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ORIGINAL ARTICLE

Remnants of a Young Monogenetic Volcanic Field and the Fragile Balance of Anthropogenic Interaction

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Abstract

The rapid development of Auckland City in New Zealand from an initial rural settlement to a global urban hub produced a characteristic footprint on the Auckland Volcanic Field (AVF). This process was facilitated by increased anthropogenic activity that has resulted in the deterioration and destruction of many volcanic landforms and caused severe archaeological, cultural, geological and educational losses in an alarmingly short timescale. The AVF has 53 volcanic centres, and of these, 17% are classified as intact, 28% are partially intact, 30% are partially destroyed, and 25% are destroyed (including 13% that have no trace left). Based on surface area, approximately 40% of volcanic deposits in the AVF have been lost. The most common causes for impacts are public land use, quarrying and urban development. Regardless, there is significant potential to be found in the balance between the losses and gains of anthropogenic impacts on volcanic landforms. In the AVF and worldwide, geological studies have often been assisted by the presence of outcrops created by quarrying, mining, transport infrastructure and other modifications of volcanic landforms. Areas of significant volcanic geoheritage worldwide are often linked with these impacted volcanoes, and the information gained from these geoheritage areas assists in the management of geodiversity and geoeducation. Several volcanic centres are currently at risk of further destruction in the near future (Crater Hill, Waitomokia, Maugataketake, Kohuroa, Three Kings, St Heliers and McLaughlins Mt) and should be prioritised for any possible research before it is too late. We propose that a geological assessment should be a requirement before and, if possible, during any land development on or near a volcanic landform. Allowing access to scientists through the course of development in areas with volcanic landforms would, in turn, aid public and governing bodies in decision-making for the future of the city and its volcanoes in terms of increased knowledge of volcanic mechanisms of the AVF and awareness of the potential associated hazards.

Keywords Geoheritage · Volcanic · Landforms · Urban development · Anthropogenic · Destruction · Auckland Volcanic Field · Auckland

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Introduction

There have been at least 1300 terrestrial volcanoes erupted in the last 10,000 years (which is likely an underestimation due to the nature of small eruptions and stratigraphic complexity in volcanic-rich areas), mostly (94%) concentrated along tectonic plate boundaries (Sigurdsson 2015; Global Volcanism Program 2023). At least 80% of nations in the world host at least one volcano that has been active in the Holocene (Brown et al. 2015; Sigurdsson 2015; Global Volcanism Program 2023). When considering the dispersal of volcanic material and associated hazards associated with volcanic eruptions, the number of nations worldwide that have been affected by volcanoes in the Holocene is much greater. More than 14% of the world's population live

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within 100 km of a Holocene volcano (Sigurdsson 2015; Freire et al. 2019). Volcanoes and their resources have been utilised by humans for millennia. They have provided natural fortification, fertile soils, ore deposits, construction materials and tourism and recreational value (Kelman and Mather 2008; Erfurt-Cooper and Cooper 2010; Sigurdsson 2015). Volcanoes also played and continue to play an important role in many cultural and religious traditions worldwide (Lowe et al. 2002; Nunn 2014; Fepuleai et al. 2017; Mackintosh 2019). Volcanic materials have been utilised since prehistoric times for various uses including cutting tools, building materials, weapons and defence during conflict (Sigurdsson 2015). In modern times, volcanic materials are mined for construction materials including aggregate, to be used in building, concrete and transport infrastructure such as roads and railways. Our long-term reliance on volcanic materials has resulted in varied impacts on the landforms of volcanic fields worldwide.

Some global examples of volcanic fields that have been impacted by human activity are provided in Table 1. A wide variety of impacts are caused by anthropogenic activity; however, the major impacts on volcanic landforms have been through quarrying (e.g. extraction of raw materials mostly for construction and housing development), land use (e.g. development for farming), urban development (e.g. section development for housing and large scale construction sites associated with community needs) and transport infrastructure (e.g. road and rail network development) (Table 1). In recent decades, geoparks, national parks and co-managed areas have been established

Table 1 Worldwide examples of anthropogenic impacts on volcanic landforms indicating the current level of human impact on the volcanic landforms and proximity to urban areas

	Country	Volcanic field	Impacts	Level of impact	Proximity to urban areas	Parks, geoparks, reserves
1	Australia	Newer Volcanic Province [5]	Q, LU	Low	Distal	Several reserves in the area
2	Cameroon	Cameroon Volcanic Line [24]	Q	Low	Distal	-
3	Canary Islands	Canary Volcanic Province [8]	UD, LU, TI	High	Proximal	Four national parks
4	Germany	Eifel Volcanic Field [9]	Q, TI, LU, UD	High	Proximal	Vulkaneifel European Geopark [3]
5	Hungary	Tokaj Mountains [20]	Q, TI, LU, UD	High	Proximal	Tokaj-Bodrogzug Landscape Protection Area [20]
6	India	Kachchh, NW Deccan Traps [13]	Q	High	Proximal	Several national parks in the area
7	Indonesia	Mount Merapi [18]	LU	Low	Proximal	Gunung Merapi National Park [22]
8	Italy	Naples [7]	LU, UD	Low	Proximal	The Vesuvius National Park [1]
9	Japan	Sakurajima [21]	LU, UD, TI	Low	Proximal	Kirishima Kinkowan National Park [23]
10	Mexico	Michoacán-Guanajuato Volcanic Field [11]	Q, UD, LU	High	Proximal	Multiple geoparks [6]
11	New Zealand	Auckland Volcanic Field [10] *(this paper)*	Q, LU, UD, TI	High	Proximal	Many reserves throughout the field
12	Nicaragua	Nejapa Volcanic Field [2]	Q, LU	Moderate	Distal	Many natural reserves throughout the chain
13	Poland	West Sudetes [15]	Q, TI	High	Distal	Several national parks in the area
14	Romania	Călimani-Gurghiu-Harghita Volcanic Range [19]	Q	High	Distal	Călimani National Park [19]
15	Spain	La Garrotxa Volcanic Zone [17]	LU, UD, TI	Moderate	Proximal	La Garrotxa Volcanic Zone Natural Park [14]
16	Taiwan	Tatun Volcano Group [16]	UD, TI	Low	Proximal	-
17	Turkey	Cappadocia Volcanic Province [10]	Q, TI	High	Proximal	Göreme Historical National Park [4]

Protected areas such as national parks, geoparks and reserves are listed where applicable

Impacts: Q – quarrying; LU – land use; UD – urban development; TI – transport infrastructure. Level of impact: Low – minimal destruction to the landforms (such as minor farming); Moderate – patchy/irregular destruction to the landforms; High – major destruction to the landforms. Proximity of urban areas: Distal – volcanic landforms are at least 2 km from any village, town or city; Proximal – villages, towns or cities built less than 1 km from volcanic landforms, often on flanks or flows

[1]Alessio and De Lucia (2017), [2]Avellán et al. (2012), [3]Bitschene (2015), [4]Brilha (2018), [5]Cas et al. (2017), [6]Cruz-Pérez et al. (2022), [7]De Natale et al. (2020), [8]Ferrer et al. (2022), [9]Gluhak and Hofmeister (2009), [10]Gravis et al. (2017), [11]Guilbaud et al. (2021), [12]Kazancı and Kuzucuoğlu (2019), [13]Kshirsagar et al. (2010), [14]Martí and Planagumà (2016), [15]Migoń and Pijet-Migoń (2016), [16]Nurmawati and Konstantinou (2018), [17]Planagumà and Martí (2018), [18]Sadono et al. (2017), [19]Szakács and Chiriță (2017), [20]Szepesi et al. (2017), [21]Todde et al. (2017), [22]Umaya et al. (2020), [23]Vafadari and Cooper (2020), [24]Zangmo et al. (2017)

to protect volcanic landforms from the impacts of urban development and destruction (Erfurt-Cooper 2011; Németh et al. 2017; Pijet-Migoń and Migoń, 2022).

The Auckland Volcanic Field (AVF) is a good example of an active volcanic field that exhibits anthropogenic impacts on volcanic landforms (Table 1). The unique, geologically diverse nature of this field, its overlap with the city of Auckland (with a third of New Zealand's population living there), its active status and the presence of a university (Auckland University- ranked 1st out of New Zealand (NZ) universities) within the field has prompted many detailed studies of the volcanic centres (e.g. Shane and Smith 2000; Lindsay et al. 2011; Augustinus et al. 2012; Hopkins et al. 2020). Anthropogenic activity in the AVF has resulted in the deterioration and destruction of many of the centres. Geoconservation bids to protect the volcanic centres in Auckland for their volcanic knowledge and cultural and societal values have had mixed success (Golson and Fowlds 1957; Hayward and Crossley 2014; Gravis and Németh 2016; Gravis et al. 2017, 2020; Németh et al. 2021b). In several cases, complete destruction has resulted in the loss of volcanic knowledge of key landforms and centres of the field (Hayward 2008; Hayward et al. 2011; Hopkins et al. 2017).

