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Phreatomagmatic volcanic hazards where rift-systems meet the sea, a study from Ambae Island, Vanuatu

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ABSTRACT

Ambae Island is a mafic stratovolcano located in the northern Vanuatu volcanic arc and has a NE-SW riftcontrolled elongated shape. Several hundred scoria cones and fissure-fed lava fields occur along its long axis. After many decades of quiescence, Ambae Island erupted on the 28th of November 2005, disrupting the lives of its 10,000 inhabitants. Its activity remained focused at the central (crater-lake filled) vent and this is where hazard-assessments were focused. These assessments initially neglected that maars, tephra cones and rings occur at each tip of the island where the eruptive activity occurred <500 and <300 yr B.P. The products of this explosive phreatomagmatic activity are located where the rift axis meets the sea. At the NE edge of the island five tephra rings occur, each comparable in size to those on the summit of Ambae. Along the NE coastline, a near-continuous cliff section exposes an up to 25 m thick succession of near-vent phreatomagmatic tephra units derived from closely spaced vents. This can be subdivided into two major lithofacies associations. The first association represents when the locus of explosions was below sea level and comprises matrixsupported, massive to weakly stratified beds of coarse ash and lapilli. These are dominant in the lowermost part of the sequence and commonly contain coral fragments, indicating that the loci of explosion were located within a reef or coral sediment near the syn-eruptive shoreline. The second type indicate more stable vent conditions and rapidly repeating explosions of high intensity, producing fine-grained tephra with undulatory bedding and cross lamination as well as megaripple bedforms. These surge and fall beds are more common in the uppermost part of the succession and form a few-m-thick pile. An older tephra succession of similar character occurs below, and buried trees in growth position, as well as those flattened within base surge beds. This implies that the centre of this eruption was very near the coastline. The processes implied by these deposits are amongst the most violent forms of volcanism on this island. In addition, the lowland and coastal areas affected by these events are the most heavily populated. This circumstance is mirrored on many similar volcanic islands, including the nearby SW Pacific examples of Taveuni (Fiji), Upolu and Savai'i (Samoa), and Ambrym (Vanuatu). These locations are paradoxically often considered safe areas during summit/central-vent eruptions, simply because they are farthest from the central sources of ash-fall and lahar hazard. The observations presented here necessitate a revision of this view.

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1. Introduction

Growing populations on active volcanic islands face complex 41 volcanic hazards (Mattioli et al., 1996; Cole et al., 1999; Arana et al., 42 2000; Cronin et al., 2001; Cronin and Neall, 2001; Carn et al., 2004; 43 Cronin et al., 2004; Malheiro, 2006). Many of these volcanic islands are 44 dominated by a central volcanic edifice. Hazards from these geogra-45 46 phically confined volcanic edifices are relatively easy to comprehend 47 for inhabitants of the islands regardless of their development state (Cronin et al., 2004). Many volcanic islands, however, may have 48 volcanic eruptions not only at their central volcanic zones but along 49

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lateral flank vents, which are often referred to as satellite volcanoes. ⁵⁰ Some island volcanoes may also have a central volcanic edifice, which ⁵¹ doesn't appear to be an actual central vent to lay people such as ⁵² Taveuni, Fiji (Cronin and Neall, 2001). In these situations, the location ⁵³ of re-awakening activity on the flanks may be difficult to forecast ⁵⁴ (Cronin et al., 2001). Flank eruptions on these structures are commonly ⁵⁵ complex, involving multiple eruption phases, rejuvenation, and ⁵⁶ complex sources. Their distributional pattern largely depends on the ⁵⁷ structural architecture, and can range from single elongated rift zones ⁵⁸ (e.g. Taveuni, Fiji) to broad and poorly defined rift structures (e.g., ⁵⁹ Savai'i, Samoa) and more evenly scattered volcanic edifices around a ⁶⁰ central vent (e.g., Jeju, South Korea). Prediction and probabilistic ⁶¹ volcanic hazard assessment is simpler in single-rift axis volcanic fields, ⁶² but where central volcanoes exist, hazard assessment is commonly ⁶³ concentrated upon them at the expense of flank features. Logistical ⁶⁴

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difficulties stand in the way of obtaining sufficient age, chemical, or
stratigraphical data to establish a refined volcanic stratigraphy in these
flank regions. As a result, hazard assessments for a volcanic island can
be very focused on the central vent system. In some cases these
structures may pose the greatest threat to the island. However, in other
cases flank eruptions may be of a comparable size and hazard potential.

71Volcanic islands have complex structures, similar to stratovolca-72noes, comprising coherent (effusive and intrusive) and clastic volcanic rocks with variable degrees of alteration, weathering and thickness 73variations, thus resulting in unique hydrogeology (Boubekraoui et al., 741998; Violette et al., 2001; Join et al., 2005). Moreover, being 75surrounded by sea influences their hydrogeology as well as the entire 76 gravitational stability of the growing volcanic edifice (Carracedo et al., 771999; Day et al., 1999; Walter et al., 2005; Munn et al., 2006). 78

In this study we concentrate on eruptions that pose hazard
 particularly in the coastal areas of a volcanic island. Eruptions along
 coastal areas commonly involve phreatomagmatic eruptions as a

result of the water saturation of the sediments in the coastal plains, or 82 within the surrounding shallow seas of the islands. This fact and the 83 growing coastal population of volcanic islands make these coastal or 84 near-shore eruptions potentially dangerous. Attention is particularly 85 highlighted on the locations where major rift axes meet the sea, where 86 the eruptions are most likely to be concentrated. In this paper we 87 document apparently young volcanic landforms and deposits forming 88 the northeastern edge of the volcanic island of Ambae (Aoba) in 89 Vanuatu (New Hebrides). These structures are interpreted in relation 90 to similar features in other SW Pacific volcanic islands and are used to 91 assess the degree of hazard posed by the rift-edge volcanism. 92

