Geochemical Evolution, Vent Structures, and Erosion History of Small-volume Volcanoes in the Miocene Intracontinental Waipiata Volcanic Field, New Zealand

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ABSTRACT. The Miocene Waipiata Volcanic Field (WVF), New Zealand, is an eroded phreatomagmatic intracontinental volcanic field that comprises the remnants of more than 55 volcanoes preserved in an area of some 5000 km^2. Three types of deposits are present: (1) vent-filling deposits comprising predominantly lava represent type 1 vents, and are inferred to be the remnants of scoria cones; they commonly have thin basal phreatomagmatic pyroclastic deposits. (2) Vents represented by predominantly pyroclastic infill are classified as type 2 vents and are inferred to have been the substructures of phreatomagmatic tuff ring/maar volcanoes. (3) Type 3 vent complexes are remnants of groups of closely spaced or overlapping vents, with voluminous lava flows preserved; they are inferred to be the remnants of compound maars and tuff rings, with magmatic explosive and effusive products. Pyroclastic rocks of most of the vents record initial groundwater-fuelled phreatomagmatic explosive activity followed by Strombolian-style eruptions. Vent clusters and alignments are largely controlled by the basement's structural pattern. A systematic compositional sequence exists at each volcano, with initial phreatomagmatic eruptive products being differentiated tephrite and phonotephrite in composition, whereas subsequent lavas are primarily basanite. Erosion rates for the WVF are calculated to be 5 to 50 m/M.y.

KEY WORDS: phreatomagmatic, scoria, tuff ring, basanite, erosion, New Zealand, Miocene, basalt, tephrite.

