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B. F. Houghton · C. J. N. Wilson · M. D. Rosenberg
I. E. M. Smith · R. J. Parker

Mixed deposits of complex magmatic and phreatomagmatic volcanism: an example from Crater Hill, Auckland, New Zealand

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Abstract A series of alternating phreatomagmatic ("wet") and magmatic ("dry") basaltic pyroclastic deposits forming the Crater Hill tuff ring in New Zealand contains one unit (M1) which can only be interpreted as the products of mixing of ejecta from simultaneous wet and dry explosions at different portions of a multiple vent system. The principal characteristics of M1 are (a) rapid lateral changes in the thicknesses of, and proportions in juvenile components in individual beds, and (b) wide ranges of juvenile clast densities in every sample. M1 appears to have been associated with an elongate source of highly variable and fluctuating magma:water ratios and magma discharge rates. This contrasts with the only other documented mixed (wet and dry) basaltic pyroclastic deposits where mixing from two point sources of quite different but stable character has been inferred.

Key words Explosive volcanism · Magmatic · Phreatomagmatic · Crater Hill · Basalt

Introduction

Crater Hill is a complex basaltic centre within the late Quaternary Auckland volcanic field in New Zealand (Fig. 1). Six of seven pyroclastic units at Crater Hill are conventional phreatomagmatic or magmatic (i.e. dry explosive) deposits. The seventh unit is most unusual for the extreme diversity of its juvenile ejecta. We suggest that this bed resulted from simultaneous magmatic and weakly and strongly phreatomagmatic eruptions from adjacent portions of an elongate vent system probably a few hundred metres in length.

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B. F. Houghton (✉) · C. J. N. Wilson · M. D. Rosenberg
Institute of Geological and Nuclear Sciences, Wairakei Research Centre, Private Bag 2000, Taupo, New Zealand

I. E. M. Smith · R. J. Parker
Department of Geology, University of Auckland, Private Bag 92019, Auckland, New Zealand

Crater Hill: landforms and stratigraphy

Crater Hill consists of four near-concentric landforms now severely modified by quarrying and highway construction. In order of decreasing age, these are the tuff ring, scoria cone 1, the lava shield and scoria cone 2 (Fig. 2). The tuff ring is near-circular, 850–900 m across and 9–15 m high. It was constructed in two principal episodes: an early phreatomagmatic phase (P1) and a later mixed magmatic/phreatomagmatic phase (M1), which is the subject of this paper. The overlying P2

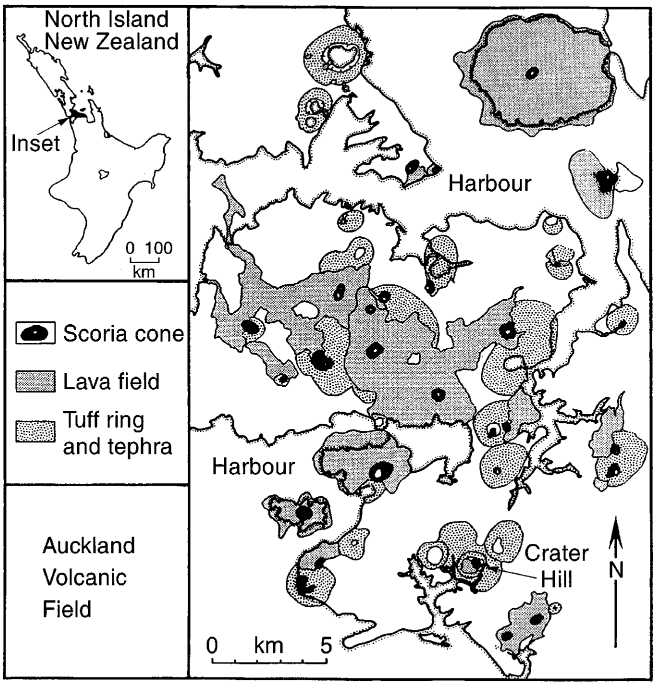

Fig. 1 Map of the Auckland volcanic field. (After Kermode 1983)

