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A complete caldera cycle at Rabaul, Papua New Guinea

1. Introduction

Many silicic calderas show repeated cycles, with long periods of minor, constructive activity culminating in large, caldera-forming explosive eruptions. It is during these periods of more minor activity that the conditions required for large caldera-forming eruptions must develop in the magmatic plumbing system. The petrology and chemistry of volcanic deposits can be used to recreate a snapshot of the conditions in the magma reservoir prior to eruption, and by comparing the petrology of series of eruptions we can see how these conditions evolve through time. We have investigated how the plumbing system of Rabaul has changed across a complete caldera cycle, from one caldera-forming eruption to the next.

2. Geological Setting

Rabaul is part of the New Britain Arc, where the Solomon Sea Plate is subducted beneath the South Bismark Plate.

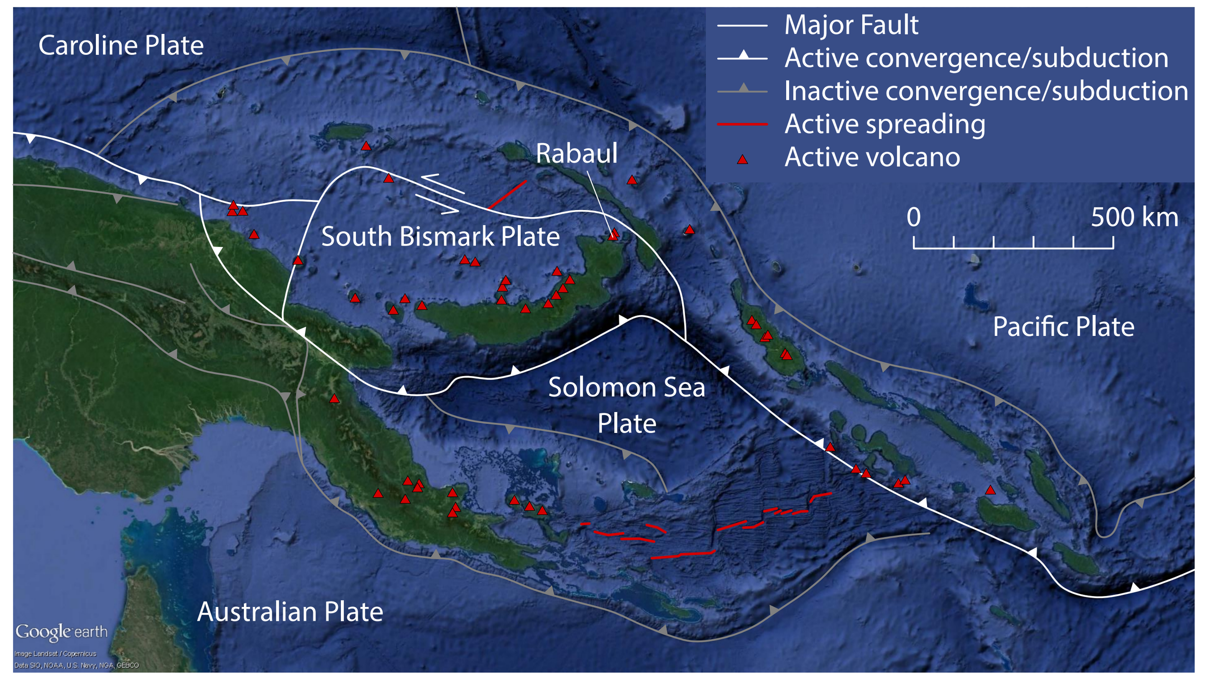


Figure 1: The tectonic setting of Rabaul

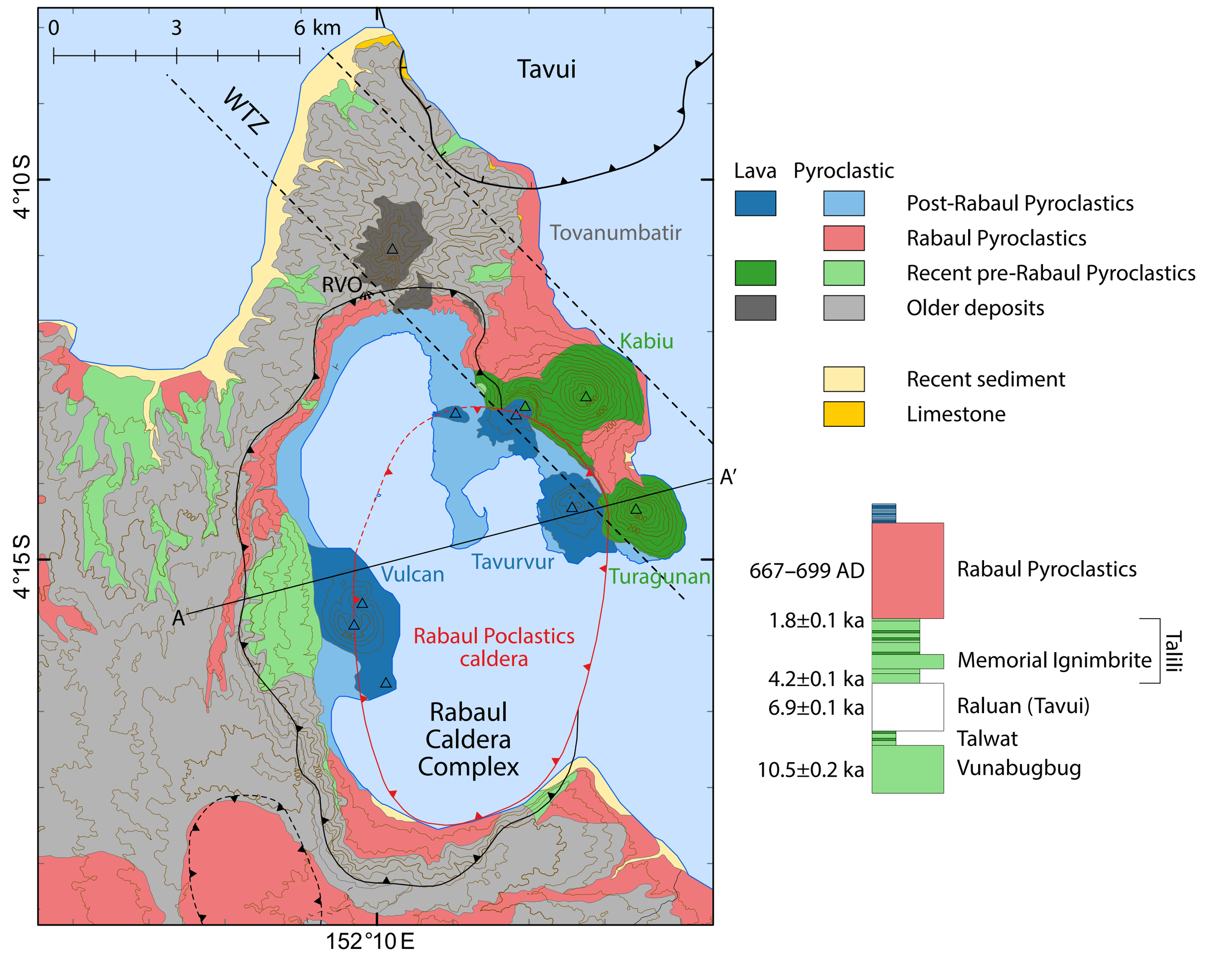
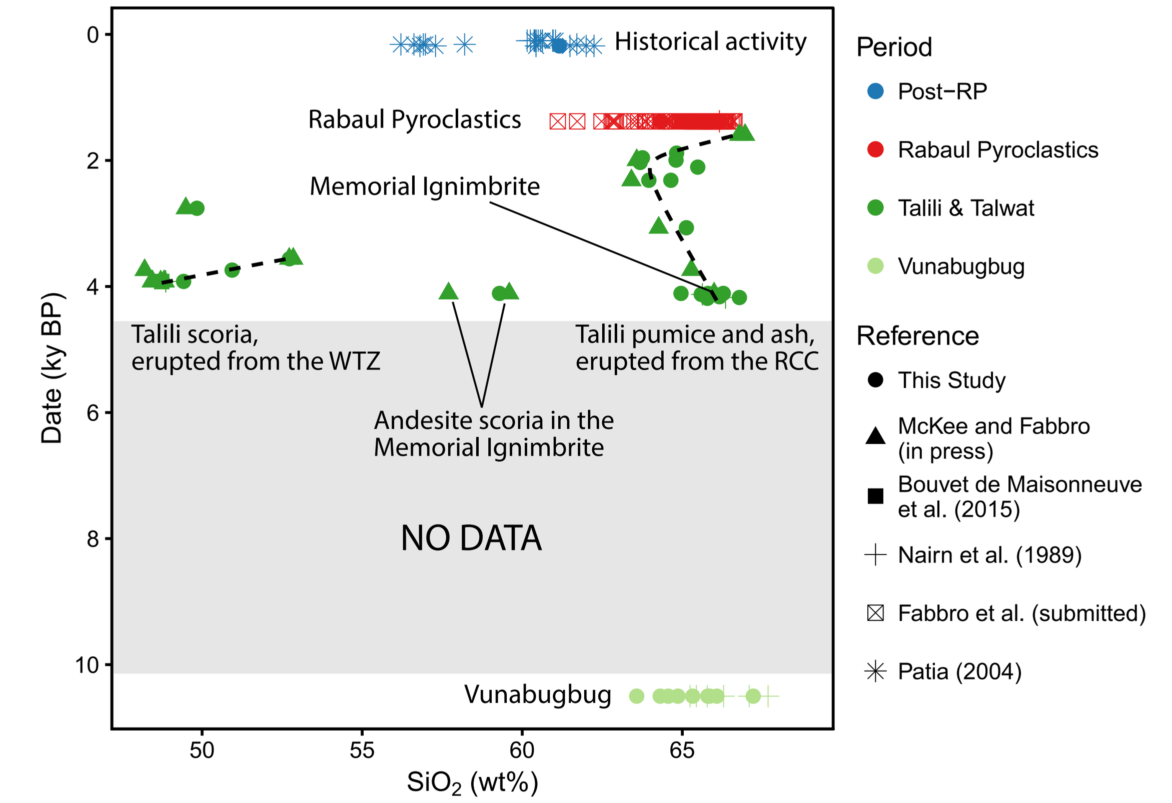


