Seismic and Ground Deformation Crises at Rabaul Caldera: Prelude to an Eruption?

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ABSTRACT

A dramatic short-term increase in seismicity and ground deformation took place at Rabaul Caldera on 19 September 1983, and marked the start of a period of frequent episodes of high seismic energy release and concurrent rapid ground deformation. Together with increased background levels of seismicity and ground deformation, these phenomena are interpreted as indications of higher rates of magma injection at shallow depths within the caldera, which greatly increases the likelihod of an eruption at Rabaul in the near future. A modest volume of magma, about 100 million m^3, could be available for eruption from two shallow reservoirs, but a somewhat deeper and much larger magma body – residual from the latest major eruption about 1400 yr BP – may also exist beneath the caldera.

INTRODUCTION

Signs of renewed activity at volcanic calderas are viewed with considerable interest and concern by volcanologists because of the demonstrated capability of these volcanoes to erupt with great violence and cause widespread devastation. Owing to the uncertainty about the nature of precursors to large-scale eruptions at calderas, volcanologists were disturbed by the dramatic increase in seismicity and ground deformation which started at Rabaul Caldera on 19 September 1983.

The caldera at Rabaul is of medium size, measuring 14 km from north to south and 9 km from east to west (Fig. 1). Present indications are that the caldera was formed 3500 years BP, and was subsequently modified by two more major eruptions, the most recent of which was 1400 years BP (HEMING, 1974; WALKER *et al.*, 1981). Several small volcanoes have developed within the caldera since the latest major eruption, mostly around the perimeter of the caldera. The historical record of eruptions of these post-caldera volcanoes dates back to 1767 AD and includes at least five recognizable eruptive episodes, the most recent of which was in 1937-43. Two of these episodes (1878, 1937-43) involved simultaneous eruptions on opposite sides of the caldera (BROWN, 1878; SAPPER, 1910; FISHER, 1939). Dacite is probably the most abundant rock type at Rabaul, occurring as ignimbrites and airfall pumiceous tephra.

In 1971, following two major tectonic earthquakes of magnitude (M) 8.0 in the Solomon Sea (EVERINGHAM, 1975), the condition of Rabaul Caldera began a progressive change marked by uplift and tilting (Fig. 2) concentrated at a source slightly east of the centre of the caldera, and seismicity in a ring-structure (Fig. 3) believed to define the caldera bounding faults (MCKEE, 1982; MCKEE *et al.*, 1985). The seismicity was characterized by occasional swarms of hundreds of shallow (0-3 km depth) earthquakes, at intervals of several months to several

