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Dynamics of deep submarine silicic explosive eruptions in the Kermadec arc, as reflected in pumice vesicularity textures

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ABSTRACT

Despite increasing recognition of silicic pumice-bearing deposits in the deep marine environment, the processes involved in explosive silicic submarine eruptions remain in question. Here we present data on bubble sizes and number densities (number of bubbles per unit of melt matrix) for deep submarine-erupted pumices from three volcanoes (Healy, Raoul SW and Havre) along the Kermadec arc (SW Pacific) to investigate the effects of a significant (>~1 km) overlying water column and the associated increased hydrostatic pressure on magma vesiculation and fragmentation. We compare these textural data with those from chemically similar, subaerially-erupted pyroclasts from nearby Raoul volcano as well as submarine-erupted 'Tangaroan' fragments derived by non-explosive, buoyant detachment of foaming magma from Macauley volcano, also along the Kermadec arc. Deep submarine-erupted pumices are macroscopically similar (colour, density, texture) to subaerial or shallow submarine-erupted pumices, but show contrasting microscopic bubble textures. Deep submarine-erupted pyroclasts have fewer small (<10 μm diameter) bubbles and narrower bubble size distributions (BSDs) when compared to subaerially erupted pyroclasts from Raoul (35–55 μm vs. 20–70 μm range in volume based median bubble size, respectively). Bubble number density (BND) values are consistently lower than subaerial-erupted pyroclasts and do not display the same trends of decreasing BND with increasing vesicularity. We interpret these textural differences to result from deep submarine eruptions entering the water column at higher pressures than subaerial eruptions entering the atmosphere (~10 MPa vs. 0.1 MPa for a vent at 1000 mbsl). The presence of an overlying water column acts to suppress rapid acceleration of magma, as occurs in the upper conduit of subaerial eruptions, therefore suppressing coalescence, permeability development and gas loss, amounting to closed-system degassing conditions. The higher confining pressure environment of deep submarine settings hinders extensive post-fragmentation clast expansion, coalescence of bubbles, and thinning of bubble walls, causing clasts to have similar BND values regardless of their vesicularity. Although deep submarine-erupted pyroclasts are closely similar to their subaerial counterparts on the basis of bulk vesicularities and macroscopic appearance, they differ markedly in their microscopic textures, allowing them to be fingerprinted in modern and ancient pumiceous marine sediments.

1. Introduction

Eruptive conditions accompanying voluminous pumice-forming submarine eruptions have been the centre of much study and debate, driven by challenges in observations and documentation (e.g., Fiske and Matsuda, 1964; Burnham, 1983; Cas et al., 1990; Cashman and Fiske, 1991; Fiske et al., 2001; White et al., 2003; Wohletz, 2003; Busby, 2005; Downey and Lentz, 2006). For some time, it was widely accepted that pumice-forming eruptions could not occur under pressures in excess of the critical point of seawater (~2200–3000 m water depth depending on salinity), and were unlikely at >1000 m water depth (e.g., McBirney, 1963; Cas and Wright, 1987; Cas et al., 1990; Cas, 1992). This view has changed in recent years as seafloor exploration has documented an increasing number of deepwater silicic calderas and pumice outcrops, many at depths of >1000 m below sea level (mbsl). Submarine calderas and pumice deposits have now been described from the Izu–Bonin arc (Halbach et al., 1989; Fiske et al., 2001; Yuasa and Kano, 2003; Kutterolf et al., 2014), the Woodlark and eastern Manus basins (Binns, 2003), the southern Mariana arc (Bloomer and Stern, 2001) and along the Tonga–Kermadec arc (Wright et al., 1998,

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2003, 2006; Wright and Gamble, 1999; Barker et al., 2012). In addition, numerical and experimental models have aided the understanding of volatile exsolution processes and indicated that explosive eruptions can theoretically occur at pressures equivalent to water depths of >3 km (Burnham, 1983; Wohletz, 2003; Downey and Lentz, 2006; Stix and Philips, 2012), provided that dissolved volatile contents and discharge rates are sufficiently high.

