correspondence

Magma balloons or bombs?

To the Editor — Detailed analysis of volcanic materials[1] allows the study of eruptions that have not been witnessed directly. Rotella *et al.*[2] undertake the challenge of interpreting submarine volcaniclastic deposits around Macauley Volcano, part of the Kermadec Arc in the southwest Pacific Ocean. They propose a ‘Tangaroan’ eruption style, based on the textural characteristics of dredged pumice clasts. However, we argue that the analytical methodology provides an inadequate basis for the identification of a new eruption style.

The style of an eruption is determined based on a suite of parameters that define the duration, mass eruption rate and degassing behaviour of the eruption[3]. To define eruptive style, a single event must be isolated in the volcanic stratigraphy. Additionally, to link vesicle textures observed within individual clasts with magma-degassing behaviour, it must be shown either that all the samples represent a single magma type, or that a variety of magma types are associated with the same distinctive vesicle texture. Otherwise, variations in vesicle textures caused by magma degassing cannot be isolated from those resulting from variations in major element content, volatile composition and temperature. The samples used by Rotella *et al.*[2,4] were dredged along seven transects, each hundreds of metres in length. They probably originate from different eruptions, as demonstrated by the large range in chemical composition and isotopic signatures[5]. Moreover, clast density varies widely and inconsistently with composition[5]. Because individual eruptive events cannot be distinguished, and the textural and geochemical variations are relatively large, the degassing histories of clasts within the deposit cannot be attributed to a single style, much less underpin a previously unrecognized eruption type.

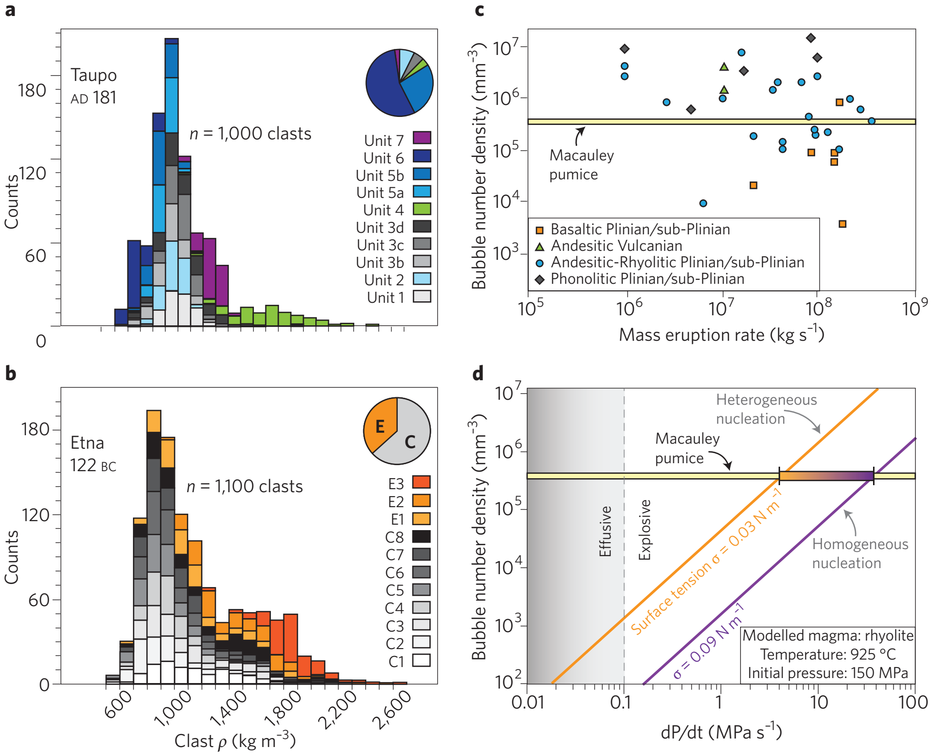

Figure 1 | Pyroclast density and bubble number density interpretations. **a**,**b**, Stacked density distribution of pyroclasts from the AD 181 Taupo (New Zealand)[5] (**a**) and 122 BC Etna (Sicily)[6] (**b**) eruptions, after merging all eruptive units. Pie charts of erupted volumes per unit show that merging distributions disregards their relative volumetric contribution. **c**, Bubble number densities within pyroclasts are not correlated with eruption rate[8]. **d**, However, they can be used to calculate decompression rates assuming either homogeneous or heterogeneous nucleation (controlled by σ). Decompression rates calculated for the Macauley magmas range between about 4 to 35 MPa s^{-1} (orange-to-purple gradient box), typical of explosive eruptions[8]. Model parameters for calculations in **d** are detailed in the Supplementary Information.

Rotella *et al.*[2] also cite bimodal clast-density distributions as evidence for a unique eruption style. However, the distributions are obtained by aggregating data from samples collected from multiple transects, thus probably from separate eruption events. Such data stacking produces a composite picture that masks the styles of individual events. To demonstrate the consequences of this procedure, we apply the same treatment to pyroclast-density data from two well-characterized, subaerial explosive sequences. The magmas have homogeneous bulk compositions and each sequence is composed of discrete eruptive units that exhibit a range of eruptive styles (Fig. 1a,b). The bimodal density distributions in our stacked data are similar to those of the Macauley samples[2], illustrating the failure of this stacking procedure to recover the degassing history of a nuanced eruptive sequence.