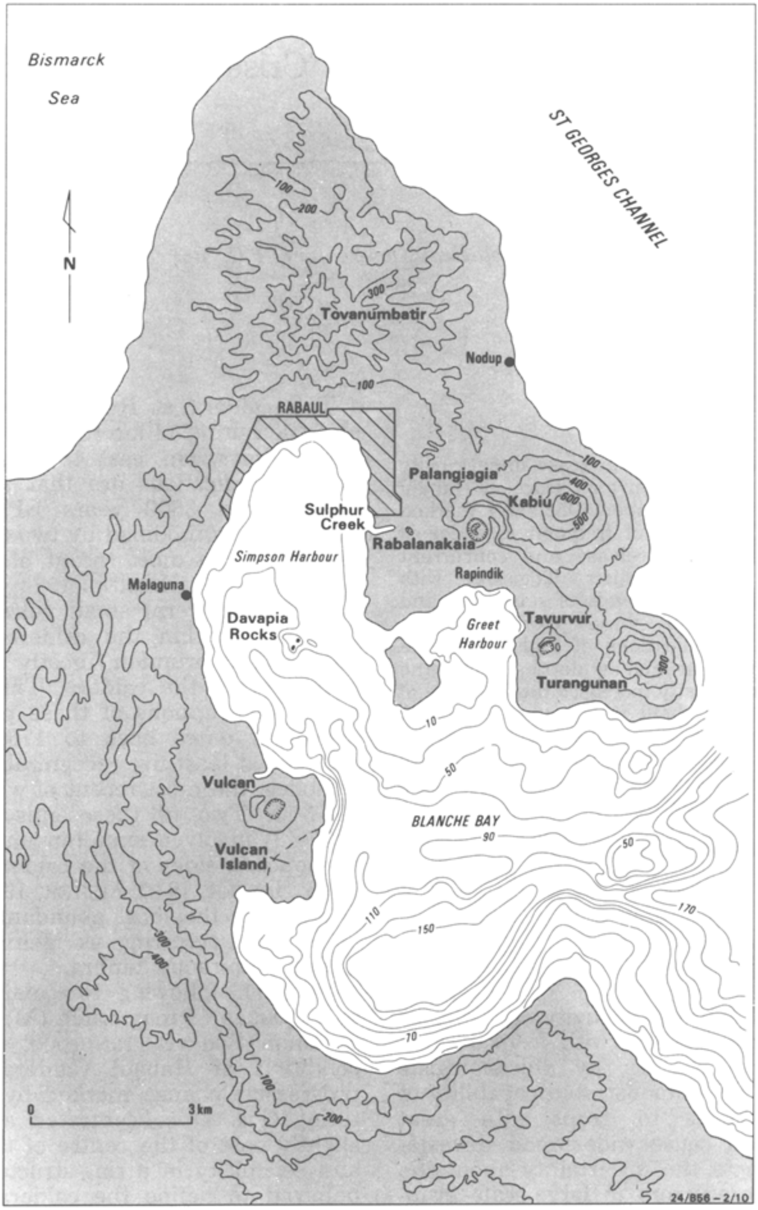

FIG. 1 - Topography and bathymetry of Rabaul Caldera, including intracaldera and satellite volcanoes. Contours on land are in metres, and isobaths are in fathoms (about 37 m intervals). After HEMING (1974) and MCKEE *et al.* (1985).

years. An increase was noted in the number of earthquakes in successive swarms, or crises (Fig. 4), and background seismicity was significantly greater than before 1971. Uplift, monitored by approximately annual levelling surveys, appeared to take place steadily (Fig. 2), although relatively large episodic elevation changes (of the order of several centimetres) may have occurred in association with the seismic crises. Gravity changes also reflected the uplift in the caldera, apparently with little or no change in subsurface density distribution.

This slowly evolving situation gave way in 1983 to a dramatic increase in seismic activity and ground deformation. This increase may have been linked to a nearby major tectonic earthquake (M 7.6, 200 km east of Rabaul) which took place in March 1983. The current phase of intensified activity at Rabaul Caldera has been marked by frequent episodes (crises) of high seismic energy release and concurrent rapid ground deformation. These phenomena are believed to signify higher rates of magma injection at shallow depths within the caldera, which greatly increases the likelihood of an eruption at Rabaul in the near future.

CRISIS PERIOD: SEPTEMBER 1983 - MAY 1984

Seismicity

Background levels of seismicity (our detectability limit is about $M_L - 1$) rose more or less stedily from a «normal» level of about 10 events per day in August 1983 to about 50 per day before the first seismic crisis on 19 September 1983 (Fig. 5). Background seismicity reached a peak of about 350 events per day in late-April 1984, but declined to about 160 events per day in May 1984. From September 1983 to May 1984, 15 major seismic crises occurred, at intervals of 1 to 47 days, and a large number of minor crises or swarms also took place. Major crises typically involved hundreds of earthquakes in the space of less than one hour. Caldera earthquakes were mostly high frequency tectonic-like events in both crisis and non-crisis periods. Small numbers of emergent (unlocatable) low frequency seismic events were also recorded, but no systematic patterns of their occurrence were observed although a higher incidence of them occasionally preceded seismic crises by a few days. Usually, the strongest events were felt at MM III-V in Rabaul town and took place at or near the beginning of a crisis. The strongest caldera earthquake in the period September 1983 to May 1984 was a magnitude (M_L) 5.1 event in the crisis of 3 March 1984. This is only slightly weaker than the strongest event in the whole period of unrest, *i.e.* since 1971, which was a magnitude (M_L) 5.2 earthquake in October 1980. The total amount of energy released seismically in the crisis period to May 1984 is provisionally estimated to be 2×10^{19} ergs.