Introduction

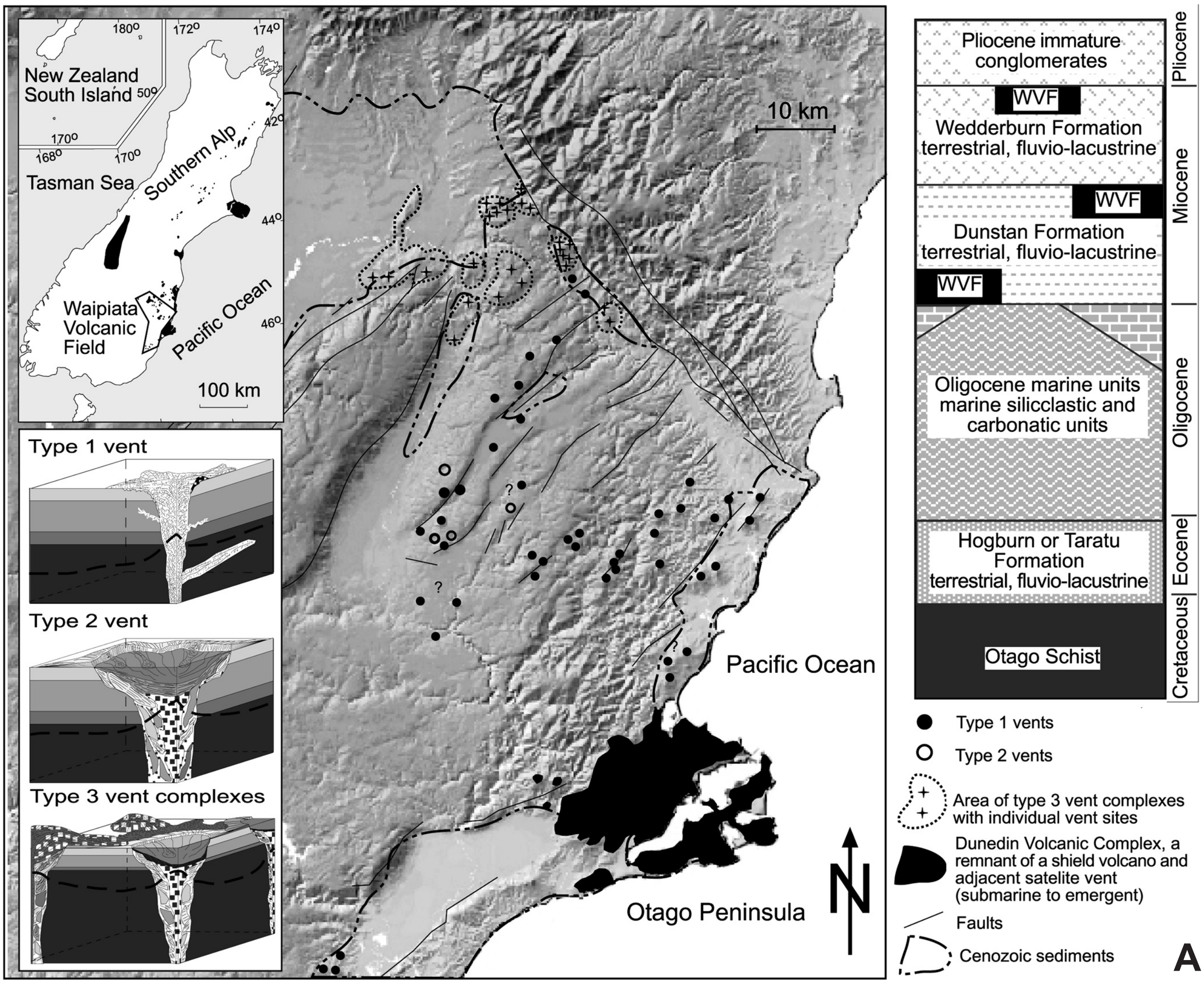
Low magma supply rates over time can result in the formation of volcanic fields rather than a single long-lived volcanic edifice. Fundamental physical characteristics of volcanic fields that are the focus of ongoing research include 1) the number, type and eruption history of individual volcanoes; 2) the timing and recurrence rates of the volcanic eruptions in a given volcanic field; 3) the distribution of volcanoes and volcanic complexes; and 4) the relationship of volcanic fields and the volcanoes within them to tectonic features such as basins, faults, and rift zones. Analysing these features at WVF provides information on Miocene magma generation and ascent beneath southern New Zealand (Fig. 1/A) (Johnson 1989). The earliest lava flows of the WVF were erupted at 21 Ma during a period of mild crustal extension related to the opening of the Tasman Sea and the separation of New Zealand from Gondwana (Adams 1981). All volcanic activity in the Otago area ceased at ~10 Ma, perhaps as a result of the change to compressional tectonics (Coombs et al. 1986). Volcanoes are considered to have developed subaerially inland Otago (Coombs et al. 1986), however, close to the present Pacific Ocean shoreline a line of evidence supports subaqueous to emergent volcanism during early stage of eruptive activity in the Miocene (Cas and Landis 1987, Cas et al. 1989, Martin 2000, 2001). In this paper a descriptive summary is given of the basic characteristics of the WVF (Németh 2001a, b, Németh et al. 2002).

Vent types

In the WVF, three type of volcanic remnants were identified in the present study according to their volcanic facies associations, ratio of preserved pyroclastic and lava units, and the size and number of identified eruptive centers (Fig. 1/A).

Type 1 vents are remnants of single-vent monogenetic volcanoes and consist predominantly of feeder dykes, lava lakes and/or lava flows (Fig. 1/A). *Type 1 vents* are concentrated on elevated parts of fold and/or fault blocks. Two major types of *type 1 vents* can be distinguished; 1) vent remnants filled completely with lava, 2) vent remnants filled with minor pyroclastic deposits which are cross-cut by feeder dykes, covered by solidified lava lakes, and/or coincide with the source sites of lava fields. Thin scoriaceous pyroclastic deposits are often accompanied by thick (>>10 m) lava piles, and it is inferred that these eruptive centers had an explosive eruptive history initially, and very likely represent deeply eroded remnants of former Strombolian scoria cones.