Figure 2: Geological map of Rabaul and schematic stratigraphic column, modified from Nairn et al. (1989). Dates from Nairn et al. (1995). A–A' is the location of the sections drawn in Figures 8 and 9.

- Several overlapping calderas make up the *Rabaul Caldera Complex* (RCC). Eruptions from within the RCC are mostly dacitic.
- To the north and east lies a zone of five dominantly mafic stratocones, the *Watom–Turagunan Zone* (WTZ).
- We have focused on the most recent complete caldera cycle, from the ~10.5-ka *Vunabugbug Ignimbrite* until the ~1.4-ka *Rabaul Pyroclastics*, and the smaller eruptions that occurred in between that make up the *Talwat* and *Talili* sequences.
- The *Raluan Ignimbrite* separates the *Talili* subgroup from the *Talwat* subgroup, but the most likely source of this eruption is *Tavui* caldera to the north of Rabaul.
- Historical activity has taken place at several locations within the most recent caldera. The most recent period of activity started in 1994 with simultaneous eruptions from *Vulcan* and *Tavurvur*, on opposite sides of the caldera.

Figure 3: (left) View of the volcanoes of the Rabaul Caldera Complex and the Watom–Turagunan Zone, taken from the Rabaul Volcano Observatory, looking south (marked as RVO on Figure 2). Labelled in blue: Vulcan, Tavurvur, Sulphur Creek and Rabalanakaia (hidden behind Palangiangia in this photo) have all been active in the last ~250 years. Labelled in green: Kabiu, Palangiangia and Turagunan have all been active in the last 4.2 ky, but with the possible exception of a lava flow from Turagunan, have not erupted since the Rabaul Pyroclastics eruption about 1.4 ka.