2. Geological setting

Ambae (Aoba) is part of the Vanuatu active volcanic arc located in 94 the northern-central part of the archipelago (Fig. 1A). The NE-SW 95 elongated island has a characteristic rift zone that has an en-echelon 96



Fig. 1. A) Location of Ambae Island, part of the Vanuatu archipelago. B) Digital elevation model of Ambae Island shows well-developed rift axis dotted with scoria cones. The central vent complex with a caldera lake (Lake Vui) confined in a large tuff ring was a place of past intra-caldera Surtseyan-style explosive eruptions such as the 2005 December eruption. N'dui N'dui village and its surrounding area is mentioned in oral traditions as a site of the AD 1670 lahar disaster. Saratamata and Longana (in white box) are the two villages where human occupation sites were identified embedded in distal scoria fall and phreatomagmatic tephra. C) An enlargement of the NE rift-edge area of Ambae where half sections of phreatomagmatic volcanoes (numbers) form a volcanic field. Numbers refer to the views shown on Fig. 4.

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offset structure on each side of the central vent system (Fig. 1B). This 97 98 complication to the rift system is related to the cross-arc stresses caused by the subduction of a slab of continental crust (the Lousiville 99 100 Ridge) beneath the central volcanic arc (Meffre and Crawford, 2001; Calmant et al., 2003). The rift system forms an incipient graben 101 structure with scoria cones, lava spatter cones and lava flows within 102and concentrated along its margins. These form a volcanic ridge 103 developed upon a basaltic (pyroxene, olivine and picritic) lava shield 104 105(Fig. 1B). Ambae emerges up to 1496 m above sea level, culminating in the Lombenben Volcano (Mount Manaro) (Fig. 1B). Overall, Ambae is 106 the most voluminous active volcanic island in the Vanuatu archipe-107 lago (Fig. 1A) with the summit standing 3900 m above the 108 surrounding seafloor. The central part of the island forms a nested 109caldera system (Warden, 1967; Warden, 1970). Two distinct caldera 110 structures (Fig. 1B) occur with the floor presently about 150 m deep 111 (Warden, 1967; Warden, 1970). The age and the origin of the caldera 112 are unknown, although the lack of a widespread evolved pyroclastic 113 succession on the island suggests it formed through gradual sub-114 sidence, possibly driven by lateral drainage of the magmatic plumbing 115

system through a flank dyke system (Warden, 1970). The caldera 116 complex is occupied by a large phreatomagmatic tephra ring enclosing 117 the 2.3-km-diameter acidic (pH 1.8) Lake Vui (Fig. 1B) (Warden, 1970; 118 Garaebiti, 2000). This body of water is one of the major concerns in 119 any volcanic hazard assessment on Ambae (Fig. 2) due to its potential 120 for lahar generation in the case of large explosive eruptions through 121 the lake (Cronin et al., 2004). The eruptive history of Ambae following 122 its emergence from the sea about 0.7 million years ago (Warden, 1970) 123 is unknown. Warden (1970) inferred that the central tuff ring and Lake 124 Vui were probably formed during eruptions around 1575 accompa- 125 nied with lava flow effusion in the northern slopes. Extensive lava 126 flows reported from traditional stories are inferred to have destroyed 127 N'dui N'dui village around 1670 on the western flanks of the island. 128 Lahar-triggering eruptions are also inferred from traditional stories 129 during an eruption in 1870. Lahars initiated by landslides probably 130 due to an eruption were reported from 1914. In both lahar events, 131 villages were destroyed with many fatalities (de la Rüe, 1956; Blot and 132 Priam, 1962; Williams and Warden, 1964). Since then, many small- 133 scale phreatic and gas-release events have occurred from Lake Vui 134



Fig. 2. An English version of the current volcanic hazard map of Ambae (after Cronin et al., 2004). The main colour zones predominantly reflect the main volcanic hazards associated with eruption triggered lahars from the summit vents.

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with acid rain and small explosions in 1995. This event caused 135 136 significant alarm on the island along with calls for partial evacuation (Robin et al., 1995). In 2005 December, Ambae had a fully developed 137 138intra-caldera Surtseyan-style eruption forming a tuff cone in the caldera lake (Németh et al., 2006). In spite of the general view that 139lahars were initiated from the central caldera lakes by volcanic 140 eruptions (Garaebiti, 2000) as well as traditional stories (Cronin et al., 141 2004), no convincing evidence of major widespread lahar deposits 142 143 have been described so far in the major tributaries surrounding the central caldera (Fig. 2). A volcanic hazard map (Cronin et al., 2004) and 144 associated exclusion zones are based primarily on central-vent events 145(Fig. 2). Large-scale eruptions are last known from Ambae several 146 generations ago (Cronin et al., 2004). However, island inhabitants are 147 reminded of its volcanic origin by periodic eruptions through Lake Vui, 148 including the most recent surtseyan episode of December, 2005 (Fig. 3) 149 (Németh et al., 2006). The four weeks of surtseyan activity formed a 150100 m high tephra cone, up to 250 m across. The same scenario 151 occurred in 1870 (Warden, 1970). Phreatic eruptions occurred in 1966 152and 1995 (Lardy et al., 1997). Apart from these events, however, the 153eruption chronology and stratigraphy of the island is largely unknown. 154Therefore, no reliable data can be used to interpret any connection 155between central and rift-axis eruptions. The last known rift volcanism 156157is a major lava field formation in the N'dui N'dui area (Warden, 1970; Cronin et al., 2004, 2008). In addition, fresh morphology of several 158 scoria cones suggests Holocene volcanism. 159

At the terminations of the rift in both sides of the island, large tuff rings are the main volcanic landforms (Fig. 1B). On the SW coast, a half section of a tuff ring forms an embayment (Fig. 1B) while in the NE a complex group of 5 tuff rings are clustered (Fig. 1C). The size and architecture of these tuff rings are comparable to the central intracaldera tuff ring.

