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# Is Efate (Vanuatu, SW Pacific) a result of subaerial or submarine eruption? An alternative model for the 1 Ma Efate Pumice Formation

**Research Article**

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**Abstract:** The Efate Pumice Formation (EPF) is a trachydacitic volcaniclastic succession widespread in the central part of Efate Island and also present on Hat and Lelepa islands to the north. The volcanic succession has been inferred to result from a major, entirely subaqueous explosive event north of Efate Island. The accumulated pumice-rich units were previously interpreted to be subaqueous pyroclastic density current deposits on the basis of their bedding, componentry and stratigraphic characteristics. Here we suggest an alternative eruptive scenario for this widespread succession. The major part of the EPF is distributed in central Efate, where pumiceous pyroclastic rock units several hundred meters thick are found within fault scarp cliffs elevated about 800 m above sea level. The basal 200 m of the pumiceous succession is composed of massive to weakly bedded pumiceous lapilli units, each 2-3 m thick. This succession is interbedded with wavy, undulatory and dune bedded pumiceous ash and fine lapilli units with characteristics of co-ignimbrite surges and ground surges. The presence of the surge beds implies that the intervening units comprise a subaerial ignimbrite-dominated succession. There are no sedimentary indicators in the basal units examined that are consistent with water-supported transportation and/or deposition. The subaerial ignimbrite sequence of the EPF is overlain by a shallow marine volcaniclastic Rentanbau Tuffs. The EPF is topped by reef limestone, which presumably preserved the underlying EPF from erosion. We here propose that the EPF was formed by a combination of initial subaerial ignimbrite-forming eruptions, followed by caldera subsidence. The upper volcaniclastic successions in our model represent intra-caldera pumiceous volcaniclastic deposits accumulated in a shallow marine environment in the resultant caldera. The present day elevated position of the succession is a result of a combination of possible caldera resurgence and ongoing arc-related uplift in the region.

**Keywords:** pumice • rhyolite • dacite • explosive • caldera • subaqueous • ignimbrite • phreatomagmatic • regional uplift • subduction



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## 1. Introduction

Increasing numbers of silicic volcanoes have been identified in island arcs [1–5]. The emplacement of these silicic eruptives is of considerable interest because it not only provides data on the magmatic, tectonic and geomorphic environment of the volcanic arc at the time of eruption but also the types and levels of potential volcanic hazards, e.g. the contrasting risk from volcanic ash between deep marine and subaerial eruption. In this paper we wish to propose an alternative model for the eruption and emplacement of the Efate Pumice Formation (EPF) to stimulate further discussion of silicic eruptions in oceanic settings.

We present evidence from our recent field work that the EPF is largely subaerial in origin but it was substantially reworked in a marine environment which, we suggest, resulted from post eruption caldera subsidence before resumption of the uplift recorded by the coral reef sequence.

## 2. Tectonic Setting of Efate

The island of Efate lies within the southern part of the Vanuatu or New Hebrides arc. This arc marks present subduction of the Indo-Australian plate estward beneath the Pacific plate, and it is currently underthrusting the North Fiji Basin (Figure 1) at about 12 cm $yr^{-1}$ [6–8]. The overall history of the South west Pacific is of successive opening of marginal basins that isolated arc ridges or slivers of continental crust since the Cretaceous [9–11]. The Vanuatu arc comprises three compositionally, temporally and geographically distinct belts of islands which reflect the three main stages of the evolution of the arc [12, 13]. The eastern belt is of Oligocene age and comprises a basement of ophiolites faulted against submarine to subaerial volcanics associated with current subduction. The c. 10-8 Ma collision of the Ontong Java Plateau with the arc reversed arc polarity and contemporaneously rotated the arc to its present, more NE orientation through opening of the North Fiji Basin. Associated subduction volcanism in the central chain of islands commenced at about 7 Ma. Since c. 3.5 Ma the D'Entrecasteaux Ridge has been in collision with the arc to form the D'Entrecasteaux Collision Zone (DCZ), initially impinging in an area between Epi and Efate but migrating north, due to its oblique orientation to the trench, to its current position facing Espiritu Santos and Malekula (Figure 1) [12, 14]. The D'Entrecasteaux Ridge is interpreted to be the northern extension of a NE dipping Eocene subduction/obduction zone that was located along the New Caledonia/Loyalty Islands Ridge (Figure 1) [15, 16]. In the central part of the arc the typical arc morphology of arc, trench and ocean basin are obscured by the collision [14]. The geology of the arc in the region of Efate is further complicated by a seismic gap or tear in the slab and subduction of seamounts [17, 18]. Arc segments south and north of the DCZ are geochemically distinct from the DCZ segment in having more radiogenic Pb and Sr compositions [19].

## 3. Geology of Efate and Adjacent Islands

The Efate Islands are located on the southern margin of the D'Entrecasteaux Collision Zone and comprise the largest island of Efate, together with a number of smaller, adjacent islands, the largest of which are Nguna, Emau and Pele (Figures 1 and 2). Geologically Efate comprises a trachydacite-dominated volcanic centre in which the predominant unit is the Efate Pumice Formation, a >0.5 km thick sequence of siliceous pyroclastic and volcaniclastic rocks forming elevated hills in the central part of Efate (Figure 2B) that are Pleistocene (<1 Ma) in age [20]. Although Raos and McPhie [20] suggest an age of ca 1 Ma for the Efate Pumice Formation, this appears to be based on a K-Ar date on Quoin Hill basalt of 1.14 Ma [21] as the basalts are stratigraphically younger than the EPF. This must be considered a minimum age. An age of 1.5 Ma for the EPF has also been considered [22]. Here we assume an age of the EPF between 1.14 and 1.5 Ma, in the absence of further data.

