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Exploding lakes in Vanuatu — “Surtseyan-style” eruptions witnessed on Ambae Island

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After a long silence, Lake Vui on Ambae Island burst into spectacular life on November 28, 2005, disrupting the lives of the 10,000 inhabitants on this sleepy tropical island in the SW Pacific. “Surtseyan-style” explosions burst through the Island’s summit lake waters, forming a new tuff-cone, and threatening to form deadly lahars or volcanic floods. Such eruptions are rarely well observed, and these fleeting opportunities provide a chance to match volcanic processes with rock-sequences common in the geologic record ...

Fire and water...

When magma rises and erupts in dry environments, its explosive fragmentation is driven by the exsolution and expansion of gases that were trapped within it under high pressures at depth. However, in wet environments, magma is dominantly fragmented through a conversion of thermal energy to mechanical energy when the >1000°C magma meets water. This contact leads to a chain-reaction process often referred to as molten-fuel-coolant-interaction (MFCI) (Zimanowski et al., 1991; Zimanowski et al., 1997; Zimanowski, 1998). The MFCI process leads not only to pulverisation and chilling of the magma, but also the resulting shock waves permeate and disrupt surrounding rock and sediment (Wohletz, 1986; Zimanowski, 1998). “Phreatomagmatic explosions are those which occur when hot magma comes into contact with surface or groundwater. Two types occur: one where water enters a vent and the other where lava flows into water. The products of these two types are readily distinguished in the field by the lack of appreciable quantities of basement rock ejecta in deposits formed when lava runs into water and explodes.” (Stearns, 1953). The so-called “Surtla” eruptions take place entirely under water, and leave behind only a lens-shaped mound of rock fragments, known as pyroclasts. By contrast, “Surtseyan” eruptions breach the water surface, to build a tephra ring or low cone (Kokelaar, 1983; Kokelaar and Durant, 1983; Fisher and Schmincke, 1984; Cas et al., 1989). Both names derive from classic observations of eruptions in 1957 off the SW coast of Iceland (Thorarinsson, 1965, 1967; Kokelaar, 1983; Kokelaar and Durant, 1983; White and Houghton, 2000). In both these types of explosive eruption, in a simplified model, the ratio of water to magma is high; hence the excess water strongly lowers the energy transfer to water, resulting in less overall vaporisation and less-efficient conversion to mechanical energy. Recent studies, however, show that water-to-magma ratios variation and their link to the potential mechanical energy transfer is not obvious (Zimanowski et al. 1991; Zimanowski, 1998). In theoretical considerations the physical conditions of the eruptive environment (i.e. water-rich; sea, lakes, gravels, versus water-poor; fine-grained sediments) and/or the vent geometry and dynamics may be equally important controlling factors of the

thermal-to-mechanical energy transfer, and therefore the magnitude of the explosions (e.g. White, 1996a, b). In a simplistic way, in subaqueous settings the water depth is considered to be a critical, but not the only control on explosive energy. Particularly, if a subaqueous pyroclastic mound grows during an eruption, explosive energy may increase as the water depth above its summit and vent area decreases (Sheridan and Wohletz, 1983; Wohletz and McQueen, 1984). In such cases, the vent geometry and dynamics during the course of the eruption and the ever changing eruptive environment could also play an equal role to that of the magma-water ratio changes (e.g. Németh et al., 2001; Sohn and Park, 2005; Auer et al., 2006).