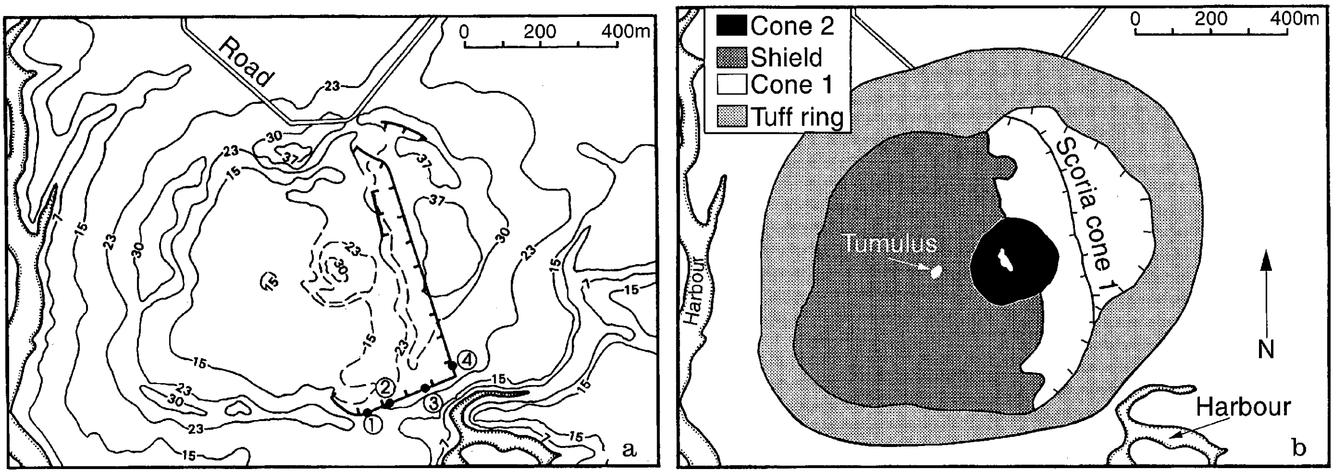

Fig. 2 **a** Topographic and **b** landform maps of Crater Hill volcanic centre. *Dashed contours* represent features now removed by quarrying. *Numbered localities* are those referred to in the text and in subsequent figures. Contours are in metres

Fig. 3 Southeastern quarry face at Crater Hill. The overall thickness of unit M1 is relatively uniform, but single beds thicken and thin significantly. The *arrow* indicates the location of subunit M1d. Below this the principal subunits, a and c, thin from right (west) to left (east). The reverse holds for subunits g and i above M1d. The quarry face is approximately 15 m high

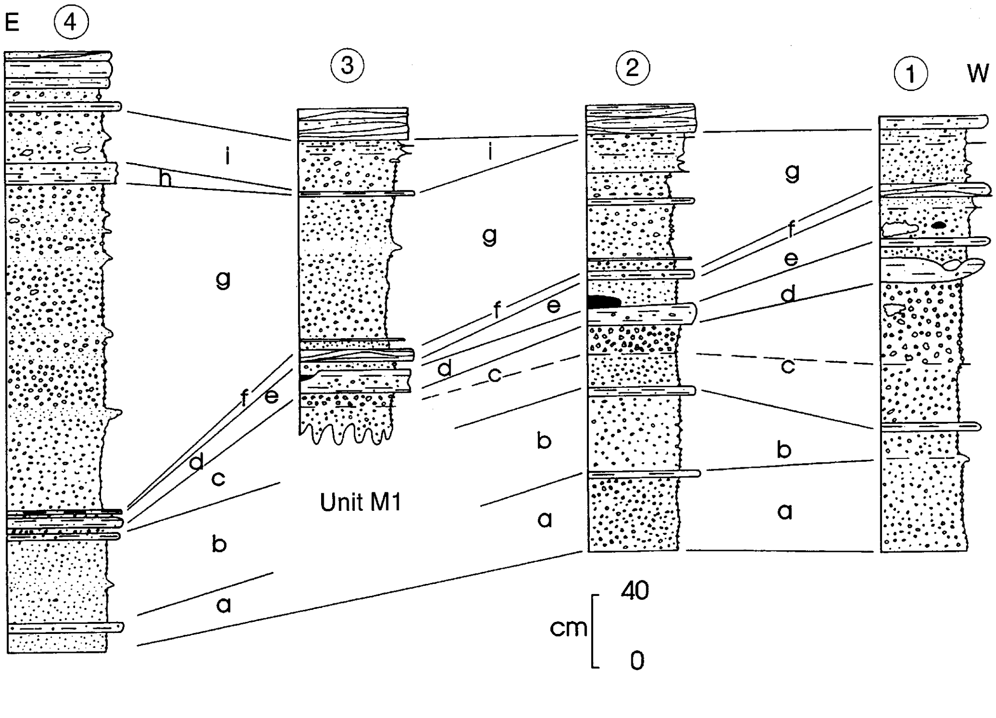

Fig. 4 Stratigraphy of unit M1 at localities 1–4 (Fig. 2). Note the rapid thickness changes in single lapilli fall beds. *Letters* refer to subunits used in correlations