The silicic lithologies on Efate are overlain by basalts of the Basalt Volcanoes Formation (BVF), as defined by Ash, et al., [23]. The BVF basalts were erupted in two episodes from 0.7 Ma; the older episode comprises subaerial and shallow subaqueous lava, breccia and intrusive rocks that form the remnant composite cones of Quoin Hill and Mt Fatmalapa (Figure 1) and the younger comprises the subaerial pahoehoe lavas, autobreccias and pyroclastic rocks of Nguna, Emau and Pele Islands (Figures 1, 2A, C, D) [24]. Development of at least 5 coral reef terraces over the last 0.3 Ma [25] records uplift of at least 600 m subsequent to the emplacement of the BVF rocks and places a minimum age on the BVF formation [26].

## 4. Efate Pumice Formation

The EPF represents a major explosive pumice eruption in the Vanuatu Arc at about 1-1.5 Ma and was interpreted as predominantly deposits from submarine eruption [20]. Stratigraphically the EPF comprises a minimum of 500 m of pumiceous pyroclastic beds of up to 5 m thickness each with an estimated minimum bulk volume of 85 $km^3$ [20]. The lower part of the EPF is formed by the Efate Pumice Breccias [27], which are described as massive to graded stratified pumice breccia locally interbedded with pumice sand and silt (Figure 3). No exposure of the base of the unit has yet been found. The pumice clasts are angu-

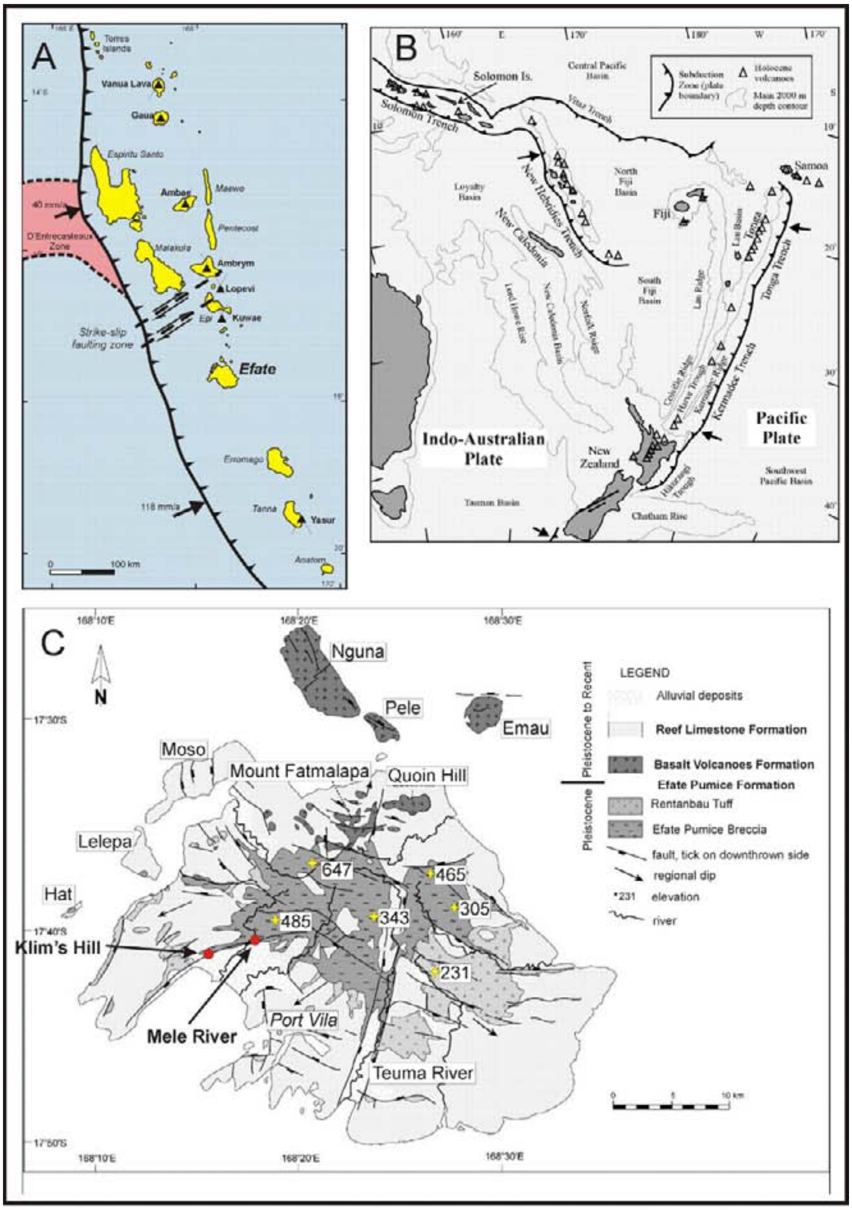


**Figure 1.** Overview map of the Vanuatu archipelago with the location of Efate Island
Overview map of the major geotectonic features associated with the SW Pacific
Simplified geology map of Efate (after Ash et al 1978) with mentioned locations.

lar, ragged glassy tube pumice with subordinate perlite to obsidian and dense lava clasts in a volcanic glass shard- and crystal-rich matrix (Figures 4, 5) with a grain size distribution showing abundance of fine ash (Figures 6A and 6B).

The upper part of the EPF consists of Rentanbau Tuffs (RT) (Figure 1). These tuffs comprise thinly bedded to finely laminated (Figure 7) volcanic glass shard-rich sands and silts containing calcareous microfossils (Figures 8 and 9) commonly used as indicators of a shallow marine depositional environment [28, 29]. They were interpreted as a product of phreatomagmatic eruption as sea water accessed the vents because of the presence of arcuate fracture surfaces on the glass shards [20].

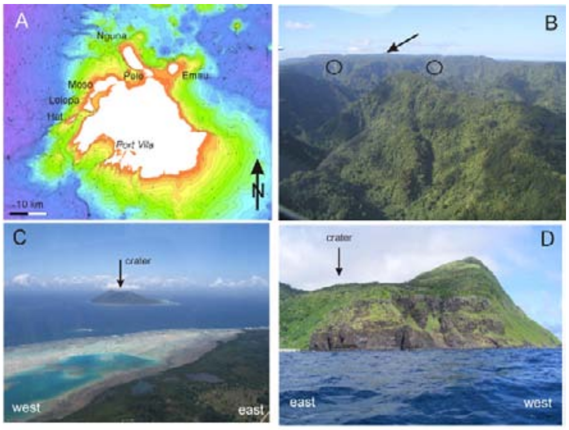


**Figure 2.** Bathymetry around Efate after Krueger and Sharma (2008).
Overview of the interior of Efate. Circles mark large cliff sections of Efate Pumice Formation units. Arrow marks the elevated old coral reefs in the highest topography position.
Oblique areal view of northern Efate with off shore volcanic islands of the Basalt Volcanoes Formation. Arrow points to the well-preserved crater of Emau.
Horizontal lava units in the basal section of the Emau volcanic cone.


