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Deformation regime and long-term precursors to eruption at large calderas: Rabaul, Papua New Guinea

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A B S T R A C T

Eruptions at large calderas are normally preceded by variable rates of unrest that continue for decades or more. A classic example is the 1994 eruption of Rabaul caldera, in Papua New Guinea, which began after 23 years of surface uplift and volcano-tectonic (VT) seismicity at rates that changed unevenly with time by an order of magnitude. Although the VT event rate and uplift rate peaked in 1983–1985, eruptions only began a decade later and followed just 27 hours of anomalous changes in precursory signal. Here we argue that the entire 23 years of unrest belongs to a single sequence of damage accumulation in the crust and that, in 1991–1992, the crust's response to applied stress changed from quasi-elastic (elastic deformation with minor fault movement) to inelastic (deformation predominantly by fault movement alone). The change in behaviour yields limiting trends in the variation of VT event rate with deformation and can be quantified with a mean-field model for an elastic crust that contains a dispersed population of small faults. The results show that identifying the deformation regime for elastic–brittle crust provides new criteria for using precursory time series to evaluate the potential for eruption. They suggest that, in the quasi-elastic regime, short-term increases in rates of deformation and VT events are unreliable indicators of an imminent eruption, but that, in the inelastic regime, the precursory rates may follow hyperbolic increases with time and offer the promise of developing forecasts of eruption as much as months beforehand.

1. Introduction

Large calderas, with surface areas of 100 km^2 or more, are among the most populated active volcanoes on Earth. At least 138 have records of historical unrest (Newhall and Dzurisin, 1988) and examples that have provoked recent emergencies include Rabaul in Papua New Guinea (McKee et al., 1984; Nairn et al., 1995), Campi Flegrei in Italy (Barberi et al., 1984), Long Valley in the USA (Hill et al., 2002), and Santorini in Greece (Parks et al., 2012). During such emergencies, elevated unrest continues for ∼0.1–1 years and is characterised by caldera-wide uplift and volcano-tectonic (VT) events within the caldera to depths of kilometres. Most episodes do not culminate in eruption and their activity has been attributed to a combination of the intrusion of magma at depths of about 5 km or less and increased rates of fluid circulation in near-surface hydrothermal systems (McKee et al., 1984; Battaglia and Vasco, 2006; Geyer and Gottsmann, 2010; Woo and Kilburn, 2010; Bodnar et al., 2007; Parks et al., 2012; Acocella et al., 2015).

Even though short-term emergencies tend to be evaluated independently as regards the probability of eruption (McKee et al., 1984; Hill, 2006), it has long been recognised that they may belong to longer-term unrest that will trigger an eruption only when a cumulative threshold has been exceeded (Newhall and Dzurisin, 1988; De Natale et al., 2006; Hill, 2006; Acocella et al., 2015). However, the connection between long-term unrest and eruption potential has been described only qualitatively. Using data from Rabaul caldera, we argue (1) that VT and deformation precursors at large calderas may belong to a unified sequence that can be quantified over decadal timescales, and (2) that conditions for eruption are determined by the transition from a quasi-elastic to inelastic response of the crust to applied stress. The results confirm that, on their own, short-term changes in rates of unrest are unreliable guides to the potential for eruption. They also identify new practical procedures for evaluating a caldera's approach to eruption.

2. Long-term unrest at Rabaul caldera

Among large calderas, Rabaul has a unique modern record of precursory unrest that lasted for more than two decades, between 1971 and 1994, and included a non-eruptive emergency during 1983–1985 before eruptions began on 19 September 1994.

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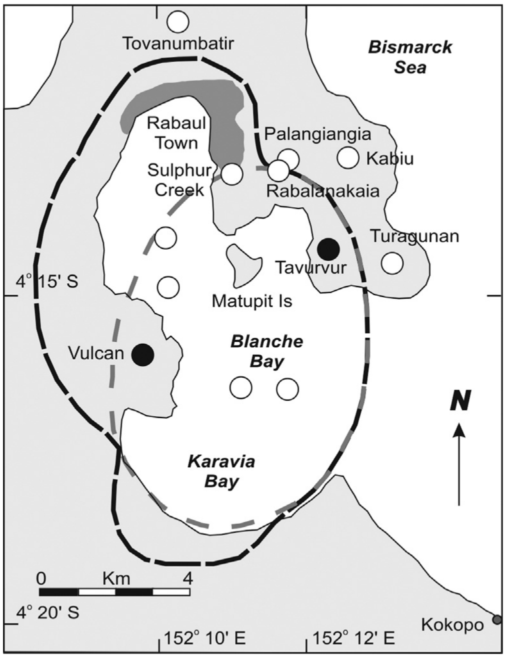

Fig. 1. Map of Rabaul caldera, showing the outlines of the Blanche Bay complex of nested calderas (*large black dashes*) and of the most recent collapse in 1400 BP (*small, grey dashes*). The 1971–1994 unrest ended with simultaneous eruptions from Tavurvur and Vulcan (*black circles*) and provoked evacuation of Rabaul Town. Previous eruptions (*white circles*) have occurred within and outside the Blanche Bay complex. (Modified from Johnson et al., 2010.)

