp (Fig. 18). To the east of this face, the top of the tuff ring appears to be lower with a thicker sequence of flows over it (Fig. 19). Separating the northern face [3] from the northeastern face [4] is an area of basalt flows that have been disrupted by quarrying activities and make it difficult to determine the original structure.



Fig. 18. Portion of the northern face [3] showing the tuff ring overtopped by two thin basalt flows. A steep unconformity (left) within the tuff is inferred to be a slump scarp that has been "repaired" by deposition of base-surge tuff in the depression. The base of the photo shows the top of a concrete wall constructed to catch rocks falling off the face onto the driveway below. Photo: BW Hayward.



Fig. 19. The upper eastern end of the northern face [3] consists of 6 m thickness of basalt flows overlying a low saddle in the tuff ring (behind planted garden). Photo: BW Hayward 2025.

4. Northeastern quarry face

The vertical northeastern face [4] curves around the edge of the highest remaining part of the Wiri Volcano (47 m asl) containing Wiri Lava Cave Scientific Reserve (Fig. 10). It is now partly hidden by large industrial buildings constructed close to some of the face. The southern end of this face shows the lower northeastern slopes (20º) of the scoria cone overlain by lava flows (Fig. 20) with the sequence thickening away from the cone (Fig. 21).



Fig. 20. The lower slopes of the scoria cone (reddish) overlain by thin lava flows at the southern end of the northeastern face [4], seen between buildings. Photo: BW Hayward, 2025.



Fig. 21. The southern end of the northeastern face [4] consists of the lower northeastern slopes (20º) of the scoria cone (reddish) overlain by lava flows that become a thicker sequence away from the cone (right), with the lower flows probably exuded from near the base of the scoria cone. This face is mostly hidden now behind a large building. Photo: David Fraser 2017.

The middle section of this face is partly obscured by a large building, but here the scoria appears to have been intruded by a sill of basalt lava (Fig. 22). Further north the whole face is composed of massive basalt (Fig. 23), which is hard to interpret but may be a mass intruding into the scoria or lava ponded in a small moat between the base of the scoria cone

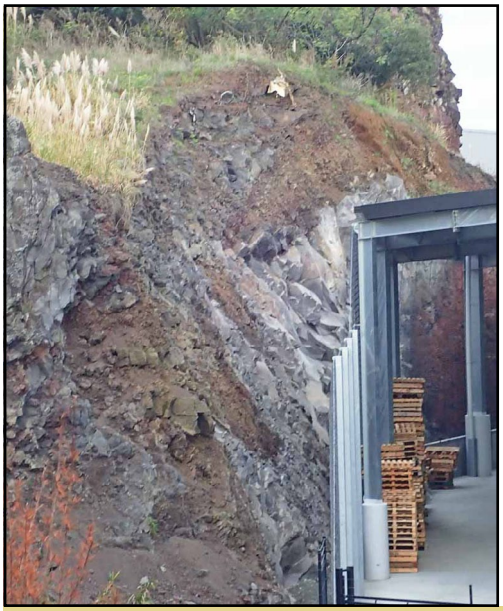




Fig. 23. The northern end of the northeastern face consists of a mass of basalt lava, the structure of which is not clear. It is possibly lava that was intruded into the scoria cone or it could be lava extruded into and ponded within a small moat between the scoria cone and tuff ring. Photo: BW Hayward, 2025.

Fig. 22. This part of the northeastern face is partly hidden by the adjacent building. It appears to be a sill of light grey basalt lava intruded into the lower slopes of the scoria cone. Photo: BW Hayward, 2025.

and the tuff ring. In 2005, a knoll composed of two dikes intruding scoria was left unquarried at the base of this face (Fig. 24) but has since been removed and no sign of it remains.

Wiri Lava Cave occurs within this remnant of the original volcano. It starts as a lava-lined conduit through the scoria before exiting the scoria and continuing on within a flow to the north (Fig. 25) (Crossley 2014, Hayward & Crossley 2014). Clearly, lava was intruding through the lower parts of the scoria cone to feed the flows, including the one containing the cave. The cave cross-section shows the conduit first rises up before widening and flowing down inside the lower slopes of the scoria cone. It is possible that the conduit was actually flowing up and over the crest of the buried tuff ring (Fig. 9, but not shown in the cross-section in Fig. 25).



Fig. 24. Two intersecting dikes (lower) intrude scoria at the base of the northeastern face. Photographed in 2005 but now removed. Photo: BW Hayward.

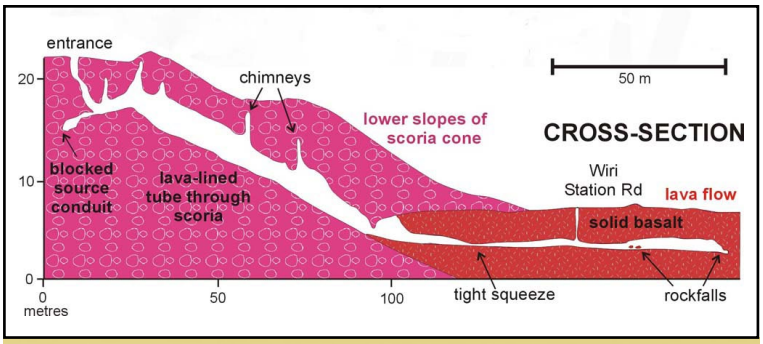


Fig. 25. Cross-section through Wiri Lava Cave, which heads north from the cave entrance close to the highest point of the remnants of the volcano. Note the cave conduit starts by flowing upwards before heading down within the scoria (pink) and finally breaks out at the foot of the cone feeding a lava flow (red). Note the exaggerated vertical scale. From Hayward (2017) based on a survey by Kermode and Rickard in 1964.

Summary

Landform: Wiri Volcano comprised a relatively small scoria cone, built up to 60 m high above the surrounding land and reportedly with its highest point 79 m asl (NZ Railways contoured plan 1915). A small fountaining crater was present on the top possibly with a slightly lower lip on the eastern side (Firth 1930, Searle 1961). The scoria cone would have had smooth slopes of about 30º, but these were modified into terraces by pre-European Māori (Fig. 26). The scoria cone was completely surrounded by a rocky lava flow field composed of numerous basalt flows that had been extruded from the lower portions of the cone. Around the lower slopes on the northern half of the cone there was a semicircular pedestal of basalt lava flows that dropped steeply away to the lava flow field beyond. We now know that this pedestal was formed by thin lava flows overtopping a buried, semicircular tuff ring (Fig. 27).