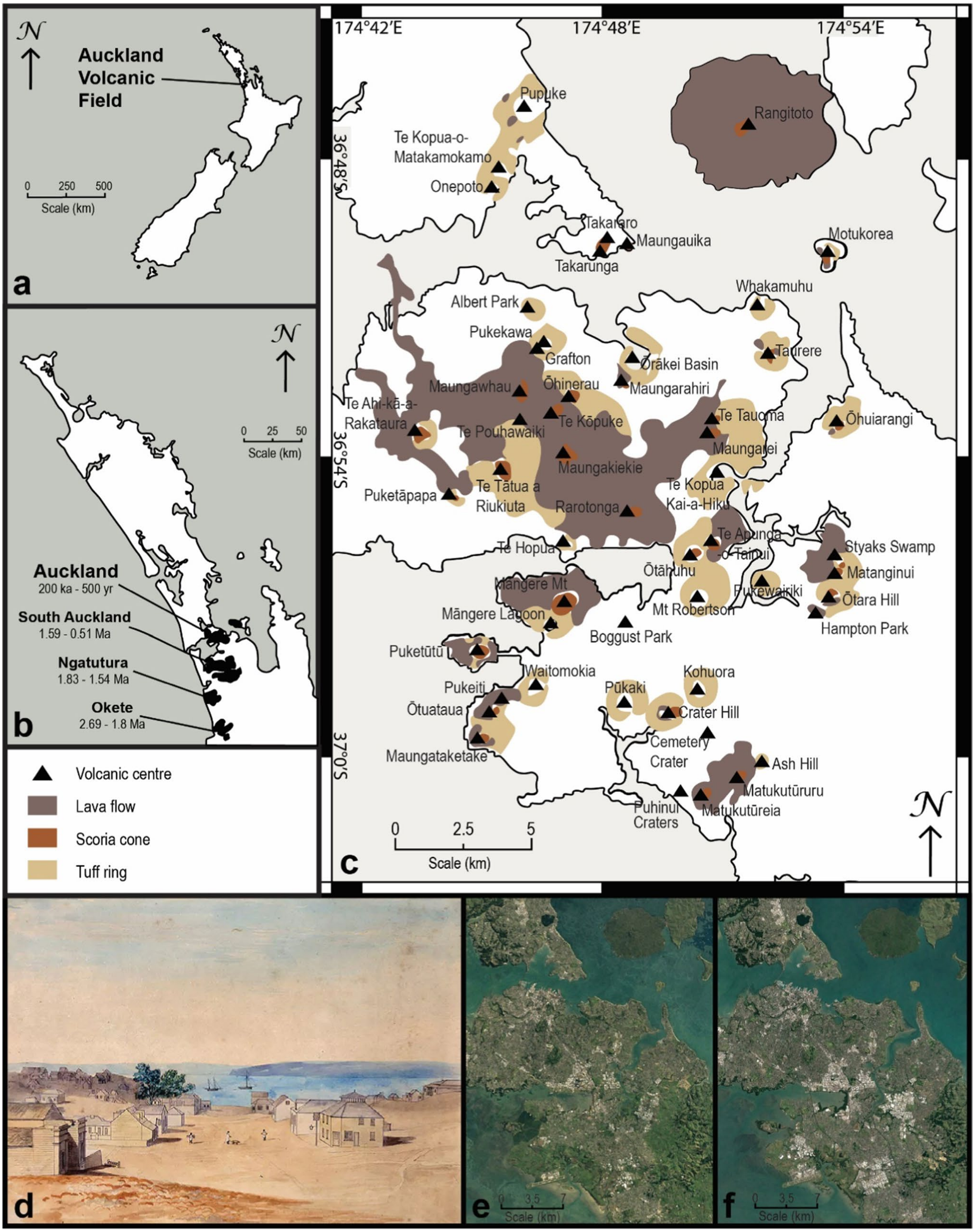
This paper examines the Auckland Volcanic Field as it was before the introduction of anthropogenic impacts and as it is today. The aims of this study are to (1) conduct a comprehensive qualitative and quantitative study of the anthropogenic impact on volcanic landforms and causes of impact in the AVF and (2) highlight the importance of preserving these landforms and the wealth of information that can be gained from each of them, even when partially destroyed. This study combined structured literature reviews, site visits (recording and photographing the current state of the volcanic centres) and GIS-based volume estimations of eruptive products for comparison with historical data sets. We summarise the landforms of all 53 volcanic centres in the AVF and discuss the history of quarrying in Auckland and the impact it has had on the volcanic field. Furthermore, we summarise the impacts to, and current preservation state of, each of the centres and highlight where there are future needs in terms of geoconservation and geological understanding of the field. To the best of our knowledge, a summary and overview of the current state of a volcanic field, as well as a quantitative and qualitative assessment of deposits affected or destroyed, has not been academically published.

The Auckland Volcanic Field

The Auckland Volcanic Field (AVF) is an active Quaternary monogenetic volcanic field located on the North Island of New Zealand (Fig. 1a,b). In 1864, early European explorer and geologist Ferdinand von Hochstetter described Auckland as 'one of the most remarkable volcanic districts of the Earth' and 'a truly classical soil for the study of volcanic formations' (Hochstetter 1864). The field has been active for around 200,000 years (Leonard et al. 2017; Hopkins et al. 2020) with eruptions at 53 volcanic centres during that time (Fig. 1c). The monogenetic volcanic landforms range from tuff rings and maars to lava flow fields (Lindsay et al. 2011; Hopkins et al. 2020), with the exception of the youngest centre, Rangitoto (Needham et al. 2011; Linnell et al. 2016). Rangitoto was formed by two separate eruptions – Rangitoto 1 produced an underlying maar with a tuff ring and a northern scoria cone 553 ± 7 cal. years BP, and Rangitoto 2 produced a large shield volcano and central and southern scoria cones 504 ± 5 cal. years BP (Needham et al. 2011; Shane et al. 2013; Linnell et al. 2016; Hayward et al. 2022). The 53 volcanic centres have produced a complex volcanic stratigraphy throughout Auckland, with many older deposits and potentially entire volcanic centres obscured by younger ones (Affleck et al. 2001). Due to the abundance of water (groundwater and surface) in the Auckland area, the majority (83%) of volcanoes began with phreatomagmatic activity and commonly (60%) transitioned to Hawaiian, Strombolian or effusive activity (Kereszturi et al. 2014).

The city of Auckland is New Zealand's most populated city with 1.7 million people (Auckland City Council 2021). It is the largest in New Zealand and covers the same area as the AVF, around 360 km^2. New Zealand was the last substantial landmass to be colonised by humans (Anderson 1991; Newnham et al. 1998; Brooking 2004), and humans have lived in what is now the Auckland area for around 750 years (Newnham et al. 1998; Lowe et al. 2000; Smith 2012). The first human modification of volcanic centres in Auckland was due to the formation of pās (Māori fortifications) and associated terraces and pits (Barr and Graham 1920; Golson and Fowlds 1957; Hayward 1983). Urban development of Auckland City began in 1840 (Fig. 1d) when it was declared New Zealand's capital city (Hochstetter 1864; Brooking 2004; Arbury 2019) (shifting to Wellington in 1865), with rapid population and industrial growth in the area thereafter (Fig. 1e,f) (Chalmers and Hall 1989; Edbrooke et al. 2003; Brooking 2004).

The 53 volcanic centres in the AVF are listed in Table 2, with a summary of the original landforms of each centre, including tuff rings and maars, scoria cones (and small scoria mounds) and lava flows. Where possible, the maximum lava flow deposit length was estimated, including instances where lava did not breach a crater. A count of each landform type has also been recorded, as well as the layout of landforms, such as whether the volcano has a single landform, landforms centred on a single vent, landforms clustered together, or landforms that appear to have any alignments in a particular direction (e.g. Von Veh and Németh 2009). All landform data are based on the closest


Auckland
Volcanic
Field
0 250 500
Scale (km)
a
Auckland
200 ka - 500 yr
South Auckland
1.59 - 0.51 Ma
Ngatutura
1.83 - 1.54 Ma
Okete
2.69 - 1.8 Ma
0 25 50
Scale (km)
b
Volcanic centre
Lava flow
Scoria cone
Tuff ring
174°42′E
174°48′E
174°54′E
36°48′S
36°54′S
37°0′S
Pupuke
Te Kopua-o-Matakamokamo
Onepoto
Rangitoto
Takararo
Maungauika
Takarunga
Motukorea
Whakamuhu
Albert Park
Pukekawa
Grafton
Taurere
Ōrākei Basin
Maungarahiri
Maungawhau
Ōhinerau
Te Ahi-kā-a-Rakataura
Te Pouhawaiki
Te Kōpuke
Te Tauoma
Ōhuiarangi
Maungarei
Maungakiekie
Te Tātua a Riukiuta
Puketāpapa
Te Kopua Kai-a-Hiku
Rarotonga
Te Apunga-o-Tainui
Styaks Swamp
Te Hopua
Ōtāhuhu
Matanginui
Māngere Mt
Pukewairiki
Ōtara Hill
Māngere Lagoon
Mt Robertson
Hampton Park
Boggust Park
Puketūtū
Waitomokia
Kohuora
Pukeiti
Pūkaki
Ōtuataua
Crater Hill
Cemetery Crater
Maungataketake
Ash Hill
Matukutūruru
Puhinui Craters
Matukutūreia
0 2.5 5
Scale (km)
c
d
e
Scale (km)
f
Scale (km)

◂**Fig. 1** (**a**) The Auckland Volcanic Field (AVF) in New Zealand. (**b**) Location of the AVF and related preceding intraplate volcanic fields in the North Island (Briggs et al. 1994). (**c**) Deposits of volcanic centres in the AVF (Edbrooke 2001; Cassidy and Locke 2010; Hopkins et al. 2017). (**d**) Depiction of Queen Street and the Auckland Harbour from the year Auckland City was founded (Ashworth 1843). (**e**) Auckland City satellite imagery from 1984 (Landsat and Copernicus 1984), with comparison to (**f**) satellite imagery from 2020 (Landsat and Copernicus 2020)

estimates of original landforms from literature review and historical images. Underlined volcanic centres were originally the site of a Māori pā (Taylor 1961; Hayward 1983, 2019b; Mathews 2015).

Volcanic Remnants

Importance and Significance of the Volcanic Centres in the Auckland Volcanic Field

For the Māori people, the volcanoes of New Zealand are sacred (Lowe et al. 2002; Bernbaum 2006). They hold significant importance and are directly tied to their culture, traditions, history and how they interpret the world and its creation (Lowe et al. 2002; Sigurdsson 2015; Hayward 2019b; Mackintosh 2019). The volcanoes in Auckland were key to the very existence of their ancestors and continue to remain a significant part of their identity and traditions today (Mackintosh 2019; Tūpuna Maunga o Tāmaki Makaurau Authority 2019). Volcanic cones, craters and castle and moat structures are naturally defendable places where human habitations worldwide have commonly been initiated in the past (Ort et al. 2008; Davidson 2011; MacInnes et al. 2014; Benfer and Ocás, 2017). Before European colonisation, volcanic cones in Auckland were used as fortified pās for the Māori tribes, with terraces for defence and storage pits dug around the slopes of the cones (Hochstetter 1864; Golson and Fowlds 1957) (Table 2). Pās were also seen as symbols of community and identity, and they were key hubs for housing food stores and seeds, provided prime soils for agriculture, and were a physical representation of hierarchy with the chief living at the summit (Hayward 1983; Lowe et al. 2002; Allen 2015). Dwellings for the rest of the tribe and kumara fields typically stretched out around the cones (Hochstetter 1864). The soil and vegetation cover of the volcanic cones resulted in an ease of landscaping, planting food and digging foundations for dwellings (Bulmer 1994; Davidson 2011). There were an estimated 198 pās in the Auckland area (Fig. 2) (Hayward 1983). Once Auckland had been colonised by Europeans, ownership of these cones commonly passed out of Māori hands (Morad and Jay 2003), and therefore, the decisions of what happened to the landforms were made by people other than the traditional land owners.

