The evolution of a hyperactive caldera system: A record of magma storage across the caldera cycle at Rabaul, Papua New Guinea

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Figure 1: Rabaul Caldera, taken from the Rabaul Volcano Observatory (Figure 2), looking southeast. The labels are coloured based on their last eruption (Figure 3). Vulcan, Tavurvur, Sulphur Creek, and Rabalanakaia (hidden behind Palangiangia in this photo) have all been active in the last ~250 years. 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 at ~1.4 ka.

1. Introduction

Many calderas show cycles of large, explosive eruptions interspersed with minor activity. Despite improvements in our ability to forecasting the onset of eruptions, it is still difficult to forecast their sizes. To address this, we focused on Rabaul, Papua New Guinea, where at least 4 large ignimbrites have been erupted over the last 20 ky alongside numerous smaller eruptions. Our data spans a complete caldera cycle, from the penultimate (~10.5-ka Vunabugbug Ignimbrite) to the most recent (~1.4-ka Rabaul Pyroclastics) caldera-forming eruptions.

2. The last complete caldera cycle at Rabaul

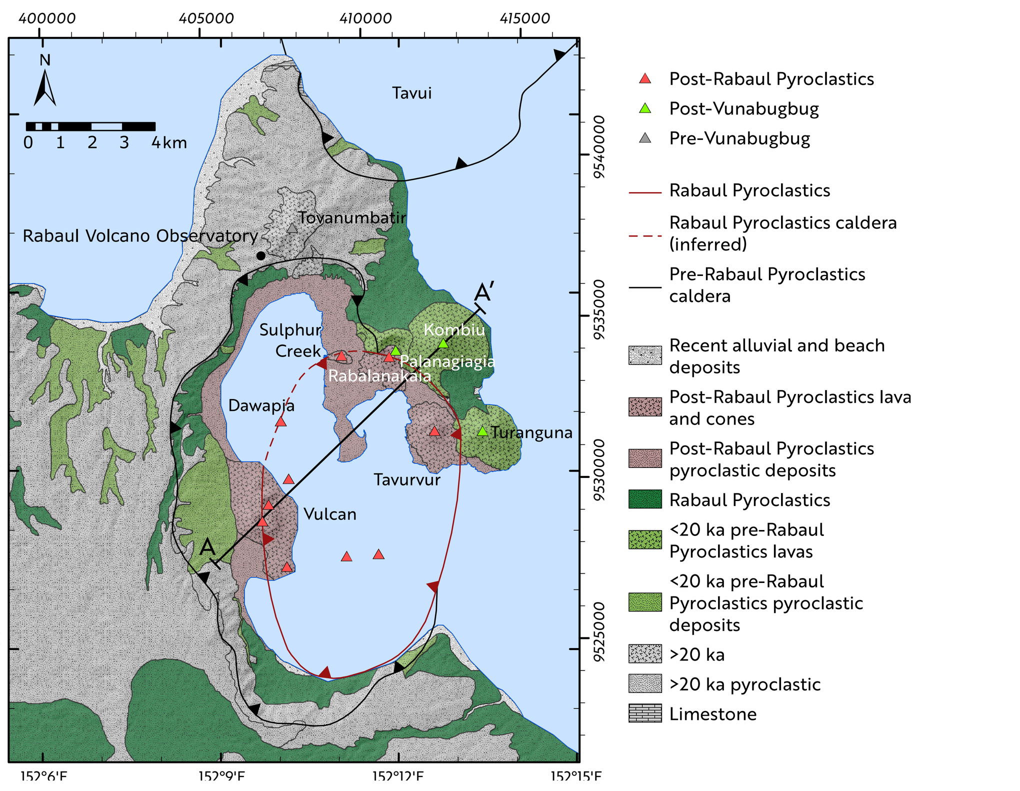

Figure 2: Geological map of the Rabaul area, after Nairn et al. (1989). The line A–A′ shows the location of the cross sections in Figure 6.

Rabaul consists of several overlapping calderas, with several dominantly mafic stratovolcanoes lying to the north and east (Figure 1). After the penultimate caldera-forming eruption (Vunabugbug Ignimbrite), there was a period with little recorded volcanic activity; either there were few eruptions or the eruptions were too small to deposit material outside of the caldera. Activity picked up at ~4.4 ka with Talili phases 1–2 (Figure 3), explosive dacitic eruptions from vents within the caldera. This culminated in the ~4.1 ka Memorial Ignimbrite, a dominantly dacitic eruption that also included andesitic scoria. Immediately above the Memorial Ignimbrite lie three mafic scoria falls (Talili Phase 3) that were erupted from the mafic stratovolcanoes outside of the caldera. Dacitic activity then recommenced from vents within the caldera (Talili phases 4–7), culminating in the caldera-forming Rabaul Pyroclastics. Post-caldera activity has consisted of the eruption of dacites and hybrid andesites from multiple vents within the caldera.