The caldera lies on the northeastern coast of New Britain Island in Papua New Guinea (Fig. 1). At least five episodes of collapse have occurred since the Late Pleistocene across an area about 14 by 9 km across, most of which is now submerged beneath Blanche Bay and opens eastward into the Bismarck Sea (Nairn et al., 1995). The most recent caldera collapse occurred 1400 years ago (Nairn et al., 1995). It formed an elliptical structure, about 10 by 6.5 km across and aligned approximately North–South, since when andesitic-dacitic eruptions have occurred around its margin at Tavurvur, Vulcan, Rabalanakaia and Sulphur Creek (Fig. 1; Nairn et al., 1995; Wood et al., 1995; Johnson et al., 2010). The historical record dates back to the 18th Century and consists of at least six events, in 1767, 1791, 1850, 1878, 1937–43 and 1994–Present (McKee et al., 1985; Blong and McKee, 1995; Johnson et al., 2010). During the last three eruptions, activity started almost simultaneously at Vulcan and Tavurvur, on opposite sides of the caldera (Fig. 1), with the later stages becoming restricted to Tavurvur (Blong and McKee, 1995).

Unrest before the 1994 eruptions was recognised in late 1971 after 54 years of quiescence (McKee et al., 1984; Mori et al., 1989). Six months after two tectonic earthquakes of local magnitude (M_L) 8.0 had occurred in the Solomon Sea (Everingham, 1975), volcano-tectonic (VT) earthquakes began to be detected at mean rates greater than the previously typical values of 50–100 events per month (McKee et al., 1985). They were located at depths of about 4 km or less and associated with normal and subsidiary reverse fault displacements (Mori and McKee, 1987; Mori et al., 1989; Nairn et al., 1995; Jones and Stewart, 1997; Johnson et al., 2010). Their epicentres were concentrated within the topographic expression of the 1400 BP caldera (Fig. 2), indicating a narrower zone of ring faults at shallow depth (Mori et al., 1989). Approaching 2×10^5 VT events were recorded throughout unrest (Fig. 3). Most had local magnitudes between about 0.5 and 2.0, although their relative frequency could not be determined reliably for the full 23 years of unrest (Mori et al., 1989; Johnson et al., 2010). Among the $\sim 10^4$ VT events recorded during the 1983–85 volcano-seismic crisis, the maximum local magnitude was 5.1 and fewer than one percent had local magnitudes greater than 3.0 (Mori et al., 1989). For unspecified completeness magnitudes, estimates of the seismic *b*-value during the crisis lie between 0.8 and 1.1 (Mori et al., 1989) and so, assuming a value of 1, fewer than 10% are expected to have had local magnitudes greater than 2.0.

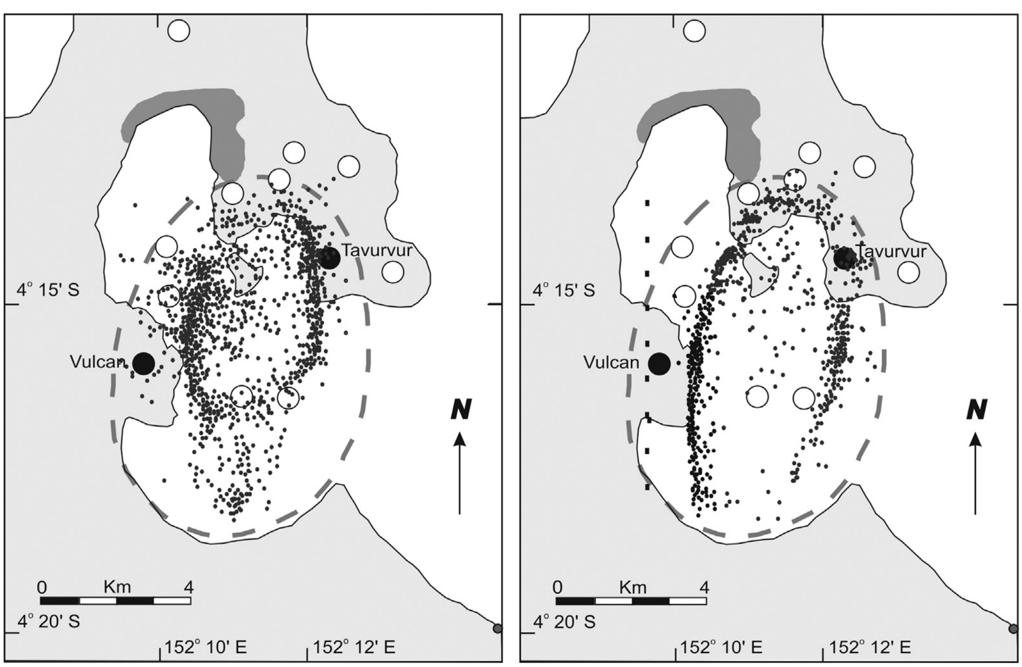

Fig. 2. The distribution of local seismicity recorded during 1971–1992. The VT events occurred at depths of less than 4 km and their epicentres (*black dots*) appear to mark an inner zone of faults associated with the 1400 BP caldera (*grey dashes*). Compared with events at depths of 2 km or less (*left*), the distribution becomes extended towards the south among events deeper than 2 km (*right*). Tavurvur and Vulcan (*black circles*) lie outside the outer margin of the more shallow VT events. See Fig. 1 for names of additional locations. (Modified from Jones and Stewart, 1997 and Saunders, 2001.)