



Transition from effusive to explosive phases in andesite eruptions — A case-study from the AD1655 eruption of Mt. Taranaki, New Zealand

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Abstract

The extrusion of viscous andesite lava forming domes can terminate in explosive activity. To understand the driving forces behind this behaviour, a study of an AD1655 eruption episode at Mt. Taranaki was carried out. We propose that simple changes in magmatic conditions of a single hydrous melt during ascent caused sudden changes in explosivity and gave rise to pumice with highly variable vesicularities and colour. Fractionation of hornblende+plagioclase+clinopyroxene+Fe–Ti oxide at the onset of magma ascent, and step-wise crystallisation of plagioclase±clinopyroxene in different parts of a single melt within the conduit was controlled by rates of initial rise, capping by an impermeable lava dome, and differential rates of vesiculation and volatile exsolution. This resulted in a vertical stratification in the conduit, comprising a viscous, hypocrySTALLINE lava cap, that overlay alternating zones of grey, brown and grey magma-foams. Horizontal gradients in geochemistry in the conduit are also indicated by different clast textures. The eruption consisted of an initial extrusive phase followed by three pulses of sub-plinian activity. Each phase or pulse, corresponded to individual layers within the conduit. Ejecta included block-and-ash flow deposits, three pyroclastic pumice-flow deposits of alternating grey, brown and grey pumice, as well as fallout deposits dominated by grey pumice. The brown magma foam contained more microlites, had a more-evolved matrix glass, and a higher temperature than the grey magma foams above and below. Its eruption destabilised the sub-plinian eruption column because it was more degassed. It fragmented less efficiently than the grey magma foams due to its lower viscosity, preventing pressure build-up in bubbles. Incomplete mixing at interfaces between brown and grey magma phases gave rise to banded pumices.

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1. Introduction

In many historic eruptions of andesitic and dacitic volcanoes an initially effusive lava emission phase was abruptly terminated by an explosive phase, often with highly hazardous consequences. Such shifts in eruptive

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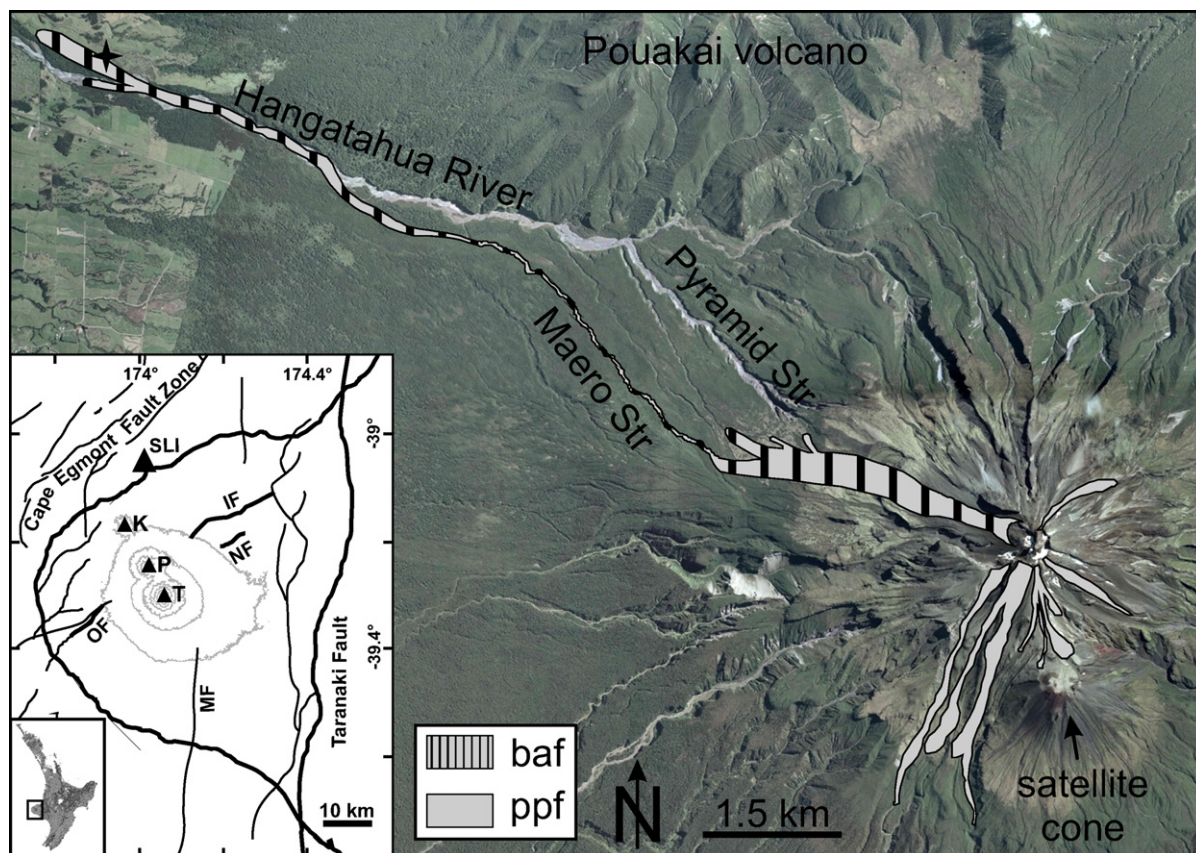


Fig. 1. Mount Taranaki (lower right) has produced mainly lava dome eruptions in the past 800 years with block-and-ash flow (BAF) deposits making up the fan between the Maero and Pyramid Stream and in the Hangatahuta River (baf – block-and-ash flow, ppf – pumice pyroclastic flow). Star (top left) indicates the most distal outcrop discussed in text. To the NNW of Mt. Taranaki are the south flanks of Pouakai volcano. The inset shows the Taranaki peninsula with the Taranaki Volcanic Lineament (SLI – Sugar Loaf Islands, K – Kaitake, P – Pouakai, T – Taranaki). Major onshore and offshore faults: IF – Inglewood fault, MF – Manaia fault, NF – Norfolk fault, OF – Oanui fault. Contours are 300 m. Modified after [Sherburn and White \(2005\)](#).

style have been related to many complex sub-surface processes such as, decompression-induced crystallisation ([Hammer et al., 2000](#)), increase in magma viscosity by increased crystallinity (predominantly microlites) and vesicularity, water-loss, temperature gradients ([Stevenson et al., 1996](#); [Manga et al., 1998](#)), as well as conduit shear processes within vesicular magmas ([Stasiuk et al., 1996](#); [Massol et al., 2001](#); [Rust et al., 2003](#); [Tuffen et al., 2003](#)), and viscous dissipation at conduit walls ([Polacci et al., 2001, 2005](#); [Rosi et al., 2004](#)). These sudden transitions in andesite eruptions are accompanied by the presence of ejecta with a wide range in vesicularity and permeability ([Klug and Cashman, 1994](#); [Gardner et al., 1998](#); [Rosi et al., 2004](#)). This includes strongly banded pumice clasts, with grey to brown bands, interpreted as mingled compositions, or products of shear processes within conduits.

Emplacement and destruction of lava domes is very common at subduction-related andesitic and dacitic

volcanoes. Partial dome collapse is commonly caused by [1] over-steepening ([Sparks et al., 2000](#)), [2] gas over-pressurisation ([Elsworth and Voight, 2001](#)), and [3] rainfall ([Matthews et al., 2002](#)). However, dome collapse and partial unroofing of the vent does not always trigger a shift in eruptive style. This was true for most of the eruptions over the last c. 1000 years at Mt. Taranaki, where several lava domes were emplaced, forming block-and-ash flows (BAFs) through dome collapse. However, one of these dome-effusion periods was terminated by an explosive sub-plinian eruption ([Druce, 1966](#)). These sub-plinian deposits, and all other unknown from sub-plinian events at this volcano, contain notably high contents (10–30%) of monolithologic dense lithics, which appear to be juvenile.

Understanding the causes of such transitions in eruptive style is critical for constructing hazard models for andesitic volcanoes and hence developing realistic eruption scenarios and volcanic emergency plans. Here we

propose an alternative model to explain some types of transitions from effusive to explosive activity, primarily through changes of magmatic conditions during ascent. This model also helps explain the production of a variety of pumice textures as well as the origin of some types of banded pumice. We base this study on the AD1655 Burrell Lapilli eruption of Mt. Taranaki, an episode in which a small-scale dome effusion event was suddenly terminated by an explosive sub-plinian eruption that covered several 100s of km² of New Zealand's central North Island in fall deposits.

2. Geological setting

Mount Taranaki/Egmont volcano is located in the west of the North Island of New Zealand and is the youngest edifice in a 0.75–0.13 Ma SE-trending volcanic alignment [Fig. 1; (Neall et al., 1986; Stewart et al., 1996)]. The volcanic history of Mt. Taranaki began c. 130,000 years ago and has been characterised by several cone-building and collapse episodes (Alloway et al., 1995). The current edifice was constructed over the last c. 10 ka (Neall et al., 1986) with activity characterised by 0.1–2 km³ sub-plinian eruptions on c. 330 yr intervals, interspersed with more frequent effusive dome- and BAF-forming events and lava flows (Alloway et al., 1995).

The latest eruptive sequence of Mt. Taranaki comprises at least nine separate episodes, collectively mapped as the Maero formation (Druce, 1966; Neall et al., 1986). Each episode was characterised by effusion of highly viscous andesitic magma to form lava domes within the summit crater and through a breach in the crater onto the uppermost NW flank. Collapses and small explosions from these lava domes generated BAFs and surges, with the largest BAFs travelling up to 13.5 km down the Hangatahua River.

The Burrell Lapilli eruption episode took place in AD1655, according to ¹⁴C dating of charcoal in a Maori oven that was buried by tephra fall (Wellman, 1962) and dendrochronology dating of trees damaged by the fall (Druce, 1966). In earlier descriptions of this eruption, pumice fallout deposits were mapped to the ESE (Druce, 1966). Three lobes, directed to the NE, SE, and ESE, were recognised based on grain size analyses (Topping, 1972). The pumice flows and BAFs associated with the Burrell Lapilli are newly described in this study.