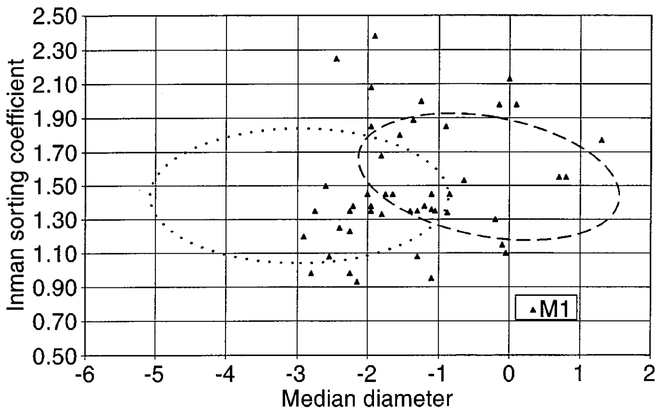

Fig. 5 Plot of Median diameter (Mdϕ) and Inman sorting coefficient ($\sigma\phi$) for all samples from unit M1 at Crater Hill. *Dashed* and *dotted lines* enclose all other phreatomagmatic [P1, P2] and magmatic (i.e. Strombolian [M3] and Hawaiian [M2, M4]) deposits at Crater Hill, which are included for comparison

phase coincided with collapse of the inner walls of the tuff ring to form a maar, and growth of scoria cone 1 (Fig. 2) followed in phase M2 and subsequently. The pyroclastic units are well exposed in the eastern and southern quadrants along two quarry faces (Fig. 3), although M1 lies mostly below the quarry floor along the E face.

Deposits of phase M1

The M1 deposit, formed during the later stages of tuff ring construction, is predominantly of pyroclastic fall origin, consisting of black and brown matrix-poor lapilli beds with minor protruding ash ribs (Figs. 3 and 4). Juvenile clasts make up more than 95% by weight of most samples. This feature and its matrix-poor character are similar to the later magmatic deposits at Crater Hill (M2–M4). However, M1 is well bedded, always containing minor amounts of lithic clasts, and its juvenile clasts show an extremely wide range of vesicularity. In addition, clast morphologies vary widely, from angular and blocky, accompanying low vesicularities, to ragged (Strombolian) or fluidal (Hawaiian) with high vesicularities. The overall features of M1 are less compatible with the pure end-member magmatic eruption styles shown by units M2–M4.

M1 can be subdivided into nine major lapilli fall and thick ash beds (beds a to i) and numerous thinner fine ash layers (Fig. 4). The thick ash beds show low-angle cross-stratification, internal erosional relationships and lensoidal concentrations of lapilli, taken together as evidence for emplacement by pyroclastic surges. These ash-rich beds contain steep-sided sags beneath bombs and blocks implying that they were deposited in a wet plastic state. The overall thickness of M1 is relatively uniform along strike (Fig. 3), but the thicknesses of the individual beds vary greatly over a distance of 300 m (Fig. 4). Beds a, c, d and e thicken westward, whereas b, g, h and i thicken to the east.

Grain-size characteristics of M1

Most samples from M1 have grain-size medians and Inman sorting coefficients overlapping with and intermediate between Crater Hill magmatic (Strombolian and Hawaiian) and phreatomagmatic beds (Fig. 5). The grain-size data alone do not give any indication of the complex origin of this unit.