Figure 3: Composite stratigraphy of the Rabaul area since the Vunabugbug Ignimbrite, modified from Nairn et al. (1989) and McKee and Fabbro (2018). Ages in italics are ^{14}C ages; brown ages are from soil, grey are from charcoal, and blue are from shells and coral. [a]Nairn et al. (1989), [b]McKee et al. (2015), [c]McKee and Duncan (2016), [d]McKee and Fabbro (2018).

3. Fractional crystallisation or magma mixing

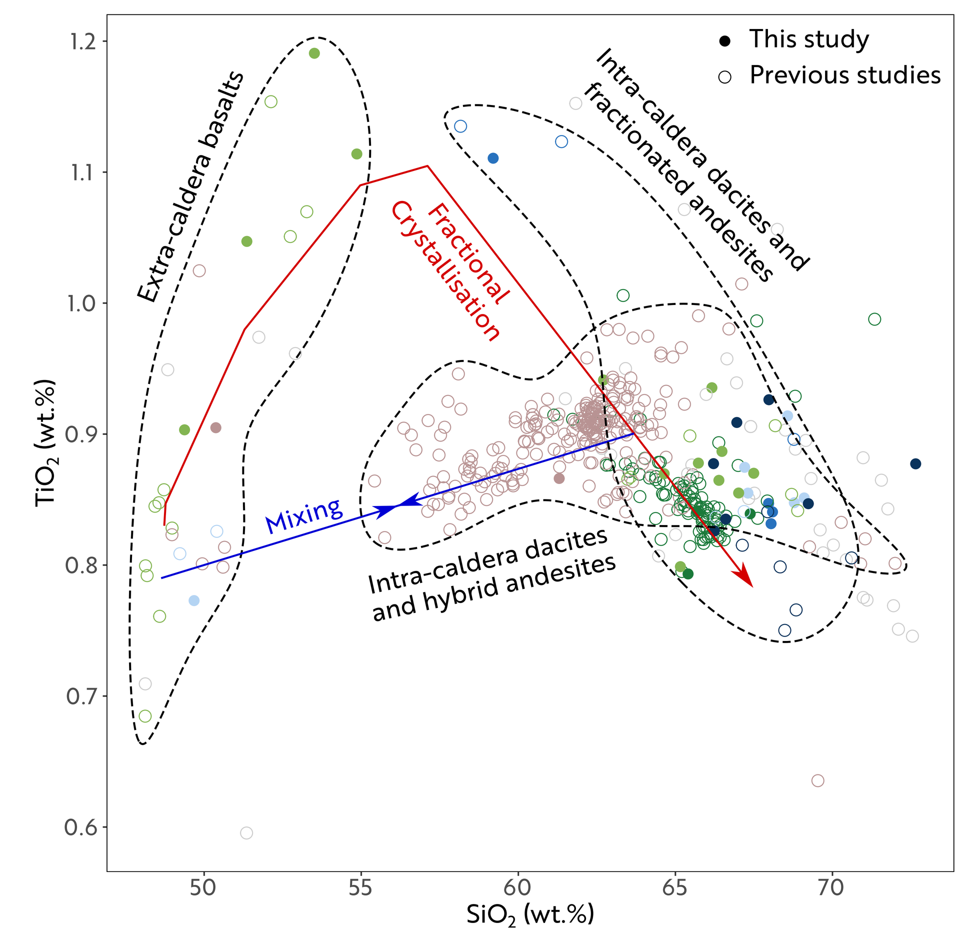

Figure 4: Whole-rock compositions of magmas from Rabaul. Includes data from Heming and Carmichael (1973), Heming (1974), Nairn et al. (1989), Patia (2004), Bouvet de Maisonneuve et al. (2015), McKee and Fabbro (2018), and Fabbro et al. (2020).

Fractional crystallisation leads to curved trends on many Harker plots, such as SiO_2 vs TiO_2, whereas Magma mixing produces straight lines that can cut across these curves (Figure 4).

The post-Rabaul Pyroclastics eruptions fall on mixing trends, suggesting they were formed by the mixing of basalt and dacite.

The Rabaul Pyroclastics (including andesitic enclaves and glass), the pre-Rabaul Pyroclastics, Memorial Ignimbrite (including andesitic scoria), and the pre-Memorial Ignimbrite magmas all lie on the fractionation trend. This suggests that there was little mixing between dacite and basalt, and any recharge magma was fractionated andesite.