3. Methodology

For petrographic, mineral chemistry, and textural studies, pumice samples were impregnated with the

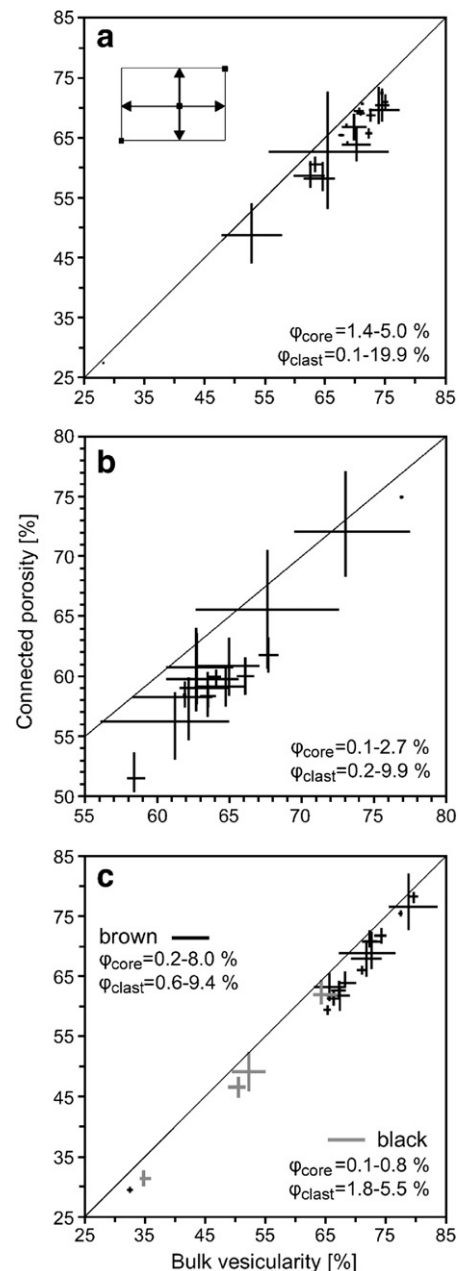


Fig. 2. Variations in bulk vesicularity and connected porosity of single clasts for grey pumice (a), banded pumice (b), and black and brown pumice (c). Crosses represent the range in vesicularity per clast using minimum, mean and maximum values (see inset in a). Variations in bulk vesicularity refer to single cores cut in two (ϕ_{core}) and overall clast variations with multiple cores (ϕ_{clast}). Note different scale in b). See text for details.

low viscosity polymer, methyl methacrylate and polymerised by Cobalt-60 gamma radiation. Glass and mineral microprobe analyses were carried out on polished thin sections of impregnated pumices and dense

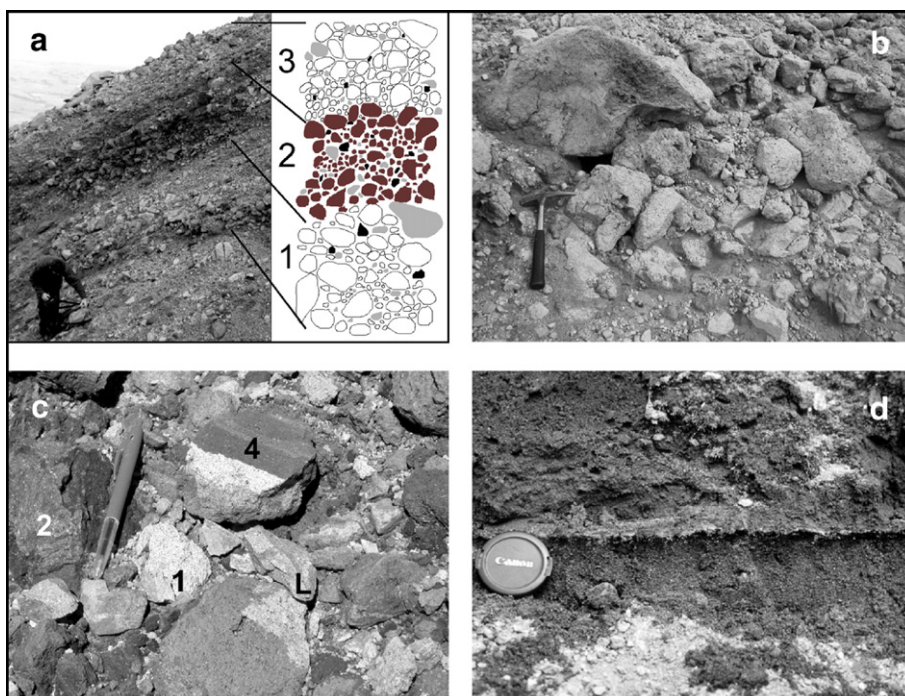


Fig. 3. Field photographs of a) succession of three pumice pyroclastic flow deposits on upper south flanks; sketch shows general assembly of pumice types and grey dense lithics, b) grey pumice clasts of unit 3, c) eroded surface into unit 2 showing scattered grey pumice [1] from airfall, brown pumice [2], banded pale grey to dark brown pumice [4], and dense fractured andesite clasts [L]; d) lower contact of a distal BAF deposit, c. 13.5 km from source (star in Fig. 1). See text for field description.

clasts using an energy dispersive spectrometer (JEOL JXA-840) with an accelerating voltage of 15 kV, a beam current of 600 pA and 100 s live time. Glass analyses were performed with beam defocused to 20 μm diameter.

For bulk rock geochemistry, pumice and lithic clast specimens were crushed and ground using a tungsten carbide mill. Major and trace elements were measured on prepared glass discs and powder pellets, respectively, using X-ray fluorescence spectrometry (Siemens SRS 3000) and calibrated to a suite of 36 international standards at the University of Auckland.

Porosity and permeability measurements were made using cores (approx. 2.54 cm diameter and height) of clasts that were drilled in two or three mutually perpendicular orientations (depending on sample size). From the known volume (V_{cylinder}) and mass of the cores, the bulk density (ρ_{bulk}) was determined. A He-pycnometer was used to measure the helium accessible volume (V_{He}) of the sample, resulting in an estimate of skeletal density (ρ_{skeletal}). However, even rocks of dense appearance commonly possess isolated cavities and cracks, and vesiculated rocks usually have isolated

pores (V_{iso}) in addition to a connected pore network, and therefore ρ_{skeletal} is always lower than ρ_{solid} . In order to determine ρ_{solid} , representative samples of grey ($n=6$), brown ($n=4$) and black ($n=2$) clasts were powdered and their volume determined by He-pycnometry. The isolated pore volume, V_{iso} , can then be calculated and the bulk vesicularity determined by $\phi = (V_{\text{He}} + V_{\text{iso}}) / V_{\text{cylinder}}$.

Long drilled cores cut into two were analysed for reproducibility and homogeneity in a specific orientation. Pumice samples appear homogeneous, with differences in ϕ of 0.1 to 8.0% over the range of $\phi = 34.2\text{--}83.6\%$. However, single larger pumice clasts with up to seven drilled cores per sample in multiple orientations showed differences in ϕ of up to 19.9% (Fig. 2).

The gas permeability of pumice cores was measured in a capillary flow porometer with air as the working gas using calculations after Rust and Cashman (2004) and Wright et al. (2007).

Scanning electron microscopy images of carbon-coated samples were collected at Massey University and the University of Oregon using accelerating voltages of 20 kV and 10 kV, respectively.

4. Results

4.1. Field observations

4.1.1. Fall deposits

The pumice fall deposits are well exposed on the steeper parts of the mountain near walking tracks, whereas outside the National Park boundary on flatter terrain, exposures are rare or the unit is disturbed by soil tillage.

The proximal to medial deposits (within 10 km) are characterised by pale grey and pale brown (weathered) subrounded to subangular pumice and darker grey angular to subangular lithics (commonly dense grey andesite). Overall, between 10 and 15% lithic clasts are scattered throughout the fall unit, with fewer, larger clasts near the base and finer, more-abundant clasts near the top. Reverse grading of the whole unit is also oc-

asionally observed. Rare accessory clasts also occur, including iron-stained, weathered, and hydrothermally altered andesites. While lithic clast abundances vary greatly between exposures, there is an overall decrease with distance from dispersal axis and source.

4.1.2. Pumice pyroclastic flow deposits

Pumice pyroclastic flows associated with the Burrell Lapilli eruption travelled predominantly down the southern flanks (Fig. 3a), but were also deposited on the upper southeastern and northeastern sectors (Fig. 4b). Three flow units are preserved on the southern flank.

The basal unit (1) is up to 1.5 m thick and comprises pale grey pumice of up to 70 cm in diameter in a medium- to coarse-ash matrix. The subrounded to rounded pumice block and lapilli are uniform in colour or contain patches or bands of darker grey. They also commonly contain inclusions of grey, angular, dense

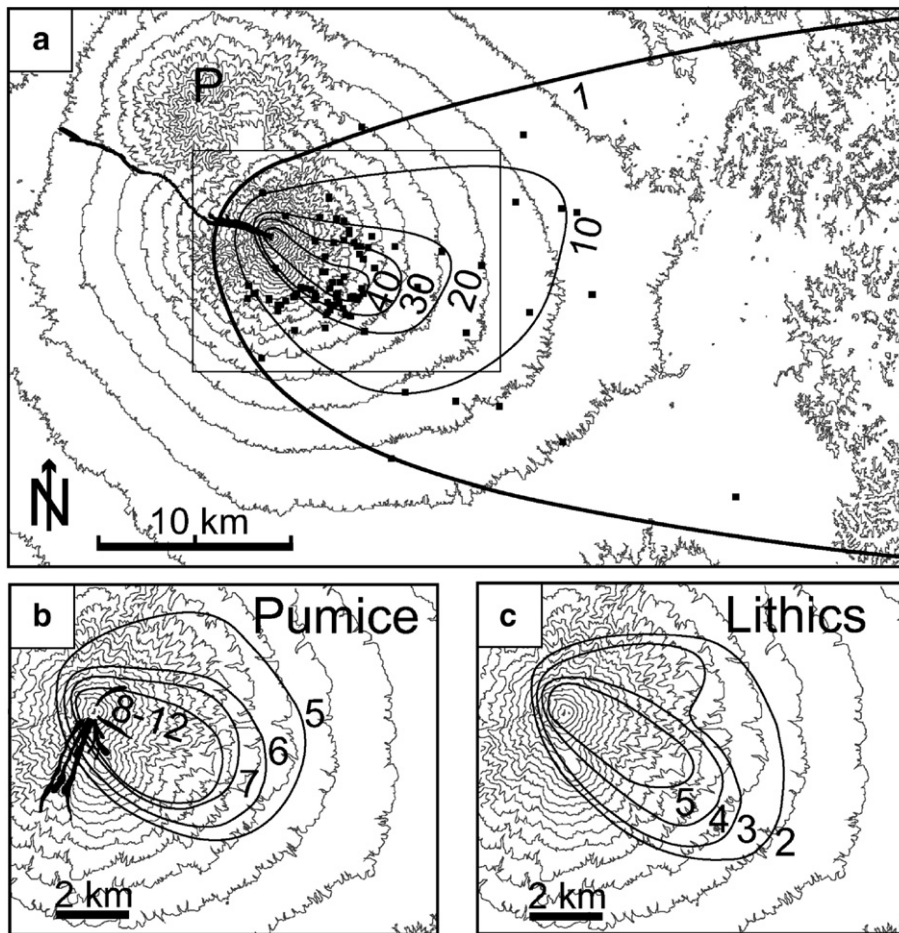


Fig. 4. Distribution of Burrell Lapilli deposits: a) isopachs in cm including the BAF deposit (black) to the NW for reference, black squares represent mapping locations for fall deposits only, P – Pouakai volcano, contours 100 m; b) isopleths for pumice clasts and pumice pyroclastic flow deposits on the upper flanks (black), see inset in a) for location; c) isopleths for lithic clasts, same outline as in b). Numbers in b) and c) are clast diameters in cm.

lithic lapilli. Larger pumice blocks are concentrated at or near the upper surface of the unit. Lithic clasts up to 50 cm in diameter are present throughout the unit, most commonly as grey and dark grey dense andesites. The dense grey andesites are often bread-crust, jigsaw-jointed or fractured (Fig. 3c). Occasionally, their concentration increases upwards through the unit. Rare hydrothermally altered and other dense andesite lithologies are present.