Tuff ring: The initial explosive (phreatomagmatic) crater and surrounding tuff ring was completely buried and is now only known through exposed faces [1–3] and several boreholes. At ~220 m diameter (Fig. 9), the tuff ring was one of the smallest of those known for any of Auckland's main volcanoes. The depth and shape of the small, enclosed explosion crater is unknown but must have been quite deep as it accommodated at least two significant slumps of tuff ring back into it during eruption. The tuff ring was absent or extremely low around the southern half of the volcano and only built as a semicircle to an elevation of up to 15 m above the land surface around the northern half of the volcano (Fig. 9). The tuff ring crescent was not at an even height but had one or more low saddles that later lava flows had filled. The earlier deposits in the tuff ring were largely produced by phreatic explosions that deposited one or more thick beds of tuff breccia containing numerous clasts of country rock having been thrown out as the volcano "cleared its throat". Upper parts of the tuff ring are mostly well-bedded base surge deposits.



Fig. 26. View from the northwest over the least quarried part of Wiri Mt in 1957 showing the extensive Māori terracing of the scoria cone slopes. The junction of Wiri Station Rd and Roscommon Rd is in the left foreground. White circle is entrance to Wiri Lava Cave as a reference point. Photo: Jack Golson, University of Auckland Library.

Scoria cone: Once most of the water was used up that powered the phreatomagmatic eruptions, dry strombolian fountaining produced scoria that built a scoria cone. Higher in the scoria cone there were rootless lava flows produced by fountaining of less solid scoria on to the upper scoria slopes. As the eruption progressed, the erupting lava cooled and became more viscous, producing denser spatter rather than frothy scoria.

Lava flows: Following eruption of most of the scoria cone, gas-poor lava rose in the throat of the volcano and pushed its way along conduits through the base of the scoria cone to flow out as extensive lava flows (Fig. 27). There was probably a narrow moat between the northern base of the scoria cone and the tuff ring, and this filled with thin lava flows, some of which flowed out through a saddle low point on the tuff ring crest before the entire tuff ring was overtopped by thin flows, creating the pedestal around the northern half of the cone (Fig. 27). In the northeast, the scoria cone had grown to fill the moat and overtop the lower tuff ring and thereby block the moat (Fig. 26). In the northeastern quarry face [4] several dike and sill intrusions of lava (flow feeding conduits) into the lower scoria cone are still visible and in one place a larger mass of basalt seems to have pushed its way into the loose scoria before congealing.

Today all that is left of once majestic Matukutūruru/Wiri Mt Volcano are some of the lower northern slopes composed of scoria overlain by lava flows in the east (and containing Wiri Lava Cave) and tuff ring overtopped by lava flows in the north and northwest. The rubbly blocks of basalt along the crest of the northern and northeastern faces [2, 3] are remnants of the thin lava flows that flowed over the top of the tuff ring that have been disrupted and moved around by bulldozers during quarrying.

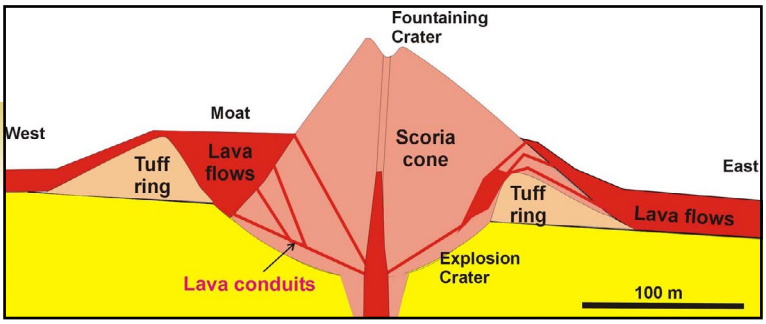


Fig. 27. Inferred west-east cross-section through Wiri Volcano before it was largely quarried away.

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Appendix

Summary of units intersected in boreholes in vicinity of Wiri Volcano. Data from New Zealand Geotechnical Database (https://nzgd.org.nz/)

a. Core 68225. 50 m east of Wiri lava cave entrance. Elevations above sea level – 10 m = top of Tauranga Gp; 14 m = top of tuff; 35 m = top of basalt flows and core.

b. Core 68224. Langley-Tacoma Rds junction. 9 m = top Waitemata Gp; 16.5 m = top Tauranga Gp; 17 m = top of tuff; 5 m – top basalt flow and core.

c. Core 71092. Halfway between Langley Rd and Bolderwood Pl. 16 m = top Tauranga Gp.; 20 m = top fill and core.

d. Core 68222. Langley Rd, 50 m w of Mayo Rd. 21 m = top Tauranga Gp; 21.5 m top tuff; 25 m = top basalt flow and core.

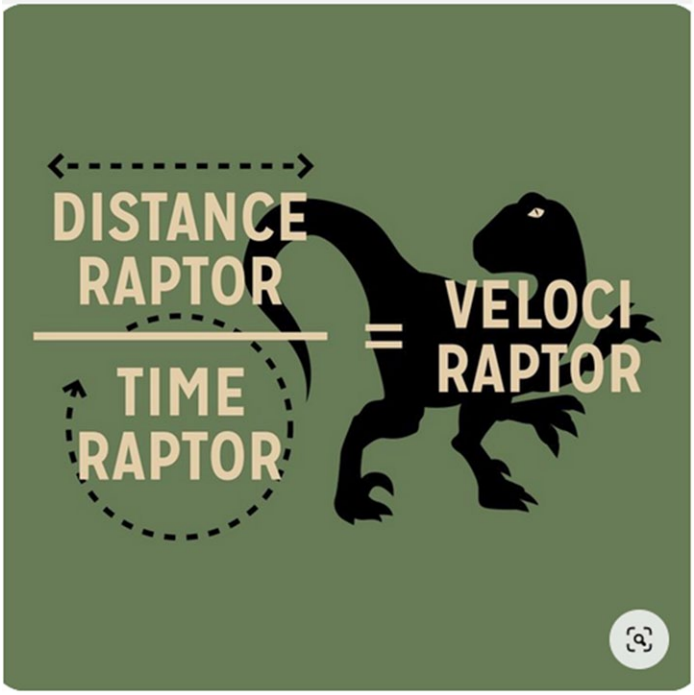
e. Core 68226. N side Matukutūruru Rd, 50 W of Tacoma Rd junction. 20 m = top Tauranga Gp.; 26.5 m top tuff massive phreatomagmatic breccia; 27.5 m top fill and core.

f. Core 68227. 50 m Sth of Wiri Lava Cave entrance. 11 m = top Tauranga Gp, 10º slope; 15 m = top tuff, massive phreatomagmatic breccia, top 45º; 14.5 m top baked scoriaceous tuff; 20 m = top fill and core.

g. Core 68228. 50 m E of Sth end remaining cliff on Roscommon Rd. 17 m = top Tauranga Gp; 17.5 m = top of tuff; 25 m = top of 3 basalt flows separated by scoriaceous horizons, and core.

h. Core 68276. Halfway between 68227 and 68228. -20 m to 16 m = massive basalt throughout to top of core at 16 m.