For the people living in Auckland City today, the visual presence of the volcanic centres in the area is key to their sense of belonging (Allen et al. 2021), local identity and nostalgia for the landscape (Mackintosh 2019). The volcanic centres help to provide green open spaces that are key to the character of the city (Auckland Council 2016; Tūpuna Maunga o Tāmaki Makaurau Authority 2019) and vital for recreational uses (Hayward 2019b; Mackintosh 2019). The views provided by the volcanic cones are 'of great value to Auckland's identity and the quality of the environment and should be protected' (Tūpuna Maunga o Tāmaki Makaurau Authority 2019). As the management authority of 15 of the volcanic centres in the AVF (on behalf of the original Māori owners of the land), it is the intention of the Tūpuna Maunga o Tāmaki Makaurau Authority (2019) that 'the visual and physical integrity and the historic, archaeological and cultural values of Auckland's volcanic features that are of local, regional, national and/or international significance are protected and, where practicable, enhanced'.

The connections that remain between the volcanic landscape of the AVF and the Māori people continue to provide them with their unique identity and relationship to the land around them (Mackintosh 2019; Tūpuna Maunga o Tāmaki Makaurau Authority 2019). Even after a volcanic centre has been quarried and destroyed, a cultural connection to the site plays an important role in present-day Māori traditions and is still considered to be sacred land (Mackintosh 2019).

Volcanic landscapes provide not only an archaeological record of the area but also the histories and experiences of the people who lived there (e.g. Gravis et al. 2017; Hayward 2019b; Auckland War Memorial Museum 2023). Volcanic regions are also significant places for geotourism and education worldwide (Sigurdsson 2015; Németh et al. 2017, 2021a; Quesada-Valverde and Quesada-Román, 2023). Geologically, the significance of the volcanic centres in the AVF lies in their relatively young age, ease of access and striking examples of simple to complex monogenetic volcanism on coastal and water-saturated plains in a field that is still active (e.g. Golson and Fowlds 1957; Houghton et al. 1996; Németh et al. 2012; Agustín-Flores et al. 2014).

History of Quarrying and Conservation Attempts in the Auckland Volcanic Field

The European settlement of Auckland ensured that the volcanic cones in the area became foundational to the creation and expansion of the city (Tūpuna Maunga o Tāmaki Makaurau Authority 2019). Soon after Auckland was declared the capital of New Zealand in 1840 (Brooking 2004), all the 'volcanic hills' in Auckland were reserved as public parks (initially protected for their aesthetic value), with the exception of Three Kings (Government 1886). Most volcanic centres saved any destruction at the onset of

Table 2 Landform summaries for each volcanic centre in the AVF based on recorded observations or closest estimates of original landforms

Volcanic centre	Landform summary	Landform count			Layout
		Maar/tuff ring	S. cone	Lava flow	
Albert Park	Tuff ring, scoria cone E side, lava flows [23, 24]	1	1	UN	Al E
Ash Hill	Tuff cone [10]	1	0	0	S
Auckland Domain/Pukekawa	Maar with small scoria cone [6] and lava lake [13]	1	1	670 m [3]	V
Boggust Park	Tuff ring, breached by sea [13]	1	0	0	S
Cemetery Crater	Tuff ring [13]	1	0	0	S
Crater Hill	Tuff ring, 2 scoria cones and lava shield [7, 19, 23], small crater N rim [11, 13], lava-filled crater, Self's and Underground Press lava caves [13]	1	2	600 m [3, 16]	Al SSW
Grafton	Tuff ring, scoria cone, lava-filled crater [13, 19]	1	1	CR	V
Green Mt/Matanginui	Tuff ring, central scoria cone, lava flows filled crater and overflowed, lava caves [7, 13, 24]	1	2	2 km N and W [3, 13]	V
Hampton Park	Tuff ring, welded scoria cone, lava flows [13]	1	1	690 m [3]	V
Kohuora	Tuff ring complex, 4 or more tuff ring craters clustered in an L shape [13, 23]	6+	0	0	CL
Little Rangitoto/Maungarahiri	Small scoria cone [13], some small lava flows [24]	0	1	270 m [3]	S
Māngere Lagoon	Large maar and small scoria cone [13, 22]	1	1	0	V
Māngere Mt/Te Pane-o-Mataoho	Buried tuff ring [8], large scoria cone, three craters on summit [7, 13, 22]	1	1 (3+)	1 km+ [13]	CL
Maungataketake/Elletts Mt	Tuff ring, scoria cone complex ≥ 2 vents, two peaks, lava flowed around cones [7, 13, 24]	1	2+	CR, 525 m [3]	CL
McLaughlins Mt/Matukutūreia	Large scoria cone, small tuff crater on SW edge of lava flows [7, 13, 23]	1	1	500 m [13]	Al SW
McLennan Hills/Te Apunga-o-Tainui	4 scoria cones within tuff ring, lava flows overflowed crater, small shield volcano [13, 23]	1	4	1675 m N, E and S [3]	CL
Motukorea/ Browns Island	Tuff-scoria-lava flow complex [2, 18, 19], scoria cone and mound complex [4]	1	1	2000 m [12, 18]	CL
Mt Albert/Te Ahi-kā-a-Rakataura	Tuff-scoria-lava flow complex [12, 24], lava flowed to Waitemata Harbour [12]	1	1	3250 m [3]	CL
Mt Cambria/Takararo	Scoria cone, possible small lava flow to S [12]	0	1	UN to S [15]	S
Mt Eden/Maungawhau	2 overlapping scoria cones and extensive lava flows from base [12, 19, 24]	0	2	3025 m [3, 12]	Al N-S
Mt Hobson/Ōhinerau	1 scoria cone with lava flows [12, 24], lava flowed to Newmarket railway station [12]	0	1	750 m [3]	V
Mt Richmond/Ōtāhuhu	Tuff ring complex (non-circular) with 9+ [15] scoria cones and ≥ 2 inner craters [12]	1+	9+	0	Al NE
Mt Robertson	Tuff ring with central scoria cone [23]	1	1	0	V
Mt Roskill/Puketāpapa	Tuff ring and central double scoria cone (from 2 nearby vents), lava flows [12, 24]	1	2	500 m N [12] 2400 m W	Al N
Mt Smart/Rarotonga	Buried tuff ring [12, 17] with scoria cone and lava flows [12, 24], lava caves [15]	1	1	1750 m [3]	S

Table 2 (continued)

Volcanic centre	Landform summary	Landform count			Layout
		Maar/tuff ring	S. cone	Lava flow	
Mt St John/Te Kōpuke	Scoria cone and lava flows [12, 24], Auckland's longest [12]	0	1	8500 m + to NW [12]	S
Mt Victoria/Takarunga	Scoria cone and lava flows [12], used as European naval forts	0	1	590 m S and E [3,12]	S
Mt Wellington/Maungarei	Minor tuff ring, scoria cone and lava flows to shoreline [12, 19], tallest cone [12], lava caves [15]	1	2	Approx 6000 m [12]	CL
North Head/Maungauika	Tuff cone, scoria cone and lava flows [12], used as European naval forts [12]	1	1	350 m [12]	Al NE
One Tree Hill/Maungakiekie	Large, complex scoria cone with extensive lava flow field [12, 24]	0	1	3575 m [3, 12]	CL
Onepoto/Te Kopua-o-Matakerepo	Maar [5]	1	0	0	S
Ōrākei Basin	Maar [19, 21]	1	0	0	S
Ōtara Hill/Smales Mt	Tuff–scoria–lava complex, rafted scoria mounds within crater [7, 12, 19]	1	1	2–500 m [3, 12]	V
Ōtuataua	Initial tuff ring, scoria cone and extensive lava flows [7, 12, 22], Māori use on lava flows	1	1	8–900 m W and NW [3, 12]	Al NW
Panmure Basin/Te Kopua Kai-a-Hiku	Maar [19] with small scoria cone	1	1	0	V
Pigeon Mt/ Ōhuiarangi	Tuff ring, scoria cone, lava flow [10], small satellite tuff ring erupted through rim [11]	2	1	700 m [3, 12]	Al NW
Puhinui Craters	3 small shallow tuff rings, elliptical craters [12]	3	0	0	Al NE
Pūkaki Lagoon	Maar [6, 7, 23]	1	0	0	S
Pukeiti/Puketapapakanga-a-Hape	Scoriaceous spatter cone with lava flows [7, 21], Lino Lava Cave 90-m long [12]	0	1	1000 m N [12]	S
Pukewairiki/Highbrook Park	Maar [6], lava-filled crater, satellite tuff ring [11]	2	0	0	Al E
Puketūtū/Te Motu-a-Hiaroa	Tuff-scoria-lava flow complex [19], tuff ring, 3 scoria cones and a lava field [7, 12, 19, 22]	1	6 + ?	Approx. 500 m [12]	CL
Lake Pupuke	Maar, scoria and lava complex [19], maar erupted through a lava shield and scoria [12]	1	1	Approx. 2000 m [3,12]	Al NE
Purchas Hill/Te Tauoma	Twin scoria cones, small tuff ring [12, 19]	1	2	0	CL
Rangitoto	Shield volcano [12], 2 scoria and 2 spatter cones, large lava shield [20, 25], basal tuff ring [14, 20]	1	4	3700 m [3]	CL
St Heliers/Whakamuhu	Tuff ring [12, 24]	1	0	0	S
Styaks Swamp	Maar [7, 12], swampy floor	1	0	0	S
Tank Farm/Te Kopua-o-Mataka-mokamo	Tuff ring [12], intertidal mangrove forest and fringing salt marsh [12]	1	0	0	S
Taylors Hill/Taurere	Tuff-scoria-lava complex [19], partial tuff ring, scoria cones and mounds from ≥ 5 vents [12, 24]	1	7 +	4–500 m E and NW [12]	CL
Te Hopua/Gloucester Park	Tuff ring [12, 24]	1	0	0	S
Te Pou Hawaiki	Scoria cone, buried tuff ring, possible lava flows [1, 12]	1	1	1000 m N [1]	Al NNW
Three Kings/Te Tātua a Riukiuta	Tuff-scoria-lava complex [19, 24], lava lake, lava caves [15]	1	3 + 12 M	3000 m N [13]	CL