In the Surtla phase of eruption, mostly subaqueous pyroclastic density currents carry fragmented pyroclastic particles away from the vent (White, 1996a; White, 2000). However, after the explosions breach the water surface, aerial transport begins to dominate; that is, dense eruption columns are formed, generating fallout-dominated deposits (called tephra) as well as deposits from horizontally moving base surges (Lorenz, 1974a, b). The relative ratio between fallout versus base-surge dominated deposits is variable, as has been documented from Surtsey (Lorenz, 1974b). As a result, a tephra cone grows above the water level, commonly forming a crescent-shaped or sub-circular island (Lorenz, 1974; Sohn and Chough, 1992; White, 2001). These islands are very fragile, being made up of loose fragmental tephra deposits, and are strongly at the mercy of wave action. In most cases, they are short-lived, as in the case of Graham Island, which formed in 1831 just south of Sicily, sparking a three-way international dispute over its ownership before it disappeared beneath the waves eight months later (Colantoni et al., 1975). In rare cases, these islands can be efficiently armoured by solid rock if the eruption becomes “dry” and a lava fountain forms in the last phase of the sequence, commonly leading to the formation of a small lava shield in the crater, as at Surtsey (Lorenz, 1974b). It has also been reported that immediate and ongoing palagonitisation of the volcanic glass shards in the fine tephra could rapidly form hard and impermeable beds in the ejecta pile (Thorarinsson, 1965; Jakobsson, 1972).

The smoking gun...

In spite of the common presence of pyroclastic rocks in the geological record that are deduced to be from Surtseyan or phreatomagmatic eruptions, few direct observations enable these links to be made. Such eruptions are commonly brief and unheralded, hence they are often missed by trained observers. Occasions when much or part of such eruptive sequences have been observed include the type locality of Surtsey in Iceland (1963) (Thorarinsson et al., 1964; Thorarinsson, 1965, 1967), Capelinhos in Azores (1957) (Cole et al., 2001), Taal in the Philippines (1965) (Moore et al., 1966; Waters and Fisher, 1971) and Kavachi in the Solomon Islands (2000) (Baker et al., 2002). Surtseyan-style eruptions in crater or caldera lakes are even less well-observed; the 1996 eruption within Karymskoye lake in Kamchatka, Russia is one of the best described so far (Belousov and Belousova, 2001; Zobin et al., 2003). Here we provide an initial

observation-based record of a Surtseyan eruption that took place on Ambae Island in the Vanuatu volcanic arc. A subsequent report about the analytical studies as well as more quantitative interpretations of the vent and conduit processes is in preparation.

Ambae Island, Vanuatu

Ambae (Aoba) is part of the active Melanesian volcanic arc, and is located in the central part of the Vanuatu archipelago (Figure 1A). The island is in a lozenge shape, elongated along the NE–SW axis around a central rift zone that is marked by a chain of scoria cones and fissure-fed lava fields (Figure 1B). The island basement comprises predominantly thin sheets of basaltic lava flows and interbedded hydro-volcanic deposits. The subaerial part of the island is known as Lombenben Volcano, which rises to 1,496 m (Figure 1B). However, bathymetry data show that the entire edifice actually rises around 3,900 m from the ocean floor, making it volumetrically the largest of all the Vanuatu volcanoes. At the summit, two distinct crater structures occur, surrounded by crescentic segments of caldera wall escarpments (Figure 1C). The caldera floor lies about 150 m below the rim. The timing and cause of the caldera formation are unclear. However, there are no known widespread pyroclastic successions to indicate large-scale explosive volcanism from the caldera (Warden, 1967, 1969). This suggests that the caldera was formed through gradual episodic subsidence, probably driven by lateral drainage of magma out to the island flanks from its central plumbing system.

Inside the caldera complex a large phreato-magmatic tephra ring forms a broad gently outward-sloping volcanic edifice about 150 m above the caldera floor (Figure 1C). This tephra ring encloses the 2.1 km diameter acidic Lake Vui, which is commonly pale green or grey due to its high sulphur and suspended sediment content (Figure 2). The lake holds 40–50 million m³ of water which is typically at a pH of 1.2 to 1.8 (Garaebiti, 2000). This water mass, sitting at c. 1,400 m elevation, is the major concern in any volcanic hazard assessment on Ambae, due to its potential as a lahar or volcanic flood source (Cronin et al., 2004). Eruptions through other similar crater lakes have explosively ejected large volumes of water and water-saturated sediment onto surrounding slopes to generate lahars (Cronin et al., 1997; Mastin and Witter, 2000). Between the outer flank of the summit tephra ring and the caldera scarps, the < 11 million m³ fresh-water Lake Manaro Lakua occurs (Figures 1C and 2). A third swampy depression holding the seasonal Lake Manaro Ngoru appears to occupy another volcanic crater structure (Figures 1C and 2).