Finally, Rotella *et al.*[2] analysed in detail a single ‘gradient clast’, interpreted to represent the contact between the quenched rim and expanded interior of a pumice clast. They suggest the gradient clast is the remnant of a distinct parcel, or bleb of magmatic foam that detached from the volcanic conduit, but we present an alternative interpretation (Supplementary Information). The bubble number densities (BNDs) calculated for this clast span an order of magnitude, similar to values inferred for highly explosive, high mass eruption rate (MER > 10^6 kg s^{-1}) subaerial events[6–8] (Fig. 1c). However, because BNDs depend on water concentration and diffusivity, the availability of nucleation substrates and magma temperature[9], the values are too scattered to allow discrimination of MER. Instead, BNDs can be used to assess eruption style through calculation[9] of magma decompression rate, dP/dt (Fig. 1d). Calculated dP/dt for the Macauley pumice varies from about 4 to 35 MPa s^{-1}. These ascent rates impose high levels of shear strain[10] and should promote magma fragmentation in the conduit. Rapid magma ascent is also consistent with the absence of microlite crystallization in the Macauley magmas[2]. The high BNDs therefore do not support the low-to-intermediate magma discharge rates that would be consistent with bleb detachment[2]. Rather, the Macauley data seem to preserve evidence of an explosive style, consistent with recognized styles of submarine pumice eruptions[11]. ❐

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Additional information

Supplementary information accompanies this paper on www.nature.com/naturegeoscience.

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Authors' reply — Shea *et al.* raise three issues pertaining to our work[1]. First, they argue that our pyroclasts were potentially from different eruptions or magma types with different degassing histories. However, we do not require the Tangaroan pyroclasts to be from a single eruption; indeed, we propose that this style can apply to magmas of diverse compositions for eruptions at submarine volcanoes worldwide. At Macauley Volcano, glass chemistries for Tangaroan dredged pyroclasts are dacitic[1] and the clasts lack microlites, indicating a common history without significant degassing[2]. Furthermore, we do not claim that all dredged pyroclasts are Tangaroan in origin[3]. Some high-density microlite-bearing clasts, for example, have contrasting textures interpreted to reflect dome-forming eruptions[3].

Second, Shea *et al.* argue that our stacked density data provide a misleading representation of the density distributions for individual eruption events. However, as discussed in ref. 3, irrespective of whether the data are derived from individual stratigraphic levels, single or multiple eruption sequences or dredge hauls, the pyroclast density characteristics from the four volcanoes we have studied are consistent within and distinctive between the volcanoes and eruptive settings. We chose only one representative Tangaroan clast for detailed discussion, but descriptions and analyses of more clasts are presented elsewhere[4]. The stacking of density data presented in Fig. 1 from Shea *et al.* is misleading. The Taupo eruption density bimodality (Fig. 1a) is caused by data from differing eruption styles, recognisable from textural characteristics. The high-density mode represents microlite-rich, degassed clasts from phreatoplinian (Unit 4) and sub-lacustrine effusive (Unit 7) phases, whereas their low-density mode is caused by microlite-poor, highly explosive plinian eruptions[5]. In contrast, the Tangaroan-style pyroclasts we have studied span both density modes. Individual fragments are linked by the density values and textures across the gradient clasts[1].

Third, Shea *et al.* compare our data to selected data from pyroclasts with differing magma compositions and crystal contents (Fig. 1c). They assert that the Tangaroan discharge rate was equally high and the activity explosive. This comparison is misplaced because explosively erupted magmas with similar compositions to ours show higher bubble number density (BND) values. For example, the Mount St Helens eruption in Washington in 1980 generated clasts with BND values of 8.2×10^8 cm^{-3} (ref. 6) and the Mount Mazama eruption in Oregon around 7,700 years ago generated clasts with BND values of 6.0×10^9 cm^{-3} (ref. 7). In contrast to Shea *et al.*, we conclude that BND values from natural pyroclasts are often higher than those obtained through experiments[8] or numerical simulations[9]. The equations[9] on which Shea *et al.* construct their comparative argument are based on a single, homogenous nucleation event that produces bubbles with a narrow size range. Such conditions are more easily replicated in experimental simulations. Natural pyroclasts, however, may result from multiple nucleation events or continuous nucleation before fragmentation (for example, ref. 10 and references therein).

Comparison between the denser, quenched rims of the Tangaroan clasts from Macauley Volcano and subaerially erupted pyroclasts with similar chemistries and crystal contents taken from Raoul Volcano (also part of the Kermadec Arc in the southwest Pacific Ocean) shows that the BND values of the Tangaroan clast rims are significantly lower than the BND values of 2.6×10^9 to 1.9×10^{10} cm^{-3} measured for the Raoul clasts that were erupted in explosive events[4]. We therefore conclude that when relevant data are compared on an equal basis, our proposal for the Tangaroan eruption style remains fully justified and open to further application. ❐

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