166 **3. Morphology of rift-edge phreatomagmatic volcanoes**

The geometry of the structures (broad crater, low crater rim and gently dipping pyroclastic units) indicates that the volcanic landforms in the NE side of Ambae are tuff rings similar to those identified in the coastal areas of Jeju Island (Korea) (Sohn, 1996). However, the original morphology of these volcanic landforms is modified and their 171 preserved volcanic successions are rather thick compared with the 172 Korean examples. They likely represent transitional landforms be- 173 tween tuff rings and fully developed tuff cones. 174

In addition to the 5 on-shore tuff rings (Fig. 4A), the northern 175 coastline morphology indicates that another structure is located just 176 offshore (Fig. 1C). Under their heavy tropical vegetation cover (Fig. 4B), 177 their morphology is extremely fresh (Fig. 1C). The young ages of these 178 tuff rings are confirmed by local legends and traditional knowledge 179 of village communities (Cronin et al., 2004). The preserved crater 180 diameters range from about 250 m to 1500 m across, with rims up to 181 100 m high. The crater floors are flat and filled with swamps and 182 shallow lakes (Fig. 4B), and the inner crater rim is marked by steep, 183 sub-vertical cliffs mantled with colluvium. No characteristic gully 184 networks occur on the cones. Two are breached by the sea and form 185 bays (Fig. 4C, D), either dry (Fig. 4E) or containing a lake (Fig. 4D). The 186 tuff rings are used for public grounds of a large school and a regional 187 hospital (Fig. 4E) or as fresh-water reservoirs (Fig. 4F). The deposits of 188 the tuff rings are overlapping and their close spacing suggests some 189 were formed in a relatively short period of time. It is not sure whether 190 these are stand-alone eruption sites or whether they were derived 191 from magmas drained through lateral dyke systems similar to the 192 phreatomagmatic rift-edge volcanic fields in the nearby Ambrym 193 Island about 30 km to the south where at least 7 phreatomagmatic 194 volcanoes were formed in 1913 following a central vent eruption in 195 the summit of Ambrym (Frater, 1917; Gregory, 1917; Robin et al., 1993; 196 Németh and Cronin, 2007). 197

4. Pyroclastic successions of phreatomagmatic volcanoes

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Pyroclastic successions of the tuff rings in the NE edge of the island 199 crop out along the shoreline and along a road cut. These outcrops give 200 data about the lateral extent of the tephra associated with the ex- 201 plosive eruption of the monogenetic volcanoes in the rift edge. They 202 will be described following the full description of the half sections of 203 the proximal, cone-building pyroclastic units. 204

In the road cuts, pyroclastic sequences of the tuff ring 4B (on 205 Figs. 1C and 4B) are exposed, while the northern coastline comprises a 206



Fig. 3. Intra-caldera Surtseyan-style explosive eruption in December 2005 built a tuff cone in the caldera lake.

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Fig. 4. Phreatomagmatic volcanoes from NE Ambae demonstrate a great variety of sizes and preservation conditions. On "A" dotted line marks the approximate position of the rift axes. The airfield is circled. The view numbers are shown on Fig. 1C. On "B" the crater is occupied by a swamp. On "C" and "D" a phreatomagmatic volcano is shown with breached crater rim that gave way to enter the sea. According to local legends (e.g. Cronin et al., 2004) before the sea gained access to the crater it was filled with fresh water lake, similar to another phreatomagmatic volcano shown on "F". A school perfectly set in the dry crater of the westernmost phreatomagmatic volcano (E).

near-continuous proximal-to-distal sequence of phreatomagmatic 207deposits that can be traced as part of the 4C tuff ring (on Figs. 1C 208 and 4C). The base of the 4C sequence is separated by an immature soil 209horizon from an older sequence of phreatomagmatic deposits 210211apparently sourced from an offshore vent site (Fig. 5B and C). There is no outcrop from the otherwise morphologically well-preserved 2124E or 4F tuff rings (on Figs. 1C, 4 E, and F). Along some of the road 213sections, textural differences between the upper pyroclastic units 214show two different source vents, the 4B and 4C craters (Fig. 5D). The 215exposed pyroclastic units are fairly monotonous and can be distin-216 guished into 4 major lithofacies. The volumetrically dominant 217 lithofacies is a well bedded, thinly cross-bedded, poorly sorted tuff 218 with common ripple and mega-ripple features (L1). This makes up 219approximately 60% of the exposed pyroclastic units. The L1 lithofacies 220is interbedded with unsorted lapilli tuff composed of 10 cm-thick 221individual units showing slightly undulating bedding planes (L2). The 222 L2 lithofacies comprises c. 20% of the volume. In the proximal areas of 223 224 the 4C tuff ring, volcanic-lithic rich bomb and block horizons form a 225 tuff breccia (L3) that can be traced along the coastal exposures. This lithofacies comprises about 15% of the total volume of exposed 226 deposits. Scoriaceous lapilli beds with uniform bed thickness and 227 parallel bedding planes (L4) can be identified sporadically throughout 228 the exposed cliffs. This lithofacies comprises about 5% of the total 229 volume of the exposed pyroclastic units. Along the coastline exposures 230 the proportion of L3 lithofacies is larger in the proximal areas of the 4C 231 phreatomagmatic volcano. In distal areas about 1 km away from the 232 4C tuff ring, the proportions of L1 and L2 lithofacies gradually increase. 233