**Figure 3.** Outcrop view of the Klim's Hill section exposing thick succession of the Efate Pumice Breccia. Note the coarse grained trains of pumice in the section.
Pumice lapilli rich part of the Efate Pumice Breccia from the Mele River section. Note the grey, pumice lapilli (arrows) in a fine ash matrix.
Stratified lapilli and ash inter-bed between two matrix-supported pumiceous breccia (pb) units from the Mele River section. Arrows mark the contact between massive and stratified pumiceous lapilli and ash units.
Coarse-grained (cg) fine-depleted lapilli inter-bed in massive ash-supported pumiceous ignimbrite units from the Mele River section. Note the angular shape vesicular lapilli (arrows).

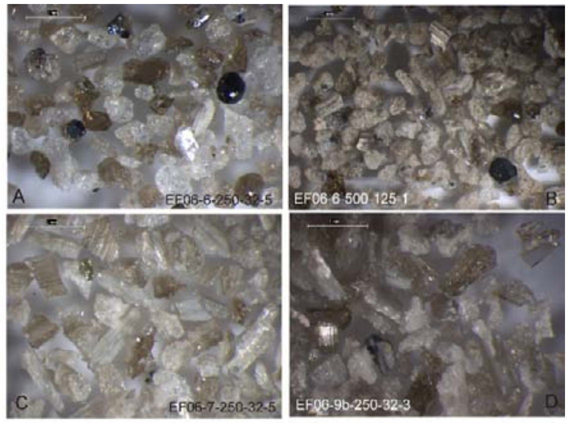


**Figure 4.** Optical microscope images of sieved samples from the pumiceous Efate Pumice Breccia beds. Note the occasional abundance of less vesicular volcanic glass shards (brown, dark in "A") and the general stretched texture of the pumice ash ("B"). The stretched pumice ash particles are fresh ("C") and dominate the particle population in each grain size fractions ("C" and "D").

## 4.1. Efate Pumice Breccias

The Efate Pumice Breccias are exposed in road cuttings in the central to western part of the island and a cross section through many of the units is exposed in the fault scarp forming Klem's Hill (Figures 1 and 2A). Parts of the sequence are accessible in canyons along the Mele River which cut into the Klem's Hill scarp and other outcrops of more restricted vertical extent occur, particularly on the north side of the island (Figure 1). Because the Mele River and Klem's Hill sections are the most extensive we focus on the units in them, with observations augmented by data from other outcrops examined.

### *4.1.1. Mele River Section*

In Mele River (Figure 1) the stratigraphic units comprise a number of individual semi-consolidated matrix-supported massive to weakly stratified pumiceous pyroclastic rock units inferred to be ignimbrites [30, 31] (Figure 3A). These beds are interbedded with moderately to well-sorted fine to coarse dm-thick ash units that evenly mantle the depositional surfaces (e.g. no erosional contact) and we contend they are of airfall origin. These ash beds are commonly covered by thin (cm-to-mm), undulating finely laminated to cross-laminated fine ash beds typical of pyroclastic deposits of surge origin [30, 31].

The units generally dip gently to the SE. The lowermost unit comprises a minimum 4 m thick pale grey, poorly sorted pumiceous lapilli tuff with massive to weakly stratified texture and sparse c. 1 cm pumice lapilli in a sandy ash matrix (Figure 3A). The pumice clasts increase only

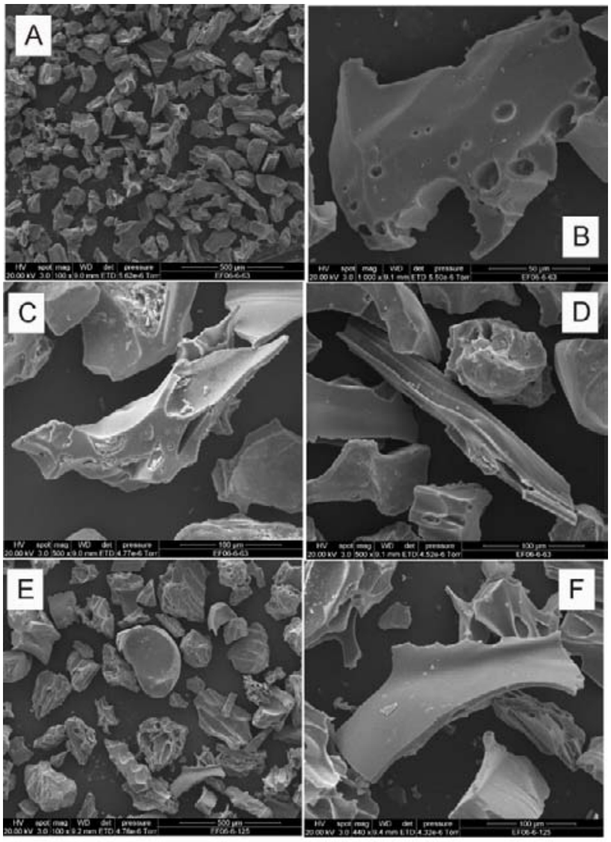


**Figure 5.** SEM images of ash samples from the Efate Pumice Breccia. The fine fractions of the samples were homogeneous and dominated by woody pumice particles (A). Dense volcanic glass shards with blocky shapes were also present (B), as well as curvi-planar (C) or flake-like (D) but vesicular particles. The fine ash fraction also contained occasional dense glassy particles with droplet-like boundaries (E). Fine bubble wall shards (F) were rare particle types.