Table 2 (continued)

Volcanic centre	Landform summary	Landform count			Layout
		Maar/tuff ring	S. cone	Lava flow	
Waitomokia/Moerangi	Maar, tuff ring and scoria cone complex [7, 9]	6+	3	CR	Al NE
Wiri Mt/Matukutūruru	Tuff rings and scoria cone [7, 9, 23]	3	1	1300 m [3, 9, 23]	Al SW

Underlined volcanic centres were originally the site of a Māori pā. Landforms: M – small mounds. Lava flows: based on approximate termination distance from the vent (please note all superscript numbers are references, not units of measurement); UN – extent unknown; CR – lava did not breach crater. Layout: S – single landform; V – landforms centred on one vent; CL – landforms clustered together; Al – apparent alignment

[1]Affleck et al. (2001), [2]Agustin-Flores et al. (2015), [3]Allen and Smith (1994), [4]Allen et al. (1996) [5]Augustinus et al. (2012), [6]Cassidy et al. (2007), [7]Firth (1930), [8]Foote et al. (2017), [9]Foote et al. (2022), [10]Hayward (2008), [11]Hayward (2015), [12]Hayward (2018), [13]Hayward (2019b), [14]Hayward et al. (2022), [15]Hochstetter (1864), [16]Houghton et al. (1999), [17]Magill and Blong (2005), [18]McGee et al. (2012), [19]McGee et al. (2013), [20]Needham et al. (2011), [21]Németh et al. (2012), [22]Searle (1959), [23]Searle (1961), [24]Searle (1962), [25]Shane et al. (2013)

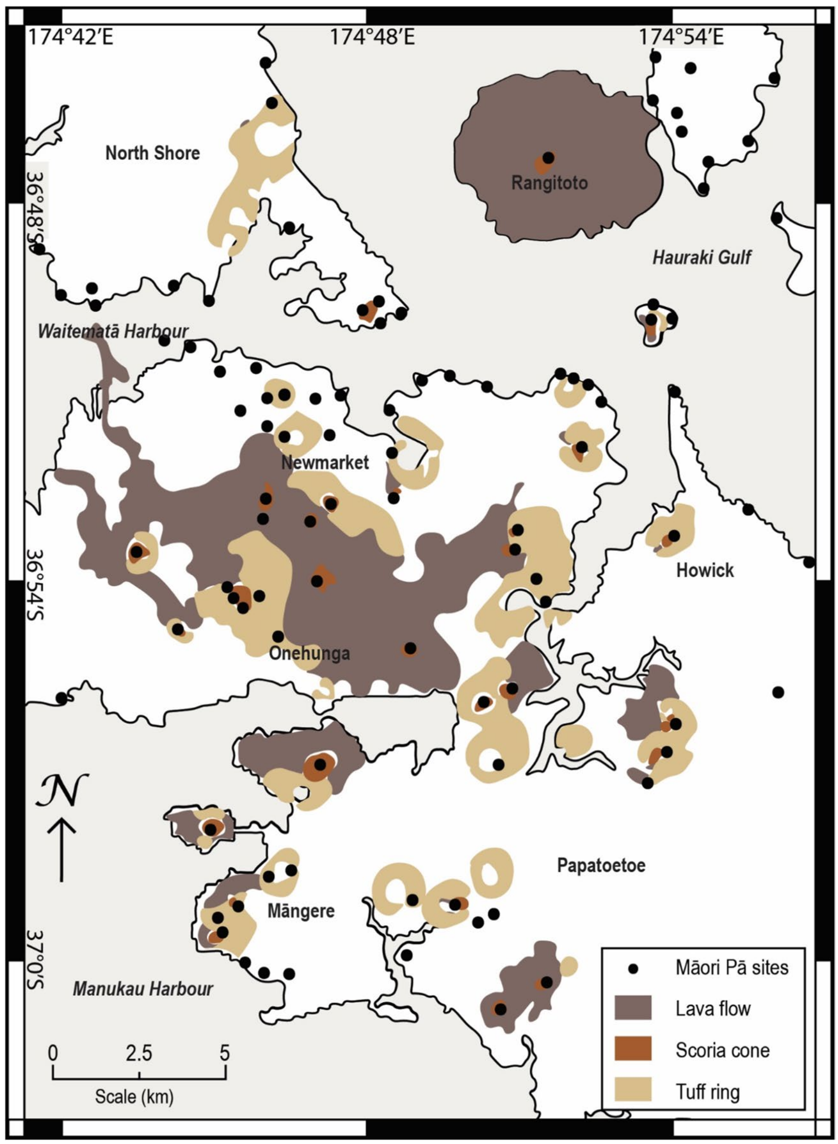


Fig. 2 Known original Māori pā sites in the Auckland area. The type of volcanic landform is illustrated by coloured fill (Edbrooke 2001; Cassidy and Locke 2010; Hopkins et al. 2017)

the development of the city due to the abundance of timber in the area which was readily used for building (Mathews 2015) instead of relying on the volcanic landforms to provide building materials. However, within twenty years of

Auckland's development, early wooden houses were starting to be replaced with stone buildings made with basalt from nearby cones; a common source of which was lava flows from Mount Eden (Hochstetter 1864; Hayward et al. 2011). St Andrew's Presbyterian Church, for example, is the oldest stone church in New Zealand and was built in 1847 with basalt from Mt Hobson (Ōhinerau) lava flows (Hayward 2019b). By this point, there were two main roads within Auckland that served as major routes for transportation: the Great North Road and the Great South Road; materials for both were sourced from quarries along their paths, including Mount Eden (Maungawhau), One Tree Hill (Maungakiekie) and Mount Wellington (Maungarei) (Fig. 3c,f,g) (Hochstetter 1864; Hayward et al. 2011). Volcanic centres along the path of newly established railway trunk lines suffered the same fate, as ballast and rail track underlays required for their construction and expansion were sourced from Wiri Mt (Matukutūruru), Mount Smart (Rarotonga) and Mount Albert (Te Ahi-kā-a-Rakataura) (Fig. 3a,b) (Mathews 2015; Németh et al. 2021b). Several other key roads in Auckland began as pathways for the Māori people and were later converted by settlers using volcanic material, including Manukau Road, Symonds Street and Remuera Road (Mackintosh 2019).

The Scenery Preservation Board was founded in 1906 (Roche 2017) in order to establish scenic reserves in Auckland that protect important contributors to the 'aesthetic vision' of the area, including volcanic cones. In 1914, the Mayor of Auckland petitioned parliament to protect the volcanic cones in the area from further destruction by quarrying and suggested they all be reserved as public domains (Pishief and Adam 2015). The most obvious and largest cones in Auckland (e.g. Mt Roskill (Puketāpapa), Mt St John (Te Kōpuke)) were the ones most likely to be preserved and protected, with smaller cones and less imposing landforms far more likely to be quarried (Mathews 2015; Mackintosh 2019). These

Fig. 3 Quarrying throughout Auckland City over the last 100 years. (**a**) Wiri Quarry (Matukutūruru) supplying railway ballast (Collections 1922); (**b**) Mount Smart Quarry (Rarotonga) with railway wagons in the foreground (New Zealand Herald 1935); (**c**) Mount Eden Quarry (Maungawhau), digger at work (Auckland City Council, circa 1952); (**d**) Māngere Sewage Treatment Plant oxidation ponds construction at the site of Māngere Lagoon, with Puketūtū Island (Te Motu-a-Hiaroa) causeway in background (Auckland Metropolitan Drainage Board 1959); (**e**) Smales Mt (Ōtara Hill) with bulldozer working the quarry (La Roche 1980); (**f**) Winstone Quarry on the north side of Mount Wellington (Maungarei), active for 65 years (Page 1989b); (**g**) Quarry danger sign, Mount Wellington (Maungarei) (Page 1989a); (**h**) Entrance to Ihumātao Quarries Scoria Pit Ltd site (Alford 2003); (**i**) Three Kings Quarry (Te Tātua a Riukiuta) looking North (Elliot 2016)

prominent cones were further protected in the 1970s by council measures, deeming them to be of ‘regional significance’ (Mathews 2015). The Department of Conservation (DOC) was established in 1987 in order to protect ‘the intrinsic and cultural values of the country’s natural and historic resources’ (Booth 1993). Since its foundation, the DOC has played an important role in the development and protection of regional recreational parks and landforms (e.g. Rangitoto Island, Maungauika/North Head Historic Reserve, Tiritiri Matangi Island) (Department of Conservation 2023).

The development of Auckland City was rapid from its onset, and one of the main reasons it has been able to foster such a strong growth and development rate has been its proximity to key resources, the foremost of these being from volcanoes (Golson and Fowlds 1957). Many of the major Auckland roads and railways that are still used today were built using these resources (Hochstetter 1864; Mathews 2015; Németh et al. 2021b). The ability to develop such a strong transport system early on in the life of the city has enabled Auckland to grow and expand quickly (Chalmers and Hall 1989; Brooking 2004). Greater transport distances to provide ballast and roading materials would have resulted in an increased cost and time to produce infrastructure and could have significantly altered the development of the city. Throughout the development of Auckland, from its establishment as a city to present day, decisions by government and local councils have affected which volcanic centres have been utilised for a range of impacts related to the city’s development, including quarrying, water storage, waste storage and management, residential and industrial expansion and recreation (Tūpuna Maunga o Tāmaki Makaurau Authority 2019; Németh et al. 2021b). As noted by Mathews (2015), ‘The volcanoes were re-worked into new entities whose boundaries are not geological but defined by lawyer’s pen and encroaching houses’. Today, the destruction of the volcanic centres continues due to a sustained demand for easily acquirable rock (Németh et al. 2021b). Quarries at several centres are still operating, and the remains of several more are used as rubbish storage for the city, including Puketūtū (Te Motu-a-Hiaroa) and Green Mt (Matanginui) (Németh et al. 2021b).