3. Eruption history of Rabaul since ~10.5 ka



1.4 ka: The >11 km^3 caldera-forming *Rabaul Pyroclastics* eruption.

5–1.4 ka: the *Talili* subgroup; at least 11 explosive eruptions. >4.4 km^3 of dacite was erupted from the RCC, and >0.7 km^3 of basalt was erupted from the WTZ. Most of the basaltic deposits are scoria falls or flows, while most of the dacitic deposits are fine ash with pumice and accretionary lapilli found in some units. The largest Talili eruption was the 4.1-ka dacitic Memorial Ignimbrite, that left pyroclastic flow deposits up to at least 3 m thick, and has a minor ($\ll$1%) andesitic scoria component.

10.5–5 ka: Only a few, scattered deposits from explosive eruptions are preserved—the *Talwat* subgroup. Mostly fine ash.

10.5 ka: the *Vunabugbug Ignimbrite* discharges ~5 km^3 of dacite. The eruption probably formed a (partially) water-filled caldera, as many of the following Talili eruptions were phreatomagmatic.

Figure 4: (left) Changes in composition over the past ~10.5 ka, including the large, caldera-forming Vunabugbug and Rabaul Pyroclastics eruptions.

4. Variations in the whole-rock and mineral chemistry with stratigraphy

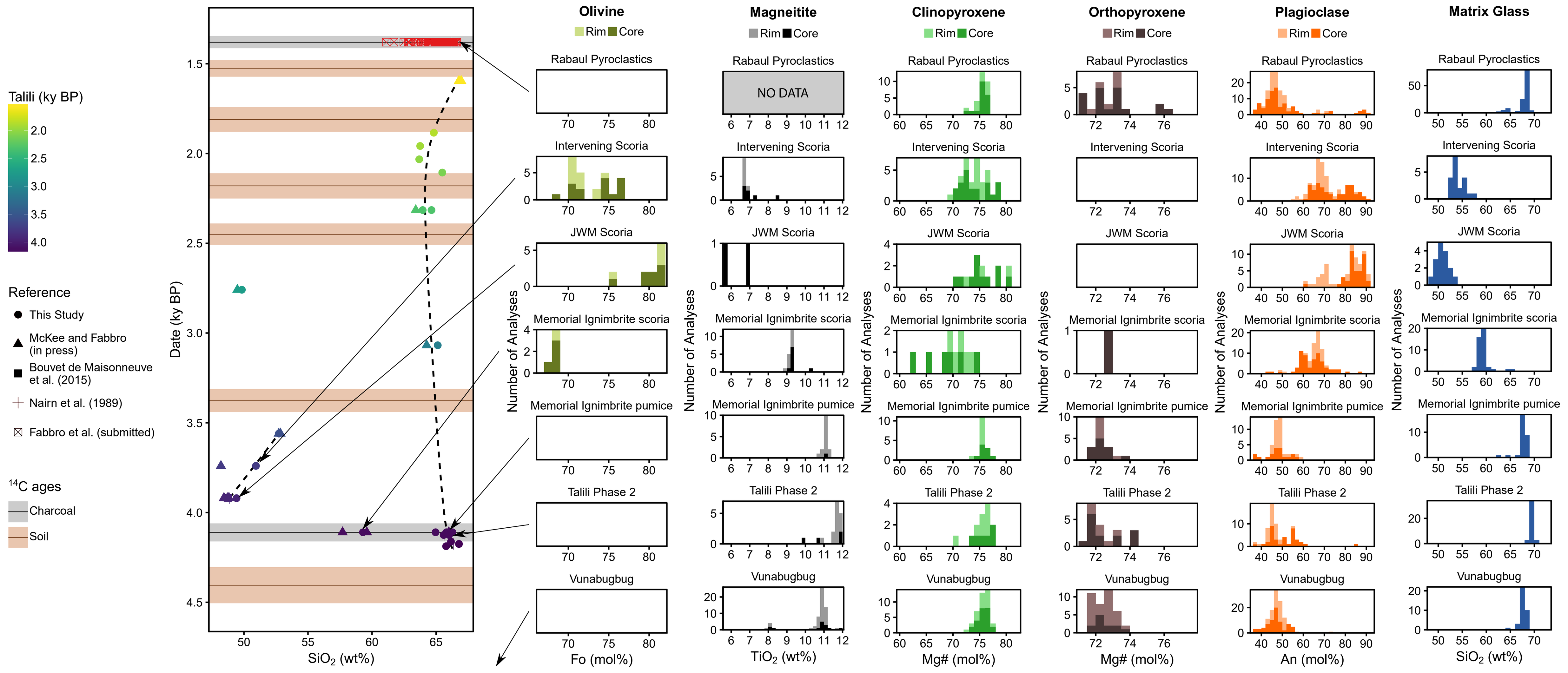


Figure 5: Variations in the whole-rock and mineral chemistry from the Vunabugbug eruption to the Rabaul Pyroclastics eruption

- The dacites erupted from the RCC show a trend towards less evolved compositions through time, although this trend reverses with the last eruption before the Rabaul Pyroclastics.
- Olivine is found in both the basalts and the andesitic scoria in the Memorial Ignimbrite. Its chemistry varies as expected with the whole-rock chemistry.
- Magnetite TiO_2 contents are correlated with the overall evolution (and temperature) of the magma.
- Clinopyroxene is found in all the units analysed, and is remarkably consistent in composition across the whole range of whole-rock compositions.
- Orthopyroxene is only found in the dacitic units (the single orthopyroxene found in the Memorial Ignimbrite andesitic scoria was probably transferred from the Memorial Ignimbrite dacite).
- Plagioclase is found in every unit. In the dacites, its composition remains relatively constant, whereas there is more variation in the basalts.
- Matrix glass compositions follow the whole-rock compositions, with the exception of the Rabaul Pyroclastics, where fractionated andesite glass is found as streaks towards the top of the deposits