Since the early 1990s, activity has occurred in Lake Vui through a single vent area, with a series of heating-cooling cycles that culminated in a small one-day phreatic (steam-driven) eruption in 1995 (Robin et al., 1995). This event caused considerable panic amongst the island's inhabitants and an aborted attempt at evacuation was made. In 1996, the active crater area in Lake Vui was at a depth of about 150 m (Metaxian et al., 1996) and with a diameter of about 50 m. Historic eruptions on Ambae were documented in 1575, 1670 and 1870 (Warden, 1969). The latest of these events is believed to have built a small cone inside Lake Vui. The remnants of this cone are two islands located in the western side of the lake, covered with stunted trees that were killed during the 1995 unrest.

Figure 1 Ambae is part of the Vanuatu volcanic arc (A), and forms a NE–SW elongated island with a rift zone along its long-axis (B). In the summit area a complex caldera forms a 150 m depression, partially filled with a tephra ring 2.3 km across, within which Lake Vui is located (Its rim is marked by a continuous black line) (C). Two arrows point to the two pre-existing islands inferred to have been formed during the last major eruption on the island in 1870. The white circle represents the approximate location of the new vent, and the white rectangle shows the location of the main on-ground observation point.

Figure 2 The summit region of Ambae on 12 July, 2005. The only hint of activity at this time is a distinctive pale area of upwelling in the general area of the eruption site. The two older islands are clearly visible. Between these islands the new volcano (The dashed line shows its position) emerged sometime after 27 November 2005.

Surtseyan eruptions

On 27 November 2005, vapour plumes and ash columns from the summit of Ambae alerted the local inhabitants and domestic pilots to the start of the new eruption. The steam plume grew over the next few days, although difficult access to the summit region meant that the first reliable observations were on 3–4 December 2005. By this stage, shallow subaqueous explosions were taking place between the two existing islands inside Lake Vui (Figure 3). Air and ground surveys confirmed that a new small crescentic island had developed on the northern side of the active vent, and that a Surtseyan-style eruption was in progress. Surveys were made from fixed-wing aircraft that were able to approach to within about 300 m of the eruption plume. Ground surveys were made from an observation point on the northern shore of Lake Vui, approximately 700 m away from the eruption site. The initial volcanic island was approximately 10 m high and only around 100 m long. Every 30 seconds an explosion took place, forming dense “cock’s-tail” jets of hot rock debris that reached between 50 m and 100 m high. These jets initially appeared black (Figure 3A), but rapidly condensing steam turned the clouds white as they collapsed back into Lake Vui, and formed small, radial, lake-surface-hugging clouds or base surges that travelled not more than 200 m over the lake surface from the eruption sites (Figure 3B). The base surges were estimated to travel about 50 m to 100 m per second on the basis of the available video footage. The jets were charged with water and mud, and appeared to contain only rare larger ballistic bombs of juvenile origin. A semi-continuous steam-dominated eruption cloud of up to 500 m elevation was fed by these ongoing explosions. On several photographs the eruption clouds leaving the vent are very dark. This could be the result of the superheated water vapor still being translucent before starting to condense and form white steam

at a greater distance from the vent. The white steam blocks the view to the pyroclasts. This observation is supported by the fact that several times during air-surveys the aircraft flew into the white cloud and still pyroclasts were visible from the aircraft windows. The radially moving base surges (Figure 3B) contained only low particle concentrations and high vapour content. More vigorous eruptions produced denser and more sustained eruption columns up to 150 m above the water surface (Figure 3B). At this time, there were no signs of waves in the lake generated by the surges or by subaqueous pyroclastic density currents. The vent during this phase was always below the water surface, with subaqueous pyroclastic density currents continually building up a surrounding platform. Many of the outbursts produced umbrella-like expanding steam envelopes similar to those described during subaqueous explosions in the Karymskoye Lake in Kamchatka, Russia (Belousov and Belousova, 2001). A day later (5 December), the subaerial tephra banks had grown significantly to form two crescentic sections of up to 15–20 m high (Figure 3C). The rate of each eruptive pulse was similar, producing cock’s-tail jets rich in muddy sediment. Most jets were vertical, and fell back into the vent zone, although some of the larger explosions were directed toward the east (Figures 3C and D). Base surges formed especially after larger eruptive bursts, and travelled about 150 m from their source before stalling. None of the explosions in this stage was energetic enough to disrupt large volumes of lake water or to eject water or sediment to the edge of the lake.

