Volcano-tectonic earthquakes and magma reservoirs; their influences on volcanic eruptions in Rabaul caldera

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Abstract

Since seismic monitoring began in the late 1960s the seismicity in Rabaul caldera has been marked by intra-caldera high frequency volcano-tectonic earthquakes. The hypocentral distribution of these earthquakes defines an outward-dipping elliptical ring-fault in shallow depths. Before the 1994 eruption other prominent seismicity includes a swarm of earthquakes that occurred in May 1992 away from the caldera in a northeasterly direction.

After the eruption the intra-caldera seismicity decreased significantly. The majority of the locatable events have been located on the southern section of the ring-fault. These events have been overshadowed by a group of earthquakes that occurred northeast of the caldera.

Observations between the ongoing eruptions at Tavurvur and the periodic episodes of northeasterly earthquakes between 1995 and 2005 show interesting correlations. Notable episodes of northeasterly earthquakes have been followed by intensified or renewed eruptive activity. The lead-time between earthquakes and either one of the types of eruptive activity is between few and several months. We speculate that the northeast earthquakes mark episodes of intrusions of a second magma source into the caldera magma reservoir allowing magma mixing to occur, hence resulting in the ongoing eruption at Tavurvur. The tomographic results suggest up to three possible magma reservoirs. The proximity of the northeast earthquakes to the north-northeasterly low velocity anomaly and other information suggests this anomaly is a magma reservoir and is the source of magma injected into the caldera reservoir.

Introduction

Since seismic monitoring began in the late 1960s the seismicity in Rabaul caldera has been marked by intra-caldera high frequency volcano-tectonic earthquakes. Before the 1994 eruption, other prominent seismicity was a swarm of earthquakes in May 1992 that occurred away from the caldera, in a northeasterly direction. The hypocentral locations of the earthquakes define an outward-dipping elliptical ring-fault in shallow depths (Mori and McKee, 1987) (Fig. 1a). After the eruption the intra-caldera seismicity decreased significantly. Most of the locatable intra-events have been located on the southern section of the ring-fault. These events have been overshadowed by a group of earthquakes that are located in a northeasterly direction from the caldera (Fig. 1b). The epicentral distribution of the latter group shows a northeast-southwest trend, however this feature may be an artifact of the location program due to station distribution. Nevertheless, there has been some correlation between the northeast earthquakes and the ongoing eruptions at Tavurvur between 1995 and 2005.

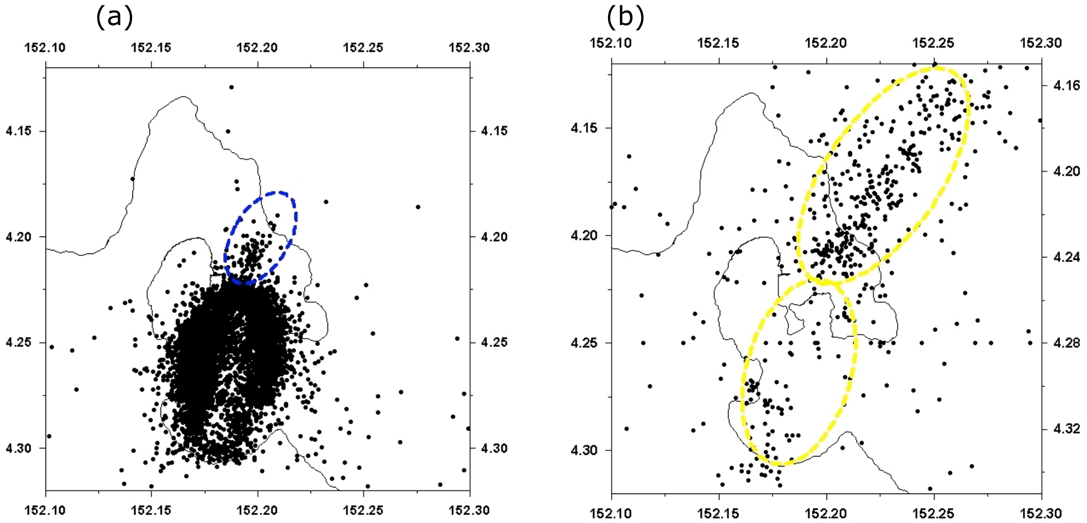

Fig. 1: Seismicity of Rabaul Caldera, (a) before the 1994 eruption, and (b) after the eruption. The pre-eruption northeast earthquakes are marked by the dashed ellipse in (a).