The middle unit (2) is up to 2 m thick and comprises subangular to rounded, brown to dark-brown pumice up to 45 cm in diameter. Common lithics of grey and dark-grey dense andesites are concentrated toward the base of the unit (c.10% by volume), while glassy black, vesicular to semi-vesicular clasts are evenly distributed throughout it (c.5% by volume). Grey, dense, bread-crust and jointed blocks are rare. Accidental lithics comprise hydrothermally altered or weathered andesite and iron-stained clasts. The lower and upper contacts are gradational and marked by concentrations of banded pumice (Fig. 3c). Unit 2 is in part consolidated and is the only unit to show partial welding textures. In places, it is also strongly oxidised. The partially welded parts of the unit form small ridges on the volcano flanks above 1900 m, capping and preserving the friable unit 1. Deposits of unit 2 are more restricted than the others and are found only within 1.2 km of the crater rim.

The uppermost unit (3) is >1 m thick, but often partly eroded. Near the summit, it contains pumice clasts up to 70 cm in diameter, which are usually concentrated on the surface, along with dense grey bombs and blocks (Fig. 3b).

Units 1 and 3 are generally similar in clast composition and texture and occur separately or together up to 3.3 km from the crater rim.

4.1.3. Block-and-ash flow deposits

A fan of Maero formation BAF and related deposits occur on the NW sector of Mt. Taranaki. Since the last events in AD1755 and c.1860, box-canyons of up to 80 m have been eroded into the unconsolidated volcanoclastics.

The primary BAF deposits often contain charcoaled twigs, branches or logs, hence the stratigraphic sequence is well constrained by radiocarbon dates. One sub-set of the deposits can be related to the Burrell Lapilli event. The most distal exposed Burrell related BAF deposit is found 13.5 km from source beside Hangatahua River (Fig. 4a). It consists of a brownish-grey, 1.75 m thick, medium ash matrix-supported diamicton with 45% lapilli to fine block-sized clasts of dense grey andesite, with rare weathered and hydrothermally altered andesite

and occasional grey pumice. Pumice is not strongly represented in the -1.5 to -1ϕ fractions, comprising c. 6% by volume.

The deposit drapes a 1 cm charred humus layer containing charcoal twigs (Fig. 3d), and charcoal logs are imbricated throughout the unit. The natural remnant magnetism of 10 clasts measured with a portable flux-gate magnetometer shows coherent alignment in six directions for 8 clasts, indicating a deposition temperature above or near the Curie point. This deposit can be correlated upstream through a succession of units in the Maero Stream. Characteristics of these nearer-source deposits are similar, with only very rare pumice clasts present.

4.2. Volume estimates

The minimum fall volume was estimated as $3.2 \times 10^8 \text{ m}^3$, by applying $V = 13.08 T_0 b t^2$ (based on Cole and Stephenson, 1972) to the mapped isopachs (Table 1) where T_0 is the extrapolated maximum thickness and bt the distance over which the thickness of the deposit halves (see also Pyle, 1989).

ArcGIS was used to calculate the minimum bulk volume of pumice flow and BAF deposits, at $1.3 \times 10^6 \text{ m}^3$ and $2.5 \times 10^6 \text{ m}^3$, respectively (Table 1). On a volumetric basis, the Burrell Lapilli eruption is classified as a VEI 4 sub-plinian eruption (c.f. Newhall and Self, 1982). Applying the model of Carey and

Table 1
Minimum volume and mass calculations of erupted tephra

	Bulk volume [m ³]	Mass [kg]	DRE volume [m ³]	Lithic content [%]	DRE pumice [m ³]	DRE lithics [m ³]
Fall	3.2E + 08	2.8E + 11	1.1E + 08	14 wt.% ^a	9.6E + 07	1.6E + 07
BAF	2.5E + 06	5.2E + 09	2.1E + 06	90 vol.% ^b	2.1E + 05	1.9E + 06
Pumice	1.3E + 06	1.7E + 09	7.1E + 05	10 vol.% ^b	6.4E + 05	7.1E + 04
PF ^c						
Total	3.3E + 08	2.8E + 11	1.2E + 08		9.7E + 07	1.8E + 07
Bulk density Fall				850		[kg m ⁻³]
Bulk density BAF				2100		[kg m ⁻³]
Bulk density pumice PF ^c				1300		[kg m ⁻³]
Bulk density pumice				900		[kg m ⁻³]
Bulk density lithics				2300		[kg m ⁻³]
Magma density				2450		[kg m ⁻³]

^a Estimates based on lithic-pumice counts in wt.% from grain size fractions -4 to 0ϕ .

^b Overall deposit estimate.

^c Pumice pyroclastic flow.

Sparks (1986) the eruption column is estimated to have been up to 14 km.

Lithic contents of the fall deposit were counted in the -4 to 0ϕ grain size fractions of 5 samples at varying distances from source. The volumetric lithic content shows an exponential decrease with distance, with maximum lithic contents between 28 and 39 wt.% (approx. 13–20 vol.%) at distances of 2.5 to 2.9 km. By 9.8 km, it had dropped to 19 wt.% (approx. 8 vol.%). These estimates include a combination of juvenile and accidental clasts, since distinguishing them was difficult optically. Using an overall lithic population of 14%, a lithic volume of $1.7 \times 10^7 \text{ m}^3$ (Table 1) is contained in the fall, corresponding closely to the theoretical maximum volume that a dome could occupy in the present crater dimensions (c. $2 \times 10^7 \text{ m}^3$). Given that some of the dome is probably also contained in the BAF, the lithics in the fall probably also derive from the upper conduit.

4.3. Clast types and textures

The different clast types of the Burrell Lapilli eruption episode provide insights into the eruptive processes and the mechanisms of pumice formation. For simplicity, all clasts that developed individual vesicles

within their groundmass are termed pumice, regardless of whether an interconnected bubble network is developed or not. Those clasts that only display cracks and cavities are collectively termed lithics. For quantitative analyses, pumice samples were categorized into four groups based on their colour; [1] uniform pale grey, [2] brown, [3] black, and [4] banded to transitional pumice clasts ranging from pale grey to dark brown.

Dense grey clasts present in BAF and fall deposits have a hypocrySTALLINE groundmass with abundant plagioclase microlites and Fe–Ti oxides, and very rare minor cracks (Fig. 5a). Pumice clasts [1], [2], and [4] have a well-developed, interconnected vesicle network with areas of coalesced vesicles that are often a few centimetres long (Fig. 5d). Black pumice clasts [3] show two vesicularity populations; semi-vesicular, with minor isolated vesicles in a glassy, microlite containing matrix (Fig. 5b), and vesicular, with more abundant isolated vesicles that display partial coalescence (Fig. 5c).

Type 1 pumice has a broad range in vesicle-size distributions (Fig. 6a) with large single and coalesced bubbles (Fig. 6c). Larger bubbles are elongated but show no deformation, and only few microlites occur in the glass. By contrast, brown pumice [2] has a broad but bimodal range in vesicle sizes (Fig. 6b). Large, coalesced

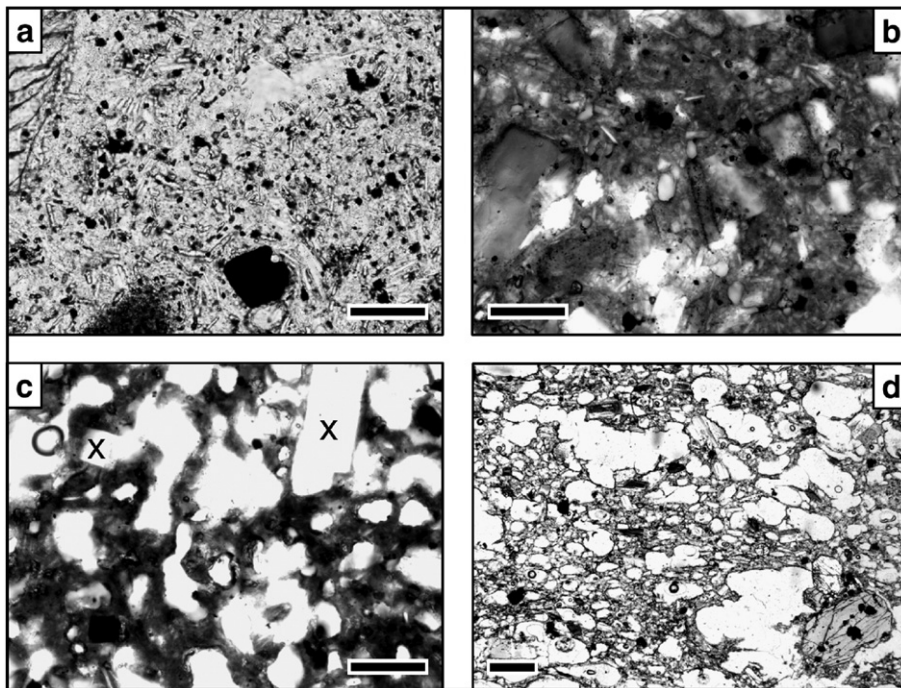


Fig. 5. Thin section photographs illustrating basic vesicularity differences of juvenile clasts. a) Dense grey lithic, b) semi-vesicular black pumice, c) vesicular black pumice with isolated and coalesced vesicles, crosses mark plagioclase crystals; d) grey pumice with isolated large single vesicles as well as larger coalesced vesicle. Scale bar is 100 μm in a–c and 500 μm in d. See text for details.

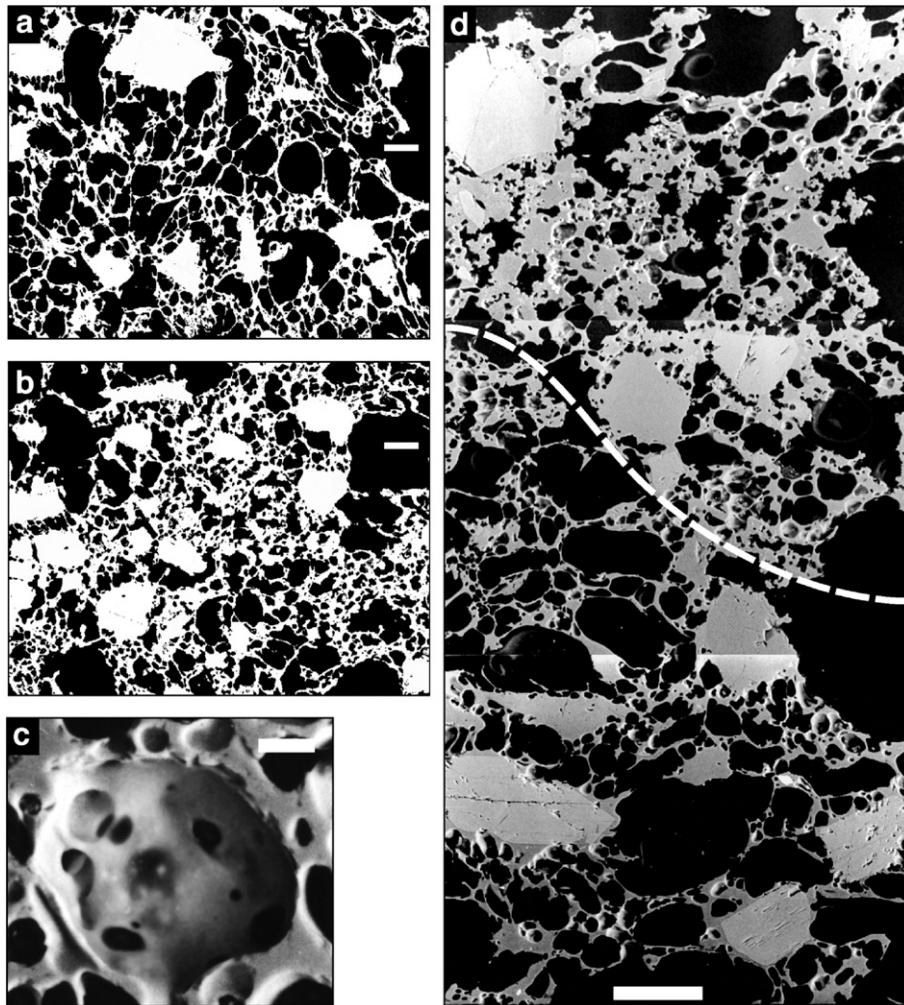


Fig. 6. SEM images of grey (a) and brown (b) pumice (note a and b are binarised; black = vesicles, white = glass + crystals); c) shows a large coalesced vesicle; d) consists of three SEM images showing the transition from grey to brown in banded pumice. Scale bar is 10 μm in (c), otherwise 100 μm .

bubbles are present, but simple large bubbles are absent. The bubble network is often deformed and bubble walls are thicker with microlites in the glass.