By this stage of events, around 3,500 people had moved from the flank of the volcano (particularly from the stream-valley areas) to refugee camps at each end of the island. The island authorities were anticipating a repeat of events in the 1870 eruption, when fatalities were reported due to lahars (Warden, 1969). The island extremities (Figure 1) are protected from lahar pathways, and are regarded as natural safe havens (Cronin et al., 2004).

By 8 December 2005, the subaerial apron of tephra had grown significantly (Figure 4) to form an elliptical island, which was open to the east. The new structure was connected to the older vegetated island to the north (Figure 4A). The new tephra ring now reached up to 70 m in height above the lake level (Figure 4B). Since 5 December 2005, the vent zone had apparently shifted northwestward by 100–150 m, and the initial tephra bank was abandoned and protruded from the side of the main edifice (Figure 4A). Eruptions still appeared to emanate from a shallow subaqueous vent, and formed more voluminous cock’s-tail jets that at times reached 200 m vertically and contained hot ballistic juvenile bombs (Figures 4B and C). These explosive jets were now partially confined and directed by a sub-vertical wall of tephra behind the vent on the northern side. Along with the subaerial jets, subaqueous pyroclastic density currents continued on a larger scale than before, generating surface waves on the lake with amplitudes of up to 1 m. These waves radiated from the flanks of the edifice, but were particularly dominant outward from the east-side embayment (Figure 4A).

The vent region was still connected to the open water body of Lake Vui through the east-facing opening in the tephra ring (Figure 4D). This gap was probably being maintained by continuous subaqueous mass-wasting or collapse of this eastern portion of the edifice—corresponding to the surface waves continually being generated from this area. In addition, other parts of the tephra apron were being constantly built up by dense fall-out deposits from the upper parts of the eruptive jets that were directed by the prevailing winds. Because of this gap, base surges were able to escape the vent zone toward the east (Figure 4B). Larger explosive events initiated pyroclastic surges

Figure 3 Photos of the new eruption on 4–5 December, 2005 (A) at 0830–0845 local time, small-scale cock’s tail jets and steam clouds covered the active vent zone with a small emergent island. Spall domes were pierced by continuous uprush of muddy tephra, which reached about 150 m above the water surface (B). Vertical jet-collapse appeared to dominate, with small steam-charged base surges not reaching much beyond 50 m from the source (C). At c. 1200 local time on 5 December from a vantage point c. 800 m from the vent on the northern side of Lake Vui, the foundations of a small cone c. 15 m in height had been built. The eruption columns in each of the explosive bursts were charged with muddy sediments, that disintegrated while falling back to the vent zone. (D) Larger explosive bursts initiated small and dilute base surges, however, they did not cause significant wave action in Lake Vui.

Figure 4 Aerial survey on 8 December 2005 shows that a near-complete tephra cone had built up, joining onto one of the pre-existing islands (A). The highest point of the cone is on its western side. High-energy subaqueous pyroclastic density currents generated surface waves in the lake. Spectacular cock's-tail jet from the centre of the vent forms ash-charged columns distributing tephra over the growing tephra cone (B). Some of the explosions were directed by confinement by the western vent walls (C). Note also that ballistic bombs and steaming clasts cover the cone surface, indicating high juvenile content in these explosions. The vent zone is partially sheltered from direct contact with the water mass of Lake Vui. However, a c. 75 m wide gap remains open to the lake (D). The vent also appears to have migrated at least 100 m to the west with the initially-formed tephra banks (on 4–5 December), being isolated on the northern side of the opening in the cone.