slightly in abundance towards the top of the unit and large lithic clasts are absent, however fine lapilli sized volcanic lithic clasts are common. The upper boundary is sharp and overlain by a series of units of cm-scale bedded coarse and medium ash. The lowermost ash unit comprises 30 mm of reverse then normally graded coarse ash and is succeeded by 80 mm of massive medium ash with scattered 10 mm light and 3 mm dark pumice clasts. The next unit is 70 mm of laminated and cross bedded fine ash with pinch and swell structures. It also contains ash pellets that are not armoured and do not show any concentric structure. A single, rounded pebble lies on the surface of this unit. The overlying 220 mm thick unit is a medium ash with 15-20% pumice lapilli up to 15 mm in diameter that are concentrated in the central 150 mm of the unit. The uppermost ash unit comprises c. 10 mm coarse and fine ash laminations over a 300 mm interval.

The sequence of ash units is overlain by a 2 m thick pumice-rich massive lapilli tuff unit with approximately 60% (visual estimate) of pumice clasts up to 100 mm diameter. Smaller (50 mm) clasts of friable, dark pumice are occasionally present and rare dense, dark volcanic lithics occur. The upper part of the outcrop appears to comprise bedded sands and silts of the base of the Rentanbau Tuffs and their vertical extent is not exposed at this locality.

The change in depositional regime upwards into the Rentanbau Formation suggests the exposure in the mouth of the Mele River canyon is through the mid- to upper part of the Efate Pumice Formation (Figure 1).

The base of the section is typical of pumiceous deposits accumulated from ignimbrite forming eruptions. While there is no evidence of very hot emplacement conditions such as gas escape pipes, welding, particle agglutination or hydrothermal mineral assemblages, the massive, pumiceous, thickly bedded nature of the deposits is consistent with subaerial accumulation of pyroclasts from ignimbrites, similar to non-welded subaerial ignimbrite deposits in the central North Island of New Zealand [32, 33] and elsewhere [34–36]. The lack of hot emplacement indicators can also be due to the lack of preservation and outcrop availability. However, the well-preserved pumice lapilli with no indication of water-induced alteration, abrasion or water-triggered saturation, as expected in fully or partially subaqueously emplaced pyroclastic flow deposits [37, 38], all point to transportation and deposition from pumiceous pyroclastic flows accumulated in a subaerial rather than submarine setting. The presence of thin deposits forming basal and cover beds over massive to weakly-stratified pumiceous lapilli tuff beds is consistent with ground and ash-cloud surge origin respectively, a typical facies architecture of ignimbrites [30, 39–41].

#### 4.1.2. Klem's Hill Section

On Klem's Hill a section through the upper part of the EPF is also exposed, although here the Rentanbau Tuffs have been removed by erosion. The section comprises >20 m of massive to weakly-stratified pumiceous lapilli and ash containing pumice clasts with a maximum size of 100 mm. Volcanic lithic fragments of cm-to-dm in diameter are rare but have been recognized. The massive nature, pumiceous texture and abundance of fine ash of the deposit is consistent with ignimbrite derived deposition in subaerial conditions, similar to the sections from Mele River.

At the eastern end of the outcrop the pumiceous lapilli and ash unit is capped with c. 1 m of complex undulating to cross-bedded/cross-laminated ash inferred to be of

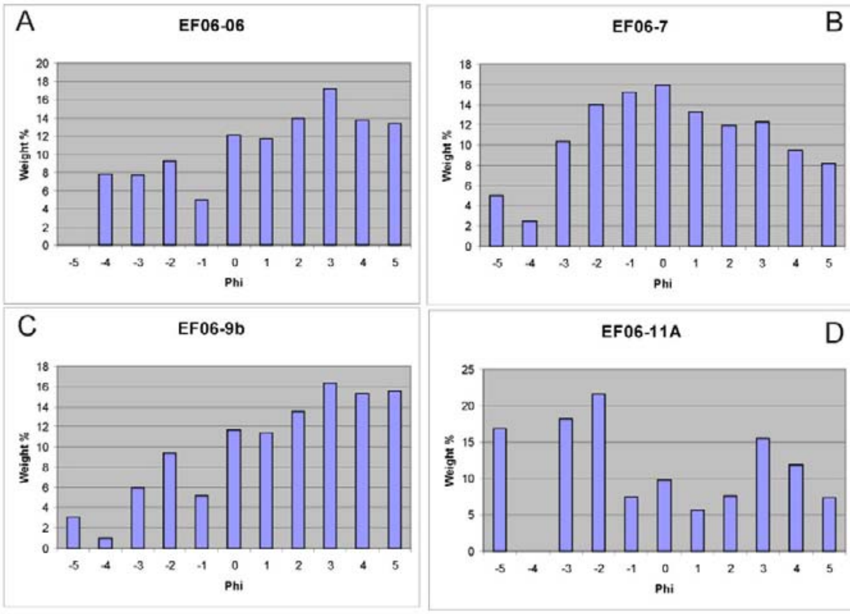


**Figure 6.** Sieve analysis data from samples of the Efate Pumice Breccia (A-B) showed abundance in fine ash particles in the samples. Fine ash fraction was more pronounced in the Rentanbau Tuff samples (C-D) as well as the generally more polymodal distribution pattern of grain size fractions, suggesting reworked origin of these samples.

pyroclastic surge origin. At the western end of the section the pumiceous lapilli and ash units (ignimbrites) have been eroded to form a sea cliff and shore platform. Reef debris, including coarse sand and large (c. 1 m) boulders lie on the eroded platform and the outcrop passes laterally into *in situ* coral reef. The altitude of the erosion and reef-derived deposits suggests this erosion episode was associated with the oldest of the elevated coral reefs and is clear evidence that at least part of the EPF was above sea level at that time.