Banded pumices [4] contain types [1] and [2] (Fig. 6d). The grey bands within them are often coarsely vesicular with interconnected vesicles. Black vesicular clasts [3] have comparatively small bubbles of uniform size, which also appear in thin sections to be commonly isolated (Fig. 5b).

The difference in pumice types is also expressed in their solid densities (grey: 2.74 g cm^{-3} ; brown: 2.79 g cm^{-3}).

4.4. Mineralogy and mineral chemistry

All pumice clasts contain common euhedral crystals of plagioclase, clinopyroxene, hornblende, Fe–Ti oxi-

des, and minor biotite. Often crystals are broken fragments. In the glassy, highly vesiculated rocks, microlites of plagioclase, and to a lesser extent clinopyroxene, appear predominantly at the intersection of adjacent vesicles or next to phenocrysts. In addition, hornblende and biotite crystals are fresh, showing no oxidation or breakdown reaction rims (Fig. 7a).

Grey lithics, the most abundant lithic clast type within pumice flow and fall deposits, are dense, hypocristalline, and comprise plagioclase, clinopyroxene, hornblende, Fe–Ti oxides, and biotite. Hornblende and biotite are partially oxidised, with Fe–Ti oxide reaction rims; in some cases the crystals are replaced by minute plagioclase, clinopyroxene and Fe–Ti oxides (Fig. 7c).

Black dense and vesicular clasts, common in the pumice pyroclastic flow deposits, are glassy with the

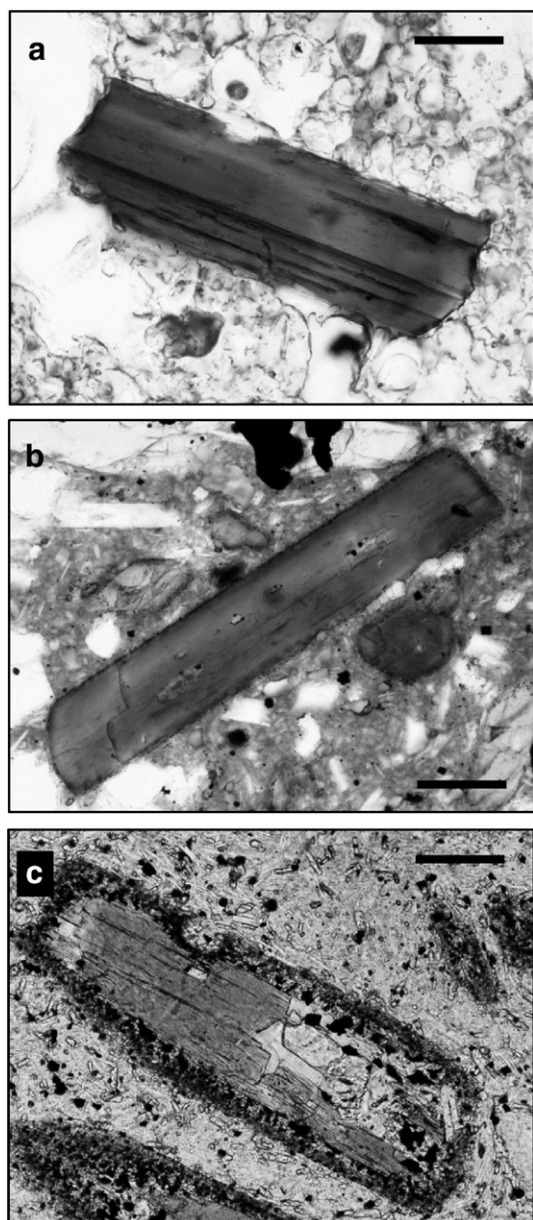


Fig. 7. Hornblende reaction textures in different clast types: a) fresh hornblende with no reaction rims in pumice, b) single Fe–Ti oxide crystals are attached to the hornblende rims in black semi-vesicular pumice, c) hornblende in dense grey lithic clast shows resorption textures and is partially replaced by clinopyroxene, plagioclase and Fe–Ti oxide crystals or is fully replaced (top right); note abundant plagioclase microlites in groundmass. Scale bar is 100 μm .

same mineral assemblage as grey, dense lithics, except with lower biotite contents. Hornblende appears fresh, with minor Fe–Ti oxide rim alteration (Fig. 7b).

4.5. Bulk rock geochemistry

Whole rock analyses of pumice clasts and juvenile lithics from the pumice pyroclastic flow, BAF and fall deposits are shown in Table 2. Pumice clasts from units 1 to 3 and black dense and vesicular lithics show very little variation in major and minor element geochemistry. Silica contents range between 55.5 and 56.0 wt.% (Fig. 8). The common grey dense lithics in the deposits show a broader range in composition, with silica varying between 56.4 and 59.5 wt.%. Data for all major elements show linear relationships (Fig. 8) with the trends being best explained by fractionation from pumice to grey lithics involving 45% hornblende, 34% plagioclase, 17% clinopyroxene, and 4% Fe–Ti oxides. This mineral assemblage represents common macroscopic and microscopic cumulates within Taranaki rocks. Sample P10 has been used as a starting composition based on its highest Mg# of 49.9. From this assumed magma composition, crystals have been subtracted from the magma composition using average mineral compositions for plagioclase and Fe–Ti oxides and average rim compositions for hornblende and clinopyroxene obtained by electron microprobe (Table 3). The modelled fractionation is in very good agreement with observed rock compositions up to 16.5% of fractionation, however, there is a considerable deviation for Al_2O_3 , FeO and MgO contents between the model and the single rock at 59.5 wt.% SiO_2 (Table 3). An alternative explanation for these trends could also be mixing or mingling of magmas, although glass compositions (see below) do not support this.

4.6. Glass composition

Glass compositions were analysed for brown (unit 2), grey pumice clasts (unit 1 and 3), and black pumice present throughout units 1–3 (Fig. 9; Table 4). The grey pumices of unit 1 range in silica content from 64.6 to 67.4 wt.% whereas the same pumice type of unit 3 only varies between 64.4 and 65.8 wt.% SiO_2 . Brown pumices (unit 2) have a higher silica content, ranging from 64.5 to 68.2 wt.%. Black pumice glass compositions differ from units 1 and 3 pumice in their higher range in silica values (64.9–69.3 wt.%), but show a very similar trend in Al_2O_3 vs. SiO_2 as observed in brown pumice with a slightly steeper slope. Glass compositions of individual lapilli are homogeneous as illustrated in the inset of Fig. 7.

The general trend of all data (thin solid line in Fig. 9) can be modelled using plagioclase microlite and clinopyroxene rim analyses. The thick line in Fig. 9

Table 2

XRF bulk rock geochemistry of Burrell Lapilli clasts. Samples are mostly from pumice flow deposits with one BAF deposit sample (P10)

Sample	SD20	SD35	TO4-22	TO4-96	P10	SD24	TO4-19	TO4-65	SD9a	SD9c
Rock type	Pumice	Pumice	Pumice	Pumice	Pumice	Pumice	Pumice	Pumice	Grey lithic	Grey lithic
Grid	E2601895	E2601895	E2601480	E2601079	E2590539	E2601895	E2601480	E2601607	E2601906	E2601906
Reference	N6210810	N6210810	N6211325	N6209350	N6217485	N6210810	N6211325	N6210926	N6210746	N6210746
SiO ₂	55.56	55.58	56.00	55.52	55.71	55.80	55.93	55.80	56.44	57.65
TiO ₂	0.770	0.761	0.768	0.770	0.780	0.753	0.754	0.757	0.772	0.760
Al ₂ O ₃	17.19	17.20	17.19	17.17	17.17	17.05	17.20	17.04	17.24	17.29
Fe ₂ O ₃	7.31	7.09	7.17	7.25	7.21	7.01	7.18	7.15	6.92	6.54
MnO	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.14
MgO	3.45	3.49	3.35	3.61	3.62	3.44	3.45	3.47	3.17	2.91
CaO	7.54	7.68	7.64	8.01	8.00	7.59	7.62	7.71	7.49	6.99
Na ₂ O	3.52	3.69	3.59	3.80	3.59	3.70	3.54	3.59	3.86	3.99
K ₂ O	2.71	2.69	2.71	2.64	2.63	2.74	2.67	2.71	2.82	3.07
P ₂ O ₅	0.27	0.27	0.27	0.27	0.26	0.27	0.26	0.27	0.28	0.28
H ₂ O	0.12	0.12	0.16	0.19	0.22	0.09	0.18	0.30	0.00	0.00
LOI	1.12	1.04	0.84	0.55	0.47	0.78	0.85	0.85	−0.08	−0.02
Total	99.70	99.75	99.84	99.93	99.81	99.36	99.80	99.78	99.28	99.83
Sc	18.8	18.8	13.0	16.2	18.7	19.8	15.6	22.5	17.0	17.0
V	201	197	202	214	202	194	199	206	192	183
Cr	42.5	44.5	48.9	54.3	56.2	51.5	45.2	47.0	29.4	22.9
Ni	11.9	8.9	10.1	13.5	13.7	17.8	11.6	12.6	7.7	8.1
Cu	76.0	81.0	26.1	77.1	42.6	110.0	51.2	111.3	47.0	62.2
Ga	18.8	20.8	19.4	19.4	19.5	19.8	19.0	19.1	21.4	22.5
Rb	70.1	68.2	72.4	68.8	69.8	70.4	71.5	71.2	69.9	77.7
Sr	584	569	574	573	574	569	566	558	602	597
Y	21.7	21.7	21.6	22.2	21.9	21.8	21.3	21.6	22.6	23.3
Nb	5.9	5.9	4.9	4.5	4.3	5.9	5.0	4.9	7.0	6.5
Ba	701	706	990	944	961	705	977	965	777	797
La	20.7	19.8	19.6	15.7	22.4	18.8	21.7	20.2	0.0	0.0
Ce	41.5	38.5	38.9	38.0	40.4	32.7	40.7	37.7	0.0	0.0
Pb	13.8	12.8	15.8	16.1	15.9	15.9	15.7	16.7	12.0	15.0
Th	13.8	8.9	7.1	8.7	7.2	11.9	6.8	7.3	0.0	0.0
U	–	–	2.8	4	4.2	–	2.1	2.8	–	–

represents the change in glass compositions by crystallisation of 76% plagioclase and 24% clinopyroxene calculated by mass balance. It is noted that unit 1 pumice data lie on a flatter slope, although still situated within the entire dataset. This may suggest a stronger involvement of clinopyroxene during late stage evolution of glass chemistry.