Figure 5 (A) By 12 December 2005, explosive activity becomes less frequent, and the smooth-surface cone had grown considerably larger, with black, initially steaming thin deposit lobes veneering the cone (Photo, M. Harrison). (B) On 13 December 2005, the explosive energy of each event was the largest seen, with base surges recorded at least 300 m radially from the vent (Photo, W. Toa). The cone was around 100 m in height by this stage. (C) On 20 December, the eruptive activity had died down considerably and the now higher cone already had a well-established pattern of rill erosion. At this stage, the vent was physically isolated from the lake by a low bench (Photo, M. Harrison). (D) By 9 January, the cone was complete, with well developed rill erosion and scalloped margins developing. The vent area remained inundated by grey muddy water at a lower level than the surrounding blue-green Lake Vui (Photo, J. Esau).

that radially covered the whole island (Figure 4B). There appeared to be a higher content of juvenile blocks and bombs in the eruptions at this stage, with the flanks being continuously covered by steaming clasts (Figure 4D). In periods between explosive outbursts, a steaming and bubbling vent zone was visible (Figure 4D).

By 12 December 2005, the frequency of individual explosions had dropped to an order of one every 3–5 minutes. However, their energy was generally higher, with plumes commonly reaching >200 m in height and containing large quantities of juvenile material. These plumes produced surge deposits that draped the growing cone, forming a smooth surface as well as covering and destroying the vegetation remnants of the older island to the north (Figure 5A). At this stage, more ash was also being produced, with common reports of ash and acid rain damage to gardens around the island, although the main plume, up to c. 2 km height, remained steam-dominated. The tuff cone had reached an elevation of 100 m in its western rim (Figure 5A). However, its vent was still open to the east. On 13 December, particularly energetic surges were witnessed that trav-

elled 2–3 times farther than during the initial phase of the eruption, reaching at least 300 m from the vent (Figure 5B). This slight change in activity appeared to represent either a slightly more efficient energy transfer in the explosions, probably due to a reduction of the total volume of water and/or water-saturated sediment to the interacting magma in the vent zone in comparison to the initial phase (Sheridan and Wohletz, 1983; Wohletz and Sheridan, 1983; Wohletz, 1986; Zimanowski, 1998; Buttner et al., 2002) and/or just greater mass ejection. Alternatively, the energy and explosive intensity change could also have been the result of changes in gas flux in the conduit causing gas pistonning, as has been demonstrated in experiments (Walder and Mastin, 2003).

After 13 December, the frequency of explosions progressively diminished, accompanied by a gradual drop in tremor. By 20 December, the cone had grown slightly to c. 500 m long, and the vent was separated by a low (1–3 m) platform from the open lake waters (Figure 5C). The deposition rate on the outer flanks of the cone must have diminished considerably, because the first signs of

rill erosion were clearly visible, with closely spaced rills 1–3 m wide and at least 1 m in depth. Ongoing steaming fed a weak plume to 1,000 m, but small periodic eruptions were still occurring every 15–20 minutes. By 9 January, the cone had completely isolated the vent area from the open lake body (Figure 5D). The vent area was inundated by grey, actively steaming water, at a level a few metres lower than the surrounding blue-green lake waters, although no explosions were witnessed at this time. On Ambae, especially above the 1,000 m contour, rain occurs almost daily, and dense tropical rainforest covers the entire caldera. Rain occurs in high-intensity storms as well as continuously over many hours. During the eruption, similar rainfall was experienced, which initiated rill erosion on the newly formed volcanic island. Rill erosion was well established on all sides of the cone, with a distinct broadening of the rills toward the base of the cone and a scalloped coastline beginning to form (Figure 5D). The eastern vent wall is particularly steep, reflecting a migration of the vent location by *c.* 200 m westward during the course of the eruption. At the time of writing, the latest observations appear to represent the end of at least this phase of the eruption, although very low levels of tremor are still occurring.

