scoria cone in Tongoa show much small-scale complexity. Where this has occurred, the cone consists of a sheeted network of slope-parallel and steeply crosscutting coherent igneous rocks, autobreccia, and locally developed peperite, all intercalated with the host pyroclastic material. These outcrops also provide information of potential use in hazard evaluation. The dykes and sills developed from the lava suggest that the studied cone must have accumulated at least 10 m of scoria on top of a still–active buried lava flow. During the eruption this buried lava may have been invisible to onlookers, but it still had a fluid core capable of feeding lava to the surface beyond the zone of rapid burial, or, perhaps more importantly of causing collapse of a growing cone by deforming within it and injecting sheets of magma upward or laterally.

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Lava lakes and shallow magmatic feeding systems of mafic volcanoes of an ocean island Ambrym, Vanuatu (New Hebrides), South Pacific

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Ambrym is an oceanic arc-volcanic island with two major active vent complexes; Marum and Benbow. These vents have been active over at least the last 300 years, producing high-volume constant degassing interspersed by strombolian, sub-Plinian, and Vulcanian eruptions which are commonly associated with phreatomagmatic explosive phases. Inside the active vent pit-craters, cross-sections of the pyroclastic successions are commonly interbedded with apparently ponded lavas from old lava lakes. However, and of greater volumetric importance in some of the vent sequences, e.g., the Marum sub-vent Niri-Mbwelesu, are coherent intrusive bodies comprising inter-connected networks of sills and dykes. The large sills are connected through a complex network of pathways to the surface and/or into the pyroclastic edifice of the volcano. These structures suggest that shallow level infiltration of melt into a mafic volcano plays an important role in the growth of such apparently pyroclastic edifices.

Keywords: Mafic · Shield volcano · Phreatomagmatic · Pit crater · Lava spatter · Sill

Introduction

Ambrym Island is located in the central part of the Vanuatu volcanic arc and form a triangular, slightly E–W elongated island