Return to Contents page



INTERPRETATION OF A MID-SLOPE LANDFORM ON MT HOBSON (ŌHINERAU): QUARRY OR PALEO-LANDSLIDE?

Beatrice Bertelli[1], Martin Brook[2]

Introduction

Mt Hobson (Ōhinerau) is a 143 m high basaltic scoria cone within the Auckland Volcanic Field (AVF). It formed during a single eruptive episode about 34,000 years ago (Hayward 2019), producing a central crater later breached by southwest-directed lava flows that carved the characteristic horseshoe depression. The cone is built of basaltic scoria (lapilli and vesicular bombs) overlain by fine pyroclastic tuffs (ash and sand), which rest unconformably atop highly weathered Miocene Waitematā Group clays and sands.

The topography has been modified by centuries of human activity, most notably pre-European Māori fortification terraces (pā). Also, 20th-century scoria quarries (two of which have been mapped and attributed to wartime extraction; Shepherd & Walter 2007) and water-storage reservoirs have been constructed. Nevertheless, the cone retains a uniform grass cover and shows no deeply-incised erosional gullies, which indicate its overall geomorphic stability.

This study focuses on a previously undocumented mid-slope depression on Mt Hobson's northeast flank, approximately opposite the Remuera Road/Ridings Road intersection. This was first identified during a reconnaissance survey of the 2023 rainfall-induced shallow landslides (Fig. 1). The depression was then confirmed by LiDAR analysis, which, despite lying adjacent to two wartime scoria quarries on the northern flank, has never previously been mapped or discussed.

Based on field observations, geomorphic evidence (Fig. 2) and simple geotechnical analyses, we propose that this feature represents an ancient landslide rather than a third quarry. Table 1 provides a summary of its characteristics, compared with the two confirmed quarries, supporting the paleo-landslide interpretation.

Geomorphic and Remote Sensing Challenges in Identifying Paleo-Landslides

Identifying ancient landslide scars on small volcanic cones is notoriously difficult. Old anthropogenic cuts (e.g. quarries, agricultural terraces) can resemble landslide scars, especially when human modifications obscure original forms. In the study area, small quarry pits and terraces had been developed by the early 20th century, complicating interpretation (Shepherd & Walter, 2007). On volcanic cones worldwide, debris-flow deposits may resemble extraction terraces, while true debris-avalanche deposits tend to be more hummocky and chaotic (Perrier

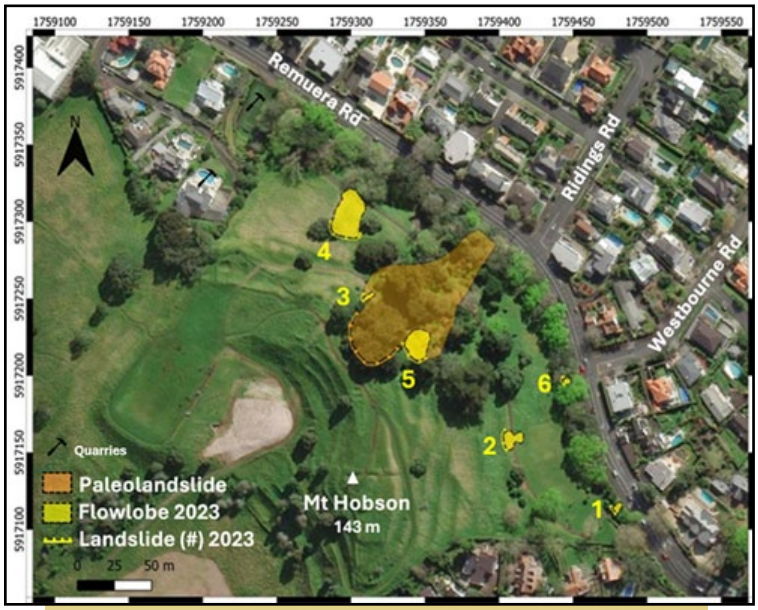


Fig. 1. QGIS map based on an ESRI aerial image, showing the location of the 2023 landslides, the paleo-landslide and known quarry sites on the northeastern slope of Mt Hobson (Auckland, New Zealand).

et al. 2009). Erosion, vegetation growth and weathering progressively mask key features, such as scarps or displaced boulders.

Marques *et al*. (2025) highlight how dense vegetation can conceal morphological features, leaving only subtle slope breaks. Landslide scarp areas are often preserved, while debris accumulation zones are removed by erosion over time. In the Mt Hobson case, the absence of any visible accumulation deposit suggests that the displaced material may have been removed or repurposed for construction. Indeed, the area where the paleo-landslide deposit would have accumulated is now fully built over, erasing any original evidence.

LiDAR and high-resolution DEMs have become essential tools for landslide mapping, and in New Zealand, GNS Science identified over 800 previously unrecognised prehistoric landslides using LiDAR predominantly in the foothills of the Hunua Ranges east of Drury (Bland *et al*. 2023). Key indicators were hummocky surface texture and arcuate scarps (Bland *et al*. 2023). LiDAR technology reveals features invisible in aerial photography or on-site inspection. As noted by numerous authors (e.g. Marques *et al*. 2025), multi-sensor

[1] Department of Earth and Chemical Sciences, University of Modena and Reggio Emilia, Modena, Italy
[2] School of Environment, University of Auckland, Auckland, New Zealand



Fig. 2. Field photographs of the paleo-landslide taken from various angles: (A) central portion of the landslide body along the walking track; (B) right-hand margin of the landslide, also along the path; (C, D) steep, densely revegetated scarps surrounding the landslide area.

Table 1. Diagnostic characteristics of the two quarries compared with the proposed paleo-landslide on Mt Hobson.