The seismicity of individual crises was usually confined to limited regions within the elliptically annular caldera seismic zone. The most active regions of this zone before September 1983 were the eastern, northeastern and western parts, rendering a pattern of seismicity resembling a pair of parentheses (Fig. 3). However, in the current crisis period, the northern part of the caldera seismic zone was also active resulting in a horseshoe-shaped concentration of seismicity (Fig. 6). The continuing low seismicity in the central part of the caldera emphasized the annular seismic pattern. Most of the earthquakes occurred at depths of 0-3 km and no trend of shallowing seismicity (which could indicate the imminent outbreak of an eruption was recognized).

Seismic «b» values (expressing the proportions of stronger and weaker earthquakes) appeared to show a weak increasing trend, from about 1.4 in September 1983 to about 1.6 in May 1984. Such a trend, signifying a proportional increase in the incidence of weaker earthquakes, could represent a decrease in rock strength, a decrease in the level of stress, or the development of a less-uniform (or more non-uniform) stress field in the caldera (SCHOLZ, 1968).

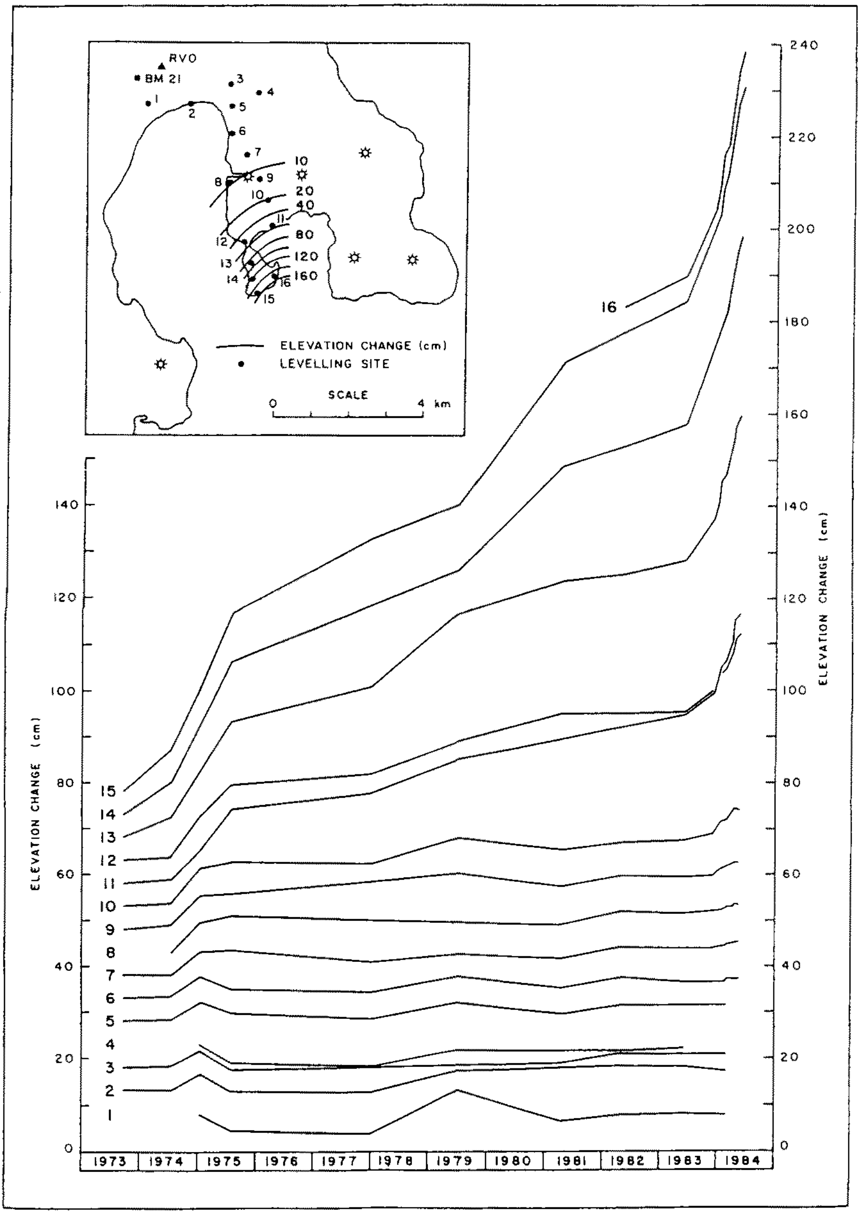

FIG. 2 - Elevation changes for September 1973 to May 1984 on stations of the Rabaul Caldera gravity network. Partial contour lines are elevation changes relative to BM21.

