

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 the 28th of November 2005, disrupting the lives of 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 found commonly in the geologic record...

Fire and water...

When magma rises and erupts in dry environments, its explosive fragmentation is driven by the exolution 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 ejecta composed of basement rock in deposits formed when lava runs into water and explodes.”* (Stearns, 1953). So-called “Surtla” eruptions take place entirely under

water, and leave only behind 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 altered the energy transfer to a larger quantity of water resulting less overall vaporisation of water and conversion of mechanical energy. Recent studies however showed that such a water to magma ratio variation and its link to the potential mechanical energy transfer is not obvious (Zimanowski et al. 1991; Zimanowski, 1998). In some theoretical considerations the eruptive environment physical condition (e.g. the environment may be rich in water (sea, lakes, gravels) or low in water like in finer-grained sediments or in hydraulically active joints) and/or the vent geometry and dynamics maybe 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 in such cases. 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 eruption course and the ever changing eruptive environment could also play an equal role to 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 to generate fallout-dominated deposits (called tephra) as well as deposits from horizontal moving base surges (Lorenz, 1974a, b). The relative ratio between fall versus base surge dominated deposits is very variable in the produced tephra cone as it has been documented from Surtsey (Lorenz, 1974b). As a result a tephra cone grows above the water level, commonly forming 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 such 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 it was the case at Surtsey (Lorenz, 1974b). It has also been reported that the immediate and ongoing palagonitisation of the volcanic glass shards in the fine tephra could form hard and impermeable beds in the ejecta construct (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, only 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 give a first observation based record of a Surtseyan eruption took place in the Ambe Island in the Vanuatu volcanic arc. In this report we focus on the observations of the course of the eruption. A subsequent report about the analytical studies as well as more quantitative interpretations of the vent, 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 has a lozenge-shape, elongated along a 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 hydrovolcanic deposits. The subaerial part of the island is known as Lombenben Volcano and it rises to 1496 m (Figure 1B). However, bathymetry data show that the entire edifice actually rises around 3900 m from the ocean floor, making it volumetrically the largest of all 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 its rim. The timing of the caldera formation and the 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 instead 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 phreatomagmatic 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 cubic meters of water which is typically at a pH of 1.2 to 1.8 (Garaebiti, 2000). This water mass, sitting at c. 1400 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 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 metres (Metaxian et al., 1996) and with a diameter of about 50 metres. Historic eruptions on Ambae have been 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.

Surtseyan eruptions

On November 27th 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 the 3rd and 4th of 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. Air surveys were taken from small airplanes that were able to approach to the eruption plume about 300 m. Ground surveys were made from an observation point from the northern shoreline 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 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 were travelled not more than 200 m over lake surface from the eruption sites (Figure 3B). The base surges were estimated to travel about 50 to 100 meter per seconds on

the basis of the available video footages. 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 and then it starts to condensate and form white steam from more distance from the vent. The white steam does not allow to see the pyroclasts anymore. This observation is supported by the fact that several times during air-survey the aircraft flown into the white cloud and still pyroclast was visible in the aircraft windows. The radially moving base surges (Figure 3B) contained only low particle concentrations and high vapour contents. 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 from subaqueous explosions in the Karymskoye Lake in Kamchatka, Russia (Belousov and Belousova, 2001). A day later, (December 5th), the subaerial tephra banks had grown significantly to formed 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 away 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 4000 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, where 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 the 8th of 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 the 5th, 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 its 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 deposits from the upper parts of the eruptive jets that were directed by the prevailing winds. Because of this gap, base surges could escape the vent zone toward the east (Figure 4B). Larger explosive events initiated pyroclastic surges that radially covered the whole island (Figure 4B). There appeared to be a higher content of juvenile blocks and bombs in the eruptions of this stage, with the flanks continuously being covered by steaming clasts (Figure 4D). In periods between explosive outbursts, a steaming and bubbling vent zone was visible (Figure 4D).

By the 12th of December, 2005, the frequency of the individual explosions had dropped, to on the order of one every 3-5 minutes. However, their energy was generally higher with plumes commonly reaching >200 m 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 to ca. 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 the 13th of December, particularly energetic surges were witnessed that travelled 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 appears 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 also could have been the result of changes in gas flux in the conduit causing gas pistoning as it has been demonstrated in experiments (Walder and Mastin, 2003).

After the 13th of December, the frequency of explosions progressively diminished, accompanied by a gradual drop in tremor (D. Charley, pers comm., 2005). By the 20th of 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). 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 1000 m, but small periodic eruptions were still occurring every 15-20 minutes. By 9 January, the cone 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 in the above than 1000 m regions, rain occur almost every day, that results heavy tropical rainforest cover in the entire caldera. Rain occurs in heavy pulses as well as continuous rain fall over hours. During the eruption similar rain fall was experienced, that 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 to at least this phase of the eruption, although very low levels of tremor are still occurring (D. Charley pers. comm., 2006).

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 demonstrating 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 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 13th December 2005), coupled with a lower frequency of explosions. However, it appears that at all times 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 muds in the conduit/vent appeared to act as a suppressant of explosions. At the time of writing it appears that the magma supply has 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 lower flanks through rill erosion from the upper cone.