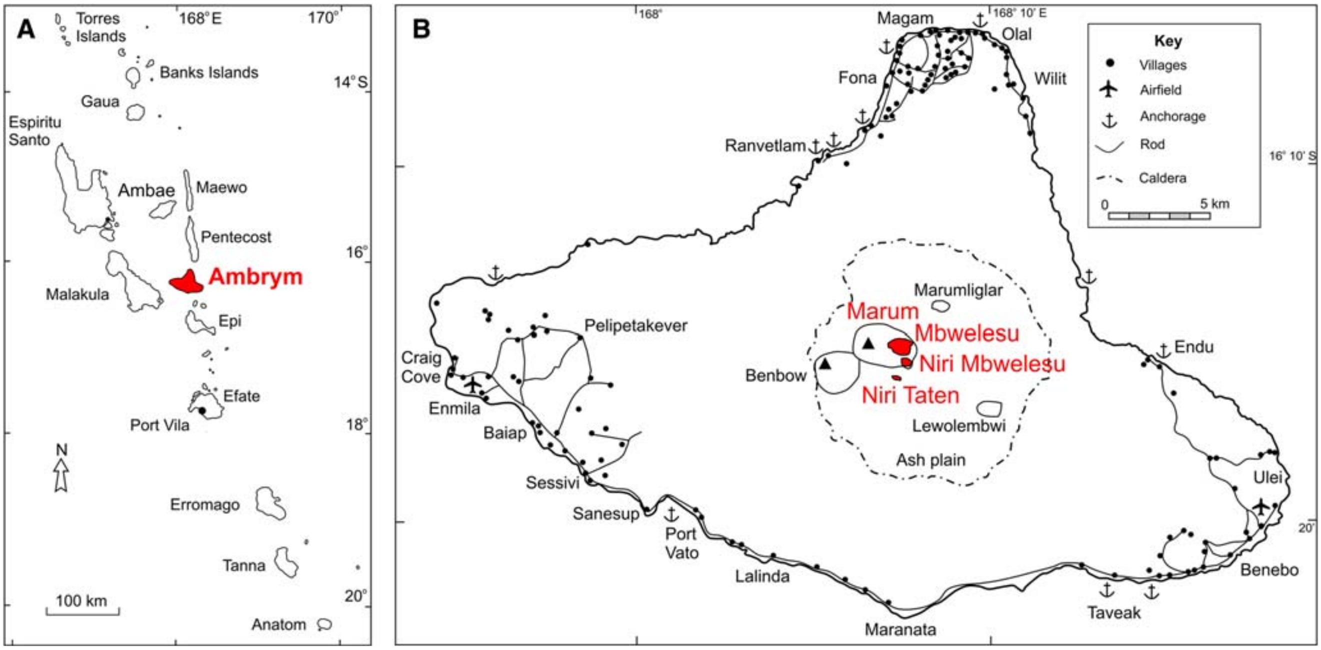

Fig. 1 Overview map of the Vanuatu arc (**a**) and Amrbym Island (**b**). *Red names* refer to the studied vents of the Marum volcanic complex

(Fig. 1). A 13 km diameter caldera forms the central part of the volcanic island which is believed to have formed about 2,000 years ago (McCall et al. 1969). The formation of the caldera has been both considered to have formed during quiet and continuous subsidence (McCall et al. 1969), and more recently, an enigmatic large phreatomagmatic explosion has been suggested as a trigger for its formation (Robin et al. 1993). Recent mapping and revisiting of key sites is underway to address this controversy. Within the caldera, two large active pyroclastic cones (Benbow and Marum) surround two vent areas that have been continuously active during historic times (Fig. 1). The exposed interior walls of Benbow are mainly pyroclastic in nature with minor interbedded lava flows, sills, and dykes outcropping. By contrast, the outwardly similar Marum has a much larger proportion of intrusive and lava flows along with the ubiquitous thick successions of phreatomagmatic and scoriaceous tephra. Marum has a number of sub-vents (Fig. 1), with all vents periodically hosting lava lakes over the last few decades. Each vent/crater of Marum is large, reaching up to 200 m in depth to either lava lake or a muddy base. On the wall of each vent in and around Marum, a great variety of half sections of lava lakes, lava ponds, and shallow level intrusions are well exposed as fine examples of the interrelationship between formation of lava lakes, shallow ponded lavas, sills, and dyke formation.

Lava lake and shallow level lava pond cross sections

In the cliff sections of Mbwelesu, and the older edifice of Marum, up to 20 m thick columnar jointed tabular mafic lava flows crop out (Fig. 2a). They have no brecciated lower and upper contact, and they have a slightly dish-like architecture, indicating their ponded, lava lake origin. These coherent lava bodies are commonly disrupted by depressions of a few tens to hundred meters wide and up to 50 m deep containing pyroclastic successions (Fig. 2a). The presence of these depressions alongside with the large number of ballistic, angular lava bombs of similar texture to those exposed in the crater wall indicate an explosive phreatic to phreatomagmatic disruption of these already solidified lava lakes from time to time. A similar process likely occurred during an eruption we witnessed in July 2005. When lava lakes periodically withdraw, the high rainfall of the summit area (> 5 m/a) rapidly causes the filling of the vent with muddy slurries such as within Niri Mbwelesu during November 2005. Re-occupation of these vents generates phreatic and phreatomagmatic explosions, local base-surge deposits, and widespread fine ash falls. Lava pods are exposed in cross section in the Niri Taten crater/conduit wall (Fig. 2b). The two large (10 m scale) lava pods are columnar jointed by texture (Fig. 2b). An older lava pod is associated with a lava spatter horizon, suggesting lava spatter eruption fed from the active lava pod (Fig. 2b). A younger lava pod developed that also fed an extensive lava spatter field. Below the spatter-covered ground surface, a coherent platy coherent lava horizon crops out with no marginal brecciated zones, indicating an intrusive emplacement (Fig. 2b). Here, we suggest that during the lava spatter eruption a very shallow intrusion has been fed from the central lava pod and truncated the older pyroclastic sequence. The recognition of these facies combinations has important implications for the style of edifice construction. In addition, from a hazard-assessment perspective, after and during lava spatter eruptions, very shallow sub-surface intrusions may destabilize the growing edifice posing unexpected collapse hazard.