Discussion

The changes in style, energy and frequency of individual explosive bursts during this eruption appear to be well correlated to a gradual decrease in the total volume of water and/or water-saturated sediments that were interacting with a relatively small volume of erupting magma. Magma-water interaction has been demonstrated to be most effective when the ratio of water to magma (melt) is about 0.3 (Wohletz and Sheridan, 1983; Wohletz and McQueen, 1984; Zimanowski, 1998). However, whilst this ratio appears to hold under experimental conditions where pure water interacts with melt, in real volcanic systems, especially in shallow subaqueous settings, the interacting coolant is actually water-saturated sediment. In the case of Ambae, lake sediments provide a fine-grained particle component in an impure coolant, which apparently damped the fuel-coolant interaction relative to an interaction with free water (White, 1996b). This results in less energetic explosions. White (1996b) also suggested that in this type of geometrical setting, the energy and style of individual explosive events may also depend on vent/conduit wall collapse and fluidisation of the saturated and unstable floor zone of the volcano. In the Ambae event, the rapid growth of the tuff cone occurred in tandem with a lateral migration of the vent westward by *c.* 200 m. This migration caused steepening and potentially periodic collapse of the eastern vent wall, choking the vent and possibly triggering some of the larger explosions witnessed. Despite this tendency, the Ambae eruption appeared to show a relatively simple case of an increasing explosivity as the vent became more isolated from the body of the lake. At the start of the Surtseyan eruptions, the direct contact of saturated sediments with the large water mass of the lake produced suppressed explosions, probably due to water/melt ratios far exceeding the optimum 0.3. As the eruption continued, a gradual enclosure of the vent zone restricted free water access to the vent, leading to a lower frequency of higher-energy eruptions. Once the vent was fully cut off from the lake waters by a low bench the explosion efficiency appeared to reach its maximum (on 13 December 2005), coupled with a lower frequency of explosions. However, it appears that the vent zone was always in contact with excess free water—presumably from lateral seepage. Hence the overall excess water and potentially a large component of lake mud in the conduit/vent appeared to act as an explosion suppressant. At the time of writing it appeared that the magma supply had diminished before the explosions could reach their greatest efficiency. This observed development of a tuff cone sequence shows that within a few days there was a progression from subaqueous pyroclastic density currents, through to surge and collapsed jetted sediment, followed by ash fall and finally redistribution of sediment to the lower flanks through rill erosion from the upper cone.

Conclusion

This preliminary report of a new eruption on Ambae's volcano demonstrates a number of the characteristic features of Surtseyan-style eruptions, events which have been rarely well observed throughout history. These events appear to be characterised by a rapidity of changing explosion style and magnitude. A new *c.* 140 m high asymmetric tephra cone was formed within Lake Vui, essentially in less than 8 days. A lateral migration of the vent, a low magma-supply rate, and the predominance of mud-rich waters appear to have kept the coolant ratios high throughout this event, dampening the magnitude of explosions. However, if the individual eruptive pulses were initiated by magmatic gas, or if magmatic degassing played an important role (e.g. gas pistonning in basaltic systems), variations in eruptive intensity could also result from changes in the amount of gas driving such events, or the amount of magma expelled (which may be independent of magma-water ratio). Experiments involving gas flux through shallowly submerged nozzles (Walder and Mastin, 2003) also find that gas expulsion can occur in discrete repeating pulses whose intensity and frequency are related to the relationship between gas flux rate, nozzle diameter, and water depth. Bigger explosions could be caused either by more efficiently converting thermal to mechanical energy, or by adding more overall energy to the pulse (Walder and Mastin, 2003). Despite this, the explosions built to a maximum intensity (with reduced frequency) around 9–10 days after the first breaching of the lake's surface by surtseyan jets. The largest of these explosions may also have been intensified by choking induced by the collapsing wall of the conduit as the vent location gradually migrated into the highest part of the cone. Within 7 days of the most explosive period of this eruption, large-scale explosions had effectively ceased, and rill erosion was already well developed on the upper flanks.

Many workers have pointed out that eruptions through crater lakes or in other shallow subaqueous environments are too complex and unpredictable for the application of existing theoretical physical models to calculate the potential evolution of such volcanoes. But the observations we present here will help the calibration of physical eruption models for phreatomagmatic events and will also help to interpret the time scales and sedimentary processes involved in tuff-cone sequences in the geological record. At the time of writing, the eruption had not entirely ceased, and this may in fact only be an early chapter in this event. In any case, over the next few months further observations will also help to constrain the rapid post-event erosion processes occurring from these sites.

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