Criterion	Quarry	Paleo-Landslide
General Morphology	Sharp edges; vertical faces or stepped benches; horizontal working platforms at multiple levels (remnants of extraction benches).	Irregular scarp, often arcuate or spoon-shaped; uneven hummocky surface with dislocated blocks; chaotic or reworked debris across the landslide body.
Drainage Patterns	Regular runoff; diverted around quarry margins; straight drainage lines converging to a single outflow point.	Closely spaced channels; parallel flow paths along the slope; intricate network of small gullies with divergent flow directions.
Substrate & Surface Evidence	Smooth surfaces; possible tool marks or chiselling traces; evidence of ramps or former access routes.	Tension cracks radiating from the head scarp; jumbled blocks; displaced and overlapping rock masses; leaning trees; root plates tilted or exposed.
Vegetation and Soil	Bare rock faces or sparse vegetation; sharp boundary between bedrock and adjacent vegetation.	Deep soil cover within the landslide body; colonised by pioneer species; patchy, uneven vegetation across the slide area; trees inclined or entrained within the displaced mass.
Historical & Cartographic Context	Often documented in 19th–20th century cadastral or topographic maps; visible as sharp, geometric cuts in historical aerial imagery or LiDAR data.	Typically undocumented; more likely of natural origin; organic, irregular shapes with lateral bulges (e.g. push-up ridges).

approaches combining aerial imagery, geologic maps and field validation are now standard in landslide detection.

Studies from Italy and the Azores reinforce the importance of identifying relict slope failures. At Ischia and Campi Flegrei (southern Italy), volcanic slopes host many historical and undocumented slides, some causing significant damage (Di Napoli *et al*. 2023). Marques *et al*. (2025) document multiple prehistoric slope collapses on the small Azorean Island of Santa Maria, demonstrating that significant landslide events can occur even on relatively small volcanic cones.

Materials and Methods

This investigation was largely theoretical, relying on existing geospatial datasets and desktop-based analyses. Elevation and terrain data were obtained from Land Information New Zealand (LINZ) and imported into QGIS as the primary geodatabase. Within QGIS (Bratislava), the GRASS and SAGA plugin toolsets were used to derive topographic profiles, calculate slope angles, and estimate key geotechnical and hydrological parameters. A literature review supplemented the GIS work, encompassing regional geomechanical studies and volcanic-landslide case histories. Fieldwork was limited to non-invasive visual inspections, since the Mt Hobson Domain is a protected site of cultural significance to Māori culture. Consequently, all mechanical properties (cohesion, internal friction angle, unit weight) were adopted from publicly available reports issued by Auckland Council and peer-reviewed publications. This methodology ensured a robust yet non-intrusive assessment of slope stability, integrating high-resolution DEM analyses (Fig. 3) with established geotechnical theory while respecting the cultural and legal protections governing Ōhinerau.

Geomechanical Interpretation

From a geotechnical standpoint, the morphology of the mid-slope depression on Mt Hobson is entirely consistent with a large, relatively shallow landslide. Using QGIS, we reconstructed the pre-failure slope geometry (Fig. 3) and applied the infinite-slope model, which is appropriate for this planar failure surface. Classical limit-equilibrium calculations, assuming zero cohesion and adopting shear-strength parameters published by Auckland Council, yield a drained factor of safety (FS) of approximately 1.29 (Fig. 3). This low FS, calculated under conservative assumptions, demonstrates that the slope is prone to failure, particularly under elevated pore-water pressures during heavy rainfall (as evidenced by six minor slides in 2023). Historical records from the Remuera Heritage Society further confirm the slope's susceptibility, as in the early 20th century, a shallow slide detached from this same flank and destroyed a nearby tram waiting station

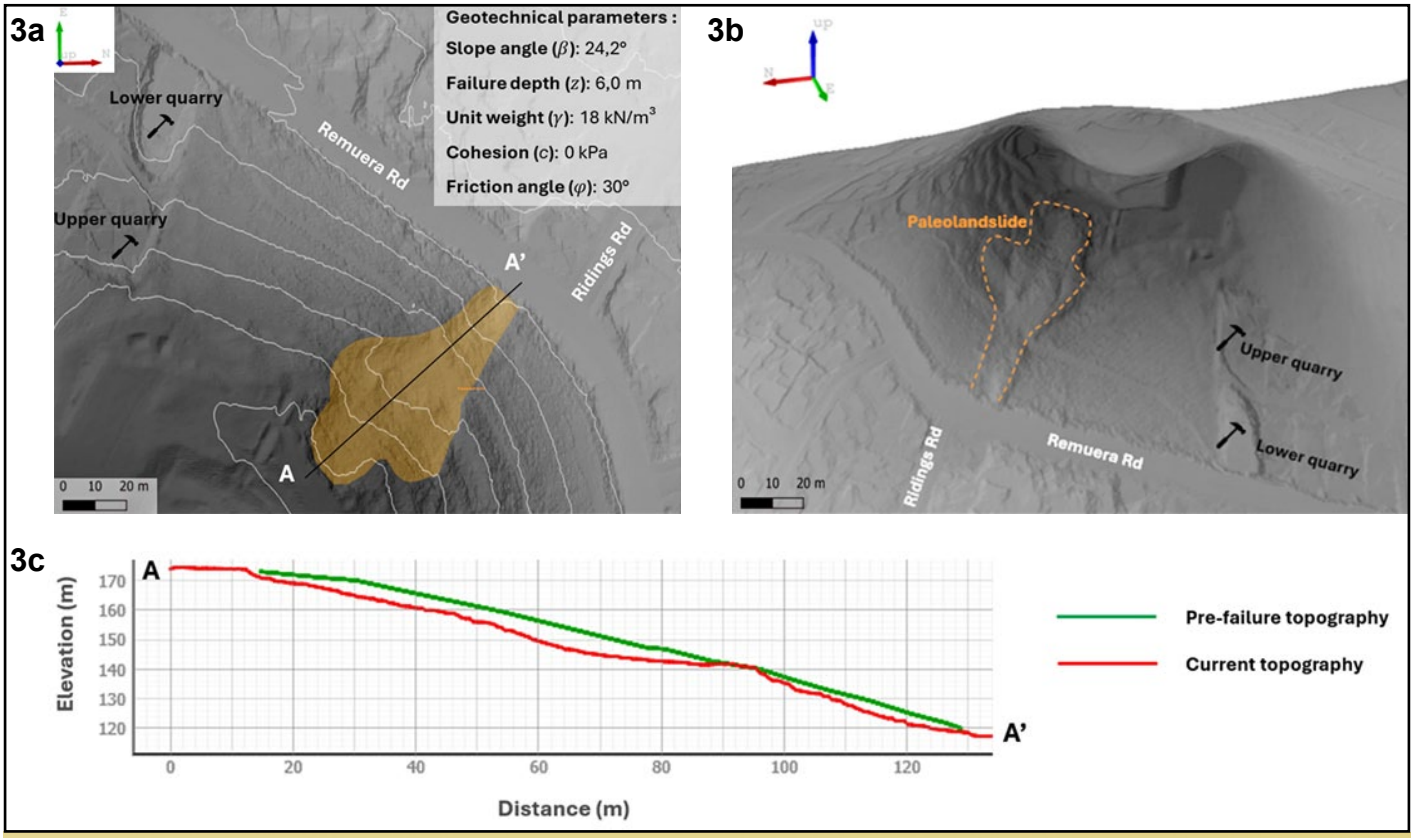


Fig. 3. QGIS-based mapping results of Mt Hobson: (3a) delineated landslide and quarry areas, with the trace of the topographic profile shown in 3c, including geotechnical parameters used in stability analyses; (3b) 3D model highlighting morphological differences between the paleo-landslide and the quarry areas; (3c) comparison between the current slope profile and the reconstructed pre-failure slope geometry.