4. Magma storage conditions

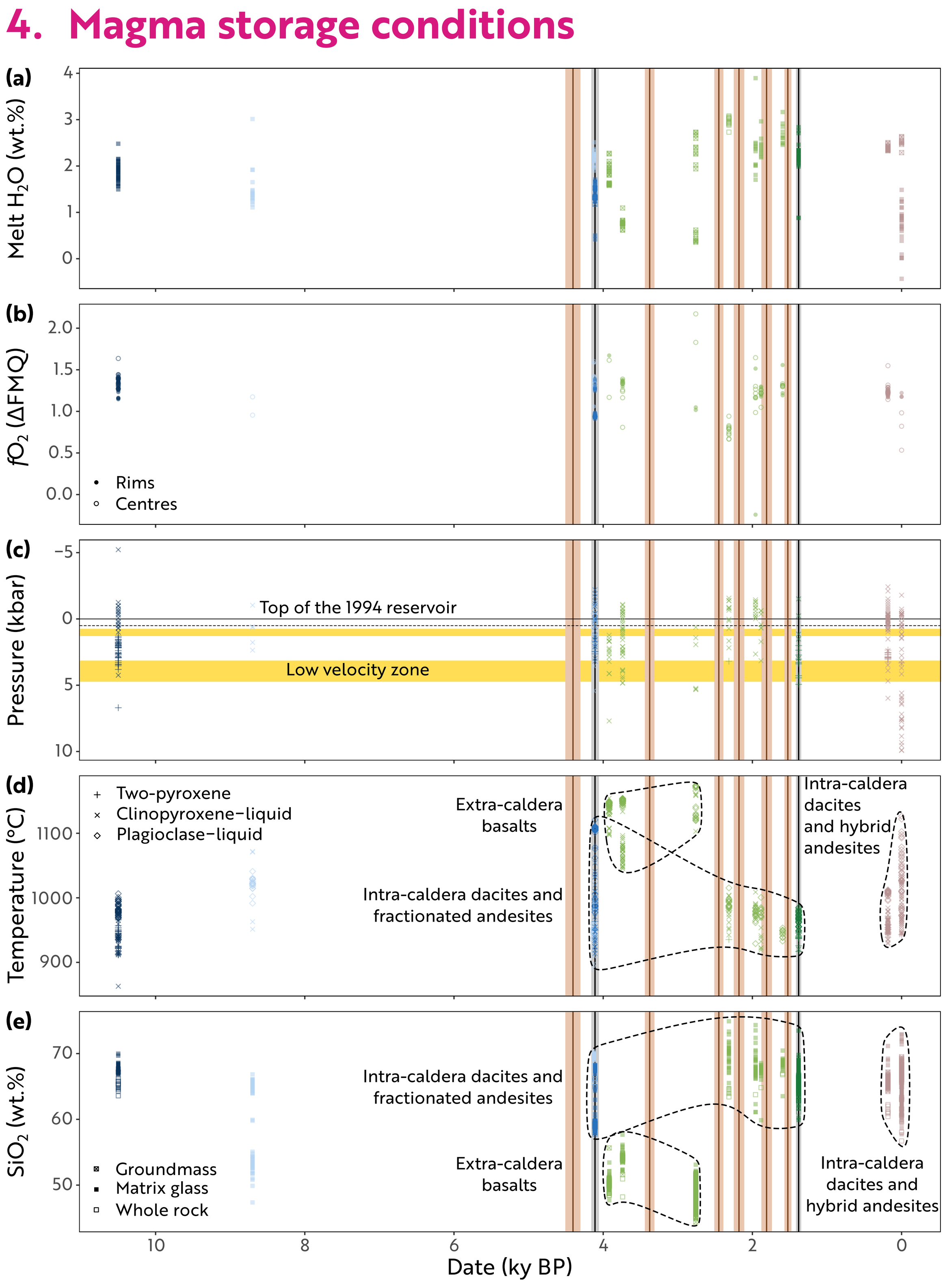

Figure 5: Magma storage conditions through time. (a) Melt H_2O content calculated using the plagioclase–liquid hygrometer of Waters and Lange (2015). (b) Oxygen fugacity calculated using the magnetite oxybarometer of Arató and Audétat (2017). (c) Pressure and (d) temperature calculated using the two-pyroxene, clinopyroxene–liquid, and plagioclase–liquid thermobarometers of Putirka (2008). (e) Whole-rock, groundmass, and matrix glass SiO_2 contents.

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

1. The Vunabugbug emptied the eruptible magma forming a caldera
2. The growth of the silicic Memorial Ignimbrite reservoir blocked the rise of basalt, as there was too great a rheological and thermal contrast. Once basalt fractionated to andesite, it could mix or mingle (Figure 6a).
3. After the Memorial Ignimbrite, basalt could bypass the sub-caldera reservoir leading to eruptions from extra-caldera vents (Figure 6b).
4. The growth of the Rabaul Pyroclastics reservoir once again blocks basalt from reaching the surface and the shallow plumbing system (Figure 6c).
5. After the Rabaul Pyroclastics, basalt can enter the shallow system. Basalt and dacite mix to form hybrid andesites (Figure 6d).