5. L1 lithofacies

5.1. Description

L1 lithofacies consists of fine-grained tuff and minor lapilli tuff 236 (Fig. 6A). It is thin-bedded with sharp and undulating bedding planes. 237 The pyroclastic deposits are poorly sorted and dominated by angular, 238 moderately altered, glassy pyroclasts. Thin ash coating on lapilli frag- 239 ments is common with thin palagonite rims on juvenile fragments. 240 The juvenile fragments constitute c. 70% of the clasts. The remainder 241

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Fig. 5. Half section of a phreatomagmatic volcano in the northern coastline (A). Numbers on "A" refer to the detailed textural photos shown on Fig. 7D and C. People are for scale in circle. On "B" the complex stratigraphy (letters are lithofacies names) is shown with an interbedded soil horizon (dotted line marks its top). Standing tree remains are in circle. A close up view shows (on "C") the immature soil horizon (U) separate two major eruptive units. Thin arrows mark a tree remain moved by the pyroclastic density currents (inferred transport direction is marked by a thick arrow). Other tree branch remains marked with circles. On "D" the proximal tuff ring section is shown where sea water gained access to the crater. Dashed line mark the projection of the relatively low dipping pyroclastic units.

of the of grains are ash-sized and predominantly microcrystalline 242 basalt fragments and subordinately coral or beach sand. Strongly 243 palagonitized, rounded lapilli tuff clasts occur occasionally. The L1 244 lithofacies in coastal exposures becomes dominant with increasing 245distance from the proximal part of the 4C tuff cone (Fig. 6A). L1 246 contains well-developed mega-ripples with wavelengths of 0.1 to 2 m 247 (Fig. 6A) and amplitudes of up to 1 m (Fig. 6B). In the middle section 248 of the coastal cliffs, a persistent horizon of mega-ripples can be 249traced over tens of metres (Fig. 6A). This lithofacies also contains rim-250type accretionary lapilli in tuff beds that commonly mantle ripples. 251252Mantling fine-grained tuff beds have low density and contain abundant fine vesicles. 253

254 5.2. Interpretation

255Beds of L1 lithofacies are interpreted to be deposited from horizontally moving pyroclastic density currents, such as base surges, 256as shown by mega-ripple bedforms, cross-bedding and common 257inverse-to-normal grading (Moore, 1967; Fisher and Waters, 1970; 258Waters and Fisher, 1971; Wohletz and Sheridan, 1979; Chough and 259Sohn, 1990; Lajoie et al., 1992; Dellino et al., 2004b). The poor sorting 260and common grain size changes at bed boundaries also suggest 261 deposition from pyroclastic density currents (White and Schmincke, 262 1999; Dellino and La Volpe, 2000; Gladstone and Sparks, 2002; Gurioli 263et al., 2002; Scolamacchia and Macias, 2005; Sulpizio et al., 2007). The 264fine-grained nature and non-cohesive texture of the individual beds 265suggest low particle concentrations and turbulence of the pyroclastic 266density currents (Yamamoto et al., 1999; Dellino et al., 2004a; Dellino 267et al., 2004b). The plastering effect upon large clasts also supports 268269 deposition from of a PDC (Vazquez and Ort, 2006; Lorenz, 2007). The

abundance of rim-type accretionary lapilli (Schumacher and 270 Schmincke, 1991; Schumacher and Schmincke, 1995), especially in 271 the more distal areas, indicates high moisture contents but not water 272 saturation in the base surges. This is also supported by the general lack 273 of post-depositional soft-sediment deformation structures such as 274 dewatering structures and slumping surfaces, which are expected in 275 wet surge deposits (Dellino et al., 1990). The flow indicators (Bogaard 276 and Schmincke, 1984) exclusively suggest a unidirectional transport 277 from the east, i.e., the presumed vent location of the 4C phreatomag- 278 matic volcano, which is at present submerged by breaching of its 279 northern rim by wave action. The thin mantle-bedded layers over 280 ripples suggest fallout from co-surge ash cloud after a series of 281 pyroclastic density currents passed the depositional sites (Dellino 282 et al., 2004a; Vazquez and Ort, 2006). The abundance of accidental 283 lithic fragments suggests that the exposed sites along the shoreline 284 are part of a phreatomagmatic volcano in which eruption the 285 excavation of country rock fragments played an important role in 286 the formation of the volcanic edifice (Godchaux et al., 1992; Aranda- 287 Gomez and Luhr, 1996; Martin and Németh, 2005). Low-density, 288 vesicle-rich tuff beds interpreted to be vesiculated (vesicular) tuffs are 289 a result of entrapment of air and condensing steam in the fine tephra 290 as it has been documented in many phreatomagmatic volcanoes 291 worldwide (Lorenz, 1974b). 292

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6.1. Description

L2 is a stratified, weakly to moderately bedded lapilli tuff (L2a) and 295 tuff (L2b) lithofacies. This lithofacies dominates the proximal areas of 296

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Fig. 6. Pyroclastic density current dominated succession in medial section (A). Inferred transportation direction is marked by the arrow. Close up view (B) of a dune in the pyroclastic density current succession indicating left to right transportation (arrow). Simplified stratigraphy log of the proximal pyroclastic successions (C) shows the distribution pattern of identified lithofacies. Lithofacies codes are explained in the text.

the 4C tuff cone (Fig. 6C), although beds become finer (i.e., L2b) with 297 increasing distance from the vent over about 500 m. L2 is dominated 298 by angular juvenile ash and lapilli with moderate palagonitisation. The 299 beds have undulating bedding planes, and they are unsorted or 300 inverse-to-normally graded. Inverse grading is more prominent in 301 coarser-grained beds (L2a). About 30 vol.% of L2 is rich in accidental 302 303 lithic clasts, including different types of coherent basaltic rocks, coral fragments (Fig. 7A) or altered and probably older lapilli tuff fragments 304 (Fig. 7B). The proportion of L2 beds is higher in the eastern side of the 305 306 coastal outcrops near the presumed vent site of the 4C tuff cone.