4.7. Porosity and permeability

Porosity ($n=221$) and permeability ($n=83$) were measured on cores of grey, brown and banded pumices and black vesicular clasts. There is a wide range in connected porosity and bulk vesicularity for all analysed clast types (Fig. 10). The dataset clearly illustrates a concentration of bulk vesicularities between c. 57 and 77%, with a broader range in isolated pore volume up to 10%. Clasts with $\phi < 54\%$ have similar

isolated pore volumes in a restricted range and these seem to decrease with decreasing ϕ . The gap in the dataset ($36.0 < \phi < 47.8\%$) may be due to low sample numbers but is more likely to be real (see Discussion). The highest ϕ values (up to 83.6%) are observed for brown pumices.

Grey pumice clasts of unit 1 and 3 show similar ranges in connected porosities from 53.1 to 73.5% and 44.1 to 72.7%, respectively, with isolated pore volumes, varying between 2.0–8.8% (unit 1) and 2.0–4.6% (unit 3). There is an overall positive correlation of permeability and connected porosity (Fig. 11a), despite the fact that permeability ranges over three orders of magnitude. For example, two grey pumice clasts with $\phi = 64.8$ and 64.9% differ considerably in permeability ($1.0 \times 10^{-11} \text{ m}^2$ and $3.0 \times 10^{-12} \text{ m}^2$). However, data from three mutually perpendicular cores per sample show no positive correlation of porosity with

SD28	TO4-1	TO4-21	TO4-24	SD34	SD39	SD9b	SD27	SD29	SD33
Grey lithic	Grey lithic	Grey lithic	Grey lithic	Grey lithic	Grey lithic	Black pumice	Black pumice	Black pumice	Black pumice
E2601895	E2601168	E2601480	E2601480	E2601895	E2601452	E2601906	E2601895	E2601895	E2601895
N6210810	N6209620	N6211325	N6211325	N6210810	N6210567	N6210746	N6210810	N6210810	N6210810
57.21	57.58	56.83	59.51	57.05	57.63	55.86	55.95	55.75	55.90
0.772	0.749	0.756	0.669	0.792	0.766	0.767	0.757	0.752	0.757
17.40	17.35	17.32	17.17	17.34	17.28	17.15	17.20	17.11	17.21
6.65	6.62	6.98	5.97	6.75	6.58	7.14	7.09	7.14	7.09
0.14	0.15	0.16	0.14	0.15	0.15	0.15	0.15	0.15	0.15
2.96	2.88	3.20	2.54	3.01	2.89	3.61	3.51	3.62	3.57
7.11	7.03	7.12	6.33	7.20	6.95	7.91	7.80	7.88	7.89
3.97	3.98	3.94	3.98	3.99	3.98	3.72	3.72	3.72	3.70
3.02	3.02	2.89	3.25	3.02	3.09	2.68	2.70	2.66	2.67
0.29	0.28	0.28	0.24	0.31	0.28	0.26	0.27	0.26	0.27
0.02	0.10	0.13	0.04	0.00	0.00	0.00	0.06	0.11	0.00
−0.05	−0.03	0.11	−0.08	−0.03	−0.02	0.26	0.37	0.48	0.42
99.70	99.70	99.71	99.75	99.79	99.81	99.73	99.57	99.62	99.63
17.0	10.8	9.5	11.7	17.0	14.0	19.0	17.9	19.2	16.9
187	184	179	151	196	183	201	195	197	196
21.9	22.4	22.5	24.2	23.9	24.9	47.7	46.8	45.6	48.8
9.6	7.2	9.1	7.9	4.1	6.0	11.0	11.0	11.7	12.9
33.5	44.0	34.3	31.1	56.0	89.3	67.5	103.6	73.9	92.6
21.1	20.6	21.0	20.0	22.0	19.8	18.6	18.9	20.0	21.9
76.7	77.2	76.1	87.2	75.6	81.1	68.7	70.7	66.4	68.7
610	608	619	550	627	597	576	577	572	578
23.4	23.6	22.1	20.7	23.1	23.7	22.2	21.9	22.1	21.9
7.3	5.6	5.3	5.6	6.6	6.1	5.6	5.0	5.2	5.0
811	1128	1181	1173	784	830	720	736	996	703
0.0	20.5	18.9	17.2	0.0	0.0	0.0	18.9	17.7	14.9
0.0	45.0	38.0	37.2	0.0	0.0	0.0	38.8	37.3	20.9
12.0	16.1	17.5	20.3	15.0	15.0	12.0	13.9	15.3	14.9
0.0	9.3	8.5	9.2	0.0	0.0	0.0	11.9	6.3	12.9
–	1.8	2.2	2.4	–	–	–	–	–	–

permeability (Fig. 11a). Above $\varphi=59.8\%$, all four investigated clast types show that the highest permeability occurs in the core samples having an intermediate bulk vesicularity value. Combining this data with the observations on pumice core samples in two mutually perpendicular directions (see inset in Fig. 11a), suggests that this is the result of an anisotropic bubble network which is present in all pumice types. In banded pumice clasts this effect is particularly strong, where coarsely vesicular bands were probably able to effectively channel the pre- and syn-eruptive gas flows.

Unusually, the permeability data for Burrell Lapilli pumice are on average one log unit higher than other silicic pumice (Fig. 11b). This could be caused by larger aperture sizes of connected bubbles and may be related to lower viscosities in the Burrell magmas (e.g. Saar and Manga, 1999). If lower viscosities cause higher permeability of pumice clasts, then greater post-

fragmentation bubble expansion (and coalescence) is highly likely.

5. Discussion

The ejecta of this eruption span a range of vesicularity, bulk silica content and colour, with systematic variations in hornblende phenocryst rim morphologies, microlite contents and 347 glass compositions. These variations are related to the order of eruption in the following way:

1. Grey lithic clasts, which probably represent the earliest-extruded magma of the AD1655 episode, are incorporated in ejecta from all phases of the eruption. These are hypocrySTALLINE rocks of low vesicularity and low permeability (the latter mostly represents cooling-induced microcracks). They have bulk rock silica contents that are 0.4 to 4 wt.% higher than co-erupted

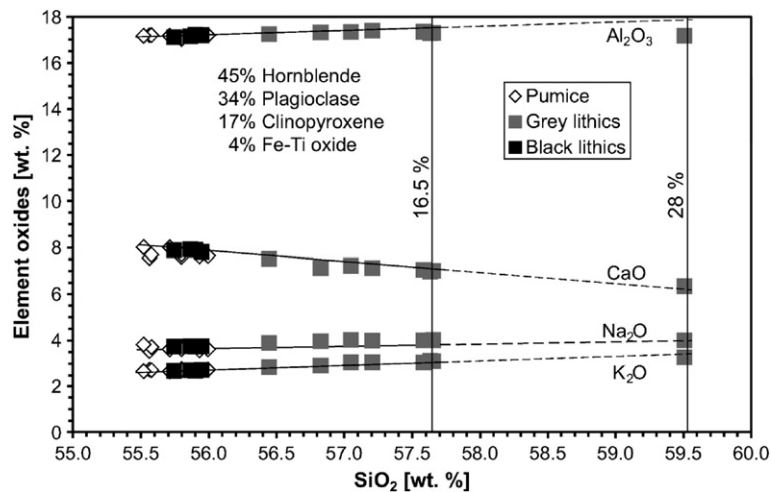


Fig. 8. Bulk rock geochemistry of pumice and grey andesite clasts in a multi element oxide vs. SiO_2 diagram. The fractionation trend pumice – grey lithics is in good agreement for the majority of clasts (solid line) with some variation for the most evolved clast (dashed line). See Table 3 for details.

pumice clasts, contain hornblende and biotite phenocrysts with strongly altered/resorbed rims and a ground-mass dominated by plagioclase and clinopyroxene.

2. Pale grey pumice with porosities of between 53–74% and the highest isolated pore volumes (up to 8.8%) represent the earliest explosive phase of the episode. This pumice contains a number of elongated large, single and coalesced vesicles within an overall broad pore-size distribution.

3. Brown pumice, displaying the highest porosities (up to 84%) was next erupted. The large single vesicles are absent from these pumices, which, compared with the early pale-grey pumice, show a more restricted pore size-distribution, a more strongly deformed network, thicker walls between bubbles, and a higher microlite content. These differences are also observed between the different coloured zones within banded clasts. Both brown and the initial pale-grey pumice have identical ranges in glass composition, between 64 and 68 wt.% SiO_2 .

4. Black clasts, erupted as a minor concomitant component during the middle stages of the explosive phase, are either low- or moderately vesicular, and are characterised by having isolated pores in a glassy microlite-rich matrix. They have a similar range in glass compositions to the brown and initial pale grey pumice, although extending slightly higher to 69 wt.% SiO_2 .

5. Banded pumice clasts predominantly comprise grey and brown pumice networks and show macroscopically complex textures of stretching, banding and folding.

6. The final explosive phase is represented by a pale-grey pumice of similar appearance to that firstly erupted.

Like the initial pumice, it has a low-moderate porosity range (<73%), but shows lower isolated pore volumes than the earliest pale-grey ejecta. This pumice also has the lowest silica glass (64–66 wt.% SiO_2), with the most restricted composition range, compared to earlier ejecta.

To understand the phases of this eruption, its transitions in eruptive style and the range in physical and chemical properties of the ejecta, a range of magmatic processes within the upper conduit need to be considered. The factors causing different clast types are discussed in chronological order and divided into pre-climactic and syn-climactic processes, which form the basis for reconstructing the eruption dynamics.

5.1. Pre-climactic conditions

5.1.1. Grey lithics

No large-scale magma reservoirs are evident in the upper crust at Taranaki (Sherburn and White, 2005), suggesting that the final magma storage level is at about 10–11 km depth. Magmas ascend through 6 km of Tertiary sediments into the 2.5 km high edifice. Gravity measurements indicate that multiple dyke intrusions have created a c. 5 km wide dyke/stock complex below Mt. Taranaki (Locke and Cassidy, 1997).