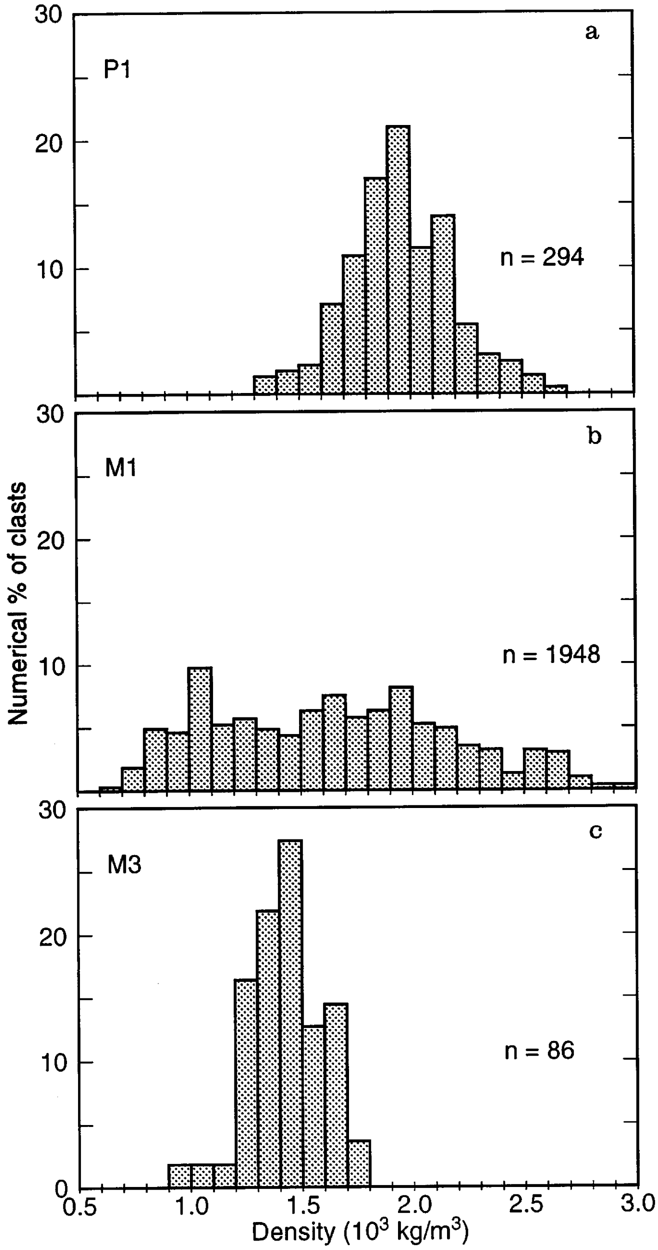

Fig. 6 Plot to compare juvenile clast density data for unit M1, vs that for units P1 (earlier phreatomagmatic tuff-ring building phase) and M3 (typical of "dry" or magmatic forming scoria cone 1 deposits) at Crater Hill

M1 clast density/vesicularity data

Single clast densities were measured in the 16- to 32-mm-size fractions of samples by water immersion (after coating clasts with a waterproof spray of film) using Archimedes' principle (see Houghton and Wilson 1989). Densities were converted to vesicularities using a DRE value of 3000 kg/m^3. Samples from M1 define an unusually broad range of juvenile clast density. The 1948 clasts measured from this unit define a flat, broad density histogram unlike any other phreatomagmatic or magmatic unit at Crater Hill (Fig. 6). Four general types of density distributions can be defined from samples from single stratigraphic horizons within M1 at separate locations (Fig. 7):

Type i: A well-defined density peak at 600–700 kg/m^3 (75–80% vesicles) with a minor tail of denser clasts
Type ii: A broad but still clearly defined peak at 1800–2000 kg/m^3 (35–40% vesicles)
Type iii: Bi- or poly-modal peaks between 600 and 2300 kg/m^3
Type iv: A very wide range of clast density with no clear peaks

The significance of these types is discussed later, after we describe the considerable lateral and vertical variability in M1.

Lateral variability

There are both significant *vertical* differences in density between samples from different beds at the same locality, and *lateral* differences between samples from the same bed at different localities. The lateral variations must be kept in mind when describing vertical changes in the clast populations; thus, we describe them first. Lateral variability is present on the scale of the entire unit. A plot of all data for all clasts collected from each locality, regardless of stratigraphic position (Fig. 8), shows a bimodality of the clast population at each site, with peaks at 700–800 kg/m^3 (73–77% vesicles), and 1800–1900 kg/m^3 (37–40% vesicles). However, at western localities, clasts of density 600–800 kg/m^3 are dominant, whereas this population is reduced in significance in the most eastern section (Fig. 8).

The lateral changes are even more striking on the scale of single beds (Fig. 9). The two beds which thin to the west were chosen because one (M1b) shows a dominance of highly vesicular scoria at all localities, whereas M1g contains clasts with much wider ranges of density and vesicularity. However, in both westward-thinning beds there is a significantly higher proportion of highly vesicular clasts at the eastern locality. In eastward thinning beds there is also higher proportion of highly vesicular clasts at the eastern locality. The thinning of beds is not accompanied by any visible change in grain size.