307 6.2. Interpretation

The beds of this lithofacies are interpreted to have been deposited 308 from laterally moving pyroclastic density currents such as base surges 309 and pyroclastic flows. The progression from L2 to L1 beds with 310 311 distance from source is similar to that described in many tuff rings, such as Hopi Butte, Arizona (Vazquez and Ort, 2006), Linosa, Italy 312 (Lajoie et al., 1992), Pinacate, Sonora (Wohletz and Sheridan, 1983; 313 Gutmann, 2002; Martin and Németh, 2006) or many tuff rings from 314Jeju Island, Korea (Sohn and Chough, 1989; Chough and Sohn, 1990; 315Sohn, 1996). The lateral facies changes of the L2 lithofacies from 316 coarse- to fine-grained subfacies suggest gradual loss of competence 317 of the pyroclastic density currents. The L2 beds appear to have formed 318 from pyroclastic density currents with high particle concentrations, 319 involving significant excavation of country rock in shallow subsurface 320explosion sites (Lorenz, 1986). The coarse grain size and abundant 321 country rock fragments from near-surface lithologies indicate stabile 322 explosion locus position of individual explosions in the near-surface 323 324 country rock (e.g. beach platform) and relatively low-efficiency 325 fragmentation itself (Lorenz, 1986; Lorenz and Kurszlaukis, 2007).

7. L3 lithofacies

7.1. Description

L3 lithofacies is most common in the proximal areas of the 4C 328 phreatomagmatic volcano (Fig. 8A). It forms thickly bedded, acciden- 329 tal-lithic bomb and lapilli-rich units (Fig. 8B). Impact sags are 330 common, penetrating and deforming the underlying finer-grained 331 beds (L1 or L2 beds). In proximal areas the pyroclastic rocks form 332 distinctive and laterally persistent beds (Fig. 8A), while in more distal 333 areas they tend to form single-bomb horizons (or trains) within an 334 unsorted coarse ash matrix (Fig. 8B). In proximal areas individual beds 335 of L3 are up to 1 m thick and comprise matrix-supported unsorted tuff 336 breccias. Within the tuff breccia, lensoidal zones of coarse lapilli are 337 common. Also in the proximal areas, L3 beds commonly exhibit 338 channel-like features with flat tops and U-shaped basal contacts. 339 Accidental lithic clasts include predominantly volcanic lithic frag- 340 ments with angular to sub-rounded shapes.

7.2. Interpretation

The beds of L3 lithofacies are interpreted to have resulted from 343 major vent-clearing explosions that excavated significant volume of 344 country rocks (White, 1989; Büchel and Lorenz, 1993; Mastrolorenzo, 345 1994; Ort et al., 1998; Vazquez and Ort, 2006). Their massive texture 346 and sheet-like architecture in proximal areas are consistent with 347 deposition from laterally moving high-particle-concentration pyro- 348 clastic density currents (Chough and Sohn, 1990; Sohn, 1996). 349 Additional country rock material was apparently added by jet-like 350 explosions (Kokelaar, 1983; Kokelaar, 1986) and entrained by the 351 gravity currents (Dellino et al., 2004a). The coarse-grained lenses in L3 352

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Fig. 7. Picked up coral fragments (circle) in a phreatomagmatic pyroclastic rock in distal succession (A). Bomb sag caused by an already diagenised lapilli tuff fragments from an older pyroclastic unit (B). Arrow marks the inferred transportation direction.

could be interpreted as scour-fill features, where passing density 353 currents erode small scours and subsequent currents leave behind lag 354 deposits (Schmincke et al., 1973; Chough and Sohn, 1990). U-shaped 355 channels similar to the channels identified in a few proximal beds of 356 L3 are commonly interpreted to be erosional channels caused by the 357 358 moving pyroclastic density currents (Crowe and Fisher, 1973; Fisher, 1977). The common association of such U-shaped channels with large 359 360 lapilli and bomb sized clasts and complex impact features suggests that these features were produced by direct debris jets, similar to 361 those described at "wet" volcanoes associated with emergent 362 volcanism (Leat and Thompson, 1988; Mueller et al., 2000). Other 363 failure mechanisms for forming U shaped channels in wet deposits 364 365 (Lorenz, 1974a; Sohn and Chough, 1992) are less likely based on the extent and geometry of the channels being closely associated with 366 primary deposits under- and overlaying the channels. 367

368 8. L4 lithofacies

369 8.1. Description

L4 lithofacies is the least common facies of the exposed pyroclastic succession of the tuff rings however it is common in small outcrops in the inter-cone areas in NE Ambae. It comprises thinly bedded scoriaceous coarse ash and lapilli with better sorting characteristics than the other lithofacies. The beds of L4 are laterally continuous over tens of metres, although thin beds tend to pinch out over a few metres. The scoriaceous ash and lapilli are fresh, angular, and equidimensional. Vesicles are smooth-walled. The scoriaceous ash and 377 lapilli are black with no alteration rims. 378

8.2. Interpretation 379

L4 represents fall deposits from strombolian-style eruption. The 380 rarity of these beds in the tuff ring units of 4C volcano indicates that 381 phreatomagmatic explosions were dominant during the eruption of 382 the 4C phreatomagmatic volcano. The irregular thicknesses of such 383 beds and their lateral discontinuity indicate that falls were short-lived 384 and may have been generated by brief, unstable lava fountains. Such 385 eruptive scenario is consistent with ascending magma that only rarely 386 pierces a wet vent zone during transient periods of higher magma 387 output rate or through relatively drier parts of the vent zone.