Type 2 vents are remnants of individual volcanoes that consist predominantly of pyroclastic rocks and/or small-volume lava flows (Fig. 1/A). *Type 2 vents* are located in the same areas as *type 1 vents*. Typical pyroclastic facies are non-volcanic-lithic-rich, grain- or matrix-supported, massive tuff breccias and lapilli tuffs that consist predominantly of accidental lithic blocks and lapilli. These facies are often interbedded with unsorted, matrix-supported, diffusely stratified tuff breccia and lapilli tuff beds. These rocks are volumetrically dominant in these vent remnants, and are interpreted to be vent-filling pyroclastic units formed by phreatomagmatic explosive eruptions. Thinly bedded, locally scour-fill cross stratified, accidental lithic-rich lapilli tuff and tuff beds form decimetre-scale blocks with uniform bedding dips toward the centre of the vent. The blocks are enclosed within other pyroclastic rocks, and indicate syn-eruptive collapse and/or subsidence (Lorenz 1986). The sedimentary textures of the facies suggest deposition from base surges. Most of the rocks of the facies contain fresh sideromelane and just a small proportion of tachylite, the proportions indicating phreatomagmatic fragmentation of the magma (White 1991). The vent remnants are topped with pyroclastic units rich in lava spatter inferred to indicate exhaustion of the water supply to the explosion sites and hence cessation of phreatomagmatic



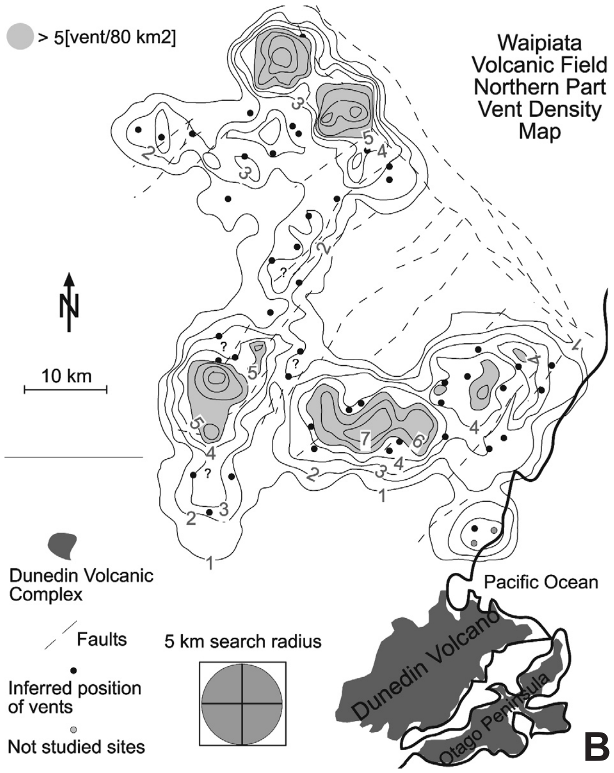


Fig. 1. A) DTM overview map of the Waipiata Volcanic Field, New Zealand, showing the distribution of different types of vents and vent complexes. Note the 3D sketches of the different type of vents and vent complexes with a dashed line marking the present stage of erosion. A separate diagram demonstrates the stratigraphic position of the volcanic rocks of the WVF. B) A vent-density contour map based on rectangular grids with spacing of 2 km and a search radius of 5 km.

fragmentation. A sudden increase in mantle-derived xenoliths in the capping units suggests relatively rapid upward movement of the magma in later stages of the eruptions (White 1991). The majority of the accidental lithic clasts are derived from the basement Otago schist, but clasts derived from Tertiary units are also present, suggesting an extensive Cenozoic sedimentary cover during volcanism (Németh 2001a, b).