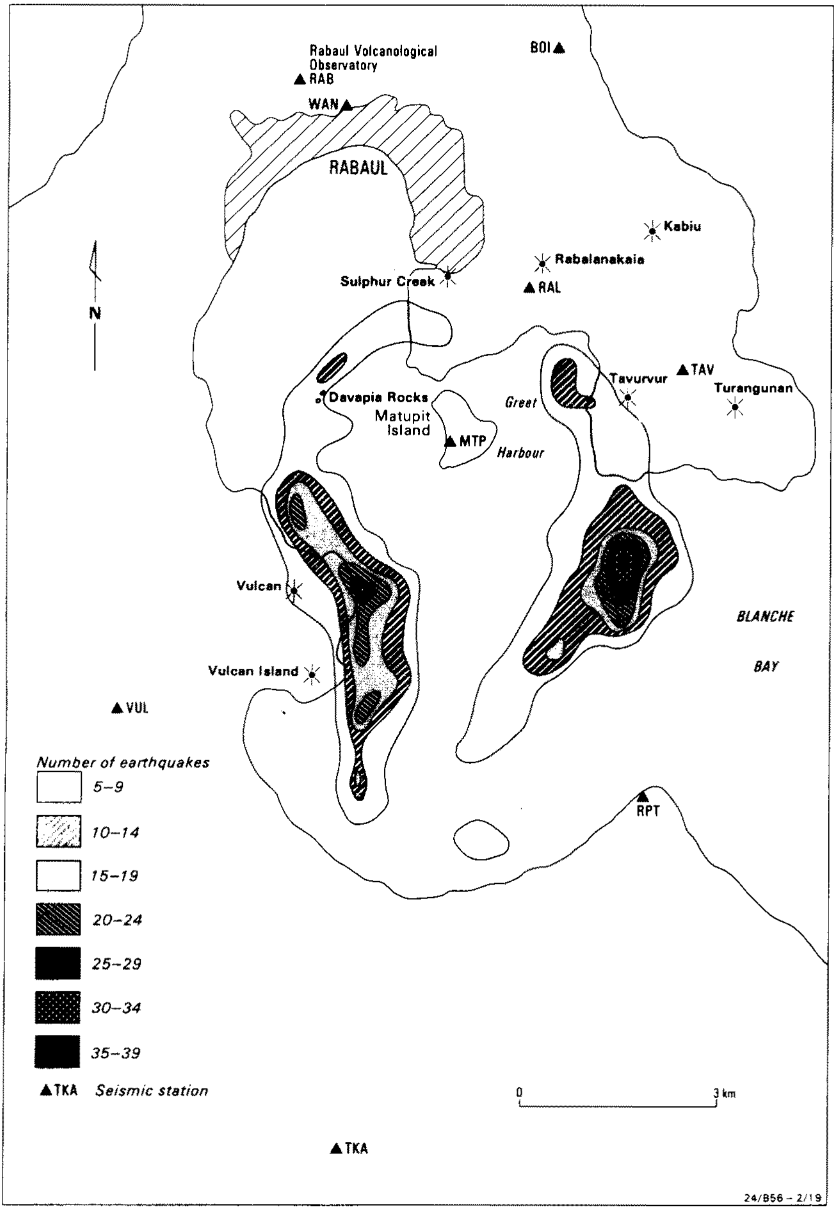

FIG. 3 – Pattern of seismicity in Rabaul Caldera for February 1977 to June 1982. Isoseismal lines refer to the number of earthquakes listed in the index. Earthquake epicentres were contoured using a grid of 500 × 500 m squares. Most of the earthquakes were at shallow depth (0-3 km). Earthquakes plotted had magnitudes $M_L \geq 1$. After McKEE *et al.* (1985).

Tilt and Uplift

Tilt measurements at Rabaul are obtained from tiltmeters (watertube and electronic), and from the use of a simple surveying technique («dry tilt levelling») on small arrays of benchmarks. Generally low rates of tilting were observed in Rabaul Caldera before 19 September 1983, the maximum rate being about 4-8 microradians per month measured at a station near the southeastern coast of Matupit Island (Fig. 7). The pattern of tilt vectors indicated a deformation source immediately southeast of Matupit Island. The sharp increase in tilt rates which occurred on 19 September was preceded by one month of slightly higher rates. A considerable amount of the tilt since 19 September 1983 took place through a sequence of rapid deformation events (crises) which accompanied the seismic crises. The biggest individual tilt crises were of the order of 50 microradians at stations about 1 km from the deformation source near Matupit Island. In addition, progressive (*i.e.* non crisis) tilting also took place, at rates of 25-30 microradians per month around Greet Harbour. The increased tilt rates during the current crisis period are shown in Fig. 7. Tilt vectors in the post-September 1983 events continued to indicate a source of deformation near Matupit Island. Since the addition of new stations to the dry tilt network in October 1983, a second source