Vertical variability

Vertical density changes in the juvenile clast assemblages are shown in Fig. 10. The lower one third to one half of M1 (beds M1a, M1b, M1c) is dominated by type i distributions, with a strong predominance of clasts of density 600–800 kg/m^3 (73–80% vesicles). These are the most vesicular clast assemblages found anywhere at Crater Hill, even among the "end-member

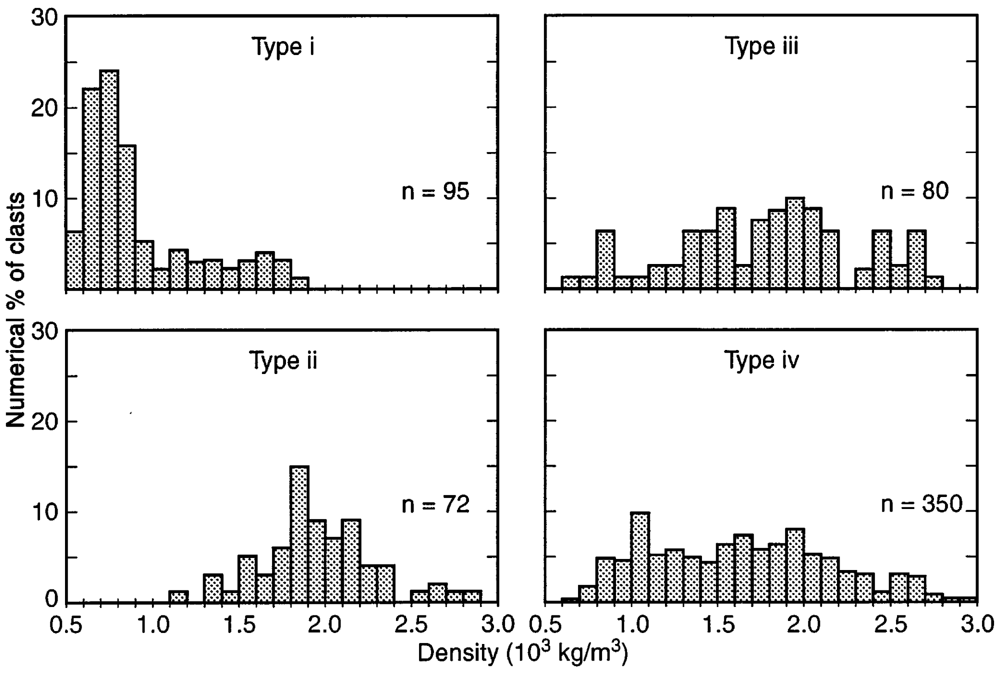

Fig. 7 Plot of juvenile clast density for four representative samples from single stratigraphic levels in M1, showing characteristic density patterns

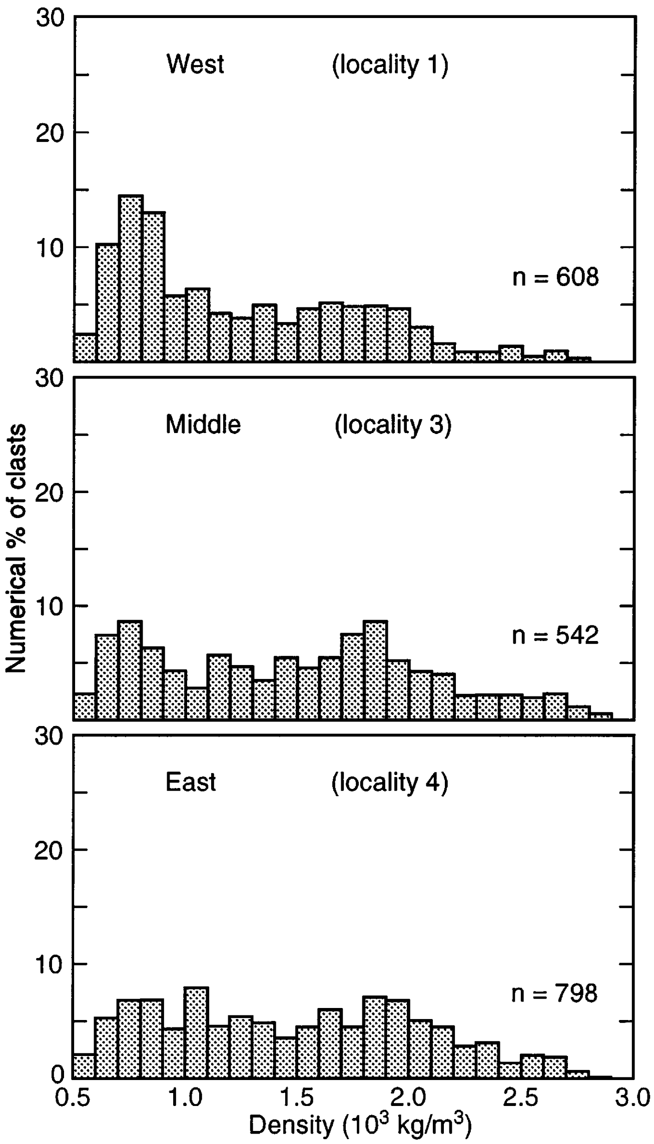

Fig. 8 Plot of density measurements, irrespective of stratigraphic position, for all juvenile clasts from M1 at three localities marked in Fig. 2

dry" Hawaiian M2 and M4 beds. M1d has a very low number of measurable clasts at most sites, and the single representative M1d sample has a type ii distribution. M1e contains a very wide range of clast densities/vesicularities of type iv. M1g is of type iii, i.e. weakly poly-modal with a significant highly vesicular component, particularly at eastern localities. M1i is dominated by a type ii distribution of clasts.

