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Drivers of explosivity and elevated hazard in basaltic fissure eruptions: The 1913 eruption of Ambrym Volcano, Vanuatu (SW-Pacific)

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ABSTRACT

Fissure-eruptions along linear structures can extend for several tens of kilometres with distinct separate manifestations of volcanism along their length. They typically involve low-viscosity mafic magmas forming long lava flows and cinder cones. Eruptions in 1894 and 1913 on Ambrym volcano, Vanuatu, showed how these mildly explosive eruptions can rapidly transform into violent explosive events, producing significant hazard and widespread volcanic ash clouds. During the 1913 episode, a fissure began in the central caldera and basaltic magmas broke out in a series of locations down the island's western flank. In all sites over 100 m in elevation, fissure outbreaks produced vigorous lava fountains and highly fluid lava flows that travelled rapidly to the shoreline. When the outbreaks propagated along the island's axis into coastal plain areas, a climactic series of explosive eruptions occurred, producing a 1.2 km long by 600 m wide maar and tephra ring. A further small tuff ring was formed later, creating a temporary island 400 m offshore. The onshore tephra ring destroyed a hospital and associated buildings. Its last evacuating occupants were close witnesses to the eruption processes. Deposits exposed in the lower portion of the tephra ring show that this part of the eruption began with a mild phreatomagmatic explosive eruption from a narrow vent, followed by a magmatic scoria-producing phase. Subsequently a complex sequence of highly explosive phreatomagmatic eruptions occurred, producing pyroclastic surges, along with repeated distinctive breccia-horizons, rich in coral and lava country rock. These features tally with eye-witness accounts to indicate that the main eruption phase was produced by a periodically shifting locus of phreatomagmatic fragmentation and eruption along a single E-W fissure. The glassy and vesicle-poor pyroclasts produced during this eruption phase were dominantly fragmented in a brittle manner by magma water interaction. Low volatile content of the magma upon fragmentation is confirmed by FTIR analysis showing $<0.5\%$ H_2O in chilled glass. These findings highlight that a degassed, mafic, fissure-fed eruption can under certain circumstances pose a major volcanic hazard if dykes intersect substrates with abundant available water.

1. Introduction

Arguably the greatest hazard to life on basaltic volcanic islands is from explosive phreatomagmatic eruptions (Németh and Cronin, 2009a). While rare, large-scale caldera-centred eruptions may occur (Robin et al., 1993), more common large-scale events are fissure-eruptions. Fissure eruptions are known in association with wide range of composition from rhyolite (Sutton et al., 2000; Nairn et al., 2001; Speed et al., 2002; Spinks et al., 2005; Wilson et al., 2006; Darragh et al., 2006; Gravley et al., 2007) to basaltic (Stothers et al., 1986; Thordarson and Self, 1993; Thordarson et al., 1996; Thordarson and Larsen, 2007). Many such fissure eruptions, involve some phreatomagmatic explosive phases (e.g. Laki fissure eruption in Iceland: Thordarson and Self, 1993), but due to their remote locations their immediate hazard has not been well studied.

Many basaltic volcanic islands display strong axial rift structures, e.g., Lanzarote (Carracedo et al., 1992) or Taveuni (Cronin and Neall, 2001), where magmas have risen in long dykes to focus below numerous vents along an alignment, or en echelon set of fissures that can be tens of kilometres long. While this differs in principle from deep, mantle-derived magmas rising at isolated monogenetic volcanoes (Connor and Conway, 2000), at each eruption site along a fissure system, the volcanic styles and scales can be highly comparable. With low-viscosity arc basalts, such as those on several of the Vanuatu islands (Robin et al., 1993; Picard et al., 1995; Peate et al., 1997; Turner et al., 1999; Raos and Crawford, 2004), the hazard is linked primarily to explosivity, and depends mainly on environmental conditions encountered by vertically and horizontally propagating dykes and fissures and the degree to which point-focussing of magma discharge occurs.

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Phreatomagmatism along fissure systems appears to be most strongly controlled by the availability and recharge of external water, and the competence of the country rock, in a similar way to a diatreme fed maar and tuff ring eruptions (Lorenz, 1986). On the islands of Ambrym, Ambae, and Lopevi in central Vanuatu (Fig. 1A), the largest of historical eruptions have involved the rise of mafic magmas along fissure systems of up to 20 km in length. Highly fluid lava flows and lava-fountains coexisted with sustained phreatomagmatic explosive eruptions along the same alignment. This implies very low-internal gas contents and little magmatic-gas control on eruption explosivity and fragmentation. Here we investigate the conditions controlling the most explosive styles exhibited along basaltic fissure eruptions on volcanic islands, by reanalysing the eyewitness accounts and explosively emplaced deposits of the largest known recent explosive eruption on Ambrym Island, Vanuatu in 1913.

The western flanks of Ambrym (Figs. 1B, C, D and E) have experienced several generations of fissure eruptions, including two major eruption sequences in 1894 (Purey-Cust, 1896) and 1913 (Gregory, 1917; McCall et al., 1969). The December 1913 eruption occurred along a rift system that extended for over 19 km, forming two major lava sheets, at least five long lava flows into the sea, numerous spatter cones and at least one elongated tuff ring (Gregory, 1917) (Fig. 1B). This phreatomagmatic eruption completely destroyed a large hospital/missionary headquarters within minutes of its onset, with the inhabitants narrowly escaping by sea. The crater was initially excavated over 16 m below sea level and formed a lagoon within its c. 1.2 km length and 0.6 km width. Subsequent coastal modification and erosion of the tuff has cut off access to the sea to form a closed depression filled by a brackish lake. An eruption a further 400 m-offshore occurred soon after this vent inception (Gregory, 1917), although it appears that the landform and major part of deposits associated with this have since been eroded by wave action.