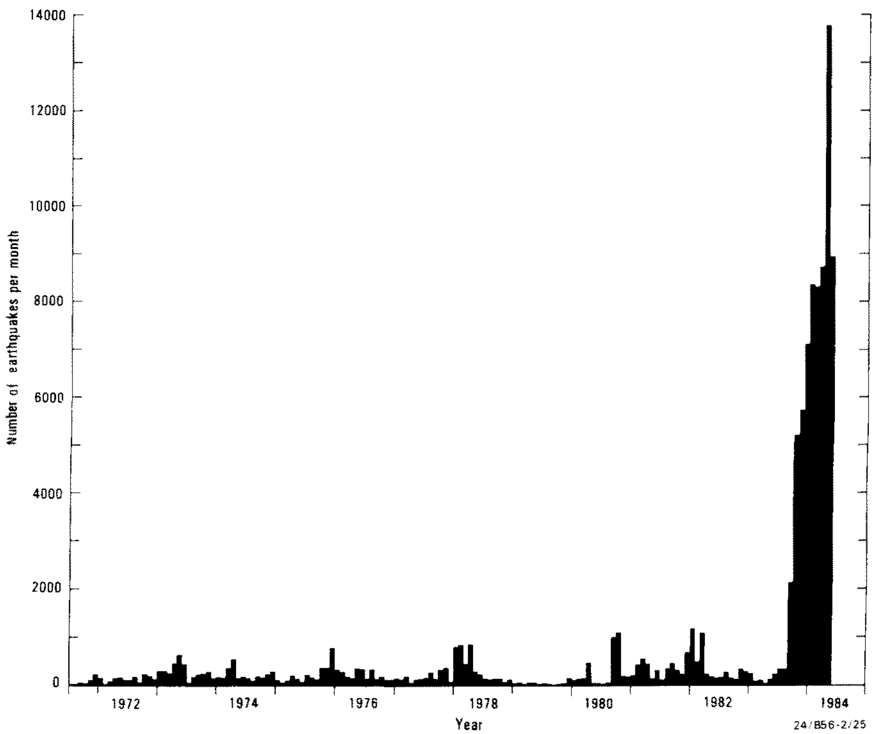

FIG. 4 – Monthly Rabaul Caldera earthquake totals for July 1971 to May 1984. The seismic detectability limit for the Rabaul seismic network is about M_L-1. After MCKEE *et al.* (1985).

of deformation has been suggested. The location of this possible second source is immediately east of the Vulcan headland (Fig. 7).

Eight levelling surveys were carried out on the main levelling line in the northern part of the caldera between November 1983 and May 1984. These surveys showed a trend of continuous uplift, with an average rate of about 50 mm per month at the southern end of Matupit Island (Fig. 2). This compares with previous rates of about 8 mm per month for the preceding decade. The increased rate of uplift is shown in Figure 8, where about 25% of the uplift since 1971 has taken place in the last year (May 1983 - May 1984). In detail, the uplift since September 1983 took place both steadily and, at times of seismic crises, episodically. The largest measured uplift in a crisis was about 60 mm.

As a first approximation, «point source» modelling (MOGI, 1958; EATON, 1962) of the sources of the tilt and uplift has been carried out. For the crisis period, analysis of the tilt data from the north-eastern part of the caldera