9. Distal pyroclastic units

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The pyroclastic succession along the northern coast line is inferred 390 to have resulted from at least 3 major eruptive events. A major break 391 between these eruption events is shown by an intercalated soil with 392 plant fragments and fossilised trees, some standing in growth position 393 (Fig. 9A). This suggests a time gap of at least several decades between 394 the two eruptive events. The standing trees preserved in the basal 395 zone of the depositional surface of the second (middle) pyroclastic 396





Fig. 8. Steeply dipping phreatomagmatic succession in proximal areas of the NE coastline half section of the phreatomagmatic volcano (A). Note the large volcanic lithic block in L3 with no impact sag under. On "B" a volcanic lithic block caused deep impact crater (white arrow marks transportation direction) that captured other coarser grained fragments from the passing pyroclastic density currents (black arrow marks the transportation direction).

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Fig. 9. Base of a pyroclastic density current succession (A) accumulated over an immature soil horizon (contact is shown by a black arrow). The pyroclastic density current deposits contain few fragments (F) from older phreatomagmatic lapilli tuffs as well as debris (D) of broken tree branches. Standing tree remnants marked by a rectangle. On "B" a close up view shows a bed flattened vegetation remnant.

unit is similar to those described from other phreatomagmatic 397 398 volcanic fields such as Auckland, New Zealand (Marra et al., 2006). The thin tree trunks and disrupted branches show no signs of thermal 399 alteration about one km away from the vent. This indicates that the 400 passing pyroclastic density currents had low velocity and low tem-401 peratures (Gurioli et al., 2002). The plastering effects on standing tree 402 403 trunks and bedding-parallel branches indicate that cohesive, moisture-rich pyroclastic density currents passed through the vegetation 404 405cover.

The contact between the middle and top pyroclastic units is obscure, but textural differences of the pyroclastic units, differing paleocurrent indicators and the overall 3D architecture imply that the topmost section of the exposures are sourced from the south from the 4B vent site (on Fig. 1C). The majority of the lower and coastal exposures are deposits sourced from the eastern 4C phreatomagmatic volcano.

Distal pyroclastic successions associated with small-volume 412 413 monogenetic volcanoes such as scoria cones and phreatomagmatic volcanoes in NE Ambae crop out near the coastline of Saratamata 414 village (Fig. 10). These sections are important from an archaeological 415 point of view because human occupation sites have been identified 416 between individual packages of pyroclastic units, a few dm-to-m 417 thick, derived from scoria cone and phreatomagmatic volcano (Bed-418 ford et al., 1999; Bedford, 2006; Cronin et al., 2008). This indicates that 419 phreatomagmatic volcanoes and other rift-edge scoria cones were 420active during the known human occupation times of Ambae, which is 421 422 estimated to be about 3000 years before present and new data indicates eruptive activity as young as <500 and <300 yr B.P. (Bedford, 423 2006; Cronin et al., 2008). 424

Near the Saratamata coast (toward Airport turnoff/Navonda) a 425 section exposes 4 well-defined volcanic units (Figs. 1 and 10). The 426 succession is topped by an about 10 cm thick, dark brown, nutty 427 structured silt loam with common scoria fine lapilli and moderately 428 rounded cobbles and pebbles of volcanic lithic and coral fragments 429 (Unit 4). In these topmost beds, brown unadorned pottery fragments 430 (up to 5 cm diameter) have been recovered. These beds are interpreted 431 to be locally reworked volcanic ash and lapilli.

This unit has a gradational contact with a package of primary and 433 secondary volcaniclastic beds (Unit 3). The topmost part of this unit is 434 a 2–10 cm thick and 30–50 cm long patches of deep brown fine scoria 435 lapilli inferred to be primary air-fall lapilli, derived from a nearby 436 scoria cone. This primary succession has a gradational contact 437 downward to a 20–30 cm thick, brown, nutty structured silt loam 438 with rare scoria lapilli and rare rounded and angular volcanic rock 439 pebbles. This succession is inferred to be locally reworked volcanic ash 440 and lapilli. In this bed, rare unadorned pottery fragments (up to 4 cm 441 diameter) have been identified. Below this bed with a gradational 442 contact a 20–30 cm thick, structureless, yellow brown silt loam with 443 rare grey and red scoria coarse lapilli fragments and rare charcoal 444 fragments have been identified. This bed has been interpreted to be 445 also locally reworked volcanic ash and lapilli.