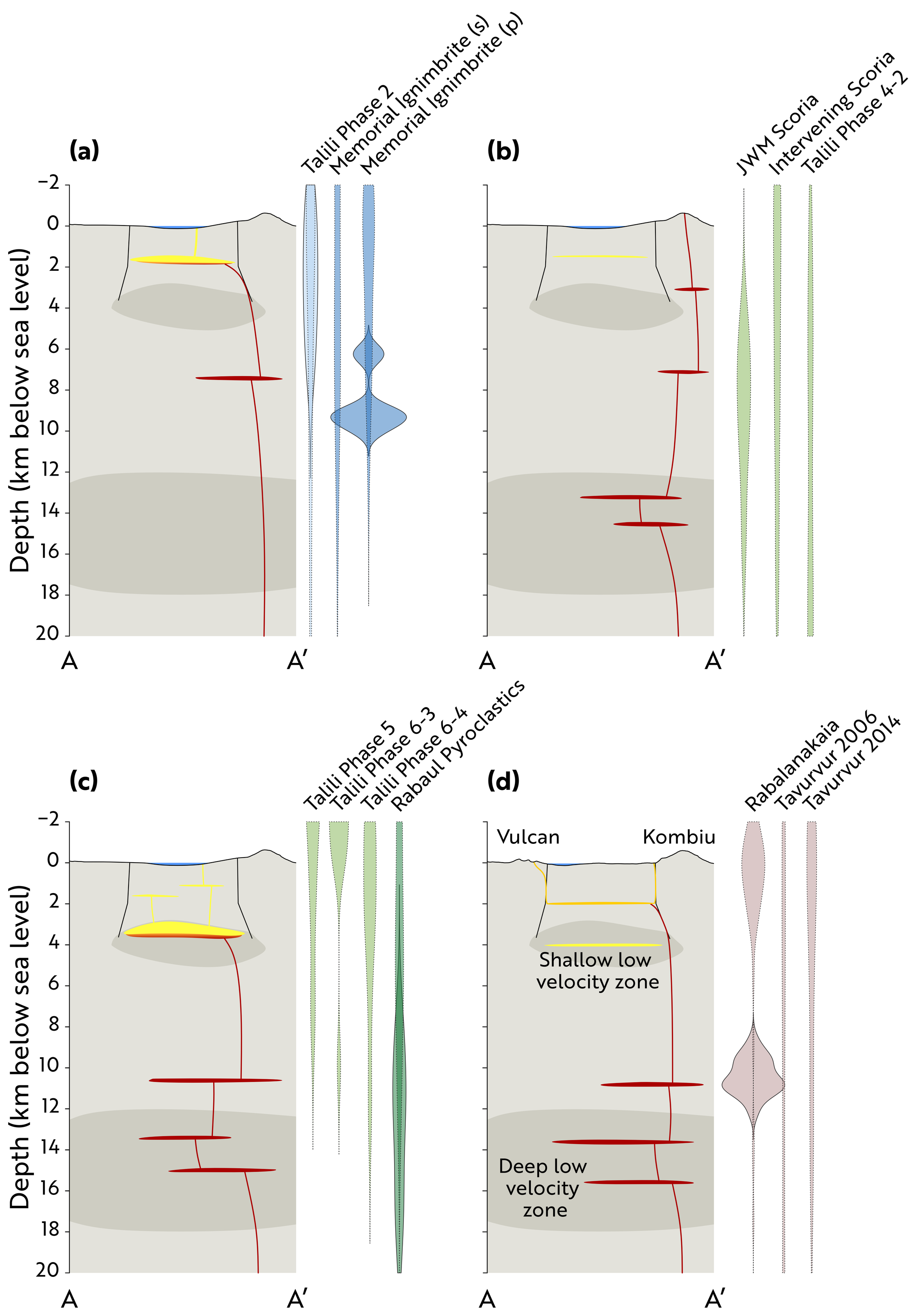

Figure 6: The magmatic plumbing system of Rabaul (a) shortly before the Memorial Ignimbrite, (b) shortly after the Memorial Ignimbrite, (c) shortly before the Rabaul Pyroclastics, and (d) the present day system. The shallow and deep low velocity zones are from the seismic tomographic studies of Finlayson et al. (2003) and Bai and Greenhalgh (2005). The histograms to the right of each cross section are the number of depths calculated using two-pyroxene (solid line) and clinopyroxene–liquid (dashed line) pairs. The location of the cross sections is shown in Figure 2.

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