indicates a focal depth of 2 km for the centre of the «Matupit» source. The possible source near Vulcan is estimated to be about 3 km deep. Assuming that the deformation sources are in fact bodies of magma, undergoing volume rather than pressure changes, the volume increase at both sources during the crisis period can be calculated to be about 15 million m^3. Slightly smaller volume changes are indicated from analysis of the corresponding uplift data. This is due to shallower source focal depth estimates.

Modelling of the deformation before the crisis period is largely restricted to levelling data because of inadequate tilt data before 1981. Analysis of all the levelling data indicates that since the start of unrest (1971), the focal depth of the Matupit source was steady at about 1.5 km and the maximum uplift at the surface was about 3.5 m. Calculations indicate that the volume of this deformation source is about 50 million m^3. This volume figure may be conservative as the source focal depth of 2 km, indicated by analysis of the recent tilt data, is probably more realistic and would imply a greater

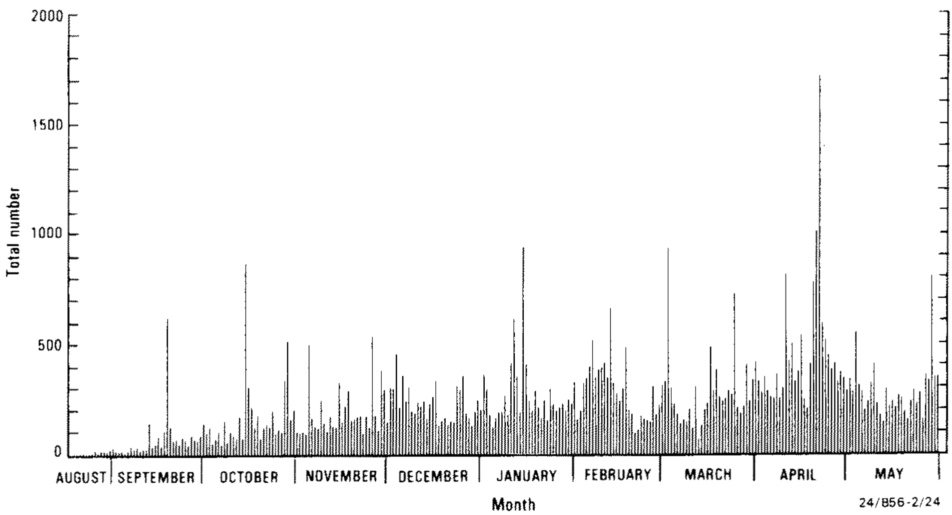

FIG. 5 – Daily Rabaul Caldera earthquake totals for 19 August 1983 to 31 May 1984. After MCKEE *et al.* (1985).