Dyke and sill complexes

A great number of lava units interpreted to be lava lakes and flows crop out in the Mwelesu and older Marum crater/conduit walls,

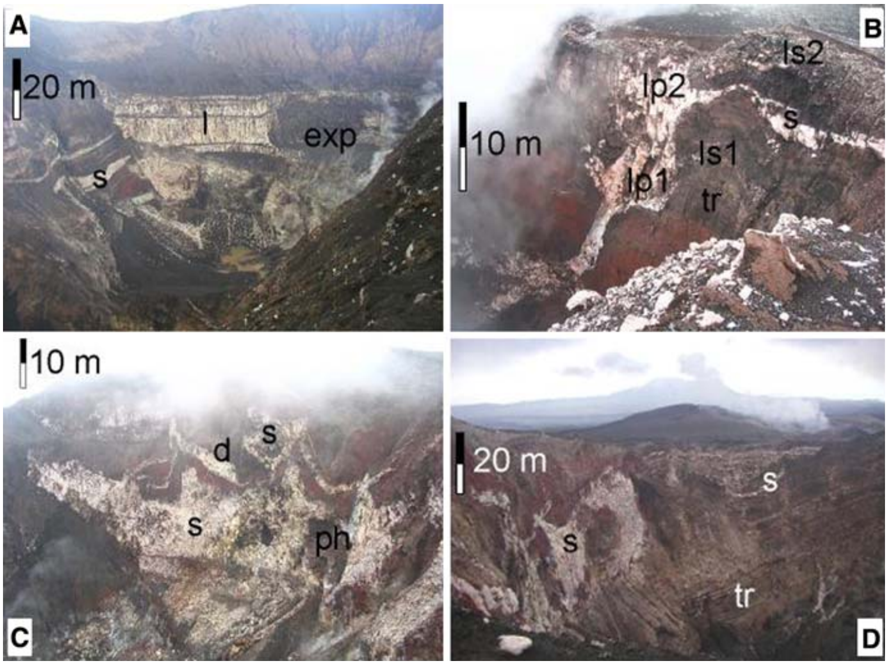

Fig. 2 **a** Overview of the Marum older vents in its western side. Note the tabular, columnar jointed coherent magmatic bodies (l) and the dish-like explosion pit (exp). In the foreground of the picture are large *white angular blocks* interpreted to be accidental volcanic lithics disrupted from the lava units exposed today in the crater wall. **b** Overview of a lava pond (lp1, lp2) and lava spatter (ls1, ls2) complex. Note the fine-grained, probably phreatomagmatic tephra (tr) exposed in the crater wall. An irregular margin sill (s) fed from the lava pod (lp2) postdate the eruption of the lava spatter (ls2). **c** A complex network of shallow intrusions in the crater wall of Niri Mbwelesu. Sills (s) are dish-like in cross-section, and dykes (d) commonly develop peperitic margins especially in contact with fine ash beds. Note the thick succession of fine-grained, base-surge, and phreatomagmatic fall (tr) dominated successions intruded by the sill complex. **d** Western crater wall of the Niri Mwelesu exposes a great succession of pyroclastic deposits occasionally intruded by thin sills that are dish-like shaped in cross-section

with only a few sills identified. By contrast, the Niri Mbwelesu crater/conduit wall exposes complex shallow level dyke and sill complexes that have been disrupted by subsequent explosive eruptions (Fig. 2c). The large number of accidental volcanic lithic clasts (pieces of sills and dykes) are present on the surrounding volcanic flanks and also result from these periodic explosions. The sills are interconnected through oblique dykes with irregular, chilled margins, and occasional peperitic contact zones, especially when in contact with fine ash and lapilli successions (Fig. 2c). The major sill exposed at Niri Mbwelesu is dish-like in cross section and about 20 m thick (Fig. 2c). Thinner interconnected intrusions also form u-shaped cross sections suggesting some sort of ponding during emplacement into the unconsolidated, commonly fine grained tephra (Fig. 2c). Similarly, a few individual u-shaped thin (m-scale) sills are exposed in the inner crater wall independently of the major sill and dyke complex (Fig. 2d).

Conclusion

The presence of large interconnected sill and dyke complexes as well as very shallow lava ponds associated with pyroclastic (spatter and socora) cones suggest that shallow intrusive processes play an important role during the eruptions of frequently active mafic volcanic centers. Moreover, the presence of such shallow sills and dykes pose significant hazard during the construction of a pyroclastic cone. The large ponded, "hidden" melt pockets in the continuously growing pyroclastic edifice are able to break through the pyroclastic wall and initiate unexpected lava flows or collapses of the cones. Also the large ponded magmatic bodies can retain heat long time, and provide preferential "pre-heated" pathways for new, fresh melt to reach the surface. Because the cross sections were generated by explosive disruption of the pyroclastic edifice, we also suggests that such exposures could expose solidified intrusive bodies that may have originated from other neighboring vents.