In this study we have attempted P-wave travel-time tomography using the Fast Marching Method, FMM (Rawlinson and Sambridge, 2004) to image the substructure of Rabaul caldera and the surrounding area in order to investigate the existence of low velocity anomalies. Since the region of study is a volcanic region some of these anomalies could be interpreted as magma bodies. Furthermore, the study investigates the proximity of the northeast earthquakes in relation to the low velocity anomalies and attempts to draw meaningful speculations on their influence on the ongoing eruptions at Tavurvur. This information could be useful for forecasting future volcanic eruptions and assist in improving disaster mitigation in Rabaul township and neighboring communities.

Data

Data used in this study include local earthquakes in and near Rabaul caldera and regional earthquakes from the New Britain – New Ireland region of Papua New Guinea (Fig. 2), recorded by the Rabaul Volcano Observatory Seismic Network (inset in Fig.2). The locations for the earthquakes were determined using the Fasthypo program (Herrman, 1979). Magnitudes for the earthquakes range between 1.0 and 7.0. As can be seen in Fig. 2, the majority of the earthquakes are located on the eastern side of the study area. Only earthquakes recorded by 5 or more stations and having horizontal and vertical uncertainties of 1.0 km or less have been used in this study. The total number of earthquakes is 674 which constitutes about 1875 rays paths.

The region of study is bounded by latitudes 3.60°S – 5.60°S and longitudes 151.20°E – 153.20°E. This area has been divided into an 81 x 81 grid, giving a total of 6561 cells with a cell size of 2.7 km. The depth range is shallow - between the surface and 40 km. There are no discontinuities in the model.

For correlation between the ongoing eruptions and occurrences of the northeast earthquakes, all significant episodes of eruptions and northeast earthquakes between the period 1995 and 2005 have been considered.

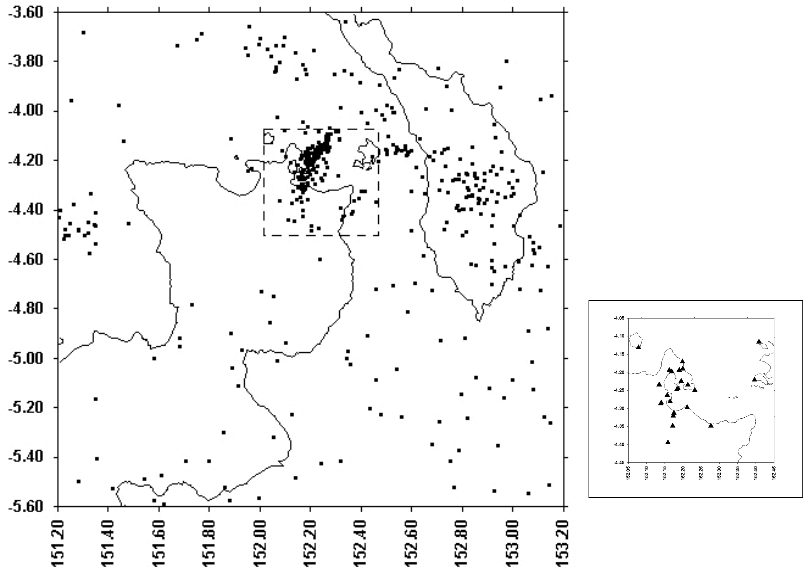

Fig. 2: Distribution of earthquakes used in this study and seismic network (inset).

Methodology

For the P-wave travel-time tomography, the Fast Marching Method (FMM) (Rawlinson and Sambridge, 2004) was utilized. FMM is a grid-based numerical algorithm ideal for wavefront construction from which traveltimes are deduced. It does this by tracking an evolving interface along a narrow band of nodes that are updated by solving the eikonal equation. The eikonal equation, which governs the propagation of seismic waves in the high-frequency limited space is represented by the gradient operator, traveltime, and slowness as a function of position.