Approach and classifications

Kereszturi et al. (2014) published data on the reconstructed original total area of volcanic deposits from each centre in the AVF (see the ‘original area’ column in Table 3). These were calculated from field measurements, geological maps, orthophotos and LiDAR digital terrain models (DTM). We use this published data to compare with our own measurements from the latest available LiDAR data (LINZ 2018a; b) (Table 3). These data were sourced from Land Information New Zealand (LINZ) and were captured for the Auckland Council by Aerial Surveys in 2016–2018. The data used were the 1 m LiDAR digital elevation model (DEM) of Auckland, with a reported vertical accuracy of ± 0.2 m and horizontal accuracy of ± 0.6 m. Satellite imagery was sourced from Sentinel Hub (2023). LiDAR DEM data, satellite imagery and geological maps (Edbrooke 2001) were used to measure the total deposit surface area remaining for each volcanic centre (see ‘current area’ column in Table 3). Using the estimated original areas published by Kereszturi et al. (2014), a percentage decrease was calculated for each centre. This value was used to assign a basic category of status for each centre to provide an overview of the field.

As there were no appropriate comparative examples of categorisation available in the literature, categories were created that best fit the situation. Categories were not evenly distributed on a percentage scale in order to appropriately reflect the visual, social and cultural aspects of impacts on a landform. Centres were categorised using the following: intact: 0–20% loss in the area; partially intact: 20–50% loss; partially destroyed: 50–80% loss; and destroyed: 80–100% loss. The current state of each centre has been summarised in Table 3 below, with the main causes of impacts listed.

Discussion

The Current State of Centres in the Auckland Volcanic Field

Of the 53 volcanic centres in the AVF (Fig. 4), 17% are classified as intact, 28% are partially intact, 30% are partially destroyed, and 25% are destroyed (including 13% that have no trace left). The measurements in Table 3 present a total estimated original deposit area of 147.65 km^2 and a total measured area (using 2016–2018 data as outlined above) of 88.58 km^2, with the difference between these measurements totalling a 59.07 km^2 loss, or 40%. To summarise, we have approximately 60% of the deposit area remaining in the AVF. Unsurprisingly, the most common causes for impacts to the volcanic centres throughout the AVF are land use and quarrying (Table 3). Urban development has also been a common impact. The AVF was built over almost 200,000 years of volcanism (Leonard et al. 2017; Hopkins et al. 2020), and in just 180 years, anthropogenic activity has destroyed or covered 40% of its surface expression to date.

Historical and Geological Losses Caused by Anthropogenic Activity

Volcanic centres provide important insights into both human history and the natural histories of the area (such as remnants of forests long removed to make way for quarrying and urban development (Mackintosh 2019)). Quarrying in

Table 3 Summary of impacts and current state of volcanic centres in the AVF, based on closest estimates of original landforms

Centre	Comments	Status				Cause of impact	Original area km^2 (ref. 43)	Current area km^2 (this paper)	Deposit loss
		I	PI	PD	D				
Albert Park	Highly weathered, mostly quarried [17, 30] lava flow remnants under the city?				x	W, Q	1.23	0	100%
Ash Hill	Completely gone by 2019 [26], site privately owned industrial land				x	Q	0.25	0	100%
Auckland Domain	Highly weathered [30], floor reclaimed, quarried on N side of cone, farming, parklands [17]		x			Q, LU	1.4	0.88	37%
Boggust Park	Floor reclaimed [16, 17, 19], inner crater and tuff ring crest in Boggust Park (managed by Auckland Council), rest of tuff ring in private land [17]		x			SB, UD, LU	0.37	0.19	48%
Cemetery Crater	Tuff ring breached to SW [17], completely gone [16, 17, 19], residential land				x	SB, UD, LU	0.19	0	100%
Crater Hill	Road through side of crater [16], farmland, 'severely modified by quarrying' [20], scoria cone quarried, tuff ring partially infilled [17, 23]		x			Q, UD	2.02	1.21	40%
Grafton	No remains [17], most deposits under commercial land/Outhwaite Park [23]				x	Q, UD	1.2	0	100%
Green Mt	Quarried away [17], scoria cone gone [17], tuff ring buried under landfill				x	Q	3.16	0	100%
Hampton Park	Lower slopes of scoria cone remain [17], lava flows used for building and landscaping, Te Puke-o-Tara Hampton Park owned by Auckland Council [17]			x		Q	1.14	0.26	77%
Kohuora	Crater floor reclaimed, filled [17, 19], greatly modified by erosion [29]			x		UD, W	1.92	0.88	54%
Little Rangitoto	Most gone by 1899 [19], partially filled, reserve, remnants under housing [17]				x	Q, UD, LU	0.46	0.01	97%
Māngere Lagoon	Tuff ring breached on SW side, tidal lagoon [7], used for Manukau sewerage scheme, now partially restored, sewer causeway on W side [11]			x		UD, SB	0.73	0.20	73%
Māngere Mt	Eastern wall extensively breached [7], partially quarried, owned by TMA [31], protected within Māngere Domain, managed by Auckland Council [17]		x			Q, LU	5.98	3.03	49%
Maungataketake	Heavily quarried, some outcrop on coast – Ihumātao [1, 25, 27], privately owned			x		Q	3.3	0.72	78%
McLaughlins Mt	Remnant of scoria cone, most of the lava flow quarried [17]				x	Q	0.97	0.18	82%
McLennan Hills	Heavily quarried [17], lava remnants in residential and industrial land				x	Q	3.57	0.49	86%
Motukorea	Tuff ring partially eroded by the sea [2], well preserved [17, 22]	x				W	1.71	1.40	18%
Mt Albert	Upper third quarried by NZ railways (approx. 1.5 M cubic m removed) [17, 19, 30], owned by the TMA [31], domain, remnants in privately owned land [17]		x			Q, LU	5.06	2.56	50%
Mt Cambria	Quarried for a century, only stump remains[17, 19], remnants in private land			x		Q, LU	0.05	0.01	76%
Mt Eden	Multiple quarries for scoria from 1840s [17, 18, 23], owned by TMA [31], multiple reserves, privately owned land [17]		x			Q, LU	5.17	4.01	22%

Table 3 (continued)

Centre	Comments	Status				Cause of impact	Original area km² (ref. 43)	Current area km² (this paper)	Deposit loss
		I	PI	PD	D				
Mt Hobson	Two small quarries 1914–28 [17, 19], owned by the TMA [31], upper part in public reserve, lower slopes and lava flows in privately owned land [17]		x			Q, UD, LU	0.93	0.47	50%
Mt Richmond	Half quarried away[17], now owned by the TMA [31]			x		Q, UD, LU	1.57	0.54	65%
Mt Robertson	Half/top 5 m quarried for playing field [17, 19], tuff ring in private land [17]			x		Q, UD, LU	2.19	1.04	53%
Mt Roskill	Largely untouched [17, 19], owned by the TMA [31]	x				UD, LU	2.74	2.51	8%
Mt Smart	Majority quarried by NZ railways [17, 19, 30], Mt Smart Stadium, cone and lava flow under privately owned land [17], owned by the TMA [31]			x		Q, UD, LU	2.62	0.63	76%
Mt St John	Small quarry on N side, now historical reserve [17], owned by the TMA [31]	x				Q, LU	3.73	3.08	17%
Mt Victoria	Naturally breached (rafted scoria) on S side, largely untouched [17], owned by the TMA [31], lower slopes and lava flows on privately owned land [17]	x				LU	0.44	0.43	2%
Mt Wellington	Quarried from the 1850s to 1967 for roads, now owned by the TMA [31]		x			Q, UD	7.55	5.18	31%
North Head	Largely untouched [17], owned by the TMA [31]	x				LU	0.19	0.19	0%
One Tree Hill	Used for tourism, farmland, One Tree Hill Domain, Cornwall Park, lower lava flows in privately owned land [17], owned by the TMA [31]	x				LU	16.6	15.75	5%
Onepoto	Naturally breached lake, crater floor reclaimed [12, 19] farmland [4]		x			SB, LU	0.76	0.4	47%
Ōrākei Basin	Tidal lagoon, breached by sea, some crater collapse, major road through crater [17, 25, 27] tuff ring mostly in privately owned land			x		SB, UD, LU	1.74	0.45	74%
Ōtara Hill	Scoria and lava flows quarried [17], tuff ring under industrial/private land [23]			x		Q, UD, LU	1.5	0.66	56%
Ōtuataua	Man-made crater [10, 19], Otuataua Stonefield Historic Reserve [11]			x		Q	0.56	0.15	73%
Panmure Basin	Tidal lagoon breached by sea, road through one side of crater [17], now mix of privately owned land and reserves, managed by Auckland council [17]			x		SB, LU	2.39	0.82	66%
Pigeon Mt	Scoria cone half quarried [17, 19], owned by TMA [2], reserves/private land [17]				x	Q, UD, LU	1.13	0.19	83%
Puhinui Craters	Protected by Puhinui Reserve [14, 16]	x				LU	–	0.12	0%
Pūkaki Lagoon	Drained tidal inlet [5, 12, 17, 19], crater floor reclaimed, farmland, crater owned by local iwi: Te Ākitai Waiohua, outer slopes privately owned		x			SB, LU	2.48	1.41	43%
Pukeiti	Protected within Otuataua Stonefields Historic Reserve [10, 17, 19]			x		Q, LU	0.54	0.25	54%
Pukewairiki	Major road built through the side of crater [16, 17], public reserve managed by Highbrook Park Trust [17]		x			UD, LU	1.39	0.69	50%

Table 3 (continued)