(Remuera Heritage Society, 1947), illustrating a long-term instability trend.

Concluding remarks

Recognising paleo-landslides has direct implications for urban planning, hazard management and geological reconstruction. GNS Science emphasise that the mapping of prehistoric landslides helps guide policy and zoning decisions (Bland *et al*. 2023). Similar approaches have been adopted in other volcanic settings. Antoniou *et al*. (2017), for example, applied a GIS-based multi-criteria model to assess landslide susceptibility across the Santorini volcanic complex, producing maps now used by local authorities for planning and hazard mitigation. On urban volcanoes like Ōhinerau, identifying relict landslides informs both cultural landscape interpretation and long-term risk reduction strategies, especially in cities where volcanic landforms coexist with dense residential zones.

Acknowledgements

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Return to Contents page

RISE AND DEMISE OF MUSHROOM ROCKS AT TI POINT, LEIGH, NORTH OF AUCKLAND

Bruce W. Hayward

Auckland Geoclub has run half day field trips along the coastal walkway at Ti Point, near Leigh, on three occasions. On our 2012 visit we ventured onto the intertidal foreshore on the southeast corner of the Ti Point peninsula (Figs 1 & 2). There we discovered and photographed an unusual mushroom rock (Fig. 3). On our most recent visit in August 2025, we returned to the same section of coast to admire the mushroom rock, but it couldn't be seen. A little bit of searching soon located it, but its top had slipped off (Fig. 4). Further searching and we discovered another lower (and younger) mushroom rock nearby (Fig. 5).

Usual mode of formation of mushroom rocks

Around the world, mushroom-shaped rocks are most commonly found in arid areas and are formed by wind abrasion of softer rock beneath a cap of harder rock. Sometimes this erosion may occur in homogeneous rocks with wind-blown sand abrasion being accentuated at lower elevations just above ground level, creating a stalk beneath the mushroom cap. In New Zealand, mushroom

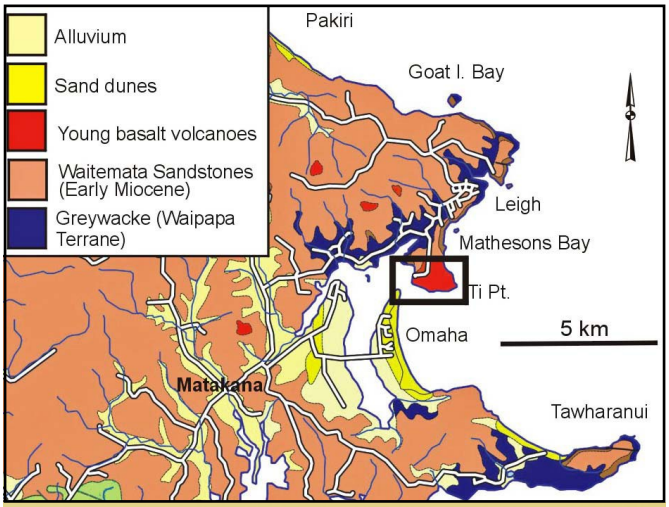


Fig. 1. Location of study site, Ti Point, near Leigh, Auckland.



Fig. 2. Oblique aerial photo of end of Ti Point, showing location (arrowed) of small bay where mushroom rocks were studied.



Fig. 3. First Ti Point mushroom rock in 2012.

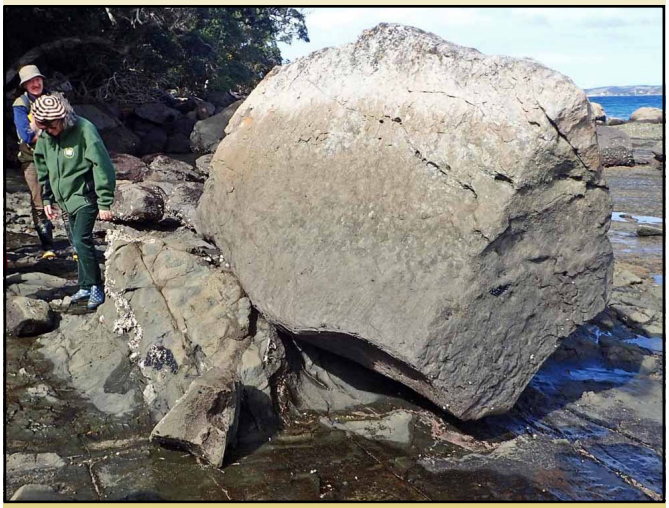


Fig. 4. Collapsed first Ti Pt mushroom rock in 2025.



Fig. 5. Lower and younger Ti Point mushroom rock in 2025.

rocks are uncommon and usually occur at and just above high tide level on a relatively sheltered rocky shoreline (e.g. Figs 6 & 7). In these instances, the rock is usually of homogeneous rock type and the greater erosion that produces the stalk is a result of the diurnal wetting and drying of the rock around high tide level (Hayward & Kenny 2012).

The pinnacles at Putangirua and some other places in New Zealand are hoodoos that are not mushroom shaped, but their formation is attributed to rain with the top of the pinnacle capped by a hard erosion-resistant cobble (Homer & Moore 1989).

Formation of Ti Point mushroom rocks

The Ti Point mushroom rocks differ from all those described above, in that they have formed between mid and high tidal level on the foreshore. Here, the intertidal zone is composed of early Miocene flysch (sandstone and mudstone of Waitematā Group) that is eroded down to a relatively flat shore platform dipping gently seaward (Fig. 8). Scattered over this rock platform are boulders of late Miocene Ti Point basalt (Hayward 2015). The boulders are all somewhat rounded and seem to be corestones derived by spheroidal weathering of the basalt that forms the steep adjacent coastal hillside. The fresh basalt corestones are either relict from eroded basalt that was above the site or more likely have slid/rolled down the hillside and landed on the shore platform. This process will have been occurring throughout the mid–late Holocene (last ~6000 years). As most of the boulders now sit directly on the sandstone shore platform, I conclude that most are able to be moved around a little in big storm waves, although the bay itself is not directly exposed to storm waves.