FMM deals with problems of discontinuities by enforcing an entropy condition where the wavefront evolves because it can only pass through a point once. The traveltime associated with a particular grid point is updated using a finite difference scheme. The implementation of the scheme requires that the order in which the nodes are updated be consistent with the direction of the flow as time progresses. FMM achieves this by systematically constructing traveltimes ahead of the wavefront from known values behind the wavefront using a narrow-band approach. In the narrow-band concept the grid points are labeled as either alive, close or far, where the alive points lie in front of the wavefront, far points lie behind the wavefront and the close points lie within the narrow band itself. The narrow-band is thus identified with points with minimum traveltime and its shape approximates the first arrival wavefront.

We have applied FMM in a regional model context in this study to produce estimates of P- and S-wave arrival times for source-receiver combinations and compare them with observed times in order to produce tomographic images based on their differences.

Preliminary results

Fig.3 shows tomographic images obtained in this study. All images show relative velocity perturbation. The colour scales are in km/s. We wish to reiterate that these results are deduced from a regional model, hence some of the interpretations may not represent true in-situ structures, as they seem, from a local model context. However, we have used knowledge of the local environment (from the first author) to derive some of these interpretations without introducing bias.

Fig.3 (a-d) shows a subset of horizontal depth slices at 1, 3, 6 and 8 km. The 1 km depth slice shows the general area of Rabaul having a slow travel time anomaly. This could be consistent with a surface geology consisting mainly of soft volcanic deposits. However it fails to pick up the slightly higher velocity zones marking the caldera rim. The 3 km depth slice maintains the low velocity anomaly but is becoming a bit more focused around the caldera area. Other distinct features include two low anomaly lobes fanning out to the northeast and east from the main low anomaly and the high velocity anomalies north and south of the caldera, probably associated with the caldera rim. At 6 km depth the low velocity anomaly at the center of the caldera is still present but it has become more confined to the caldera. Furthermore the low velocity anomaly to the northeast is still maintained, but its connection with the low anomaly to the east presents a complicated picture when associating them with magma reservoirs. At 8 km depth, the low velocity anomaly beneath the caldera is still present. Interestingly the low velocity anomaly to the northeast is also maintained. The high velocity features marking the caldera boundary are also maintained at this depth.

Fig.3e and Fig. 3f are north-south and east-west cross-sections, respectively. The cross-sections are taken at longitude 152.19°E and latitude 4.26°S, respectively, passing through the center of the caldera. Both cross-sections show a low velocity anomaly to about 5 km beneath the caldera. Between 5 km and about 6-7 km the low velocity anomaly becomes patchy like a discontinuity, featuring pockets of high velocity structures, before another low velocity anomaly begins at about 7-8 km depth. The latter feature becomes ambiguous at depths greater than 12 km.

From the above descriptions we infer about three possible low velocity anomalies; the shallow and intermediate depth anomalies in the central part of the caldera and the northeasterly anomaly. The shallow and intermediate depth anomalies appear to be connected as indicated by the patchy features linking the two.

Discussion

This study complements similar studies conducted for Rabaul caldera (Gudmundsson et al., 1999; Finlayson et al., 2003; Bai and Greenhalgh, 2005). Generally, besides the low velocity anomaly in the central part of the caldera at 3-5 km depth, the results of this study are consistent with Bai and Greenhalgh (2005) on the suggestion of a second low velocity anomaly in the same area at slightly greater depths, but quite different. Bai and Greenhalgh (2005) put the top of the second anomaly at about 12 km. Our study puts the top of the second low velocity anomaly at about 8 km. Similarly, like Bai and Greenhalgh (2005), our study suggests that the two bodies are connected, but details of this are complicated. Furthermore, this study agrees with Bai and Greenhalgh (2005) about the suggestion of another low velocity anomaly away from the caldera in a northeasterly direction. Bai and Greenhalgh (2005) have associated this with Tavui caldera, hence the Tavui source. The location of the anomaly determined in this study approximately coincides with the result of Bai and Greenhalgh (2005) (Fig. 13b), but strictly speaking it falls well away from Tavui Caldera. To be more precise it is located slightly south-southeast from Tavui caldera, offshore near Korere-Nodup and approximately coincides with the locations of the so-called northeast earthquakes.