Type 3 vent complexes are remnants of complex terrestrial volcanoes that consisted of overlapping maars, tuff rings and scoria cones accompanied by extensive lava lakes and/or valley-filling lava flows (Fig. 1/A). These volcanic centres often had simultaneous eruptions from more than one of their vents, producing intercalated beds of explosive and effusive products. Hence, a *type 3 vent complex* is a group of coalesced *type 2 +/−type 1 vents*. *Type 3 vent complexes* are preserved to high stratigraphic levels, and locally include deposits formed on the paleo-ground surface adjacent to the volcano; they thus represent the best preserved, least eroded volcanic remnants in the field, in which shallow-level and surficial complexities can still be studied. The main criteria used to recognize *type 3 vent complexes* are: 1) close relationships among neighbouring (hundreds of metres) vents, 2) presence of lava flow units sourced from more than one site. *Type 3 vent complexes* tend to be located on the northern side of the WVF. The lower pyroclastic infillings of vents in *type 3 complexes* are very similar to deposits described for *type 2 vents*, though a wider variety of facies was identified. Some of these (for instance tuff units characterized by dune-bedding, and/or accretionary lapilli, and/or vesiculated tuff) are typical of medial to distal deposits

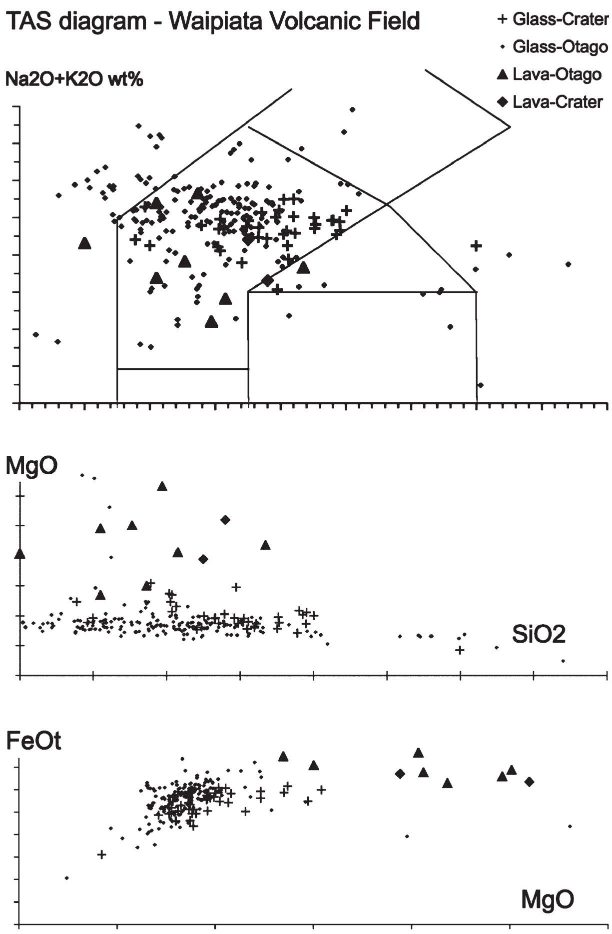


Fig. 2. Major element diagrams of volcanic rocks from the WVF. "Glass-Crater" and "Lava-Crater" indicate data derived from a single locality called "The Crater" (type 2 vent). "Glass-Otago" and "Lava-Otago" indicates data derived from volcanic field-wide locations. Note the separation of volcanic glass and lava rock data fields, especially on the SiO_2 versus MgO, and MgO versus FeO_t diagrams. Volcanic glass data were derived from electron microprobe analyses of glass shards and compared with XRF whole-rock data from lava rocks.

of phreatomagmatic tuff rings. Different types of scoriaceous, structureless to weakly bedded, tuff breccia, lapilli tuff, and tuff beds are preserved in thick piles (>10 m) as capping units, indicating that "dry" magmatic explosive phases preceded or accompanied the effusion of lava. Clastogenic lava flows are commonly preserved in dish-like structures. Spatter-rich pyroclastic beds are intercalated with thinly bedded sideromelane-rich pyroclastic beds, suggesting simultaneous deposition from magmatic and phreatomagmatic activity at closely spaced vents (Houghton and Schmincke 1995).