In the subaerial environment, the dynamics of explosive pumice-forming eruptions are widely documented, with in-situ field studies, eye-witness observations and experimental and theoretical models providing an extensive understanding of eruption processes, from bubble nucleation and vesiculation through to plume dynamics (e.g., Sparks, 1986; Woods, 1988; Cashman and Mangan, 1994; Klug and Cashman, 1994; Sparks et al., 1997; Cichy et al., 2011; Gonnermann and Houghton, 2012). Parallels have not been widely drawn, however, to silicic eruptions in the submarine environment, as many of the relevant parameters are difficult to model and constrain due to: (1) the vastly different conditions and range of unconstrained variables (e.g., multiple phases present, large density contrasts, and processes occurring within the probable range of the critical point of seawater) (e.g., McBirney, 1963; Kano et al., 1996; Wohletz, 2003; Downey and Lentz, 2006; Woods, 2010), and (2) the difficulty of sampling and interpreting deposits in the comparatively inaccessible and grossly under-observed submarine environment (e.g., Halbach et al., 1989; Fiske et al., 2001; Hekinian et al., 2008). Therefore, many questions remain about the effect(s) that a large overlying water column has on silicic explosive eruption processes. In this paper we advance the current knowledge of submarine silicic explosive eruptions through a quantitative investigation of vesicularity textures in deep submarine-erupted pumice pyroclasts.

Quantitative 2-D textural studies of subaerial-erupted pyroclasts have provided valuable insights into magma storage, ascent and eruption conditions for silicic explosive eruptions both in natural (e.g., Toramaru, 1990; Klug and Cashman, 1994; Polacci et al., 2001, 2003; Klug et al., 2002; Houghton et al., 2003, 2010; Gurioli et al., 2005; Carey et al., 2009; Giachetti et al., 2010, 2011; Shea et al., 2010; Alfano et al., 2012; Rotella et al., 2013, 2014) and experimentally derived pyroclasts (e.g., Hurwitz and Navon, 1994; Mangan and Sisson, 2000; Mourtada-Bonnefoi and Laporte, 2004; Burgisser and Gardner, 2005; Gardner and Ketcham, 2011). This study uses a similar approach by measuring bubble size and number density characteristics from 2D thin section images. Pyroclast bubble textural data and major element glass chemistry in clasts from three deep submarine volcanoes (Healy, Raoul SW, Havre) are compared to subaerially erupted pyroclastic deposits sampled within stratigraphic intervals from Raoul volcano (Rotella et al., 2014) and submarine-erupted ‘Tangaroan’ pyroclasts dredged from the seafloor around Macauley volcano, which are interpreted to have been generated non-explosively at intermediate eruption rates (Rotella et al., 2013). By comparing and contrasting vesicle textures from each eruptive setting, we show that the presence of a deep overlying water column significantly affects vesiculation processes during eruption and that deep submarine-erupted pumices may be uniquely distinguishable by their vesicle microtextures.

2. Geological setting and sample collection

The Kermadec arc (Fig. 1) results from intra-oceanic subduction of the Pacific plate beneath the Indo-Australian plate to the northeast of New Zealand (Smith and Price, 2006, for overview). The arc consists dominantly of submarine volcanoes, with only Raoul, Macauley, Curtis and L'Esperance volcanoes being partially emergent (Fig. 1). The occurrence of silicic explosive volcanism along the arc has long been apparent in subaerial deposits (e.g., Brothers and Martin, 1970; Lloyd and Nathan, 1981; Lloyd et al., 1996). However, not until detailed bathymetric mapping and submarine sampling was undertaken was it recognised that submarine caldera-related, silicic explosive volcanism is widespread (e.g., Wright and Gamble, 1999; Haase et al., 2002; Wright et al., 2002, 2003, 2006; Graham et al., 2008). The Kermadec arc volcanoes offer the opportunity to compare and contrast eruptions in the subaerial and deep submarine environments as they have explosively erupted silicic magmas within the last 10 kyr (Lloyd and Nathan, 1981; Lloyd et al., 1996; Worthington et al., 1999; Wright, 2001; Smith et al., 2003a,b, 2006; Wright et al., 2003, 2006; Barker et al., 2012, 2013; Carey et al., 2014; Rotella et al., 2014). Samples for this study were acquired during the 2007 voyage of the R.V. *Tangaroa* (TAN0706) by seafloor dredging at Healy and Raoul SW volcanoes, and by the H.M.N.Z.S. *Canterbury* shipboard crew and scientists on 9 August 2012 from a floating pumice raft which resulted from the 19 to 20 July eruption of Havre volcano.