Centre	Comments	Status				Cause of impact	Original area km^2 (ref. 43)	Current area km^2 (this paper)	Deposit loss
		I	PI	PD	D				
Puketūtū	Over half quarried [17], used for Auckland Airport, currently sewage landfill			x		Q, UD, LU	3.99	1.33	67%
Lake Pupuke	Small scoria cone quarried by Smales Quarry [17, 19], the only permanent fresh-water crater lake in AVF [17], four public reserves, varied land use	x				W, Q, LU	6.44	5.64	12%
Purchas Hill	Heavily quarried [17, 23], N scoria cone in planned reserve [3], rest under privately owned and industrial land [17]		x			Q, UD, LU	1.64	1.19	27%
Rangitoto	Essentially untouched by quarrying [17, 24]	x				W	26.24	24.97	5%
St Heliers	N side eroded by sea-cliff recession, eastern edge eroded [30], original swamp drained [16, 19], within Glover Park, private land use on outer edges [17]		x			W, SB, LU	0.39	0.24	39%
Styaks Swamp	Completely gone [17, 19], partially filled swamp for industrial subdivision [17]				x	UD, LU	1.58	0	100%
Tank Farm	Tidal lagoon, lagoon was breached naturally then reclaimed [19]		x			SB, LU	1.04	0.77	26%
Taylors Hill	Half quarried away [19], Taylors Hill Reserve, remnants in private land [17]		x			Q, LU	0.78	0.39	50%
Te Hopua	Crater breached by sea, drained tidal inlet [16, 17], motorway through crater, crater floor is now Gloucester Park [17]				x	SB, UD, LU	0.35	0.07	81%
Te Pou Hawaiki	Tuff ring buried, remnants covered by lava flows from Mt Eden [17, 19]				x	Q, UD	1.42	0	100%
Three Kings	One scoria cone remains (reserve) [17, 30], partly owned by the TMA [31]			x		Q, LU	8.73	2.4	73%
Waitomokia	Wedding's Quarry [15], scoria cones quarried for Manukau Sewerage Scheme, tuff ring severely damaged by land use, one tuff outcrop remains [9]			x		Q, LU	1.22	0.45	63%
Wiri Mt	Owned by TMA [31], Wiri Quarry, quarried by NZ railways, lava cave protected by DOC [6, 17, 26], industrial area, single tuff and scoria outcrops remain[8]				x	Q, UD, LU	2.9	0.13	96%

Underlined centres were former Māori pās. TMA – Tūpuna Maunga Authority; DOC – Department of Conservation. Status: I – intact; PI – partially intact; PD – partially destroyed; D – destroyed. Causes of impact: W – weathering/erosion; SB – breached by sea; Q – quarrying; UD – urban development; LU – land use. For this study, urban development includes residential and industrial development and transport infrastructure, and land use includes impacts such as farming and landscape modification for the development of recreational areas

[1]Agustín-Flores et al. (2014), [2]Agustin-Flores et al. (2015), [3]Auckland Council (2016), [4]Augustinus et al. (2012), [5]Cassidy et al. (1999), [6]Department of Conservation (1990), [7]Firth (1930), [8]Foote et al. (2022), [9]Foote et al. (2023), [10]Gravis et al. (2017), [11]Gravis et al. (2020), [12]Hayward et al. (2002), [13]Hayward et al. (2011), [14]Hayward et al. (2012), [15]Hayward (2013), [16]Hayward (2015), [17]Hayward (2019b), [18]Hochstetter (1864), [19]Hopkins et al. (2017), [20]Houghton et al. (1999), [21]Kereszturi et al. (2014), [22]McGee et al. (2012), [23]McGee et al. (2013), [24]Needham et al. (2011), [25]Németh et al. (2012), [26]Németh et al. (2021b), [27]Peti and Augustinus (2019), [28]Ricketts (1977), [29]Searle (1961), [30]Searle (1962), [31]Tūpuna Maunga o Tāmaki Makaurau Authority (2019)

the AVF has destroyed numerous archaeological sites (e.g. Ihumātao Peninsula, Otuataua Stonefields, Three Kings (Fox 1977; Mackintosh 2019)) and remnants of local Māori culture and history (Stone 2001). The geological and educational losses caused by anthropogenic modifications to this field have also been severe (Fig. 5).

For example, Maungataketake (Elletts Mt), located on the culturally and historically significant Ihumatao Peninsula, has been heavily quarried since at least 2005 (Fig. 3h), with few deposits remaining. It is privately owned with limited access to its scientific study. Németh et al. (2021b) drew attention to outer exposures of the

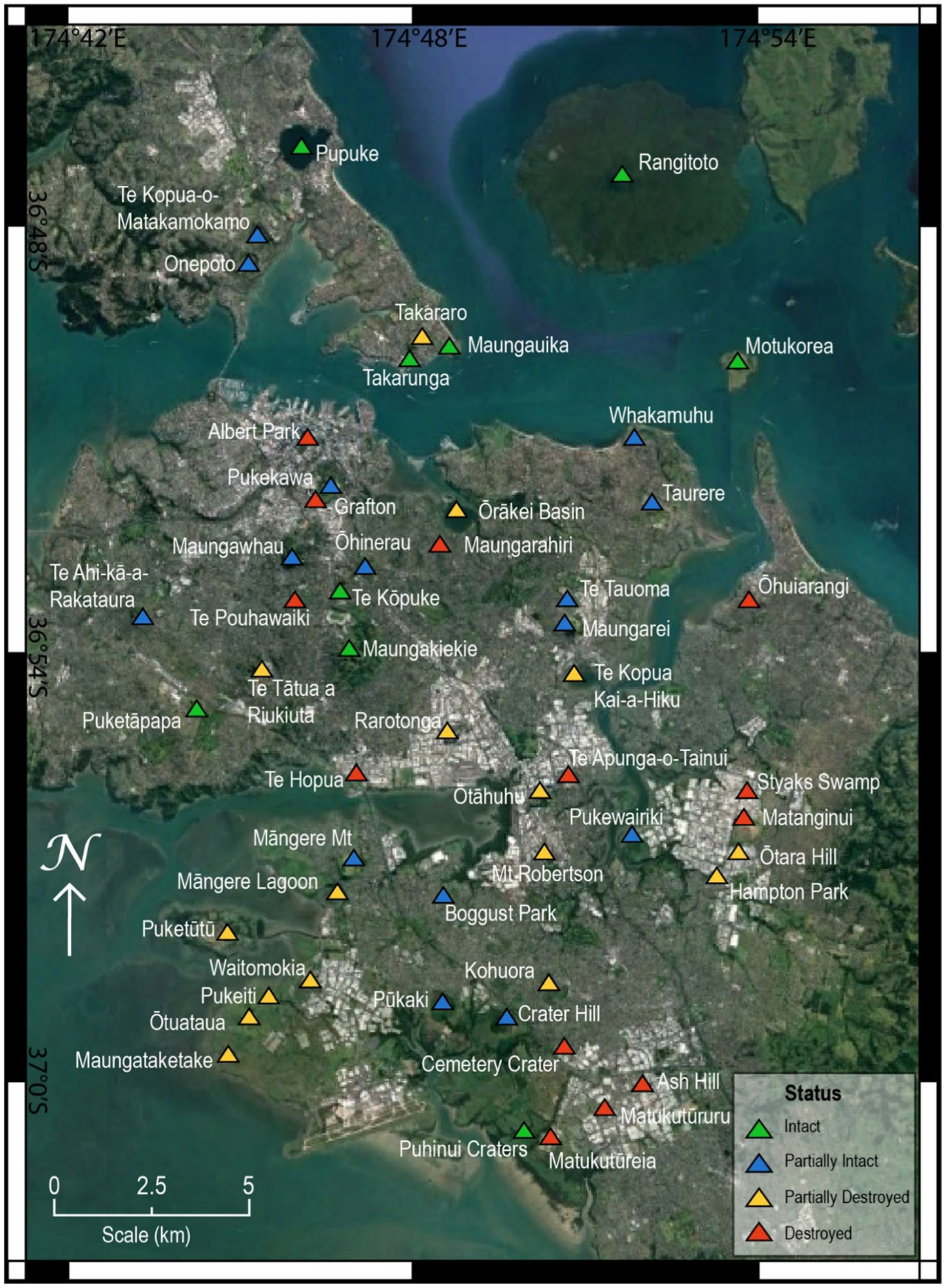


Fig. 4 Current status of each volcanic centre in the AVF. Classification of the state of each centre is represented by triangle symbols shown in the key. Satellite imagery from Airbus (2023)

deposits of Maungataketake along the Ihumātao peninsula (Fig. 5a), which provide a truly unique geoheritage opportunity to study both the inner and outer proximal to distal volcanic successions in tandem to provide high-resolution data (Gravis and Németh 2016; Gravis et al. 2017). Unfortunately, due to a lack of access by volcanologists to the centre, this is unlikely to happen, and it remains classified as a future urban zone in the Auckland Unitary Plan (Auckland Council 2016).

Ōtāhuhu (Mt Richmond) was one of the most complex centres in the AVF (Table 2) and the original site of a Māori pā (Fig. 2). It originally consisted of a tuff ring with at least nine scoria cones within the crater, as recorded by Hochstetter (1864). There were also at least two smaller craters that formed within the tuff ring (Hayward 2019b). Ōtāhuhu has produced the fifth-largest eruptive volume of materials attributed to scoria cones in the AVF (Kereszturi et al. 2013). Due to its complexity and high eruptive volume, it is one of the more significant volcanic centres in the field. Unfortunately, Ōtāhuhu had already been 'badly defaced by quarrying operations' by 1961 (Searle 1961) and has since been over half quarried away (Hayward 2019b) (Table 3).