Fig. 6. Mushroom rock developed by erosion at and above high tide level in volcanic breccia on the moderately sheltered coast inside Whangaroa Harbour, Northland, early 1900s.



Fig. 7. Mushroom rock developed by solution of limestone at extreme high tide level on the relatively sheltered shore of Te Whanga Lagoon, Chatham Island. Width of photo 1 m.

The rare mushroom rocks testify to a few boulders remaining in-place for hundreds or maybe even a thousand or more years. These rocks also show that the whole shore platform has been progressively lowered by erosion, by as much as 70 cm vertically since the first mushroom rock began to form.

As sea-level was 1.5–2 m above present between 6000 and 3000 years ago, and gradually fell to present level by about 500 years ago (Hayward *et al*. 2015), it is likely that this sandstone shore platform has been lowered by a similar amount since 3000 years ago. This would give a vertical erosion rate of 0.6 mm/yr over the last 3000 years, and at a similar rate of erosion the collapsed mushroom rock with a 70 cm high stalk could have started forming about 1200 years ago and the lower and younger mushroom rock with a 40 cm high stalk could have started forming about 650 years ago, but these are very much approximations.

If the erosion of the shore platform is primarily by physical wave abrasion, perhaps aided by sand grains, then why has the mushroom's sandstone stalk not been eroded through beneath the basalt or been more abraded on the exposed seaward side? The mushroom rocks at Ti Point may have been formed slowly by the alternating wetting and drying of the shore platform's surface but not beneath the boulder. If this scenario was true, then the basalt boulder's role has not been in lessening the impact of



Fig. 8. Basalt boulders scattered over the gently sloping intertidal shore platform of Waitematā Sandstone at Ti Point.

rain, waves or wind, but to provide shade to the underlying rock and greatly reduce any drying out of the underlying sandstone when the tide is low on sunny days.

Conclusion

The Ti Point mushroom rocks are highly unusual in location and mode of formation. They provide an insight into the processes and speed of shore platform erosion of a sandstone on a moderately sheltered coast.

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Return to Contents page



CAN WE REDUCE GREENHOUSE GASES FROM CEMENT PRODUCTION IN NEW ZEALAND BY PARTIAL SUBSTITUTION OF NATURAL POZZOLANS?

Ian Simpson

Introduction

I became interested in pozzolans after reading an historical novel "Pompeii" written by Robert Harris. In the novel, the central character is an engineer sent to Pompeii to repair an aqueduct. The repair required the use of a mortar made of lime and pozzolana. What was pozzolana? Pozzolana was a volcanic tephra found at Pozzuoli near Naples and used in Roman concrete. Currently a pozzolan is a material composed of silica, or both silica and aluminium, which does not show cementitious properties on its own, but when finely ground and when combined with water, reacts chemically with calcium hydroxide at standard temperatures to produce cementitious compounds (Mehta 1987). Modern examples are fly ash, which is the residua after burning coal, blast furnace slag, silica fume from silicon production in an electric arc furnace, and natural pozzolans such as pumice, ignimbrite, diatomite and metakaolin. Volcanic pozzolans are often called pozzolana.



Fig. 1. Pantheon Dome, Rome. Photo by Evangelos Arvanitis on Unsplash https://unsplash.com/@vag_danny?utm_content=creditCopyText&utm_medium=referral&utm_source=unsplash

Roman concrete has shown remarkable durability, especially for underwater structures. The concrete Parthenon in Rome was constructed two thousand years ago. The huge dome of the Pantheon was made with lime and pozzolana. At the base of the dome, heavy aggregates of travertine or limestone rubble were used with lighter pumice and scoria aggregates up to the operculum (de Fine Licht 1968) (Fig. 1).

The Portus Cosanus breakwater at Cosa, 120 km north of Rome, was also built two thousand years ago and is mostly intact, while modern Portland cement concretes would not be expected to maintain integrity in salt water over such an extended period.

Roman concrete is slower to gain full strength than Portland cement concrete but is durable and has self-sealing of fine cracks. A chemical reaction in saltwater produces a calcium silicate hydrate mineral that provides strength and durability for underwater uses. Roman concrete has small lime clasts of calcium oxide (CaO) (Fig. 2). The Romans calcined (burnt) limestone, which then needed to be slaked (mixed with water), creating slaked lime. It is not certain if the lime clasts were due to incomplete slaking or on purpose. Research from Massachusetts Institute of Technology (MIT) and Harvard University (Seymour *et al*. 2023) concluded that this was on purpose. Many archaeologists disagree because the Romans did not have the quality control to ensure that there was not unslaked lime left after mixing. Whatever the origin, the lime clasts produced the self-healing properties of Roman Concrete.

Portland Cement

Concrete production has been estimated to contribute between 5 and 8% of world greenhouse gas emissions. Carbon dioxide is produced in the production of Portland cement. The addition of pozzolans to Portland cement reduces CO_2 production proportional to the percentage of supplementary cementitious materials (SCM) as pozzolan added. In modern cement production, limestone ($CaCO_3$), clay and lesser amounts of iron ore or bauxite are ground to a fine powder, which is then heated in a one or two step process. In the two step process, the powder is heated to 850–900°C to convert the limestone to calcium oxide (CaO). This is called calcination. The calcined material is then heated further in a rotary kiln to 1450°C, which causes the materials to fuse and form clinker nodules. The clinker is rapidly air cooled, gypsum is added, and the process is completed by grinding the clinker into a fine powder. The CO_2 released is from the limestone, and from the coal or gas used for heating for calcination and clinker formation, accounts for about 80% of the greenhouse gas production from concrete.

In simple terms, the main clinker phases are of mixtures of calcium and aluminium silicates. Slaking of the cement



Fig. 2. A large-area elemental map (calcium: red, silicon: blue, aluminium: green) of a 2 cm fragment of ancient Roman concrete (right) collected from the archaeological site of Privernum, Italy (left). A calcium-rich lime clast (in red), which is responsible for the unique self-healing properties in this ancient material, is clearly visible in the lower region of the image. Images from Chandler (2023).

by the addition of water forms calcium silica hydrates, and calcium aluminates. The calcium silica hydrates provide the strength of aggregate-cement mixtures.