5. REE patterns

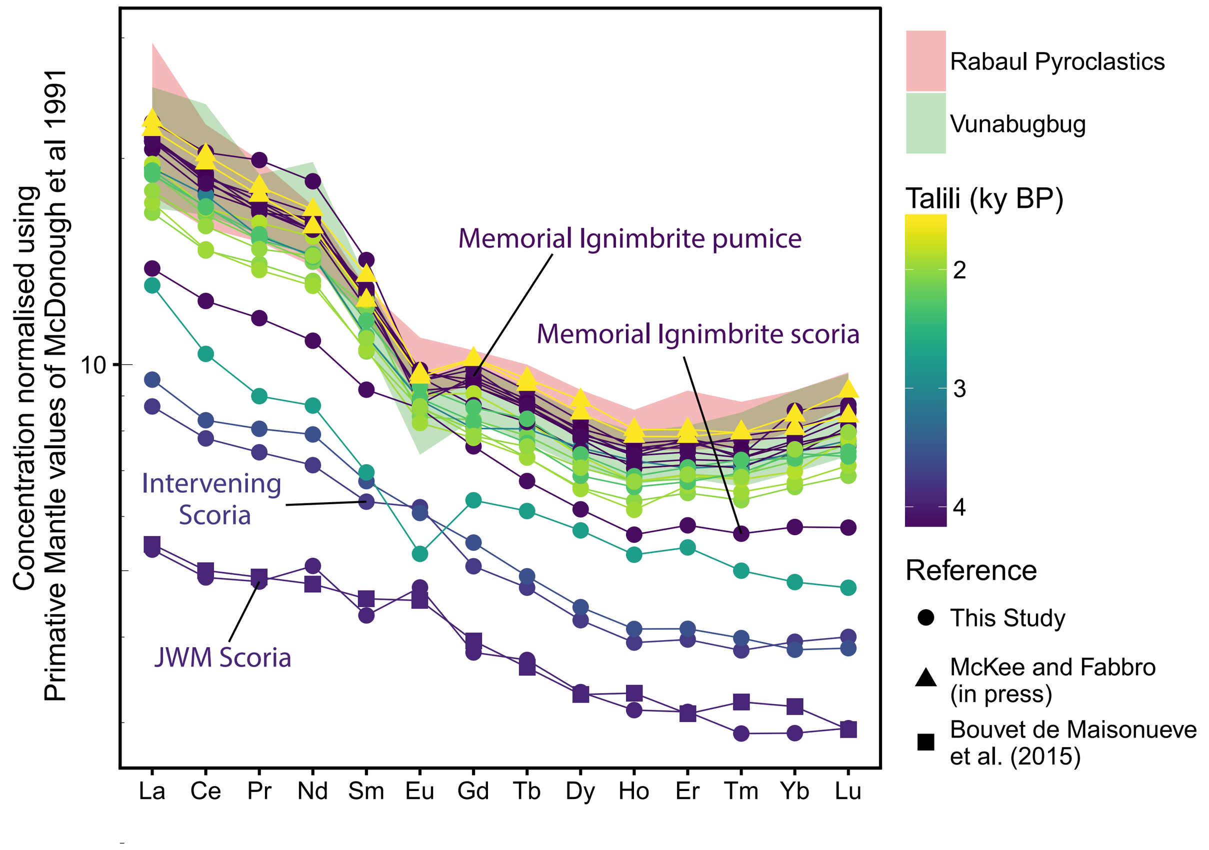


Figure 6: REE patterns of the Talili, Vunabugbug and Rabaul Pyroclastics eruptions

The whole-rock REE element concentrations show a consistent trend towards less evolved compositions of the RCC dacites through time during the Talili, which reverses with the last Talili eruption. This matches the trend seen in the whole-rock major element concentrations (Figure 5).

6. Magma mixing vs fractional crystallisation

Fractional crystallisation leads to curved trends on many Harker plots, such as SiO_2 vs TiO_2 (Figure 7).

Magma mixing produces straight lines that can cut across these curves, depending on the composition of the end-members involved.