Below Unit 3, a succession of Unit 2 with a sharp contact can be 447 traced. It is topped by a 15 cm thick, greyish brown, bedded fine- 448 medium ash tuff. It is bedded on a mm-cm scale, including vesiculated 449 beds and accretionary lapilli-bearing beds and mantling underlying 450 topography. On the basis of these features, these deposits are inter- 451 preted to be dominantly volcanic fall units, but include distal 452 pyroclastic surge deposits derived from a nearby phreatomagmatic 453 volcano. With a sharp contact, 5–10 cm thick, black/dark grey fine 454 scoria lapilli unit crops out and are interpreted to be primary volcanic 455 airfall deposits, derived from a nearby scoria cone, probably genetically 456 related to the unit above. This unit sits with a sharp contact on a 40 cm $\,457$ thick, greyish brown to pale yellow brown silt loam with yellow brown 458 weathered fine scoria lapilli and red angular coarse lapilli. Grey, 459 angular and subrounded dense lava fragments, coral fragments and 460 reddish coarse scoria pebbles are concentrated in patches along the 461 upper 5–10 cm of the unit; pottery fragments, up to 5 cm in diameter, 462 are also rarely present along this horizon. This unit is interpreted to be 463 locally reworked ash and lapilli. 464

The base of this succession (Unit 1) develops with sharp contact. It 465 is at least 50 cm thick, greyish brown, finely bedded, medium_to_fine 466 ash tuff. Bedding can be traced on a mm_to_cm scale with common 467 accretionary lapilli horizons. Mantle bedding is apparent and indicates 468 predominantly fall origin. This unit also includes distal pyroclastic 469 surge deposits derived from a nearby phreatomagmatic volcano. 470

A very similar succession has been identified closer to Saratamata 471 Village. In this distal succession, rare pottery fragments are also 472 identified between primary volcanic units, indicating human occupa- 473 tion and recurrence of small-volume monogenetic volcanism both 474 with magmatic and phreatomagmatic explosive activity in the NE rift 475 edge of Ambae. 476

The presence of cultural horizons between distal pyroclastic units 477 associated with small-volume explosive eruptions from local sources 478 such as scoria cones and phreatomagmatic volcanoes indicates that 479 volcanism in this part of the island is young (certainly younger than 480 3000 years B.P.). The cultural horizons interbedded with locally 481 reworked distal pyroclastic units also indicate that there were rela- 482 tively long (decades to hundreds of years) breaks in eruptive activity, 483 long enough to develop human settlements over volcanic eruption- 484 modified landscapes. At present, the recurrence rate and the timing of 485 individual volcanic events couldn't be established because of the lack 486 of reliable age data and possibility of lateral correlation of individual 487 pyroclastic units (due to tropical vegetation cover). However, the 488

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Fig. 10. Simplified stratigraphy logs from the cone building pyroclastic succession of one of the major phreatomagmatic volcano and from intra-cone fields in the coastal plains of eastern Ambae. Lithofacies codes are identical to those described in the text.

explosive volcanism was certainly young and repeated in this region of
the island, and it has affected almost the entire NE edge of the island in
each eruptive phase.

492 10. Discussion

493 At least three major eruptive events can be distinguished in this 494 restricted location, showing that the locus of volcanic eruptions has 495 remained stable at the NE edge of Ambae. Occurrence of soils between the eruptive units implies that renewed periodic phreatomagmatic 496 volcanism is a feature of this location. The well distinguished units 497 from sporadic distal exposures confirm the repetition of volcanic 498 events and their effect on landscape evolution of NE Ambae. This 499 implies that the rift edge(es) on Ambae should be viewed as high 500 volcanic hazard risk areas (Fig. 1). During the course of the eruption in 501 December 2005, about half of the total population of the island was 502 displaced in the area of phreatomagmatic volcanoes in the NE rift edge 503 considering that area safe.

505 The stratigraphic and archeological features of the preserved 506 pyroclastic successions from both proximal and distal sections give 507 evidence of repeated phreatomagmatic activity and attendant scoria 508cone-building eruptions in NE Ambae during the recent times, at least since human occupation took place in this part of the island. Textural 509features from the proximal half sections of the phreatomagmatic 510volcanoes such as the presence of accretionary lapilli throughout the 511sections indicate that the pyroclastic density currents were wet, 512513comprising condensed water, but they were not wet enough to generate water-saturated tephra beds and associated deformation 514515(Sohn and Chough, 1989; Rosi, 1992; Schumacher and Schmincke, 5161995). This indicates that the phreatomagmatic explosions involved 517close-to-optimal magma:water ratios to cause powerful explosions, 518and no surplus water was in the system during the magma and water interaction (Wohletz and Sheridan, 1983). The relatively high propor-519 tion of the accidental lithic fragments throughout the pyroclastic 520 521 deposits suggests that excavation of country rocks was continual and/ or the volcanic conduits were partially collapsed on occasions during 522the eruptions. The coarse-grained tuff-breccia horizons of the L3 523lithofacies also indicate vent-clearing events, and/or major conduit 524wall collapse in the course of the eruptions. They were probably 525emplaced by direct pyroclast jets. The mid-level pyroclastic unit lies 526527on a formerly vegetated surface, indicating a subaerial depositional 528environment. The presence of country rock in the phreatomagmatic pyroclastic succession suggests that the eruption of the 4C phreato-529magmatic volcano took place in a near sea-level coastal plain. Local 530legends and traditional stories mention that a fresh water lake was in 531532the volcanic depression before the outer crater wall was breached by the sea (Cronin et al., 2004). 533