## 4.2. Textural Characteristics of the Efate Pumice Breccia

Samples from various locations of the EPF have been studied by optical and scanning electron microscopy (SEM) with an aim to identify key textural features that may be indicative of magma fragmentation style and pyroclast transportation type. Each of the samples studied showed a remarkably homogeneous texture comprising mainly juvenile pumiceous pyroclasts through a lapilli to fine ash grain size spectrum (Figures 4 and 5). The pumice clasts were ragged, elongated and fresh in appearance in every grain size fraction (Figure 4A). In finer grain size fractions darker coloured, more bulky shaped volcanic glass shards with moderate vesiculation were more common (Figures 4A and B). In spite of the presence of these darker and more bulky glass shards, the majority of the juvenile particles were highly vesicular, with stretched vesicles and sharp edges (Figures 4C and D). Textural characteristics of the pyroclasts were more readily recognized in SEM images (Figure 5). The majority of the glassy pyroclasts were well preserved, and, considering the age and the potential climatic influence on the alteration of glassy particles, they were remarkably well-preserved with no signs of significant alteration other than moderate circular etching surface alteration of glassy pyroclasts (Figure 5A). In finer grain size fractions, pyroclast margins were commonly defined by larger vesicles and the interior of the shards were only moderately vesicular (Figure 5B). The finer grain size fractions also contained a greater abundance of tube-like pumices and their fragments (Figures 5C and D). Bulky, non-vesicular droplet-like glassy ash particles, as well as cuspate bubble-wall glass shards, were also common features (Figures 5E and F). The samples have nearly no volcanic or non-volcanic lithic fragments in the fine lapilli to fine ash grain size fraction; they comprise exclusively juvenile particles. Volcanic lithic fragments were generally small in comparison of the total volume of the deposits, and they were predominantly in the coarser (lapilli, coarse lapilli) grain size fractions. The grain size distribution of the EPB showed characteristic unimodality, with occasional outsized, usually pumiceous, clasts (Figures 6A and B), in contrast to the more dispersed grain size distribution pattern of the stratigraphically higher Rentabau Tuffs (Figures 6C and D).

### 4.3. Rentanbau Tuffs

Rentanbau tuffs comprise mm to dm laminated silts and sands with common soft-sediment deformation features on a mm-to-dm scale (Figure 7A). The beds are dominated by volcanic glass and subordinate fragments of fossils and reef material (Figures 8 and 9). Volcanic lithic fragments were occasional and represented in the coarse ash fraction by dark, microcrystalline grains. Beds are flat lying to gently tilted to the NE along Klem's Hill (Figure 1) and show sedimentary features indicative of traction currents; cross bedding (Figure 7B) and planar bedding (Figure 7C). Intra-formational slumping is common and indicates instability in the sediment pile.


**Figure 7.** Sections of the Rentanbau Tuff showed its textural difference in comparison to the basal Efate Pumice Breccia (A-D). The section near Klim's Hill forming the uppermost capping rock units consist of finely laminated volcaniclastic silt with undulated and deformed bedding surfaces (A) inferred to represent various dewatering structures. Near Port Vila laminated volcaniclastic succession shows a weathering profile (B) from fresh grey volcaniclastic siltstone to reddish, manganese-rich altered units. Fresh Rentanbau Tuff units are usually rich in dark volcanic glass shards that form dark colour beds or laminae in the sequence (C). In cm-to-dm-scale sized rock samples from the Rentanbau Tuff exhibit complex sedimentary textures indicating complex sedimentary environment and facies architecture (D).

### 4.4. Textural Characteristics of the Rentanbau Tuffs

Texture and componentry of the Rentanbau Tuff differs significantly from the EPB deposits. The RT samples contain more non-volcanic clasts that are commonly biogenic in origin, such as foraminifera and coral fragments (Fig-

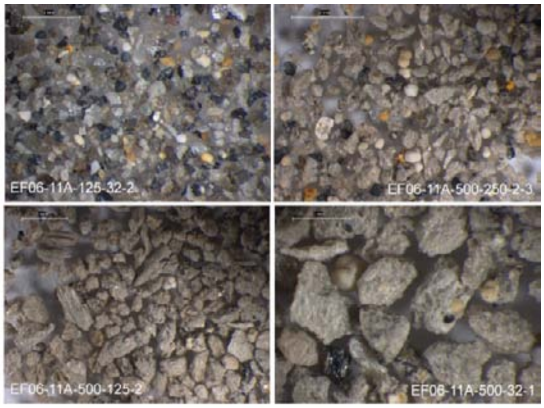


**Figure 8.** Optical microscopy images of sieved samples from the Rentanbau Tuff (A-D). Note the diverse grain population in each grain size fraction (A). The samples are rich in foraminifera (B, C) as well as glass shards (A, B) and foamy pumice ash (D).

ures 8A and B). In addition, each grain size fraction contains higher proportions of dark and bulky glassy pyroclasts with low vesicularity than any other sample studied from the EPB (Figures 8A and B). The bulky dark volcanic glass fragments seem to be more common in the finer grain sized fractions; abundant woody pumice forms the majority of the coarser grain size fractions of the RT (Figures 8C and D). In the coarser grain size fractions, pumice fragments with entrapped foraminifera have been recognized (Figure 8D). The texture of the pumiceous fragments are more complex (e.g. they have a greater variety of pumice shapes) in the RT than in samples from the EPB (Figure 9A). Particularly common clasts are those with complex vesicle shapes (Figure 9B) and dissected and fractured vesicle walls (Figure 9C). In addition, the RT samples have abundant, moderately vesicular, usually darker coloured volcanic glass shards (Figure 9D), many of them showing drop-like boundaries with irregular bubble walls (Figure 9E). The RT pumice fragments are commonly tube-like with smooth edges and circular, micron-scale etch patterns (Figure 9F). Such etch patterns are very rare in EPB while common in RT in every grain size fraction.