Dyke propagation provides a first-order control of ascent rates of the initial rising magma. Rise rate controls a series of physical and chemical processes, including degree of crystallisation, fractionation, degassing, vesiculation, viscosity and fragmentation that can be seen in the final ejecta. During rise, the typically hydrous Taranaki melts move outside the pressure/temperature and $p\text{H}_2\text{O}$ stability fields for hornblende

Table 3
Mass balance calculation for the inferred fractionation process pumice–lithics

Oxides [wt.%]	Start composition	Fractionating phases				Cumulate composition	Comparison					
		Hornblende (n=23)	Clinopyroxene (n=33)	Plagioclase (n=50)	Fe–Ti oxides (n=27)		Model at 16.5% fractionation	Observed	1 σ	Model at 28% fractionation	Observed	1 σ
Mineral proportion		45%	17%	34%	4%							
Sample	P10							SD9c			T04-24	
SiO ₂	55.71	41.90	51.62	53.07	0.13	45.94	57.64	57.65	0.01	59.51	59.51	0.00
TiO ₂	0.78	2.65	0.49	0.07	6.45	1.30	0.68	0.76	0.06	0.58	0.67	0.06
Al ₂ O ₃	17.17	11.81	2.30	27.80	2.59	15.39	17.52	17.29	0.16	17.86	17.17	0.49
FeO ^a	6.49	12.04	7.38	0.63	83.24	10.19	5.76	5.89	0.09	5.05	5.37	0.23
MnO	0.15	0.22	0.48	0.01	0.61	0.21	0.14	0.14	0.00	0.13	0.14	0.01
MgO	3.62	13.64	14.75	0.10	2.14	8.76	2.61	2.91	0.22	1.62	2.54	0.65
CaO	8.00	11.60	21.72	11.23	0.05	12.64	7.09	6.99	0.07	6.20	6.33	0.09
Na ₂ O	3.59	2.09	0.30	4.57	0.05	2.63	3.78	3.99	0.15	3.96	3.98	0.01
K ₂ O	2.63	1.14	0.04	0.56	0.02	0.69	3.01	3.07	0.04	3.38	3.25	0.10
Total	98.87	97.08	99.08	99.04	95.27	98.90	98.22	99.83		98.30	99.75	
Mg# ^b	49.9					60.5	44.6	46.9		36.4	45.8	

^a Fe₂O₃ of XRF analysis converted to FeO.

^b Mg# = 100 [Mg/(Mg + Fe²⁺ total)].

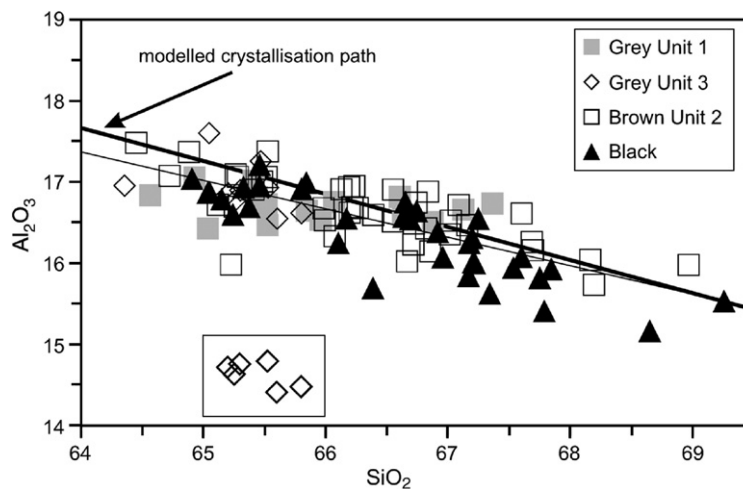


Fig. 9. Groundmass glass compositions of pumice types presented in the Al_2O_3 vs. SiO_2 diagram. Modelled glass composition changes due to plagioclase and clinopyroxene crystallisation (thick solid line) and is in good agreement with linear regression line (thin solid line). The small inset shows six data points of one lapillus (SD20) demonstrating relative glass homogeneity. The dimensions of the box are 1 wt.% for Al_2O_3 and SiO_2 .

and hence varying degrees of disequilibrium and hornblende breakdown occur that may be used to constrain magma rise processes. Decompression experiments (130–4 MPa) on Soufriere Hills andesites showed that hornblende can spend up to 6 days outside its stability field before showing any breakdown reactions (Rutherford and Devine, 2003). The upper pressure boundary for hornblende stability at Taranaki corresponds to c. 5.2 km below the summit (using densities of 2400 kg m^{-3} for the edifice and 2700 kg m^{-3} for the dyke/stock complex; Locke and Cassidy, 1997). However, Sato et al. (1999) also showed that groundmass pargasitic hornblende in Unzen dacite is stable up to 70 MPa at c. 880°C , which is equivalent to >3 km depth in a Taranaki conduit. These data imply that hornblende-breakdown reactions in Taranaki rocks likely occurred in the upper conduit and/or within a dome.

The grey, dense, dome-derived lithics have evolved from the same magma as co-erupted pumice. The difference in SiO_2 content can be modelled by fractionation of hornblende, plagioclase, clinopyroxene, and Fe–Ti oxides (see Fig. 8). The major involvement of hornblende in the fractionation process is essential because it is the only major, low-silica mineral phase (average 41.7 wt.% SiO_2) to be able to move the bulk rock silica content by 4 wt.% during ascent.

Although crystallisation and fractionation processes during ascent influence the ability of a magma to flow due to an increase in crystallinity and silica contents in the melt phase (Hammer et al., 1999), another profound impact on magma evolution is the degree of degassing. Gas escape through dyke walls is important (e.g. Tuffen

et al., 2003), especially if the dyke intrudes into porous media, although degassing along marginal shear zones is usually dominant (Jaupart and Allegre, 1991; Stasiuk et al., 1996).

Once the fractionated “grey” magma enters shallower levels, magma processes are governed by rheological changes due to increasing gas loss, particularly within the edifice, and subsequent, degassing- and decompression-induced groundmass crystallisation (Blundy and Cashman, 2001). Nucleation and growth of predominantly plagioclase microlites within the groundmass (Fig. 5) considerably increases melt and magma viscosities, thus reducing the ascent rate. As soon as a dome or cryptodome is emplaced on top of a conduit, it has such extremely low gas permeability that it forms an effective cap (Melnik and Sparks, 2002; Mueller et al., 2005). The remnant summit dome at Mt Taranaki (erupted approximately AD1850–60) has permeability that ranges between 6.7×10^{-13} and $5.8 \times 10^{-14} \text{ m}^2$ at $\phi = 16.1\text{--}23.7\%$ (Fig. 11b). However, these already low values are dominated by cooling-induced microcracks (as seen macroscopically) and the permeability at the time of emplacement would have been much lower.

5.1.2. Grey pumice (unit 1)

Sealing and/or capping the conduit leads towards a closed-degassing system and also a partial stagnation of the magma in the upper conduit. Slow rates of vesicle nucleation and growth may still occur in the upper conduit (Fig. 12a, b, to level 1) over extended periods. This slowly forces the viscous overlying magma upwards, and drives dome growth (Fig. 12b). At the same time,

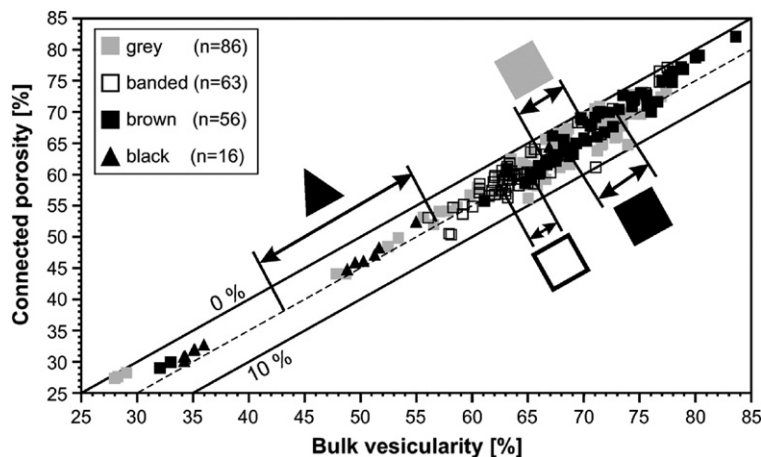


Fig. 10. Connected porosity vs. bulk vesicularity of all pumice types. Brackets represent 95% confidence limit for the mean of each pumice population. Solid lines represent 0% and 10% isolated pore volume.

brown magma is probably induced by slower volatile exsolution and hence, a higher oxidation state of the magma (Paulick and Franz, 1997). Post-depositional precipitation of Fe–Ti oxides probably led to further glass colouring but it could not have affected the glass composition (see Fig. 9).

It is inferred that, despite higher microlite contents, the brown magma foam retained higher temperature and hence had a lower viscosity than the earlier formed grey magma foam.

5.2. Syn-climactic conditions

5.2.1. Black, banded, and unit 3 grey pumice clasts

Initiation of the explosive phase caused instant vesiculation and further bubble growth in the grey (unit 1) and brown magma foams (Fig. 12c). Further, an immediate pressure drop, as well as magma ascent within the conduit caused rapid downward progression of the bubble nucleation to level 3. Here, the grey pumice of unit 3 was developed. Rapid volatile exsolution caused high degrees of undercooling of the melt, permitting syn-crystallisation of plagioclase±clinopyroxene, however, rapid ejection and cooling meant that the melt silica content was only driven up to 65.8 wt.%. The unit 3 pumice has slightly higher isolated pore volume, also suggesting a less mature bubble network than unit 1 pumice.

As the three domains of magma rose within the conduit, the slightly different viscosities contributed to further differences in clast textures. For example, the brown magma foam was easily plastically deformed, and bubbles coalesced more rapidly due to shearing of the ascending magma (Fig. 12d). Higher connected porosities and permeabilities compared to the grey magma foams

seem to be controlled by larger aperture size rather than greater vesicle size (c.f. Saar and Manga, 1999). The occurrence of black pumice clasts predominantly within unit 2 pyroclastic flows and their glass composition being similar to brown pumice (Fig. 9) suggests a genetic link. The poorly vesicular texture of black pumice and its low abundance in the pyroclastic flow deposit (c. 5% by volume) suggests that it could represent a conduit-margin variant of the brown pumice. They may have been derived under higher temperature conditions developed by friction during shearing of magma along the conduit walls (c.f. Rosi et al., 2004). Black clasts show the highest difference in permeability per clast (Fig. 11a) with only medium connected porosities of 44.8% and 47.1%, but strongly anisotropic permeable clasts with differences of 1.2 log units. The large difference in between semi-vesicular and vesicular pumice clasts ($\phi = 36.0$ –47.8%; Fig. 10) could be due to their genetic position in respect to the conduit margins, with an abrupt transition between a dense marginal facies and a porous interior facies.