Pozzolan Supplementary Cementitious Materials (SCMs) in Concrete Mixtures

When Portland cement hydrates, as well as producing calcium silica hydrates and calcium aluminates, there is calcium hydroxide produced as a byproduct of the hydraulic reactions (in engineering "hydraulic" refers to the addition of water). Calcium hydroxide can affect concrete through a process known as the alkali-silica reaction, sometimes referred to as "concrete cancer." High silica aggregates are particularly susceptible, and the outcome is cracking of the concrete. The chemical reactions associated with the alkali-silica reaction are complicated and are not dealt with here (Albinski 2022). The addition of an active pozzolan to the mix consumes free calcium hydroxide and forms further calcium silica hydrates that contribute strength gain over time. The pozzolan also slows the exothermic heat production of setting concrete, which can obviate cracking of large concrete pours because of stress from unequal heat loss from the inside to the outside. The extra calcium silica hydrates formed from the pozzolan/calcium hydroxide enhances durability and produces a denser microstructure.

In other countries there has been extensive use of fly ash as a pozzolan as it is readily available from the use of coal. New Zealand does not have adequate production of quality fly ash to make use of this pozzolan. The major user of coal is the Huntly Thermal Power Station at times of peak demand, but the ash is less suitable because of the variability from the plant being turned on and off. Blast furnace slag and silica fume are also not available in adequate quantities. These pozzolans, although waste products, have an economic value where they are produced and so import to New Zealand would not be economically practical (Sawyer *et al*. 2023).

The question arises as to whether we could use high silica tuff, pumice or diatomite as pozzolans in the New Zealand concrete industry. One problem is that not all potential pozzolans are active, and able to bind calcium hydroxide. Volcanic materials are most active when younger geologically with less weathering to clays. Determining whether a potential pozzolan is active requires a blend of chemical, thermal and mechanical tests to find the intrinsic benefits of a potential pozzolan. The detail of these tests is beyond the scope of this paper.

In the 1950s and '60s, when the Ministry of Works was building hydro dams for electricity supply, natural pozzolans were used in the Atiamuri dam using pumicite from a Kaimai deposit, and the Waipapa dam and Ohakuri dam using Whirinaki diatomite deposits from just south of Rotorua. Natural pozzolans were also used in the Tongariro Power Project, although accounts of its use are limited to a newspaper article in the Press (Siers 1965). There is no data on the testing methods used to assess the pozzolan substituted concretes on these projects. Since then, there is no record of volcanic pozzolans or diatomite

being used commercially in New Zealand. The concrete design standard recommends that blended cement must be used in marine applications, making use of recycled or low carbon materials such as fly ash, micro silica, or slag mandatory (New Zealand Standards 2006). These materials have been used in New Zealand when indicated for marine use and for durability (Mackechnie & Alexander 2009). The Central Rail Link in Auckland has used a special concrete in the wall structures using 30% fly ash and an additive to enhance short term strength development, the self-healing of cracks to stop water ingress, and to reduce water requirements (City Rail Link Ltd 2025).

Potential to use Natural Pozzolans in New Zealand

The history of Natural Pozzolana use in New Zealand was explored in a paper presented at the Concrete NZ conference in September 2023 (Sawyer *et al*. 2023). Investigation of New Zealand pozzolans was conducted in the 1950s by the NZ DSIR (Kennerley & Clelland 1959). Dr E del Ray Castillo, from the Structures Testing Laboratory at the University of Auckland, has been investigating how naturally sourced materials could replace Portland cement to produce “low carbon” concrete. He has been evaluating volcanic pozzolana from the central North Island for their activity and is also exploring the use of seashell waste from the aquaculture industry. A pilot study from this Group found that pumice and tephra from the Taupo volcanic zone achieved the criteria for use as a natural pozzolan (Ranatunga *et al*. 2024).

New Zealand has ample pumicite and diatomite resources for pozzolan use. In the ‘Mineral Wealth of New Zealand’, Thompson *et al*. 1995 have reported on the location of primary and secondary pumice deposits originating from the Taupo Volcanic Zone, with their location, and commercial mining now, or in the past. Seven sites were listed.

Diatomite is found in ancient lake deposits of diatoms and is often associated with recent volcanic sediments. A deposit at Mercer, South Auckland, is estimated to hold about 180,000 tons of extractable diatomite and pumicite. A large diatom lake deposit is present at Foulden Maar near Middlemarch but is now protected because of its unique Miocene fossil record. The Whirinaki deposit near Ngakuru in the Rotorua District was last mined in 1977. In all, ten significant sites were listed.

Conclusion

A reduction in Portland cement use by partial substitution of natural New Zealand pozzolans would reduce green-house gas production and obviate some of the problems associated with Portland cement concrete. There are ample resources of pumicite, diatomite and volcanic ash available in New Zealand.

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Return to Contents page

IDENTIFICATION OF A "NEW" TUFF RING AT TE APUNGA-O-TAINUI / MCLENNAN HILLS VOLCANO

Dougal Townsend, Graham Leonard

Earth Sciences New Zealand (formerly GNS Science), 1 Fairway Drive, Avalon 5010, PO Box 30368, Lower Hutt 5040, New Zealand

- Work for the forthcoming ESNZ/DEVORA Auckland Volcanic Field geological and geomorphological map has identified a smooth, crescent-shaped hill east of the McLennan Hills scoria cone/vent complex.
- This area was previously mapped as Auckland Volcanic Field lava or ash.
- Identification of previously unknown explosive phases associated with more of Auckland's volcanoes has implications for volcanic hazard and preparedness for the next eruptive episode.

Desktop assessment of lidar-based hill shade models for a new geological map of the Auckland Volcanic Field (Townsend & Leonard in prep.) has identified a smooth, crescent-shaped hill about 300 m to the east-northeast of the Te Apunga-o-Tainui/McLennan Hills scoria cone complex (Fig. 1). The hill and its flanks do not have the same appearance as the surrounding lava field, which in historic aerial photos exhibits well-defined lava flow ridges (Fig. 2), although most of these have since been destroyed by urban development. Geomorphology shows that the