The proximity of the northeasterly source to the basaltic volcanic centers of Kombiu, North and South Daughter, and assuming that eruptives from these volcanoes originated from this source, suggests that the Tavui source is basaltic. To some extent this interpretation is more logical to solve the ambiguity of the source of the basaltic magma, which is a key component in magma mixing in the Rabaul eruptives (Patia et al., 2002; Patia, 2003). Patia et al. (2002) and Patia (2003) alluded to the idea that the basaltic magma is at greater depths beneath the caldera. This is also possible considering the intermediate-depth low velocity anomaly beneath the caldera (Bai and Greenhalgh, 2005 and this study). However, Patia et al., (2002) and Patia (2003) have shown that the eruptives from Vulcan contain no basaltic components whilst eruptives from Tavurvur have abundant basaltic components. The absence of basaltic components in Vulcan eruptives suggest the basaltic source is not within reach from the Vulcan plumbing system, so certainly it is not from the intermediate-depth central magma reservoir. We prefer the easterly source as Roggensack et al., (1995).

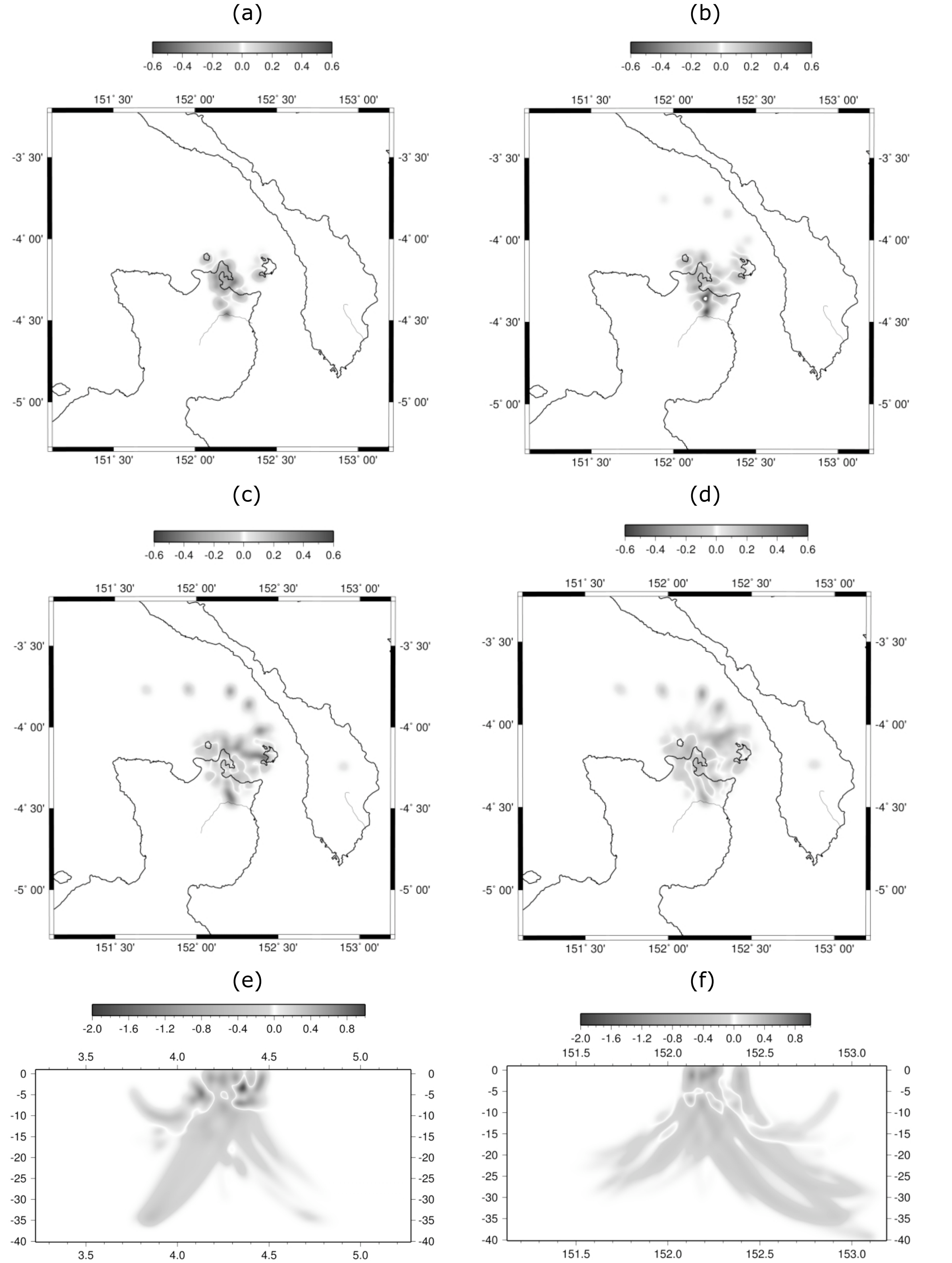

Fig. 3: Preliminary tomographic results showing relative velocity perturbations for 1, 3, 6 and 8 km depth slices (a-d), and north-south and east-west cross-sections (e-f). The north-south cross-section is sliced through longitude 152.18°E and the east-west cross-section through 4.24°S, both of them passing through the center of the caldera.