Conclusion

This preliminary report of a new eruption on Ambae 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 styles and magnitude. A new 120-140 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 produced. However if the individual eruptive pulses were initiated by magmatic gas or magmatic degassing played an important role (e.g. Strombolian or gas pistonning pulses 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 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 other shallow subaqueous too complex, and unpredictable to apply existing theoretical physical models for the potential evolution of such volcanoes. The observations we present here will help the calibration of physical eruption models for phreatomagmatic events and will also help to interpret the timescales and sedimentary processes involved in tuff-cone sequences in the geological record. At the time of

writing the eruption has 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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Fig. 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 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.

Fig. 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 eruption site. The two older islands are clearly visible. Between these islands the new volcano (dashed line shows its position) emerged sometime after the 27th of November 2005.

Fig. 3

Photos of the new eruption on 4th and 5th of December, 2005 (K. Nemeth) (A) at 0830-0845 local time, small-scale cock's tail jets and steam clouds cover the active vent zone with a small emergent portion. Spall domes were pierced by continuous uprush of muddy tephra, which reached about 150 m above the water surface (B). Vertical jet-collapse appears to dominate, with small steam-charged base surges not reaching much beyond 50 m from the source (C). At c. 1200 local time on the 5th of 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 has been built in both. The eruption columns in each of the explosive bursts are charged with muddy sediments, that disintegrate while falling back to the vent zone. (D) Larger explosive bursts initiate small and dilute base surges, however, they still do not cause significant wave action in Lake Vui.