In addition, due to variable ascent velocities across and along the conduit, the lower viscosity brown magma could partly intrude and mingle into the upper grey magma (unit 1) to produce flow banding (Fig. 12d). The same process occurred at the base of the brown magma. The banded pumices also clearly show an anisotropic bubble network (Fig. 11a). Contrary to a horizontal textural zonation of a conduit, where banded pumice forms in the outer margins and coarsely vesicular pumice occupies the core (as proposed by Polacci et al., 2001; Rosi et al., 2004; D’Orlando et al., 2005), banded pumices of the Burrell Lapilli eruption are thought to be the result of vertical gradients within the conduit. Although D’Orlando et al. (2005) also argue for a vertical

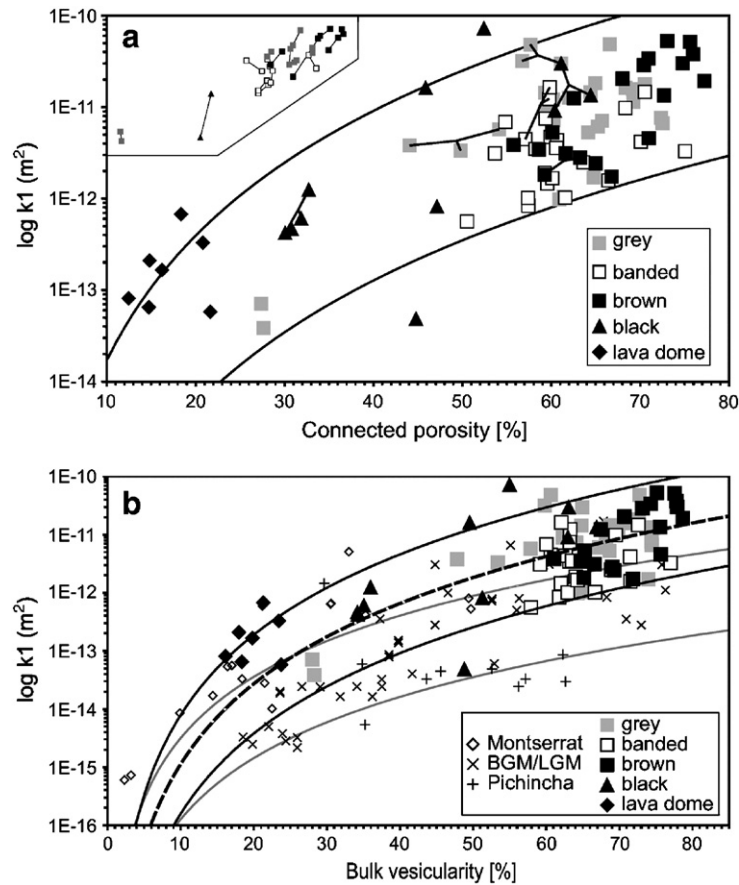


Fig. 11. Connected and bulk vesicularity vs. permeability. a) Data of this study with upper and lower data limits (black lines) of $y = 5 \times 10^{-19} x^{-5314}$ and $y = 6 \times 10^{-21} x^{-5314}$, respectively. Note that there are six specimens with three cores cut in three mutually perpendicular directions. Upper inset shows cores cut in two perpendicular directions. b) Comparison of our data with published literature: Montserrat (Melnik and Sparks, 2002), Big and Little Glass Mountains (Rust and Cashman, 2004), Pichincha (Wright et al., 2007); grey lines are limits of Klug and Cashman (1996).

zonation of a conduit, they apply it only to the degassed and variably crystalline plug of the upper conduit.

5.3. Eruption dynamics

Evolution of magmas in the dome and the upper conduit were governed by decompression-induced microlite crystallisation and growth in the melt fraction. This caused a large pressure gradient, due to excess fluid pressure in the melt as well as large viscosity differences by increasing crystallinity and melt silica content, and decreasing dissolved water contents (Sparks, 1997). Over-pressurisation from below the dome was probably an additional contributing factor for dome rupture and collapse (Fig. 12a). The dome collapse generated a large BAF, which due to the pre-existing crater morphology, was directed down the NW flank and travelled up to 13.5 km. The presence of primary grey pumice clasts within the BAF deposit further suggests over-pressur-

isation of the dome from below was a major factor. The explosive removal of lava dome material was accompanied by a vertically directed sub-plinian eruption of the fragmented grey pumice foam (unit 1) with dome clasts and associated conduit rocks incorporated and transported through the column. The strength of fragmentation was maintained until the fragmentation front reached a change in vesicularity. Variable degrees of vesicularity, viscosity and temperature down and across the stratified conduit were caused by the formation of three distinct magma foams.

The partially vesiculated brown magma foam had the lowest melt viscosity and hence the lowest pressure built-up by vesiculation. This in turn led to lower exit velocities and lower eruption column heights. In static experiments Burgisser and Gardner (2004) showed that bubble coalescence is time-dependent and was already occurred by porosities of c. 43%. A sufficiently coalesced bubble network prior to fragmentation may

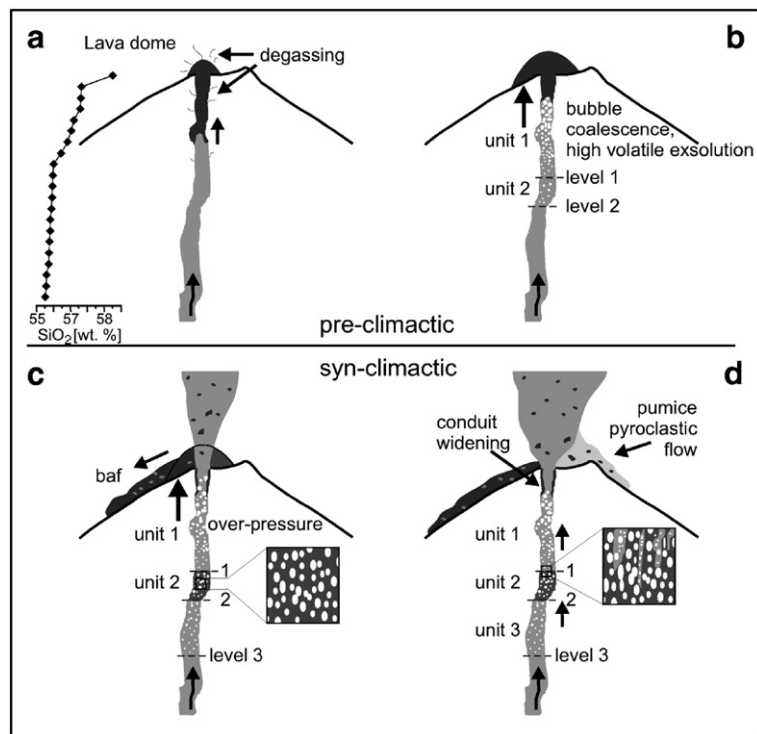


Fig. 12. Reconstruction of eruptive events during the Burrell Lapilli eruption. Changes in bulk rock silica contents are illustrated in Stage A. Bubble nucleation levels 1–3 correspond with erupted units 1–3. See text for further details.

decrease fragmentation rates, and hence could produce the low, unstable eruption columns inferred for the eruption of the brown pumice (unit 2). However, this does not exclude post-fragmentation bubble expansion and bubble deformation during emplacement as a further contributing factor to changes in bubble shapes and therefore permeabilities (e.g. Thomas et al., 1994).

Fluctuations in column height and explosive energy are common during sub-plinian and plinian eruptions where the column partially, or completely, collapses to produce pumice pyroclastic flows. This was observed, for example, during the 22nd July 1980 eruptions at Mt. St. Helens where three individual sub-plinian pulses with column heights to 14 km removed half of the pre-existing dome of $4.7 \times 10^6 \text{ m}^3$ (Christiansen and Peterson, 1981; Moore et al., 1981).

At Mt. Taranaki, no brown pumice is found in preserved fall deposits, which indicates that the brown magma was not fragmented and ejected as efficiently as the grey magma foam above and below it. The sudden drop in exit velocity associated with the eruption of brown magma foam caused instabilities within the eruption column, implying a lower energy, “boiling-over” type eruption (c.f. Taylor, 1958). Hence, grey pumice pyroclastic flows were generated before and after the brown unit (Fig. 12d). The minimum estimate

of erupted brown magma is approx. $6.9 \times 10^4 \text{ m}^3$ (DRE) corresponding to a cylindrical conduit length of c. 880 m ($r=5 \text{ m}$), a sufficient segment within the conduit to affect magma ascent and fragmentation rates. Another potential means to alter exit velocity, fragmentation rate and hence column height is to widen the vent, but this can only be achieved at the very top of the vent and, it would also have affected the fragmentation of the grey, unit 3 magma. The boiling-over type of eruption at Mt. Taranaki is also consistent with higher emplacement temperatures of brown pyroclastic flows (unit 2) compared to units 1 and 3.

Isopach and isopleth mapping suggests that the eruption column was initially directed towards the SE, and then the dispersal axis progressively rotated northeastwards. Lithic isopleths and a normal followed by inverse grading of lithic clasts in the fall deposit may also suggest that the eruption occurred in two sub-plinian pulses, or, perhaps more likely, was interrupted by a transient waning in the magma ascent rate. Pulsatory, sub-plinian eruptive periods have been observed for example at the June/July eruptions at Mt. St. Helens (Christiansen and Peterson, 1981; SEAN 05:06–07) at the 1991 pre-climactic eruptions at Mt. Pinatubo, Philippines (Hoblitt et al., 1996) and at El Chichon, Mexico (SEAN 07:03).

The total eruption column height at its highest energy phases was probably up to 14 km above the crater (based on application of the isopach and isopleth data to models from Carey and Sparks, 1986) and transported fine ash more than 250 km east and northeastwards over the North Island (Eden and Froggatt, 1996).

6. Conclusions

It has been demonstrated through this AD1655 Burrell eruption case-study that simple changes in magmatic conditions of a single hydrous andesitic magma during ascent can explain sudden changes in eruptive explosivity and hazard potential. Our model of a stratified conduit with varying magma composition, vesicularity and viscosity can explain all observed pumice variations.

Transitions from effusive to explosive phases within these types of andesitic eruption appear to be mainly governed by internal/magmatic factors, including 1) dyke propagation and sealing, 2) degree of fractionation of magma, and 3) magma ascent rate and magma volume. The faster the magma ascends and the faster the dyke is sealed to reduce gas loss, the more effectively a magma foam is developed that can fragment explosively.

Textural and colour variations of pumice clasts have been recognised at other volcanoes (Donoghue et al., 1995; Bourdier et al., 1997; Gardner et al., 1998; Clyne, 1999; Polacci et al., 2001; Rosi et al., 2004; D'Oriano et al., 2005). Where these clast variations occur within individual stages of eruptive sequences (e.g. within layered fall deposits), they could also be explained by a similar model to that described here.

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References

Alloway, B., Neall, V.E., Vucetich, C.G., 1995. Late Quaternary (post 28,000 year BP) tephrostratigraphy of northeast and central Taranaki, New Zealand. *J. R. Soc. N.Z.* 25, 385–458.

Blundy, J., Cashman, K., 2001. Ascent-driven crystallisation of dacite magmas at Mount St Helens, 1980–1986. *Contrib. Mineral. Petrol.* 140, 631–650.

Bourdier, J.L., Pratomo, I., Thouret, J.C., Boudon, G., Vincent, P.M., 1997. Observations, stratigraphy and eruptive processes of the 1990 eruption of Kelut volcano, Indonesia. *J. Volcanol. Geotherm. Res.* 79, 181–203.

Burgisser, A., Gardner, J.E., 2004. Experimental constraints on degassing and permeability in volcanic conduit flow. *Bull. Volcanol.* 67, 42–56.

Carey, S., Sparks, R.S.J., 1986. Quantitative models of the fallout and dispersal of tephra from volcanic eruption columns. *Bull. Volcanol.* 48, 109–125.

Cashman, K.V., Sturtevant, B., Papale, P., Navon, O., 2000. Magmatic fragmentation. In: Sigurdsson, H., Houghton, B.F., McNutt, S., Rhymer, H., Stix, J. (Eds.), *Encyclopedia of Volcanoes*. Academic Press, San Diego, pp. 419–430.