Magma mixing, in this case involving dacite magma from the caldera source and the basaltic magma from the Tavui area, is considered to be a key process that facilitates the ongoing eruptions at Tavurvur between 1995 and 2005. Petrological analysis on material from the eruptions confirms this (Patia et al., 2002; Patia, 2003). Obviously magma mixing can only occur when basalt magma from the Tavui area injects into the central caldera source. We interpret the northeast earthquakes as an indicator of this activity.

This inference is based on the observed correlation between the occurrence of northeast earthquakes and either intensification of eruptive activity during an ongoing eruption or resumption of eruption (Table 1). The lead-time between the occurrence of earthquakes and either intensified eruptive activity or renewed eruption varies between a few weeks and several months. The shorter response time is associated with an open system and the longer response time is associated with a partially closed system. This suggests that the lead-time will even be longer when the system is completely closed. We demonstrate this by the first-ever swarm of northeast earthquakes in May 1992, followed by the twin eruptions in September 1994. The lead-time was approximately 28 months. In retrospect of the eruption, the eruption in 1994 was preceded by 27 hours of very intense intra-caldera seismicity triggered by two moderate earthquakes. In contrast, before that the caldera system went through a very intense crisis between September 1983 and July 1985 (Mori et al., 1988), marked by high earthquake and inflation rates. An eruption was very eminent but it did not occur. Based on the preceding discussions we form the view that although an eruption was eminent between 1983 and 1985, it did not occur because there was none or no adequate magma mixing to trigger an eruption.

Table 1: Significant cross-correlation between northeast earthquakes and increased summit activity at Tavurvur between 1995 and 2005.

Swarm/EQ dates	*Level of Swarm/EQ activity*	*Type of summit activity*	*Date of Summit activity*	*Lead time between seismicity and summit activity (months)*
Aug 1995	B	ER	Nov 1995	3
Feb 1996	B	IA	May 1996	3
Jul-Aug 1996	A	IA	Oct 1996	2
Feb 2001	C	ER	Sep 2001	7
Jun-Jul 2004	C	ER	Jan 2005	7

Key: IA – Intensified Activity, ER – Eruption Resumption, A –Intense, B – Moderate, C – Low, D – Very low.

These observations suggest that magma mixing is a fundamental process for triggering eruptions in the Rabaul caldera. Furthermore, the northeast earthquakes are possible early indicators for basaltic magma injection and they can be used as precursors for forecasting future volcanic eruptions in the Rabaul caldera. This observation is of crucial importance for disaster mitigation in the township of Rabaul from future eruptions.

Conclusions

The results of this tomographic study are quite consistent with results of similar studies for Rabaul caldera (Finlayson et al., 2003; Bai and Greenhalgh, 2005). Apart from the shallow central caldera low velocity anomaly, this study agrees with Bai and Greenhalgh (2005) on two other low velocity anomalies located at intermediate depth in the central part of the caldera, and northeast from Rabaul caldera near Tavui area. This study suggests the low velocity anomaly near Tavui area is the primary source of the basaltic magma, which is injected into the caldera reservoir allowing magma mixing to occur, as determined by Patia et al. (2002) and Patia (2003).

The occurrence of the northeast earthquakes is indicative of the source near Tavui area being injected into the central caldera magma system. Observations between 1995 and 2005 indicate strong correlation between the northeast earthquakes and eruptions at Tavurvur. In all cases the northeast earthquakes preceded intensified or renewed eruptions with lead-times ranging between few and several months. This outcome could be reliably used as a precursor for forecasting future eruptions in Rabaul caldera and hence help towards disaster mitigation.

In the next phase of this work, another scheme based on Neighborhood Algorithm (Sambridge and Kennett, 2001) will be applied to invert the time differences and thus produce another set of tomographic images.

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