Summary of clast density characteristics

The key facts which emerge from the density data are:

No single M1 sample matches the typical signatures of the other magmatic or phreatomagmatic units at Crater Hill (Fig. 6)

In each bed highly vesicular clasts are more dominant in the eastern sites (Fig. 8)

Data for all clasts at single localities suggest a predominance of two modes of clast density (Fig. 8)

Single beds show pronounced lateral changes over ca. 300 m (Fig. 9)

Interpretation

Eruption mechanisms

Unit M1 is a most difficult deposit to model in conventional terms. The lack of abundant fine ash, predominance of relatively well-sorted lapilli fall deposits, and abundance of juvenile ejecta all suggest only moderate involvement of external water in fragmentation (cf. units P1–3 at Crater Hill). However, the wide ranges in density of the juvenile ejecta in most samples suggest that, for much of M1 time, magma was being fragmented at many different points during its vesiculation history. Unless the magma vesicularity was heterogeneous on a very small scale, which seems inherently unlikely, the diversity of vesicularity values implies that fragmentation was occurring over some extended region. Unit M1 does not appear to be the product of simultaneous wet and dry volcanism from discrete sources of differing yet stable eruptive styles (cf. Houghton and Schmincke 1986), because the proportions of magmatic and phreatomagmatic clasts change both vertically and laterally within the deposits. An alternative which could supply a diverse and variable assemblage of juvenile clasts is a number of sources spaced out along an elongate (fissure) vent system. Discharge rates of magma and/or the extent of magma/water interaction could have varied along the vent system, leading to production of clasts of varying vesicularity which then mixed in the eruption plume.

We suggest that different and variable water/magma ratios prevailed at different points along the vent system throughout deposition of unit M1, but eruption from either more easterly or more-westerly sources dominated discharge to the eruption column and deposition for each bed. Each level in each bed is considered to contain a mixture of clasts erupted from different vents, because of the extreme diversity of vesicularity in every sample. However, different parts of the vent system and different water/magma ratios must have prevailed at certain times to explain the rapid eastward or westward thinning of beds and the presence of beds with bi- or tri-modal density/vesicularity distributions. The intricate intercalation of beds with different eruptive styles and alternating directions of thickening (Fig. 4), together with the lateral variations in clast-density populations, preclude these thickness variations being solely due to changes in wind direction during phase M1.