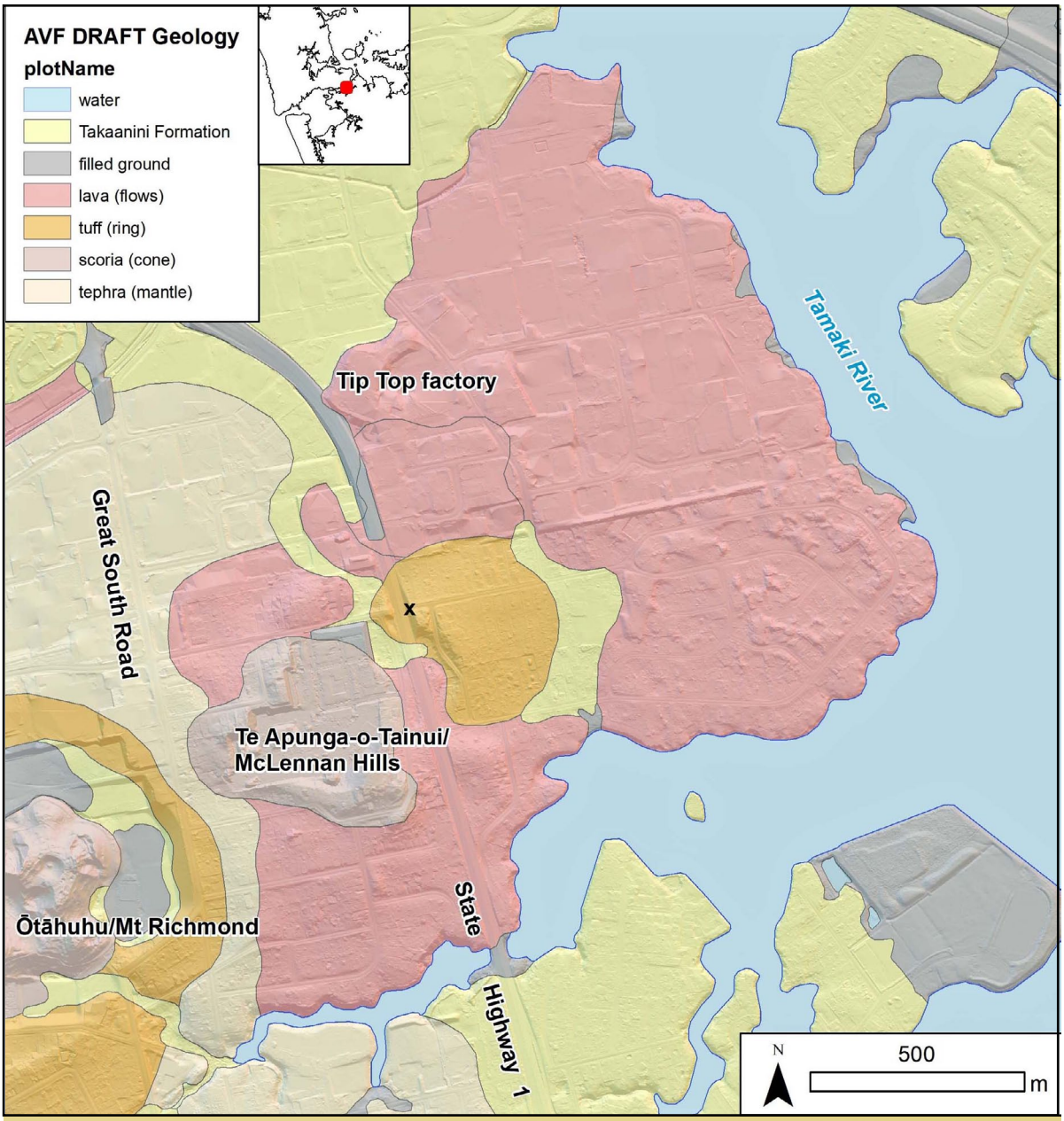


Fig. 1. Draft mapping for the ESNZ/DEVORA Auckland Volcanic Field geological map. The newly identified tuff ring remnant is at centre (coloured orange). The black **x** marks the location of the outcrop beneath the Panama Road overbridge as viewed in Fig 3. Inset map shows location within the Auckland Isthmus.



Fig. 2. A mosaic made from 1940s aerial photos (survey SN 146; Crown Copyright) covering the same area as Fig. 1 and showing the curved ridge (arrowed) to the northeast of the Te Apunga-o-Tainui/ McLennan Hills scoria cone complex, prior to urban development in the area and construction of the State Highway 1/Auckland-Hamilton Southern Motorway, which cuts through part of the tuff ring.

lava flow(s) are sourced to the west of the curved ridge and appear to bend and flow around the northern and southern sides of the hill.

This area was previously mapped as ash without any "lava at depth" (Kermode 1992) or lava (Hayward 2019), although Edbrooke (2001), whose work was based mainly on Kermode's mapping, includes this and the surrounding area within an indistinct "Auckland Basalts lithic tuff" unit surrounding Ōtāhuhu/Mt Richmond and Te Apunga-o-Tainui/McLennan Hills volcanoes, which approximates the combined ash and tuff units of Kermode (1992). This mapping unit, however, does not separate the tuff ring landform (as highlighted here) from the adjacent landscape-mantling tephra (or "ash").

Reconnaissance fieldwork in February 2025 corroborated the smooth hill along part of Panama Road, rising gently above the surrounding lava flow field and dropping steeply away to the west. An exposure on SH1 beneath the Panama Road motorway overbridge, as seen from a Google Earth street view image (Fig. 3, see Fig. 1 for location), shows bedded sediment dipping gently towards the northeast. This area is too low-lying to expose rocks from either the Tauranga or Waitematā groups so, although not observed close-up in the field, the inference is that



Fig. 3. Google Earth street view from SH1/Auckland-Hamilton Southern Motorway of the bedded layers exposed in the cutting beneath the Panama Road overbridge. Location marked on Fig. 1 by an '**x**'.

this is a remnant of a previously unrecognised tuff ring associated with Te Apunga-o-Tainui/McLennan Hills volcano. Furthermore, two NZGD bore holes (NZGD ID: BH_76495, BH_76496) intersect the feature interpreted herein as a tuff ring remnant. The logs for both of these drill holes suggest about 18 m of "AVF tuff" over Tauranga Group ("Puketoka Formation") and Waitematā Group sandstone and siltstone; neither intersected lava, thus corroborating the inference of a tuff ring.

This discovery has implications for the nature and formation of the Te Apunga-o-Tainui/McLennan Hills volcano, and may have implications for other volcanoes in the AVF that do not have mapped explosive deposits or known explosive phases associated with them. Perhaps all of Auckland's volcanoes started out with initial explosive phases (as is the generally accepted model for monogenetic volcanism), but those without mapped tuff could have their initial deposits buried by ongoing effusive activity. Many of these examples are poorly understood (e.g. Takararo/Mt Cambria), have large lava flow fields (e.g. Maungawhau/Mt Eden), and/or have complex summit scoria cone–lava flow relationships (e.g. Maungakiekie/One Tree Hill; Hayward 2019).

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Return to Contents page

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Return to Contents page

CORRESPONDING AUTHORS' CONTACT INFORMATION

Beatrice Bertelli	MSc student in geology,	**beatricebertelli00@gmail.com**
Bruce W. Hayward	Geoclub Member,	**b.hayward@geomarine.org.nz**
Ian Simpson	Geoclub Member,	**judyandian.simpson@outlook.com**
Dougal Townsend	Earth Sciences New Zealand (formerly GNS Science),	**d.townsend@gns.cri.nz**