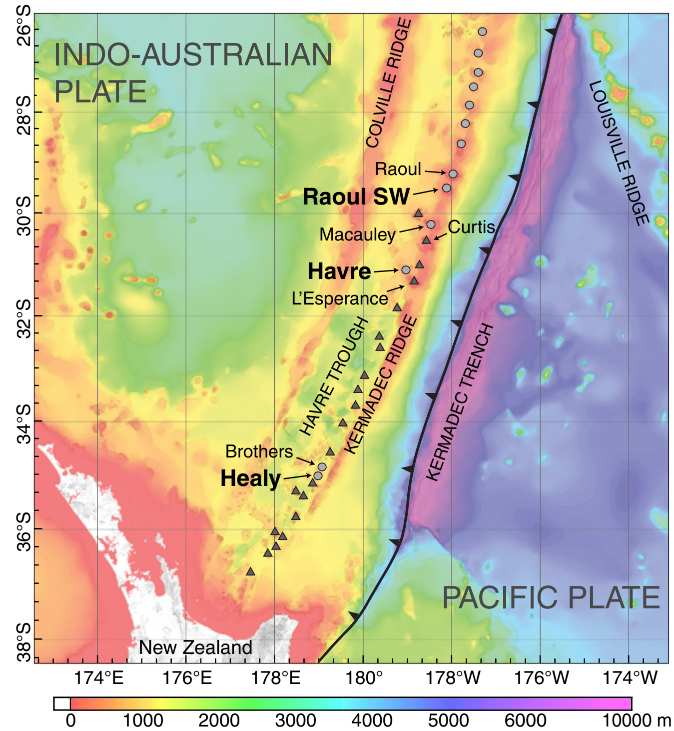

Fig. 1. Regional tectonic setting of the Kermadec arc resulting from the subduction of the Pacific plate under the Indo-Australian plate. Dark grey triangles represent basaltic–andesite volcanoes and light grey circles represent silicic caldera volcanoes. Volcanoes investigated in this study are in bold. Modified from Barker et al. (2012).

2.1. Healy volcano

Healy volcano is a wholly submerged silicic composite volcanic complex consisting of a central edifice with a smaller caldera (1.3 km diameter) at 1150 mbsl on its upper SW flank, and a larger caldera (~2 km diameter) at 1700 mbsl on its NE mid-lower flank (Fig. 2a) (Wright and Gamble, 1999; Barker et al., 2012). Sidescan sonar imagery and dredge sampling show that the volcanic complex is mantled with pumice deposits over an area of >50 km^2 (Wright and Gamble, 1999; Wright, 2001; Wright et al., 2003). Wright et al. (2003, 2006) suggested that a large recent eruption, to which they attributed 10–15 km^3 of pyroclastic material, caused the caldera collapse. Despite wide variations in clast colours and textures at Healy (Wright et al., 2006), analysed pumices occupy a narrow compositional range (69.5–71.5 wt.% SiO_2) in comparison to the broader compositional fields for eruptions sampled within the eruptive stratigraphy on Raoul volcano or dredged from the seafloor around Macauley volcano (Barker et al., 2012, 2013).