The depositional features and the areal distribution pattern of the 534535preserved pyroclastic units suggest that the entire NE edge of the 536island would be affected predominantly by pyroclastic density 537currents, scoria fall events and direct pyroclast jets from phreatomag-538 matic volcanoes in a future eruption, assuming similar eruptive activity to those that formed the preserved tuff rings. The eruption 539duration of a single phreatomagmatic volcano is estimated to be in the 540range of days to weeks on the bases of recent analogies from 541542worldwide examples (Thorarinsson, 1967; Kokelaar, 1983; Cole et al., 2001; Németh et al., 2006). Distal tephra would most certainly affect 543most of the NE peninsula of Ambae given a future eruption of similar 544nature in this part of the island. A new phreatomagmatic eruption site 545would constructed a circular crater 500-1000 m wide, with distal 546 tephra capable of reaching a few kilometres away. It is generally 547 assumed that a new vent would not open in the same place as any 548 previous vent, although recurrence of eruptions in the same site with 549550slightly shifted vents are known from several volcanic fields 551(Houghton and Schmincke, 1989; Németh et al., 2001; Németh and White, 2003; Auer et al., 2007; Brand and White, 2007). The 552stratigraphic relationships of the proximal and distal pyroclastic 553units of the phreatomagmatic volcanoes in NE Ambae suggest for-554mation vent sites can be very closely located and does not rule out 555556them being overlapping. This is also likely because vent sites are 557highly restricted to the central part of the rift zone, controlled by magma feeding along lateral dykes. A good example for this is known 558from the rift edge volcanic fields of the nearby Ambrym Island. In 559560 Ambrym Island, in 1913, new phreatomagmatic eruptions occured in 561the broad crater of an older phreatomagmatic tuff ring (Frater, 1917; Gregory, 1917). This fact implies that there can be immediate volcanic 562hazards for Ambae where recent human development (schools, water 563 reservoirs, agricultural activity) favours the relatively flat and open 564spaces provided by crater floors in NE Ambae. 565

In the case of the neighbouring Ambrym Island, there are clear eyewitness accounts as well as geological data demonstrating a coupling mechanism between summit eruptions and rift-edge, dominantly phreatomagmatic, explosive activity. In Amrbym, riftedge volcanism is almost exclusively predated by volcano-seismic and eruptive activity in the summit region of the island. Initial summit 571 eruptions were followed by rift_edge volcanism just days after as it has 572 been demonstrated in 1894 (Purey-Cust, 1896) and 1913 (Frater, 1917; 573 Gregory, 1917). This coupling mechanism was the reason to avoid 574 tragic loss of life in 1913 when the new tuff ring formed in the 575 older tuff ring region occupied by a missionary hospital (Frater, 1917; 576 Gregory, 1917). Similar coupling mechanisms between summit and 577 rift-edge volcanism are also anticipated at Ambae, although no oral 578 traditions or historic evidence is known to support this (Cronin et al., 579 2004). 580

Ambae rift-edge volcanism is very similar to that at many other 581 volcanoes of similar structure, including Taveuni in Fiji, where dozens 582 of monogenetic volcanoes developed on a basal lava shield along the 583 well-defined rift (Cronin and Neall, 2001). Eruptions along the rift axis 584 and edges show no characteristic time and space evolution trend apart 585 from occurring with highest frequency in central parts of the rift 586 where greater thicknesses of volcanic units overlap to build the 587 highest ground (Cronin et al., 2001). In spite of the apparent similarity 588 of random distribution of eruptive events along the rift, Taveuni lacks 589 a well-defined central volcanic edifice such as at Ambae and Ambrym. 590 Similar comparisons could be drawn between Ambae and the main 591 islands of Western Samoa (Upolu and Savai'i). In Upolu and Savai'i rift- 592 edge phreatomagmatism is well known (Keating, 1991; Cronin et al., 593 2000; Cronin et al., 2006), although their time relationship with other 594 rift axis volcanism is unknown and inferred to be random (Kear and 595 Wood, 1959), similar to the case of Ambae. The Western Samoan 596 islands are similar to Taveuni with no well-defined central volcano 597 other than lava shields. 598

Development of rift-edge volcanoes and volcanic fields with 599 extensive phreatomagmatism seems to show a gradual transition 600 from single composite volcanoes (common volcanic islands) to more 601 well-defined rift-edge volcanic fields. This transition is well defined by 602 initial rift-axis cone formation in the flank of Lopevi in Vanuatu 603 (Warden, 1967; Cronin et al., 2003). Such initial rift-axis volcanism 604 commonly forms phreatomagmatic volcanoes near the coastlines. It is 605 also known from volcanic islands that localisation of well-defined rift 606 axis may take time in the evolution of the volcano, and in its initial 607 stage small-volume volcanoes may form apparently randomly around 608 the central vent complex, many of them with phreatomagmatic 609 eruption history close to the sea level such as the case in Izu-Oshima 610 (Ida, 1995; Sumner, 1998) and Miyakejima (Geshi et al., 2002; 611 Yamaoka et al., 2005) in Japan.

11. Conclusion

Rift-edge phreatomagmatism has played an important role in the 614 volcanic evolution of Ambae, and it generated potentially dangerous, 615 destructive eruptions. The NE rift-edge of Ambae Island is a complex 616 monogenetic volcanic field with numerous scoria cones and at least 617 five large (km-wide) tuff rings/cones. The local legends, traditional 618 stories and, most importantly, artefacts from human occupation em- 619 bedded within scoria fall and phreatomagmatic tephra deposits 620 indicate young absolute ages (<3000 yr, B.P.) and repeated eruptions 621 in this part of Ambae Island. The lack of eyewitness accounts as well as 622 references from oral traditions from village communities is unable to 623 provide clear evidence of possible connections between central, 624 summit-vent eruptions and the formation of the rift-edge volcanic 625 fields. However, by comparison to neighbouring volcanoes of similar 626 structure (Ambrym and Lopevi) suggests a close coupling with central 627 volcanism is very likely. The pyroclastic density current-dominated 628 pyroclastic successions from exposed in the tuff cones/rings suggest 629 significant destructive forces from this volcanism, which has the 630 potential to affect the entirety of the northern area with tephra fall 631 and surges. Rift edges and broad flat crater floors in these areas on 632 Ambae and other similar volcanoes are popular sites for infrastruc- 633 ture development. However, this practice may lead to exacerbating 634

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 $_{635}$ community vulnerability to re-awakening phreatomag matism in $_{636}$ these areas.

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