Vent distribution, estimation of magma output and erosion rates

Identified vent alignments mimic the major structures of the Otago area, which are predominantly NE–SW and NW–SE-oriented faults and NW–SE shear zones (Fig. 1/B). Vents also tend to form clusters, as shown by contouring vent density using rectangular grids with a spacing of 2 km and a search radius of 5 km (Fig. 1/B). This vent-density map is somewhat generalized due to uncertainties in the reconstruction of the precise number of vents and their positions, especially of the *type 3 vent complexes*. There is a significant vent cluster at the northern margin of the WVF, and vent clustering is also apparent in the central zone of WVF. Vent alignments in the WVF are less developed than in well-documented young volcanic fields such as Yucca Mountain, Nevada (Connor et al. 2000). The total magma erupted in the WVF was calculated by estimating the total juvenile fragment volume for each volcano on the basis of the estimated volume of its lava and pyroclastic rocks. Based on different estimations (Carn 2000), the juvenile material produced by all volcanoes of the WVF may range from 9 to 40 km^3 (Németh 2001a). Erosion rates were also calculated, with the exhumation level for each vent estimated on the basis of inferred depths of formation for mapped volcanic lithofacies associations. Based on a systematic study of each vent, a range of 5 to 50 m/My of erosion has been estimated in the area of the WVF (Németh 2001a, b).

Geochemistry

Electron microprobe studies of volcanic glass from initial phreatomagmatic pyroclastic deposits of many vents and vent complexes of the WVF clearly demonstrate that the pyroclastic products are significantly more evolved than any of the associated, subsequent lava flows or dykes (Németh et al. 2002) (Fig. 2). Among lavas, basanites predominate, containing many lherzolite and other mantle-derived xenoliths; olivine nephelinite, mugearite and nepheline hawaiite are also present (e.g., Coombs et al. 1986). In general, rock types more evolved than nepheline hawaiite appear to be rare, although nepheline mugearite and lherzolite-bearing "mafic phonolite" (phonotephrite) are also known (Price and Coombs 1975). In contrast to the unevolved compositions of lava flows, volcanic glass shards from initial phreatomagmatic units were determined to be tephrite or phonotephrite. Discrimination diagrams for individual vents show well separated fields for volcanic glass and lava; the rocks are interpreted to be related to each other via crystal fractionation, predominantly controlled by settling of olivine and clinopyroxenes (Fig. 2). Because the early-tephrite, late-basanite pattern is present at many individual volcanoes, magma evolution must have taken place in some sort of magmatic plumbing system for each of these individual monogenetic volcanoes (Németh et al. 2002). Overall, it can be concluded that the recorded geochemical variation characterizes volcanoes throughout the Waipiata Volcanic Field, regardless of their position within the field or degree of complexity.

Conclusion

It can be concluded that the WVF is an eroded phreatomagmatic volcanic field, with remnants of scoria cones, tuff rings, maars, fissure vents and lava flows of various volumes. Three different types of volcanoes (*type 1, 2 and 3*) are recognized based on their complexity and on the preserved ratio between explosive and effusive magmatic products. Pyroclastic rocks of most of the Waipiata volcanoes record initial phreatomagmatic explosive activity followed by Strombolian-style eruptions. High percentages of accidental lithic fragments together with the relict sideromelane strongly suggest that the former result from subsurface phreatomagmatic explosions fuelled by groundwater. The preserved lava flows provide evidence for significant ponding and topographic control. Calculated erosion rates for the WVF are 5 to 50 m/My. A study of the accidental lithic clast population in pyroclastic rocks from deeply eroded volcanic pipes in this field indicates that the Cenozoic sedimentary cover was widespread and still complete at the time of volcanism, although no Cenozoic sedimentary rock units remain over much of the field today. Distribution of vents in the WVF indicates structural control. The total volume of magma erupted in the WVF is estimated to have been between 9 and 40 km^3 DRE. A systematic compositional sequence exists at each volcano, with initial phreatomagmatic eruptive products being variably differentiated tephrite and phonotephrite, whereas subsequent lavas are of more primitive compositions, primarily basanite.

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