The smallest tuff ring in the AVF, Ash Hill (Fig. 1), was completely removed by 2019. Minimal observations

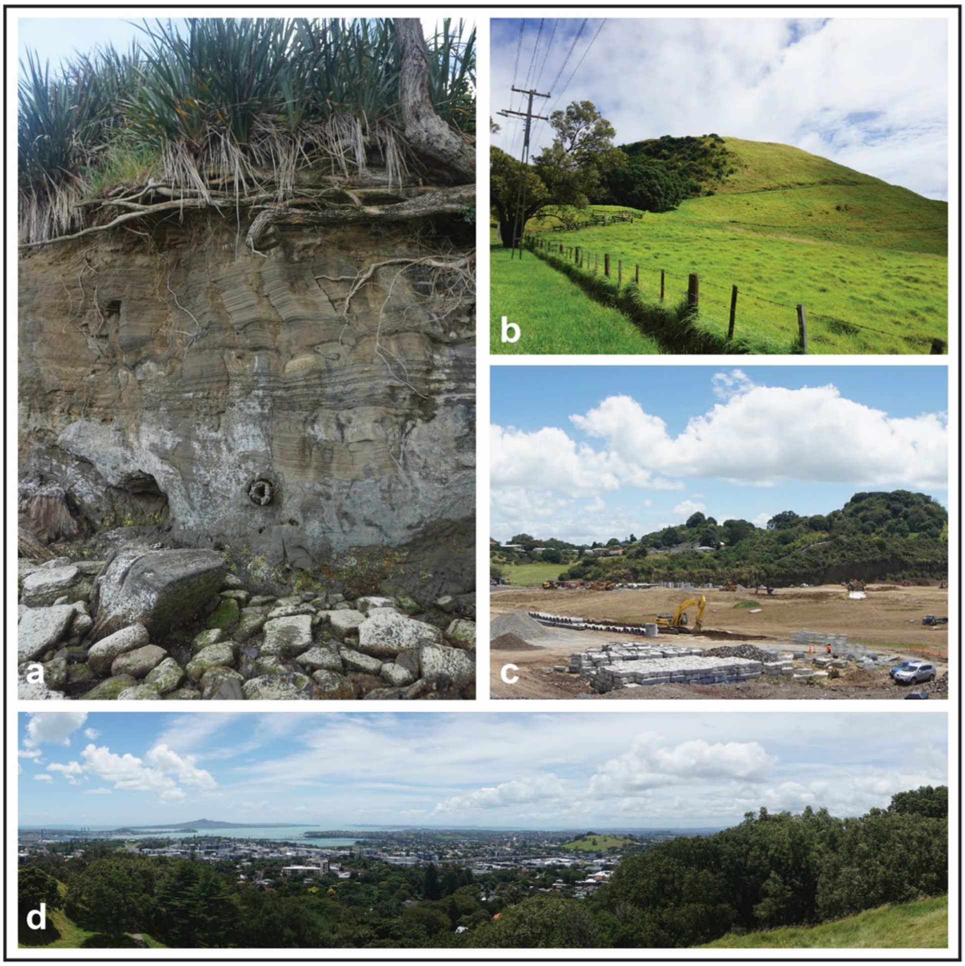


Fig. 5 Examples of some of the affected volcanic centres in Auckland. (**a**) Tuff deposits along the Ihumātao Peninsula, on the outer edge of Maungataketake (Elletts Mt), with buried fossil forest remnants visible in coastal exposures. (**b**) Mount Wellington (Maungarei) showcasing Māori terracing on its flanks and scars from quarrying operations covered in trees on one side. (**c**) The remnants of Three Kings (Te Tātua a Riukiuta) with the protected 'Big King' cone visible in the background. (**d**) View of Auckland City from Mount Eden (Maungawhau), with Rangitoto, North Head (Maungauika) and Mt Victoria (Takarunga) visible on the left (all intact; see Table 3), Orakei Basin visible ahead (partially destroyed) and Mt Hobson (Ōhinerau) and Mt Wellington (Maungarei) visible to the right (both partially intact)

of the centre were made by Hochstetter (1864); however, a full volcanological study was never made. If any deposits remain, they are now buried underneath a well-developed heavy industrial zone (Hayward 2008; Auckland Council 2016) and are unlikely ever to be seen again. Despite the size of this centre and the likelihood that it was the shortest eruption in the AVF (Németh et al. 2021b), its loss is substantial as it would have been an important end-member indicator for future eruptions.

Several campaigns have been formed to protect and preserve the volcanic landscapes in Auckland. The Save Our Unique Landscape (SOUL) campaign was created to protect the Ihumatao Peninsula from further damage and planned urban development. The area is undeniably significant in terms of Māori history and culture, as well as geological and archaeological heritage (Gravis and Németh 2016; Gravis et al. 2017; Malva 2018; Mackintosh 2019). Community interest and support have meant this area remains free of development for the time being, with an uncertain future (McCreanor et al. 2018; Gravis et al. 2020). Other geoconservation bids have been made by geologists and concerned citizens over areas such as Three Kings (Te Tātua a Riukiuta) (Fig. 5c), Crater Hill and Wiri (Matukutūruru) with limited success (Hayward and Crossley 2014; Hayward 2017, 2019a).

The Benefits and Balance of Anthropogenic Modification of Volcanic Landforms

It has been recognised worldwide that there is significant potential to be found in the balance between the losses and gains of quarrying, mining and other anthropogenic impacts on volcanic landforms (Prosser 2016; Gravis et al. 2020; Quesada-Valverde and Quesada-Román, 2023). As determined by Németh et al. (2021b), 'a balance must be defined between excavation and preservation'. Quarries and mines create opportunities for geologists to study volcanoes in greater detail beneath the surface (López-García et al. 2011) and often aid in the creation of geoheritage sites, geoparks and tourism sites after a quarry has ceased operations (Prosser 2016; Pijet-Migoń and Migoń, 2022) (Fig. 6). Abandoned quarries and mines can also help promote education regarding volcanic landforms and their history and help to showcase

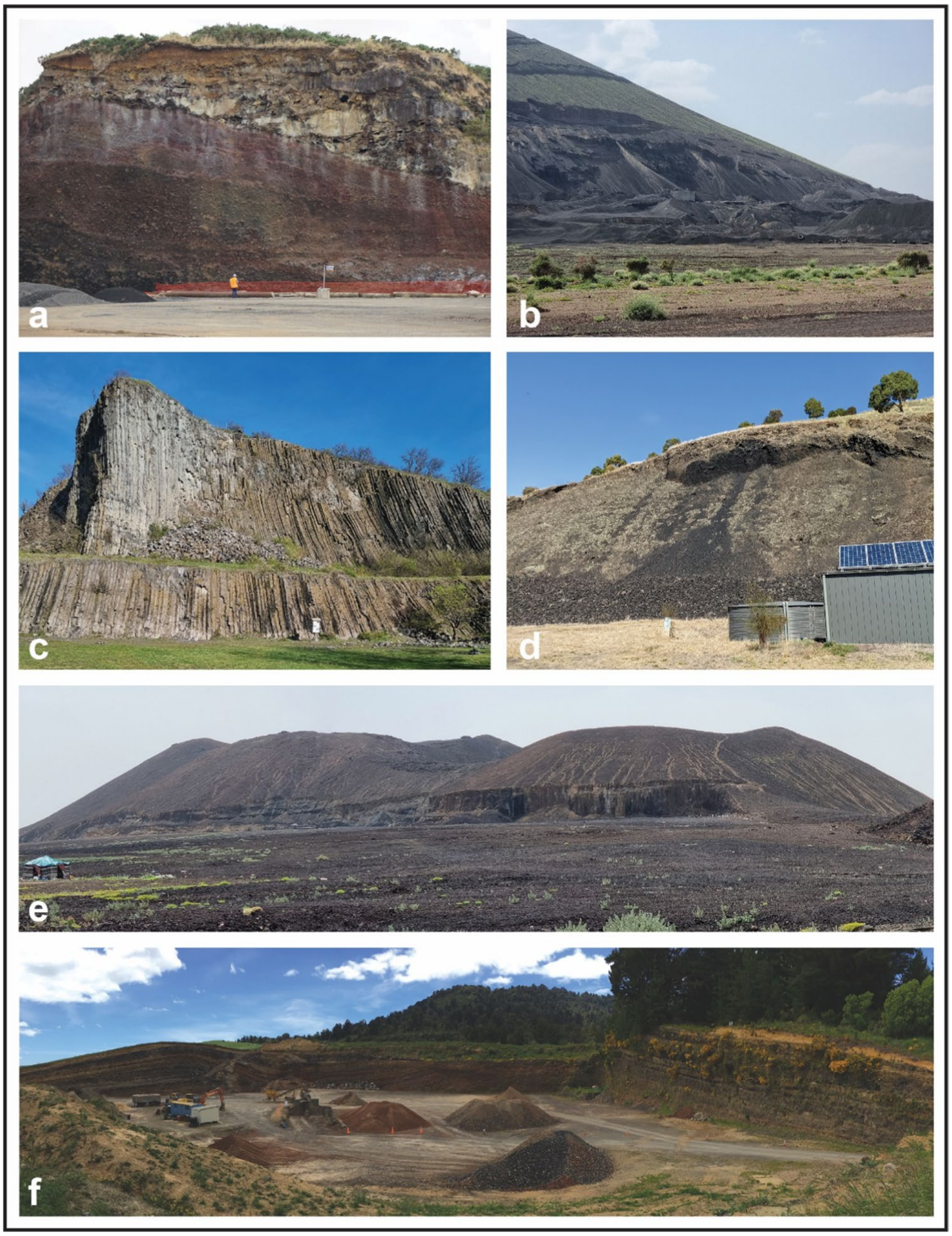


Fig. 6 Examples of spectacular outcrops exposed worldwide by anthropogenic impacts: (**a**) Stratigraphy of what was once a 90-m high scoria cone exposed by quarrying, Wiri Mountain (Matukutūruru), Auckland Volcanic Field, New Zealand (Foote et al. 2022); (**b**) Al Malsa scoria cone complex damaged by quarrying and road construction, Northern Harrat Rahat, Saudi Arabia, in the proposed Harrat Al Madinah Geopark (Downs et al. 2019); (**c**) an abandoned basalt quarry that showcases the rock types of the region and now hosts the main visitor centre of Bakony-Balaton UNESCO Global Geopark, Plio-Pleistocene Bakony-Balaton Highland Volcanic Field, Hungary (Pál and Albert 2021); (**d**) quarry face at Mount Elephant, Newer Volcanics Province, Australia (Boyce 2013); (**e**) Late Pleistocene Um Nathilah scoria cone chain, Al Madinah City, Saudi Arabia, damaged by motorway construction on the northern side (Downs et al. 2019); (**f**) active quarrying of scoria at the Ohakune Volcanic Complex, southern Taupo Volcanic Zone, New Zealand (Froggatt and Lowe 1990; Kósik et al. 2016)

the materials they have provided for the area (such as stone walls and buildings) (Hayward 2019b; Németh et al. 2021b; Pijet-Migoń and Migoń, 2022).