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Peperites and soft sediment deformation textures of a shallow subaqueous Miocene rhyolitic cryptodome and dyke complex, Pálháza, Hungary

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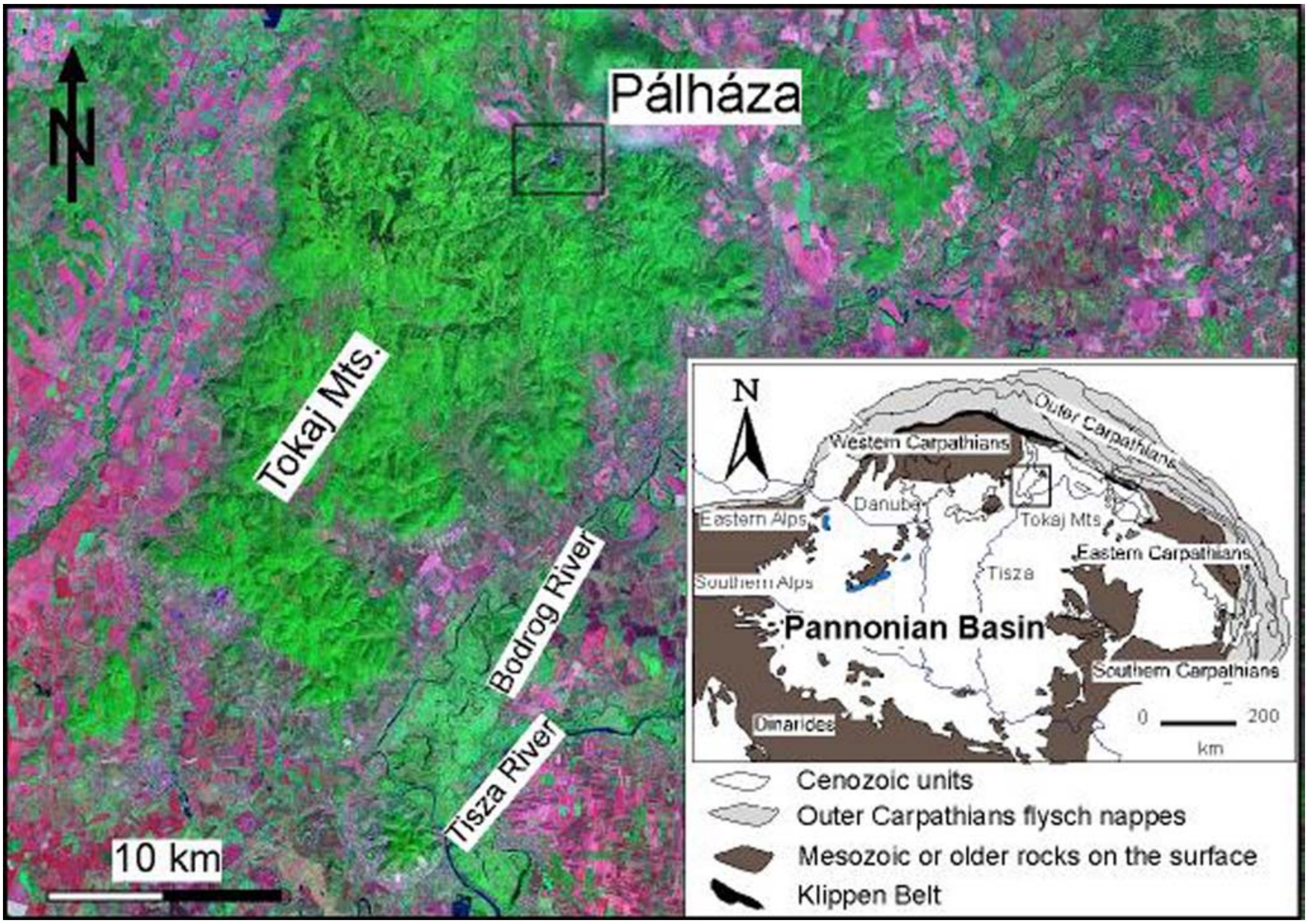

Fig. 1 Overview map of the Carpathian–Pannonian geological environment and the Tokaj Mountains in MrSID satellite image