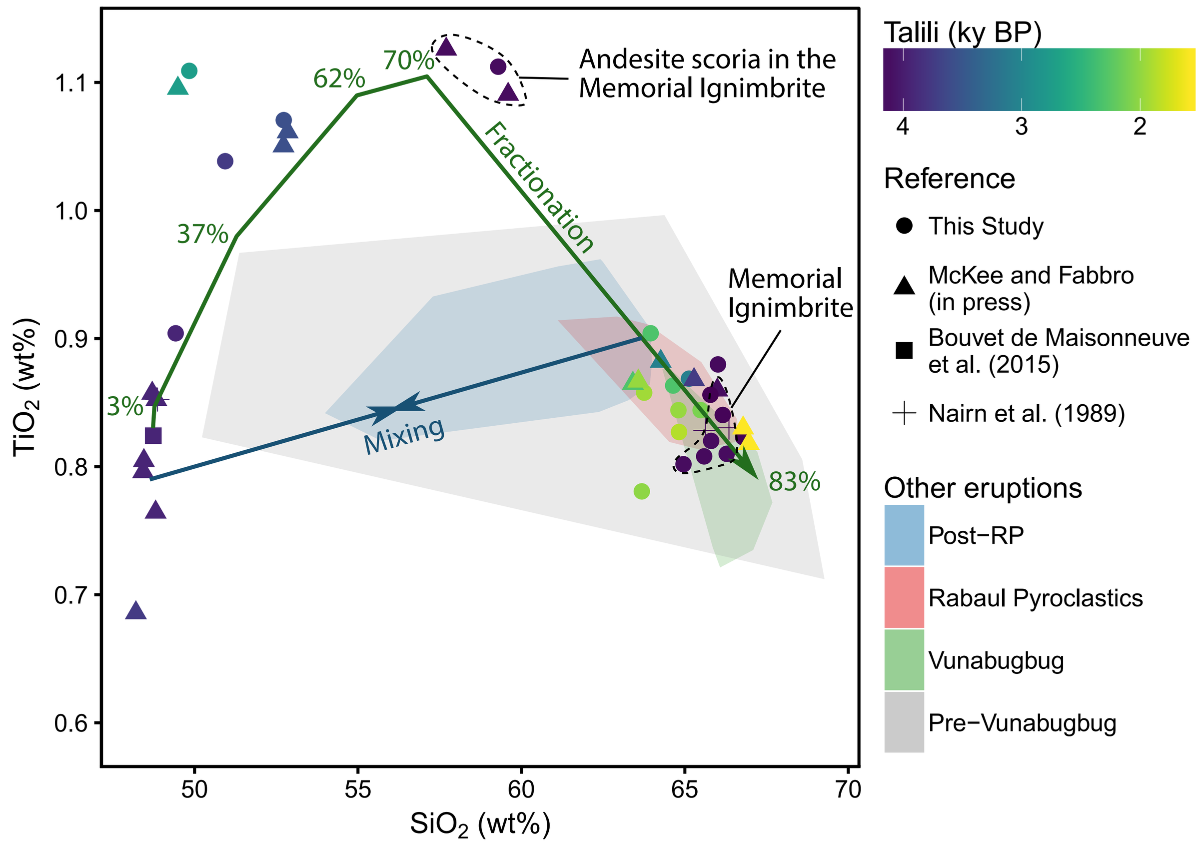


Figure 7: Composition of Rabaul magmas. Fractional crystallisation path modelled using mass balance for major elements, and partition coefficients from the GERM Partition Coefficient Database (https://earthref.org/KDD/) for trace elements.

- The post-Rabaul Pyroclastics eruptions fall on mixing rather than fractional crystallisation trends, suggesting they were formed by the mixing of basalt and dacite. This is supported by the presence of basaltic enclaves and mafic minerals in the post-Rabaul Pyroclastics deposits
- The Rabaul Pyroclastics, however, fall on the fractionation trend. This includes andesitic enclaves and glass, suggesting that the Rabaul Pyroclastics reservoir was recharged by a fractionated andesite rather than basalt.
- During the Talili period the magmas erupted from the RCC all lie on the fractionation trend. This includes the Memorial Ignimbrite andesitic scoria, which has a fractionated rather than a hybrid composition. This suggests that there was little mixing between the dacite erupted from the RCC and the basalt.

7. The history of the magmatic plumbing system across a complete caldera cycle

- The paucity of deposits from the ~6.3 ky following the Vunabugbug eruption could reflect a period of quiescence after the shallow plumbing system was emptied of eruptible magma, although it is also possible that the early post-caldera deposits were lost during the subsequent Rabaul Pyroclastics caldera collapse.
- After the Memorial Ignimbrite, the largest eruption in the Talili period, we see an increase in basaltic eruptions.
- During the Talili period, basalt was able to bypass the RCC reservoir, and erupt directly to the surface from vents in the WTZ (Figure 8).
- However, basalt did not directly interact with the dacite erupted from the RCC during the Talili period. Where mixing or mingling did occur, such as the andesite inclusions in the Memorial Ignimbrite, it is with a fractionated andesite (Figure 7).
- This is true for the Rabaul Pyroclastics eruption too: a fractionated andesite was injected into the reservoir shortly before eruption.
- A large, melt-dominated dacitic reservoir would have impeded the ascent of basalt, through rheological and density contrasts. This reservoir must have existed beneath the RCC from at least 4.2 ka.