Unit M1 contrasts with the only other well-docu-

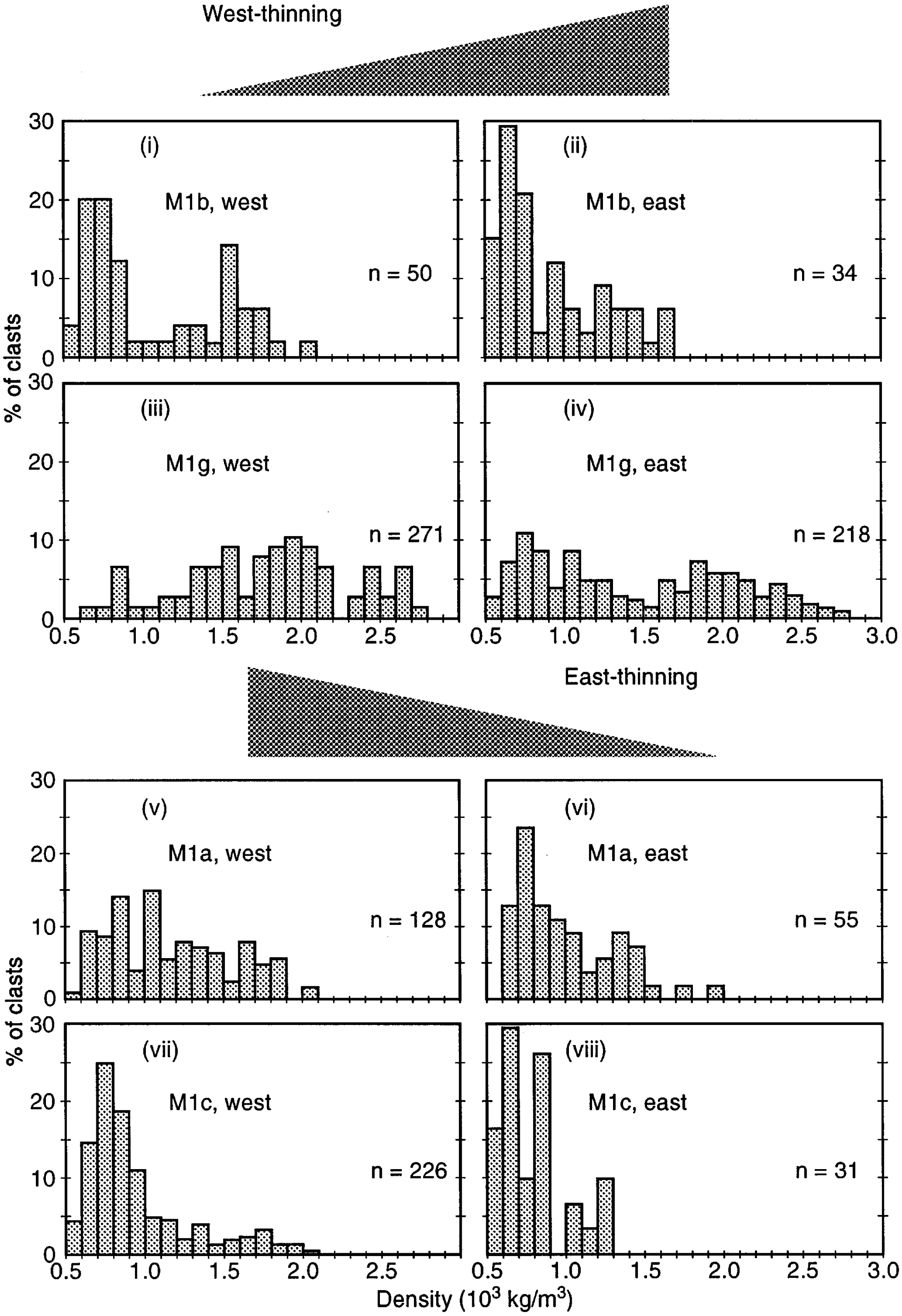

Fig. 9 Plot of juvenile clasts densities from two westward-thinning fall beds (*i, ii, iii, iv*) and two eastward-thinning fall beds (*v, vi, vii, viii*) at western (locality 1) and eastern (locality 4) localities. Note that all four units contain a significantly higher proportion of less-dense (more-vesicular) clasts at the eastern locality

mented mixed wet and dry beds (Houghton and Schmincke 1986; Houghton and Smith 1993) where two discrete sub-populations can be recognised and assigned to two discrete point sources, each of relatively uniform eruptive style. M1 appears to be associated with a multi-vent source of quite variable and fluctuating magma/water ratio.

We interpret type i and type ii clast distributions as those produced at times when one eruptive style dominated at the principal active vents. Type i distributions were produced when external water was denied access to most of the vents and magmatic volcanism predominated. On some occasions the principal magmatic vent(s) were at the eastern end of the fissure (e.g. bed M1b); at other times the main vent(s) were to the west (e.g. beds M1a, M1c). Type ii distributions resulted when uniformly phreatomagmatic conditions predominated at the principal vent(s).