## 5. Eruption and Emplacement of the Efate Pumice Breccia Units

The Efate Pumice Formation has previously been interpreted as forming by subaqueous emplacement of pyroclastic units. The clast characteristics were interpreted

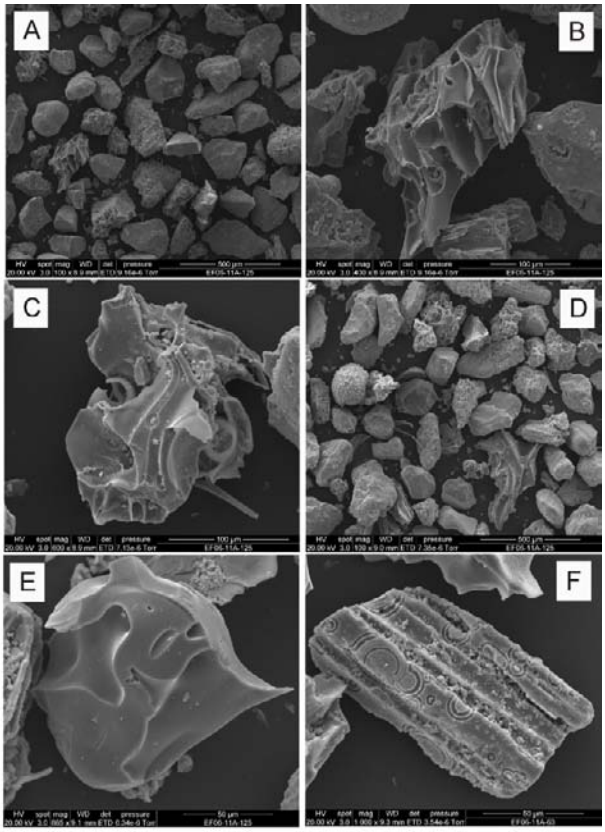


**Figure 9.** SEM images of fine ash fractions from the Rentanbau Tuff (A-F). The samples show significant difference in comparison to the samples studied from the Efate Pumice Breccia having increased amount of angular and blocky glass shards (A). The glass shards are also commonly more complex in vesicle textures (B, C). The fine ash fractions are rich in various biogenic fragments such as foraminifera and coral fragments (D). Unusual shape, angular, dense glass shards are common (E), as well as microvesicular, tube-like pumice ash that are commonly marked by circular etch marks inferred to represent bacterial digestion of volcanic glass (F).

as those generated by predominantly "dry" eruptive processes [20] but in an overall submarine environment kept dry by the force of the eruption. The generally fines-depleted nature of the deposits recognized previously was attributed to efficient elutriation during submarine transport [20]. This suggests that the pumice clasts were erupted in a pyroclastic jet that was armoured against mixing with water but subsequent mixing led to elutriation of fines and deposition of the pumice units from colder mass flow. While this line of evidence sounds convincing, we find that the EPB deposits have abundant fine ash, and are very similar in texture to non-welded subaerial ignimbrite sheets described from other volcanic regions. In addition, Raos and McPhie [20] argue for subaqueous emplacement of the EPB on the basis of fines depletion of the EPB units, which contrasts with our findings. However, fine-depleted subaerial ignimbrites have also been documented and their formation is related to turbulence in the travelling pyroclastic current [42].

Three mutually dependent criteria for identifying true pyroclastic flows in any environment are [43]; (1) presence of "pyroclastically" fragmented debris (2) facies characteristics indicating mass flow emplacement mechanisms for the pyroclastics, and (3) evidence for a hot state of emplacement. Cas and Wright [30] noted that evidence for hot emplacement was the most difficult to prove.

We first examine the massive to weakly stratified pumiceous lapilli units that we infer to be subaerial ignimbrites. The basal unit in the Mele River section is a pumice-poor ignimbrite and pumice lapilli increase in abundance towards the top. There is no evidence of crystal sorting or fines depletion in the outcrop a feature which would be consistent with deposition of pyroclastic density currents in subaqueous environment. Fine depletion has also not been recognized in micro-analytical studies, instead the basal unit samples were reasonably rich (over 15 vol%) in fine ash (e.g. Figures 5A, 6A, and B). The fine-grained nature of the unit suggests interaction with water in the vent during eruption and the distribution of pumice clearly indicates that it was emplaced from a dense (e.g. particle-rich) pyroclastic flow. The ash sequence overlying the lowermost ignimbrite is interrupted by a second thin (220 mm) ignimbrite containing pumice lapilli. The ignimbrite capping the pyroclastic sequence is pumice-rich but still retains a fines-rich matrix and crystal-lithic sorting is also absent.

If these pumiceous lapilli units were deposited subaqueously then there needed to be sustained mass discharge in order to insulate the pyroclastics from mixing with water [44]. The relatively thin nature of these units (metres-scale), particularly that of the thin ignimbrite intercalated in the ash sequence, suggests that mass discharge rates were not high in any one eruptive event. Hot pyroclastic flows emplaced in wet environments may also show evidence of loading and steam fluidised injection into the ignimbrite along the basal contact [43] and these are absent from the pumiceous lapilli units exposed in the Mele River section.

Alternatively, the units could be subaqueous pyroclastic debris flows. Characteristics of debris flows indicative of water supported processes are grading, sorting, winnowing of fines from basal parts of the deposit, sole structures, and mudstone intraclasts [45, 46]. None of these features are exhibited in the pumiceous lapilli tuff units, indicating that a primary pyroclastic flow origin is more likely.

The lowermost ash unit is interpreted here as an ash cloud surge that shows reverse sorting of coarse ash at the base then a more massive fine ash body. It is adjacent to a coarse ash sized, laminated and cross bedded unit with pinch and swell structures that we interpret as being a deposit from a pyroclastic surge. It is succeeded by a thin ignimbrite unit that is either distal or represents a low energy eruption pulse. The base of the ignimbrite is a fine ash layer that contains ash pellets [47]. These either formed by ash clumping in a wet surge cloud or by explosive entry of hot pyroclastic flow into water [48]. The 300 mm uppermost ash unit comprises cm scale laminations of alternating fine and coarse ash and is interpreted as either deposition from an ash cloud surge or is air fall material. The ash sequence therefore also suggests that the eruptions were subaerial from the presence of pyroclastic surge deposits and the ash pellets. It has been argued that accretionary lapilli and surge can form in a cupola of gas generated water exclusion [44] but this requires high mass discharge rates [45], which are clearly not indicated in this case.