Erosion of the tephra ring during and since the eruption formed a broad, flat-lying apron of volcaniclastic deposits surrounding the main structure (Németh and Cronin, 2007). An exceptionally strong tropical cyclone season in AD 2000 caused coastal erosion to clear a near-continuous 1.5 km section of the elongated tuff-ring, allowing close examination of the proximal to distal pyroclastic facies of the deposits contained within (Fig. 1C). These, in turn, provide an insight to the nature of explosive eruption processes on such fissure-formed phreatomagmatic eruptions, along with understanding gained from studies of other historic maar eruptions, e.g. of the AD 1977 Ukinrek maar in Alaska (Kienle et al., 1980; Self et al., 1980; Büchel and Lorenz, 1993; Ort et al., 2000; Pirrung et al., 2008).

Rift-edge volcanism is well-known on ocean islands in many tectonic settings, such as Hawaii (USA), Ambae (Vanuatu), Izu-Oshima (Japan), Tenerife (Spain) and Jeju (Korea). Detailed study of the volcanic structures and the processes that generated them are, however, comparatively rare (Sohn et al., 2008; Németh and Cronin, 2009a). The volcanism is commonly phreatomagmatic and the deposits form the foundation for the lateral growth of volcanic islands (Cole et al., 2001; Németh and Cronin, 2009a). Being at the interface of land and sea means its activity poses volcanic hazards to adjacent coastal communities. Such volcanism in many parts of the SW Pacific is recorded in oral tradition (Nunn, 2003; Németh and Cronin, 2009b).

2. Geological setting and morphology of the tephra ting

Ambrym has one of the highest magma-production rates along the Vanuatu arc (Fig. 1A) and consists of a 35 by 50 km slightly east–west elongated triangular island with a central caldera system (McCall et al., 1969; Carney et al., 1985; Robin et al., 1993). Extending east and west from the caldera, the island is cross-cut by an active fissure zone containing many scoria cones and fissure-fed lava flows. The northern part of the volcano is considered the oldest and is inferred to be part of an old shield volcano including old fissure vents (McCall et al, 1969). Within the central 12 km-wide caldera at about 800 m above sea level, two active volcanoes are located, Marum and Benbow. These both have multiple pit craters that are frequently active, producing small-volume Strombolian, phreatomagmatic and sub-Plinian eruptions feeding extensive sedimentary systems within and outside the caldera (Németh et al., 2009). It has been proposed that about 2200 years ago a cataclysmic phreatomagmatic eruption lead to the formation of a giant tuff ring and subsequently to the formation of a mafic caldera (Robin et al., 1993). The formation process of the caldera remains ambiguous, due to the poor exposure of deposits definitively linked to a giant tuff cone or a caldera-forming eruption.

In the western and eastern edges of Ambrym, many tuff rings have developed at or near sea level, apparently as a result of interaction of fissure-fed magma and near-surface water and/or water saturated sediments. These typically display 1000 m-diameter craters with low (<100 m) rims. Many of these phreatomagmatic volcanoes erupted in recent pre-historic and historic times. Among the eruption records, the most recent and violent eruptive tephra ring eruptions took place in the years of 1896 and 1913 at the western edge of Ambrym (Purey-Cust, 1896; Frater, 1917; Gregory, 1917). In west Ambrym, a cliff section at sea level exposes phreatomagmatic tephra units up to ~15 m thick (Fig. 1B). The tephra ring surrounds an oval depression, a shallow water filled maar (Fig. 1B). The highest point of the tephra ring is ~85 m above sea level at its northern margin, and its form is best preserved along the western and northern flanks (Fig. 1B and C). The outer flanks slope gently (<10°) outward, with units to the east mantling lava flows and older scoria cones (Figs. 1C, D and E). The tephra ring is partially open to the north and temporary re-connection to the sea occurs after strong wave action during cyclones (Fig. 1B). The tephra ring passes gradually westward into a volcaniclastic debris fan, thinning out over several hundred metres. The tephra ring was formed in a low-lying plain that was possibly the floor of an older volcanic crater (Frater, 1917). In addition, a concurrent eruption, centred c. 400 m offshore may have contributed to the deposits. From both sources, shallow beds of coral were disrupted and coral fragments are dispersed throughout parts of the sequence. The entire structure is now covered by tropical shrubs and trees. The wide crater and low surrounding rim are similar to young monogenetic tephra/tuff rings worldwide. Tephra is preserved up to approximately 1 km outward from the crater rim.

Within a month of the eruptions water depth in the deepest part of the lagoon in the centre of the tuff ring was measured at 15 m, indicating between 20 and 30 m of crater floor subsidence/excavation through the eruption, which is similar to many maar volcanoes (Lorenz, 1986). Surveys several months later revealed the crater floor was up to 37 m deep, indicating ongoing post-eruptive subsidence of the maar crater.

3. AD 1894 and 1913 Ambrym eruptions

3.1. October 1894 rift-edge eruptions

At 0600 hrs on 16 October 1894 an ash cloud erupted from the central vent of Benbow and covered much of the western flanks of the island. Soon afterward, lava flows commenced toward the sea. A “dense black wall” of ash was observed from the top of an old tuff ring, (Dip Point) in the western edge of Ambrym (Purey-Cust, 1896). Scoriaceous coarse ash was deposited across most of western Ambrym. The eruption was accompanied by strong volcanotectonic earthquakes with associated landslides, including the western shore cliffs. Lava entered the sea in many locations along the NW coast. Initial contact of lava with the sea produced no explosion, although a few seconds later, littoral explosions began, generating extensive steam-charged jets of lava fragments, radiating ocean surface waves, and over-riding steam clouds. The scale of the central-vent activity appears to have been similar to that observed during a series of central