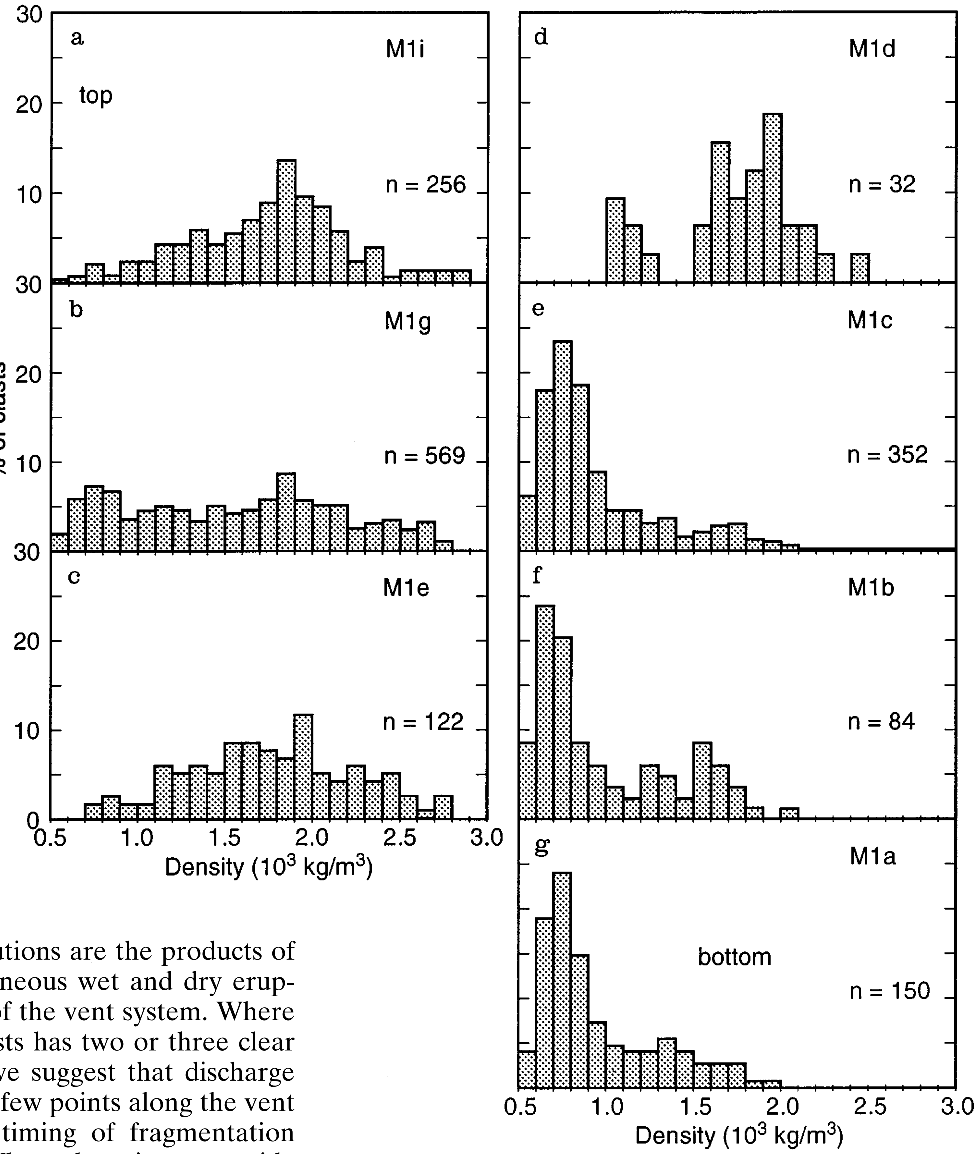

Fig. 10a–g Vertical variability in density of juvenile clasts between subunits of M1. Histograms plot density values for all clasts collected from each bed, regardless of locality

Type iii and type iv distributions are the products of mixing of ejecta from simultaneous wet and dry eruptions from different portions of the vent system. Where the population of juvenile clasts has two or three clear vesicularity modes (type iii) we suggest that discharge was concentrated at relatively few points along the vent system, each with a unique timing of fragmentation with respect to vesiculation. Where there is a very wide range of vesicularity and no sharp vesicularity mode (type iv), discharge was probably at a more uniform rate along the vent system.

Eruptive history

A near symmetrical tuff ring formed rapidly during P1 volcanism, and there is no indication of anything other than a constant, high water: magma ratio at this stage of the eruption. Some factor(s) then led to a decreased, but variable, water: magma ratio and deposition of M1. Either a decrease in the flux of water to the point of fragmentation or an increased discharge rate of magma could have accomplished this. The first could have resulted from migration of the fragmentation away from the level of an aquifer in the pre-eruptive sediments, but the second alternative seems more probable. A general feature of alternating phreatomagmatic/magmatic eruptions is that the discharge rate is higher during magmatic phases (Houghton and Nairn 1991) implying that magma flux is the principal control. The start of M1 volcanism was straightforward, with the bulk of the magma fragmenting at the peak of its vesiculation, with negligible involvement of external water. These relatively stable conditions did not persist. We suggest that the diversity of juvenile clasts in the remainder of M1 was produced by an extension of the vent system, possibly as a line of vents along a fissure. Discharge rates of magma and/or the extent of magma/water interaction then varied between vents, leading to production of clasts of variable vesicularity which were then mixed in the eruption column.

Western sources prevailed during the first half of M1 especially for beds M1a and M1c, culminating in essentially "end-member" dry Hawaiian fire-fountaining during M1c, whereas eastern sources prevailed for the second half. M1 volcanism was terminated by crater collapse, and renewed phreatomagmatic volcanism then cleared the vent system, forming P2 deposits.

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