The ash pellets indicate that the ash cloud was wet enough for aggregation of ash to occur. Given the marine setting and the likelihood that the vent was near sea level, some phreatomagmatic activity is inevitable. However, the delicate structure of the pellets suggests that they would have been unlikely to have survived water transport and accumulated as direct air fall rather than settling through a water column. Thus the evidence from both the ignimbrites and the ash units indicates a subaerial rather than marine eruption. A pumice-rich ignimbrite caps the pyroclastic sequence.

Above an obscured section of cliff face in the Mele River section the uppermost visible units appear to be shallow subaqueous epiclastic sediments of volcanic origin showing features such as parallel and cross bedding that clearly indicate deposition in water and working by traction currents. These sediments are similar in appearance to, and are probable correlatives of, the Rentanbau Tuffs.

## 6. Topographical Relationships and Uplift

Although the Efate Pumice Breccia is the oldest stratigraphic unit identified, it is exposed at high elevations in cliffs around and in the central part of the island. The presence of reef limestone platforms cut into the EPB implies that the EPB must have been near sea level at some stage post emplacement at a water depth that was favourable to the development of a fringed reef system and its associated ecology, a few metres to tens of metres deep at most. The fact that the reef limestone is today preserved as units up to 50 m thick indicates a considerable period of time in which the reef was active, based on reef growth data from modern fringed reefs from the SW Pacific (reefs rarely accrete vertically at rates of more than 10 mm year$^{-1}$, and in most cases grows at rates considerably less than this [49]). Uplift rates for Efate estimated from coral reef data are about 1 mm yr$^{-1}$ [25, 26], which is consistent for the regional uplift across this part of the Vanuatu Arc [50]. Thus uplift of Efate to its present elevation above sea level can be entirely ascribed to late Pleistocene to Holocene regional uplift.

Further, the marginal areas of the elevated EPB blocks in the centre of the island are composed of the relatively flat bedded volcaniclastic sandstone and silt beds of the the RT, surrounding and partially overlying the island's center. The RT is clearly dominated by reworked pyroclastic deposits, comprising pumiceous as well as volcanic lithic fragment-rich zones that are mixed with sediment containing marine biogenic material. The foramineferal assemblages recovered from the RT indicate only tens of metres water depth. The RT units also contain some pyroclastic beds inferred to be emplaced from primary pyroclastic density currents, suggesting primary explosive eruptions, consistent with an emergent Surtseyan eruptive style volcano. It is very likely that the RT are a complex volcaniclastic–pyroclastic rock assemblage that represent volcanism-influenced sedimentation over a large area over a relatively long time period (tens of thousands of years), representing most of the total time span of the emplacement of the EPF, and the evidence is consistent with eruption at or near sea level with shallow post-eruption sedimentation and reef formation.

The presence of ignimbrites in the EPB suggests a subaerial environment of deposition, probably near sea level. The RT was, in contrast to EPB, deposited under shallow marine conditions and the latter stages of Efate's history is of slow emergence due to regional uplift. The collision of the D'Entrecasteaux Ridge at c. 3.5 Ma caused shallowing and uplift of the forearc, eliminating the trench in this area and generating widespread silicic volcanism [51]. It therefore seems likely that Efate has never been submerged to significant depths and largely only subjected to eustatic changes in sea level through the early to mid-Pleistocene.

## 7. Evolution of the Efate Silicic Volcano

There is little evidence of a submarine vent or caldera structure in the bathymetry [52] around Efate. Given the similarity of Efate to the other edifices along this sector of the arc (Erromango, Tanna), it is likely that Efate Island also marks the location of the vent system, consistent with the presence of pyroclastic surge deposits considered to have accumulated from short run out ground hugging currents from nearby vent(s). As the vent is buried, there is no direct evidence of size or geometry of the vent zone but we can infer from the eruption of ignimbrites, the volume of eruption and post eruptive subsidence that it was most likely a caldera-forming eruption. We therefore suggest that Efate erupted as a silicic, near-sea level caldera with associated marine sedimentation in a shallow caldera basin. An initial eruption, largely controlled by the silicic magma volatile content, produced a predominantly "dry", magmatic explosive eruption that formed the basal EPB. This eruption was formed in a relatively flat-lying, near-sea level environment, potentially similar to those that exist today in the coastal parts of Espiritu Santo or Malekula in the Vanuatu arc. The existence of some sort of elevated plateau-like environment around Efate is feasible, as a shallow shelf broadly (can be traced over 50 km from the present day coastline) surrounds the island, providing a potentially flat lying landmass nearly four times the size of the present day Efate (comparable with the size of Espiritu Santo today). The potential subaerial exposure of such large landmass is supported by many canyon-like features on the sea floor that can be connected to existing valleys on the island [53]. This suggests that it is reasonable to envision an eruptive environment that was near-sea level, partially subaerial at the time of the volcanism similar to that inferred for the now submerged Kuwae caldera [54, 55] that destroyed a once large landmass (Kuwae), of which the present day islands of Epi, Tongoa and other smaller islands are remnants. While the origin and potential climatic effect of the Kuwae eruption is under debate [56–58], it is generally accepted that a near sea-level, large silicic caldera was formed by the eruption, suggesting that such caldera-forming eruptions were not uncommon in the volcanic history of Vanuatu. Unfortunately there is little direct evidence of the sea level and the probable environment about a million years ago in the Efate group.