Christiansen, R.L., Peterson, D.W., 1981. Chronology of the 1980 eruptive activity. In: Lipman, P.W., Mullineaux, D.R. (Eds.), *The 1980 eruptions of Mount St. Helens*, Washington. U.S. Geol. Surv. Prof. Pap., vol. 1250, pp. 17–30.

Clyne, M.A., 1999. A complex magma mixing origin for rocks erupted in 1915, Lassen Peak, California. *J. Petrol.* 40, 105–132.

Cole, J.W., Stephenson, T.M., 1972. Calculation of the volume of a tephra deposit: Appendix. In: Cole, J.W. (Ed.), *Distribution of High-Alumina basalts in the Taupo Volcanic Zone*. Publication of Geology Department, Victoria University of Wellington, vol. 1. 15 pp.

Donoghue, S.L., Gamble, G.A., Palmer, A.S., Stewart, R.B., 1995. Magma mingling in an andesite pyroclastic flow of the Pourahu Member, Ruapehu volcano, New Zealand. *J. Volcanol. Geotherm. Res.* 68, 177–191.

D'Oriano, C., et al., 2005. Changes in eruptive style during the AD 1538 Monte Nuovo eruption (Phlegrean Fields, Italy): the role of syn-eruptive crystallization. *Bull. Volcanol.* 67, 601–621.

Druce, A.P., 1966. Tree-ring dating of recent volcanic ash and lapilli, Mt. Egmont. *N.Z. J. Bot.* 4, 3–41.

Eden, D.N., Froggatt, P.C., 1996. A 6500-year-old history of tephra deposition recorded in the sediments of Lake Tutira, eastern North Island, New Zealand. *Quat. Int.* 34–6, 55–64.

Elsworth, D., Voight, B., 2001. The mechanics of harmonic gas pressurization and failure of lava domes. *Geophys. J. Int.* 145, 187–198.

Gardner, C.A., Cashman, K.V., Neal, C.A., 1998. Tephra-fall deposits from the 1992 eruption of Crater Peak, Alaska: implications of clast textures for eruptive processes. *Bull. Volcanol.* 59, 537–555.

Hammer, J.E., Rutherford, M., 2002. An experimental study of the kinetics of decompression-induced crystallization in silicic melt. *J. Geophys. Res.* 107, 1–24.

Hammer, J.E., Cashman, K.V., Hoblitt, R.P., Newman, S., 1999. Degassing and microlite crystallization during pre-climactic events of the 1991 eruption of Mt. Pinatubo, Philippines. *Bull. Volcanol.* 60, 355–380.

Hammer, J.E., Cashman, K.V., Voight, B., 2000. Magmatic processes revealed by textural and compositional trends in Merapi dome lavas. *J. Volcanol. Geotherm. Res.* 100, 165–192.

Hoblitt, R.P., Wolfe, E.W., Scott, W.E., Couchman, M.R., Pallister, J.S., Javier, D., 1996. The preclimactic eruptions of Mount Pinatubo, June 1991. In: Newhall, C.G., Punongbayan, R.S. (Eds.), *Fire and Mud: Eruptions and Lahars of Mount Pinatubo*, Philippines. University of Washington Press, Hong Kong, pp. 457–511.

Jaupart, C., Allegre, C.J., 1991. Gas content, eruption rate and instabilities of eruption regime in silicic volcanoes. *Earth Planet. Sci. Lett.* 102, 413–429.

- Klug, C., Cashman, K.V., 1994. Vesiculation of May 18, 1980, Mount St-Helens Magma. *Geology* 22, 468–472.
- Klug, C., Cashman, K.V., 1996. Permeability development in vesiculating magmas: implications for fragmentation. *Bull. Volcanol.* 58, 87–100.
- Klug, C., Cashman, K.V., Bacon, C.R., 2002. Structure and physical characteristics of pumice from the climactic eruption of Mount Mazama (Crater Lake), Oregon. *Bull. Volcanol.* 64, 486–501.
- Locke, C.A., Cassidy, J., 1997. Egmont Volcano, New Zealand: three-dimensional structure and its implications for evolution. *J. Volcanol. Geotherm. Res.* 76, 149–161.
- Manga, M., Castro, J., Cashman, K.V., Loewenberg, M., 1998. Rheology of bubble bearing magmas. *J. Volcanol. Geotherm. Res.* 87, 15–28.
- Massol, H., Jaupart, C., Pepper, D.W., 2001. Ascent and decompression of viscous vesicular magma in a volcanic conduit. *J. Geophys. Res.* 106 (B8), 16223–16240.
- Mathews, A.J., Barclay, J., Carn, S., Thompson, G., Alexander, J., Herd, R., Williams, C., 2002. Rainfall-induced volcanic activity on Montserrat. *Geophys. Res. Lett.* 29, 1644.
- Melnik, O., Sparks, R.S.J., 2002. Dynamics of magma ascent and lava extrusion at Soufrière Hills Volcano, Montserrat. In: Druitt, T.H., Kokelaar, B.P. (Eds.), *The eruption of Soufrière Hills Volcano, Montserrat, from 1995 to 1999*. Geological Society, London, *Memoirs*, vol. 21, pp. 153–172.
- Moore, J.G., Lipman, P.W., Swanson, D.A., Alpha, T.R., 1981. Growth of lava domes in the crater, June 1980–January 1981. In: Lipman, P.W., Mullineaux, D.R. (Eds.), *The 1980 eruptions of Mount St. Helens*, Washington. U.S. Geol. Surv. Prof. Pap., vol. 1250, pp. 541–548.
- Mueller, S., Melnik, O., Spieler, O., Scheu, B., Dingwell, D.B., 2005. Permeability and degassing of dome lavas undergoing rapid decompression: an experimental determination. *Bull. Volcanol.* 67, 526–538.
- Neall, V.E., Stewart, R.B., Smith, I.E.M., 1986. History and petrology of the Taranaki volcanoes. *J. R. Soc. N.Z. Bull.* 23, 251–263.
- Newhall, C.G., Self, S., 1982. The Volcanic Explosivity Index (VEI) — an estimate of explosive magnitude for historical volcanism. *J. Geophys. Res.* 87, 1231–1238.
- Paulick, H., Franz, G., 1997. The color of pumice: case study on a trachytic fall deposit, Meidob volcanic field, Sudan. *Bull. Volcanol.* 59, 171–185.
- Polacci, M., Papale, P., Rosi, M., 2001. Textural heterogeneities in pumices from the climactic eruption of Mount Pinatubo, 15 June 1991, and implications for magma ascent dynamics. *Bull. Volcanol.* 63, 83–97.
- Polacci, M., Rosi, M., Landi, P., Di Muro, A., Papale, P., 2005. Novel interpretation for shift between eruptive style in some volcanoes. *EOS* 86, 333–336.
- Pyle, D.M., 1989. The thickness, volume and grain size of tephra fall deposits. *Bull. Volcanol.* 51, 1–15.
- Richet, P., Whittington, A., Holtz, F., Behrens, H., Ohlhorst, S., Wilke, M., 2000. Water and the density of silicate glasses. *Contrib. Mineral. Petrol.* 138, 337–347.
- Rosi, M., Landi, P., Polacci, M., Di Muro, A., Zandomenighi, D., 2004. Role of conduit shear on ascent of the crystal-rich magma feeding the 800-year-BP Plinian eruption of Quilotoa Volcano (Ecuador). *Bull. Volcanol.* 66, 307–321.
- Rust, A.C., Cashman, K.V., 2004. Permeability of vesicular silicic magma: inertial and hysteresis effects. *Earth Planet. Sci. Lett.* 228, 93–107.
- Rust, A.C., Manga, M., Cashman, K.V., 2003. Determining flow type, shear rate and shear stress in magmas from bubble shapes and orientations. *J. Volcanol. Geotherm. Res.* 122, 111–132.
- Rutherford, M.J., Devine, J.D., 2003. Magmatic conditions and magma ascent as indicated by hornblende phase equilibria and reactions in the 1995–2002 Soufrière Hills magma. *J. Petrol.* 44, 1433–1454.
- Saar, M.O., Manga, M., 1999. Permeability–porosity relationship in vesicular basalts. *Geophys. Res. Lett.* 26, 111–114.
- Sato, H., Nakada, S., Fujii, T., Nakamura, M., Suzuki-Kamata, K., 1999. Groundmass pargasite in the 1991–1995 dacite of Unzen volcano: phase stability experiments and volcanological implications. *J. Volcanol. Geotherm. Res.* 89, 197–212.
- Schlenger, C.M., Rosenbaum, J.G., Veblen, D.R., 1988. Fe-oxide microcrystals in welded tuff from southern Nevada: origin of remanence carriers by precipitation in volcanic glass. *Geology* 16, 556–559.
- Sherburn, S., White, R.S., 2005. Crustal seismicity in Taranaki, New Zealand using accurate hypocentres from a dense network. *Geophys. J. Int.* 162, 494–506.
- SEAN, 05:06-07. Smithsonian Institution, 1980. St. Helens, Scientific Event Alert Network, vol. 5, 6–7.
- SEAN, 07:03. Smithsonian Institution, 1982. El Chichon, Scientific Event Alert Network, vol. 7, 3.
- Sparks, R.S.J., 1997. Causes and consequences of pressurisation in lava dome eruptions. *Earth Planet. Sci. Lett.* 150, 177–189.
- Sparks, R.S.J., Murphy, M.D., Lejeune, A.M., Watts, R.B., Barclay, J., Young, S.R., 2000. Control on the emplacement of the andesite lava dome of the Soufrière Hills volcano, Montserrat by degassing-induced crystallization. *Terra Nova* 12, 14–20.
- Stasiuk, M.V., et al., 1996. Degassing during magma ascent in the Mule Creek vent (USA). *Bull. Volcanol.* 58, 117–130.
- Stevenson, R.J., Dingwell, D.B., Webb, S.L., Sharp, T.G., 1996. Viscosity of microlite-bearing rhyolitic obsidians: an experimental study. *Bull. Volcanol.* 58, 298–309.
- Stewart, R.B., Price, R.C., Smith, I.E.M., 1996. Evolution of high-K arc magma, Egmont volcano, Taranaki, New Zealand: evidence from mineral chemistry. *J. Volcanol. Geotherm. Res.* 74, 275–295.
- Taylor, G.A.M., 1958. The 1951 eruption of Mount Lamington, Papua. Department of Resources and Energy, Bureau of Mineral Resources. *Geology and Geophysics*, vol. 38, 129 pp.
- Thomas, N., Jaupart, C., Vergnolle, S., 1994. On the vesicularity of pumice. *J. Geophys. Res.* 99, 15633–15644.
- Topping, W.W., 1972. Burrell Lapilli eruptives, Mount Egmont, New Zealand. *N.Z. J. Geol. Geophys.* 15, 476–490.
- Tuffen, H., Dingwell, D.B., Pinkerton, H., 2003. Repeated fracture and healing of silicic magma generate flow banding and earthquakes? *Geology* 31, 1089–1092.
- Wellman, H.W., 1962. Holocene of the North Island of New Zealand: a coastal reconnaissance. *Trans. R. Soc. N.Z. Geol.* 1, 29–99.
- Wright, H.M.N., Cashman, K.V., Rosi, M., Cioni, R., 2007. Breadcrust bombs as indicators of Vulcanian eruption dynamics at Guagua Pichincha volcano, Ecuador. *Bull. Volcanol.* 69, 281–300.