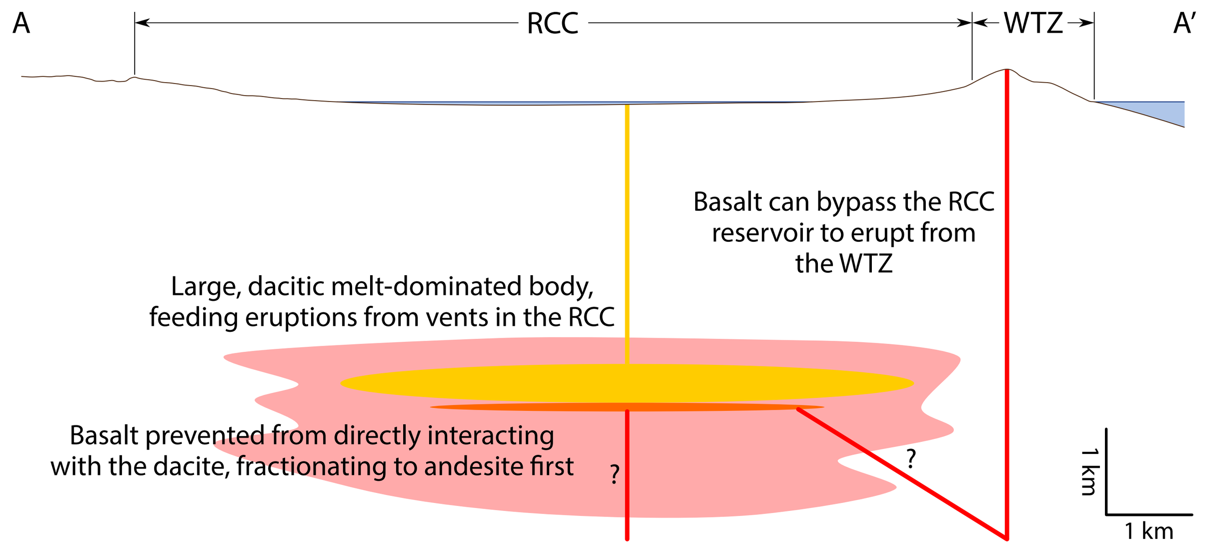


Figure 8: Schematic cross section of the plumbing system under Rabaul during the Talili period. For location, see Figure 2.

- After the Rabaul Pyroclastics, basalt could once again enter the shallow plumbing system of the RCC (Figure 9), suggesting a caldera-forming magma body no longer exists there.

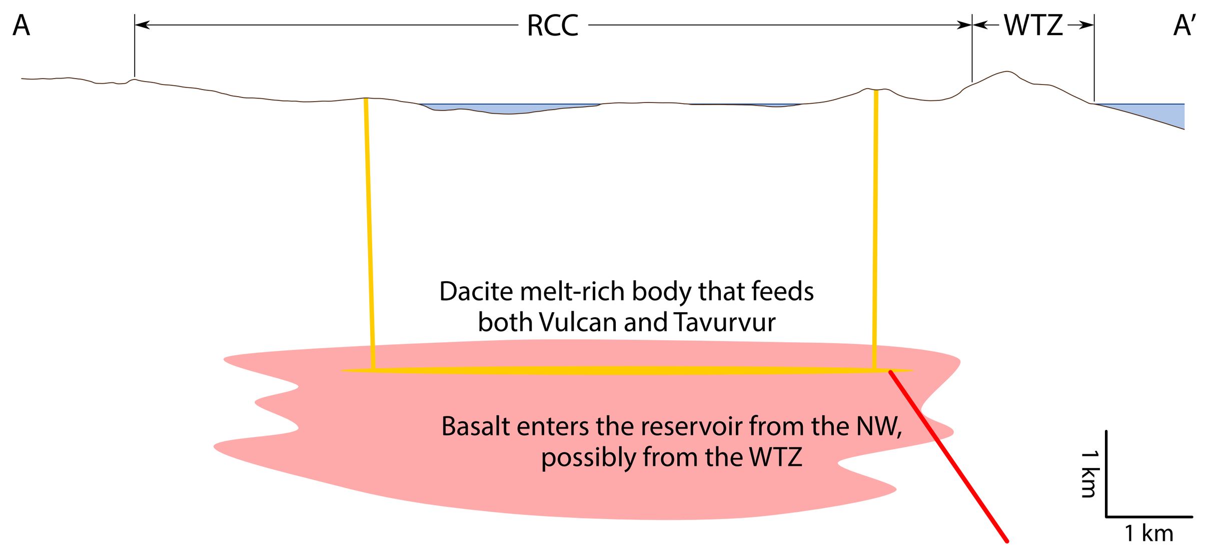


Figure 9: Schematic cross section of the present-day plumbing system under Rabaul. For location, see Figure 2.

8. Next steps

1. We have more samples to be analysed, to fill in the gaps.
   - Talwat (between the Vunabugbug and Talili)
   - Early post-Rabaul Pyroclastics lava
2. Ash samples will be sieved to search for loose crystals to analyse.
3. Trace element concentrations may be able to distinguish between crystal populations in different eruptions where major elements cannot.

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