However, more indirect evidence can be gained by examining the global changes in climate and associated changes in sea level in the Quaternary. Sea level has changed dramatically in the last million years of history in the Pacific resulting in large variations of subaerial land mass areas over short period of time [59]. The primary control on such sea level changes are considered to be global glacio-eustatic processes [60, 61]. During glacial periods, the global sea level drops significantly while during interglacial periods, major sea level rise is expected [60, 61]. In the last glacial maximum, about 18 ka, the sea level was around 150 m below the present day sea level [59, 61]. Over the past 140 ka sea level was nearly always below the present day sea level by few tens of metres, considerably enlarging the landmass of any islands in the SW Pacific. At about 105–125 ka sea level was higher than it is today as a response to glacial retreat during an interglacial period [49, 62], similar to that we experience today. The sea level then was estimated to be only about 5–10 m above the present day [62]. We have far less direct data to constrain the sea level in the older than 140 ka time periods. In spite of this lack of direct knowledge, there are several lines of evidence that can be used to constrain the likely scenario. If we accept Raos and McPhie [20] age of EPF of 1 Ma, they claim that in this time the sea level must have been significantly higher, and conversely the eruption environment to form the EPF must have been subaqueous. Moreover, it must have been deep enough (well below wave base, in the 100s of metres depth range) to be able to prevent the eruption column breaching the sea surface for a significant part of the eruption. Such an environment can be easily envisioned if significantly higher sea level existed at about 1 Ma. The known global glacio-eustatic sea level changes, however, suggest the opposite scenario, favouring subaerial conditions [49, 61, 63]. On the basis of the marine oxygen isotope record, the inferred time the EPF formed at about 1 Ma falls within a period dominated by glaciation, and falling sea levels [63]. The oxygen isotope values in the period of younger than 1 Ma showed a dramatic drop reflecting a long period when sea level must have been lower than it is today [63]. This suggests that subaerial conditions were more likely during the eruption of the EPF. Further, the space and time problem can be better managed in reconstructing the eruptive environment as a near sea-level caldera forming eruption, instead of a relatively deep sea-floor event forming pyroclastic mounds a few hundreds (significantly more than the 600 metres of preserved thickness of the EPB) of metres below sea level.

In our model, the initial silicic explosive eruptions formed large volume of trachydacitic pumiceous ignimbrites that accumulated around the vent. Shortly after the onset of the eruption, subsidence of the caldera floor occurred, trapping intra-caldera ignimbrites and associated pyroclastic products, to form the thick pile of intra-caldera pumiceous deposits of the EPB. The caldera must have been submerged at least few tens of metres below the actual sea level and the eroding pyroclastic successions provided detritus to form the volcaniclastic succession of the RT. The presence of foraminifera in the RT also suggests at least few tens of metres depth for this environment. By about 0.3 Ma the Island was emergent and coral reefs developed platforms around it. Late Pleistocene and Holocene uplift, probably episodic in detail and related to earthquake activity, then preserved a series of reefs which recorded the tectonism.

## 8. Implication to Miocene near sea-level silicic explosive volcanism in the Carpathian-Pannonian region

Eruptive products of silicic explosive volcanism are widespread in the Pannonian Basin, especially during the Miocene [64]. Several large volume explosive eruptions took place in the region that produced laterally extensive and locally thick pumiceous pyroclastic successions [64–68]. Among these units are the laterally extensive and chronologically important Lower, Middle and Upper Rhyolite Tuff units for which eruption processes, sources, and in which depositional environments they were formed are still not fully understood. While basin-wide correlation was recently shown to be promising, based on sophisticated geochemical analyses of juvenile and mineral phases [69], a general understanding of the eruptive environment of these volcanic successions remains elusive. In the Miocene the Pannonian Basin was a complex marine to island-dotted region, with very complex sedimentary environments representing alluvial plains to shallow to even deep marine conditions [70–76]. Volcanism was largely controlled by subduction and associated back-arc extension in the Pannonian basin [65, 77–80], leaving behind chains of arc volcanoes constructed from andesite to dacite effusive and explosive eruptive products [65]. In the NE edge of the evolving Pannonian Basin (e.g. Tokaj Mtns) however, a chain of large silicic (rhyolite to rhyodacite) calderas have been inferred on the basis of facies association of large volume silicic ignimbrites, reworked shallow marine volcaniclastic sediments and post-ignimbrite intermediate lava dome complexes that formed along a volcano-tectonic graben, which are now represented by extensive subaerial and shallow subaqueaous ignimbrite sheets [81–89]. In the central part of the ignimbrite sheet-covered region that were inferred to contain erosional remnants of calderas, post-caldera andesite volcanism emplaced lava fields, and intruded laccoliths and sills [90–93]. While the general understanding of the volcanic evolution of the region is fairly good, we know very little about the details of formation of the calderas, possible resurgence and post-caldera volcanism [94]. The reconstruction of the eruptive environment has fundamental problems very similar to those outlined in the case of Efate. The shallow subaqueous environment in the region and the general low lying landscape are all very similar to those reconstructed in Efate. The case study presented here demonstrated the difficulty in distinguishing subaqueous versus subaerial processes in silicic explosive volcanism. However, as we have demonstrated at Efate, careful field observations and laboratory analysis can resolve some of the issues around interpreting these complex volcanic environments. In addition, caldera resurgence can complicate any reconstruction in older paleo-volcanic sequences and needs to be considered for the Carpathian-Pannonian Region.

## 9. Conclusions

We suggest that the eruption of the siliceous EPF was subaerial rather than submarine and that Efate Island has been close to sea level for much of its history. As the base of the pyroclastic sequence of the EPF was not observed, the nature of the deposits from the early stages of the eruption are unknown but it is likely that it involved some phreatomagmatic activity, given the likely vent location near sea level. However, we interpret the lowermost observed units of the EPB as ignimbrites and associated ash and surge deposits indicative of subaerial rather than submarine eruption. As the eruption progressed it built up a low angle cone of silicic pyroclastics by a series of eruptive pulses that generated small to moderate ignimbrites, pyroclastic surges and air fall deposits rather than a single, very large paroxysmal eruption. Towards the end of the eruption the vent area is inferred to be collapsed forming a broad caldera, possibly relatively slowly, and the relatively flat-lying Rentanbau Tuffs were deposited in a shallow marine environment in and around a caldera-confined region by erosion of the pyroclastic edifice. The absence of Rentanbau Tuffs under the reef deposits on Klem's Hill (Figure 1) could either reflect erosion or that the upper pyroclastic edifice was always emergent although always near sea level. Subsequent regional uplift has raised the island to its present height and recorded the rate of uplift from the formation of coral reefs.

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