Due to the frequency of quarrying in the AVF, many geological studies in the area have been assisted by the presence of the outcrops created. Having a cross-cut view of volcanic deposits allows for a 3D representation of key indicators including deposit direction, thickness, eruption mechanisms, complex eruption style transitions (Houghton et al. 1996; Foote et al. 2023), feeder dyke characterisation and even buried landforms (Foote et al. 2022). If every volcanic landform in the AVF had been untouched by quarrying and transport infrastructure (such as motorways), our understanding of volcanic processes and evolution in this field would have been greatly reduced.

This gain of geological knowledge because of human impacts on volcanic landforms is a common occurrence worldwide (Fig. 6). During quarrying operations at Hornsby in New South Wales, Australia, a cross-section was exposed (at 100 m depth) of a previously unidentified Jurassic diatreme (Semeniuk 2022). Key inner structures of volcanoes in the Sudetes, Poland, were exposed by quarrying (Migoń and Pijet-Migoń, 2016), and due to the scarce surface exposures of landforms in the area, this was the only way volcanism could have been studied in detail. Xitle Volcano in the Trans-Mexican Volcanic Belt, Mexico

City, has been exposed by quarrying and has been a key site for studying monogenetic volcanism for many years (Walker 1993; Guilbaud et al. 2021).

Areas of significant volcanic geoheritage worldwide are often linked with anthropogenically impacted volcanic landforms, which aid in geodiversity, geoeducation and geoheritage management. This has been the case in the Canary Islands (Dóniz-Páez et al. 2020), in geoparks throughout China (Fuming et al. 2016), with the volcanic landforms through Andagua in Peru (Gałaś et al. 2018), the volcanic islands of Sardinia in Italy (Gioncada et al. 2019), the spectacular oasis-volcanic landscape of Bahariya in Egypt (Khalaf et al. 2019) and throughout harrats of the Kingdom of Saudi Arabia (Moufti et al. 2015), to name a few.

Future Impacts on Volcanic Centres of the Auckland Volcanic Field

As is made apparent when looking at the history of Auckland's volcanic landforms and the numerous attempts at conserving them from the time the city was founded, the future preservation of each volcanic centre is never set in stone, and centres that may have assurances of protection today will undoubtedly be reassessed as the demands of this vital city's continued development continue (Figs. 4 and 5) (Németh et al. 2021b). The Auckland Unitary Plan, a plan for the use of 'Auckland's natural and physical resources', was developed by the Auckland Council and introduces objectives to protect 'outstanding natural features and landscapes' (Auckland Council 2016). The plan also acknowledges the importance of the AVF volcanoes to the history of the Māori people, as well as Auckland City's identity. There are several other formal policies and acts that outline the importance of preserving and protecting the volcanic features in the AVF (Department of Conservation 1977; Ministry for the Environment 1991; Tataki Auckland Unlimited 2023). The continued destruction of volcanic landforms in Auckland is likely due to a lack of education and communication of their significance, a lack of cohesive legislation specific to these landforms, and a priority balance for each landform that weighs heavily towards urban development (Gravis et al. 2020; Németh et al. 2021a). Crater Hill (Fig. 4) is one such example and is identified as being at risk of further destruction. It was a complex centre with a tuff ring with a small crater on its rim, two scoria cones, a lava shield and two significant lava caves (McGee et al. 2013; Hayward 2019b) and is a typical example of the upper range of complexity that can be expected from future eruptions at a single centre in the AVF. Crater Hill was originally the site of a Māori pā, with housing developed on the tuff ring rim (Hayward 2019b). One of the most striking features of this centre is intercalated deposits from simultaneous 'wet' phreatomagmatic and 'dry' magmatic eruptions from multiple vents (Houghton et al. 1996). This process has only been noted in several other centres in the AVF (Agustin-Flores et al. 2015; Foote et al. 2023). Crater Hill has been severely modified by quarrying in the past, with both the scoria cones and the scoria-rich tuff ring affected (Houghton et al. 1996; Hayward 2019a). The site was partially restored after quarrying ceased; however, the deposits at this important site are damaged regardless of the aesthetic outlook (Németh et al. 2021b). There are currently legal bids by the private owners of the land to develop it into a residential zone, which have so far been met with resistance in favour of retaining the land as a protected area to preserve the volcanic landscape of the AVF (Hayward 2019a). However, when taking into account the continued demands of the growth of Auckland City, and the potential gain for the private owners, this already damaged volcanic centre is unlikely to exist much longer (Mathews 2015; Mackintosh 2019; Németh et al. 2021b), and recent city plans have already classed all but the middle part as a rural production zone (Auckland Council 2016).

Other centres that will be impacted due to city plans (Auckland Council 2016) are Waitomokia (Moerangi) (Figs. 1 and 4), with all but one corner is classed as a light industry zone; Maungataketake (Elletts Mt) (Figs. 3h, 5a), classed as a future urban zone; the northern section of Kohuora (Figs. 1, 4), classed as a single housing zone; and Three Kings (Te Tātua a Riukiuta) (Figs. 1, 4, 5c), classed as an apartment zone with the exception of a section of the original landform that covers one of the three scoria cones, Te Tātua o Riu-ki-uta 'Big King', which was successfully made into a reserve in 1949 (Pishief and Adam 2015).

Future Opportunities for the Auckland Volcanic Field

Any geoconservational opportunities for the volcanic landforms of the AVF lie in communication, policy and education. As with any increase in geological knowledge, a better understanding of the current landform status of the field (Table 3, Fig. 4) will aid the public and governing bodies in making decisions regarding land management and urban development for the future of the city (Németh and Németh 2023). An increase in geological understanding of the current landforms of the field is not enough, however, to ensure these landforms are protected. This information and therefore the decisions impacting the future of this field must be made open to the public, who may be unaware they are living on top of and surrounded by the remnants of culturally significant volcanic landscapes. Increased awareness and education must be a priority going forward, as geoheritage is made stronger by public involvement (Németh et al. 2017). Geoheritage and geoeducation have proven to be successful in Auckland (e.g. Māngere Mountain Education Centre (Gravis et al. 2020)), and funded development of geoheritage and geoeducation should be made a priority if any positive change is to be made for the future in terms of volcanic landform conservation (Németh and Németh 2023).

Regarding future geological studies within the AVF, increased communication and education could prevent the loss of field research before it is too late (e.g. Green Mt (Matanginui), Albert Park, Ash Hill; Table 3), by assisting with prioritisation and communication with landholders and governing bodies.

In terms of the volcanic centres that will soon be impacted by city plans (mentioned above: Crater Hill, Maungataketake, Kohuora and Three Kings), field research should be arranged where possible. For example, Wiri Mt and Waitomokia are now classed as (heavy and light, respectively) industry zones, but sampling, measurements and studies were completed before their spectacular outcrops were further destroyed and access issues prevented further study. There are also other volcanic centres whose existence and outcrop access are soon likely to further deteriorate as urban development and pressures increase over time. These include St Heliers (Whakamuhu) (Jones 1967; Spörli et al. 2015) and McLaughlins Mt (Matukutūreia) (Searle 1961) and should be prioritised if at all possible for any research before it is too late.

Ideally, a geological assessment should be included in the planning policy requirements for any land development that coincides with a volcanic landform, along with archaeological and geotechnical assessments. This could be for a certain period of time before works commenced and at certain points throughout the development process (The benefits and balance of anthropogenic modification of volcanic landforms). Access would allow scientists to collect data and samples and make effective 3D observations of the structure to create virtual reconstructions.

Conclusions

Due to the rapid development of Auckland City over the last 180 years, anthropogenic activity has caused severe archaeological, cultural, geological, and educational losses. Of the 53 volcanic centres in the AVF, 17% are classified as intact, 28% are partially intact, 30% are partially destroyed, and 25% are destroyed (including 13% that have no trace left). Based on surface area, approximately 60% of deposits remain in the AVF, and the most common causes for impacts are public land use, quarrying and urban development. Within around 180 years of human activity since European colonisation, we estimate that 40% of the original surface extent has been lost. Compiling a full account of all volcanic landforms in a volcanic field allows for the understanding of the field as a whole to ensure that preparations for future eruptions are not only based on centres with ease of access or exposure. We conclude that several volcanic centres are currently at risk of further destruction in the near future: Crater Hill, Waitomokia, Maugataketake, Kohuroa, Three Kings, St Heliers and McLaughlins Mt, and should be prioritised for any possible research before it is too late.

Funded geoheritage and geoeducation development must be a priority going forward to assist the education of the public, who should be aware of the decisions affecting the future of this field and the extent of its cultural and historical significance. We propose that a geological assessment should be a requirement before and, if possible, during any land development on or near a volcanic landform. Many geological studies globally have been assisted by the presence of outcrops created by quarrying, mining, transport infrastructure and other modifications of volcanic landforms. If access was granted in every situation where these landforms were to be impacted, it would result in a significant increase in geological knowledge and improve the geoheritage value and management of geoeducation in Auckland. The history of this young monogenetic volcanic field can help us to understand what to expect in the future, both in terms of volcanic activity and management of volcanic landforms. Allowing access (where safe and practicable) to scientists through the course of development in these areas would, in turn, aid the public and governing bodies in decision-making for the future of the city and its volcanic landforms in terms of increased knowledge of volcanic mechanisms of the AVF and awareness of the potential associated hazards.

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Data Availability The data that support the findings of this study are available from the corresponding author, [AF], upon reasonable request.

Declarations

The concept for the paper was developed by April Foote. Material preparation, data analysis and interpretations were completed by April Foote under the supervision of Heather Handley and Károly Németh. The manuscript was written by April Foote with supervision and edits

provided by Heather Handley and Károly Németh. All authors read and approved the final manuscript.

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