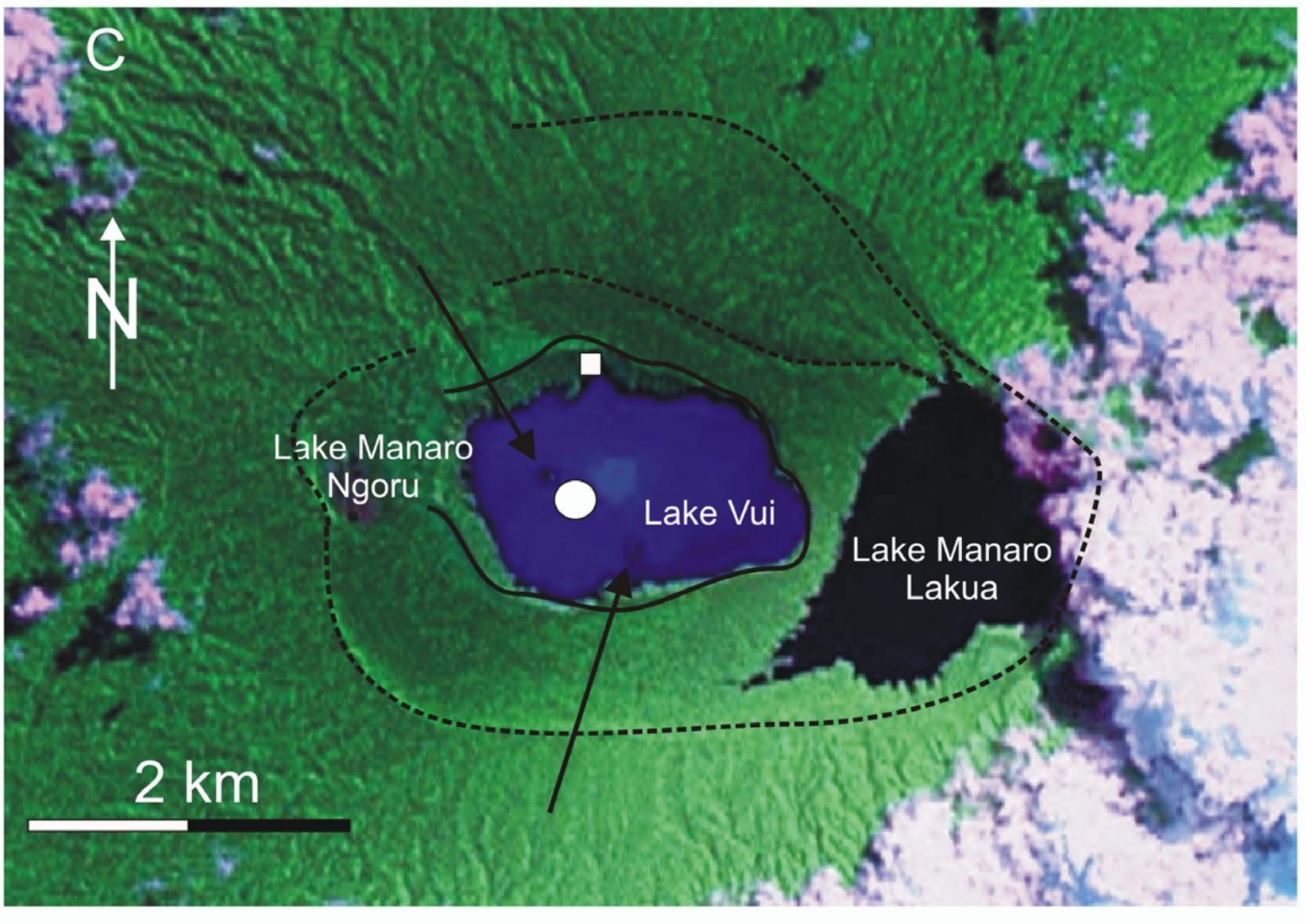
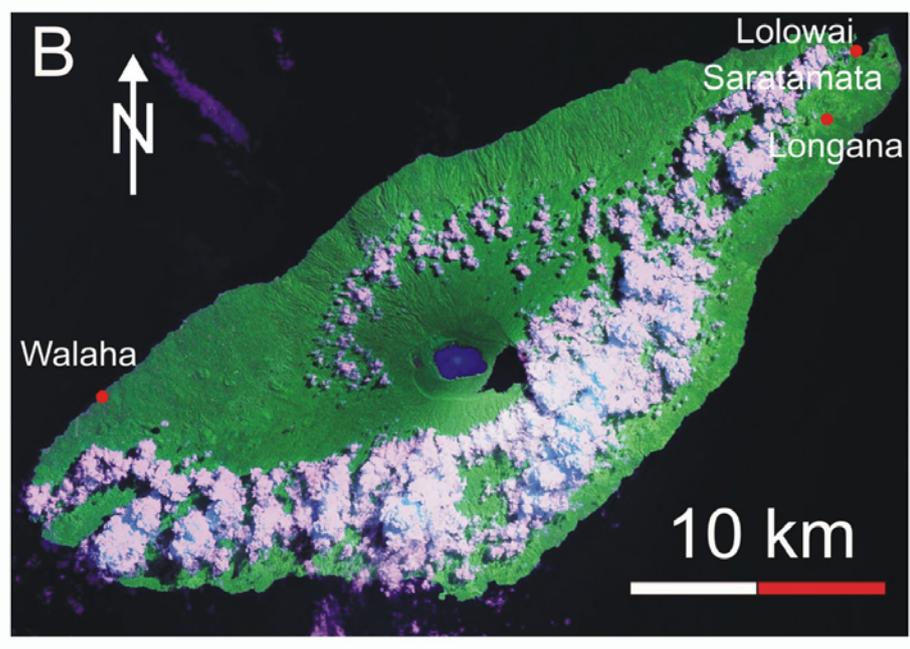
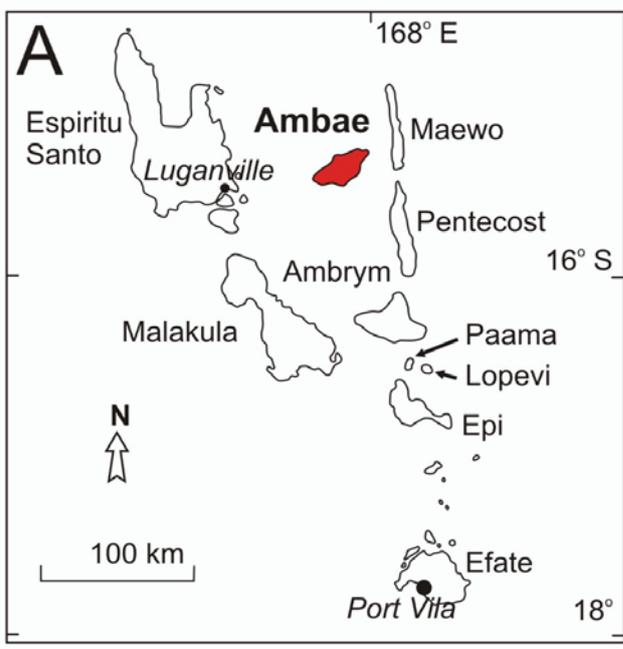
Fig. 4

Aerial survey on 8th December, 2005 (K. Nemeth) shows 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 cocktail's jet from the centre of the vent forms ash charged columns distributing tephra over the growing tephra cone (B). Some of the explosions are directed by confinement on the western vent walls (C). Note also 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 shallow 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 4th and 5th of December) being isolated at the northern side of the opening in the cone.

Fig. 5

(A) By 12th December, 2005 explosive activity has become less frequent and the smooth-surface cone has grown considerably larger with black, initially steaming thin deposit lobes veneering the cone (Photo, M. Harrison). (B) On the 13th the explosive energy of each events are the largest seen, with base surges recorded at least 300 m radially from the vent (Photo, W. Toa). The cone was around 100 m height by this

stage. (C) On the 20th of December, the eruptive activity has died-down considerably and the now higher cone has already a well-established pattern of rill erosion. At this stage the vent is physically isolated from the lake by a low bench (Photo, M. Harrison). (D) By the 9th of January, the cone is complete, with well developed rill erosion and scalloped margins developing. The vent area remains inundated by grey muddy water at a lower level than the surrounding blue-green Lake Vui (Photo, J. Esau)



Pentecost island

Lake Manaro Lakua

Lake Vui





A



B



C



D