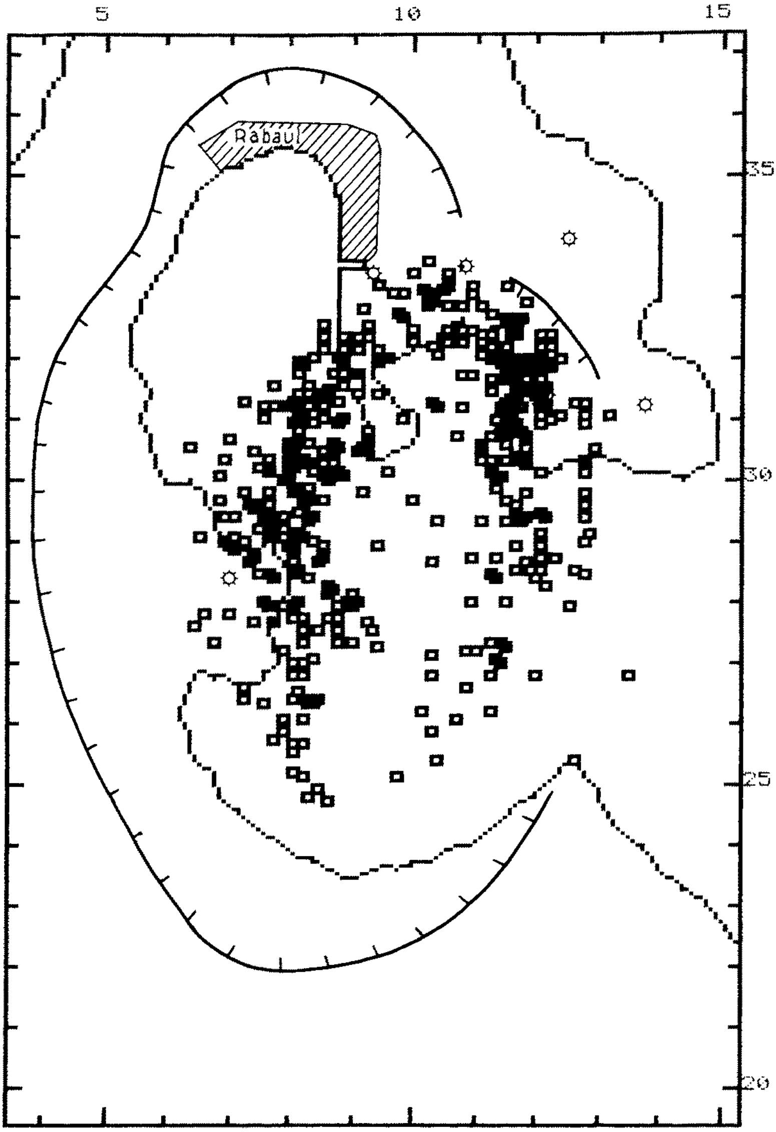

FIG. 6 – Earthquake epicentres in Rabaul Caldera for the period 1 September 1983 to 31 May 1984, and topography including caldera outline and intra-caldera and satellite volcanoes (sunbursts). Earthquake locations have rms errors ≤ 200 ms derived from registrations on usually 7 or more stations. About 95% of the earthquakes were at shallow depth (0-3 km). Earthquakes plotted had magnitudes $M_L \geq 1$. Grid is from the 1:50,000 scale topographic map Blanche Bay Sheet 6245 111, and has 1 km intervals.

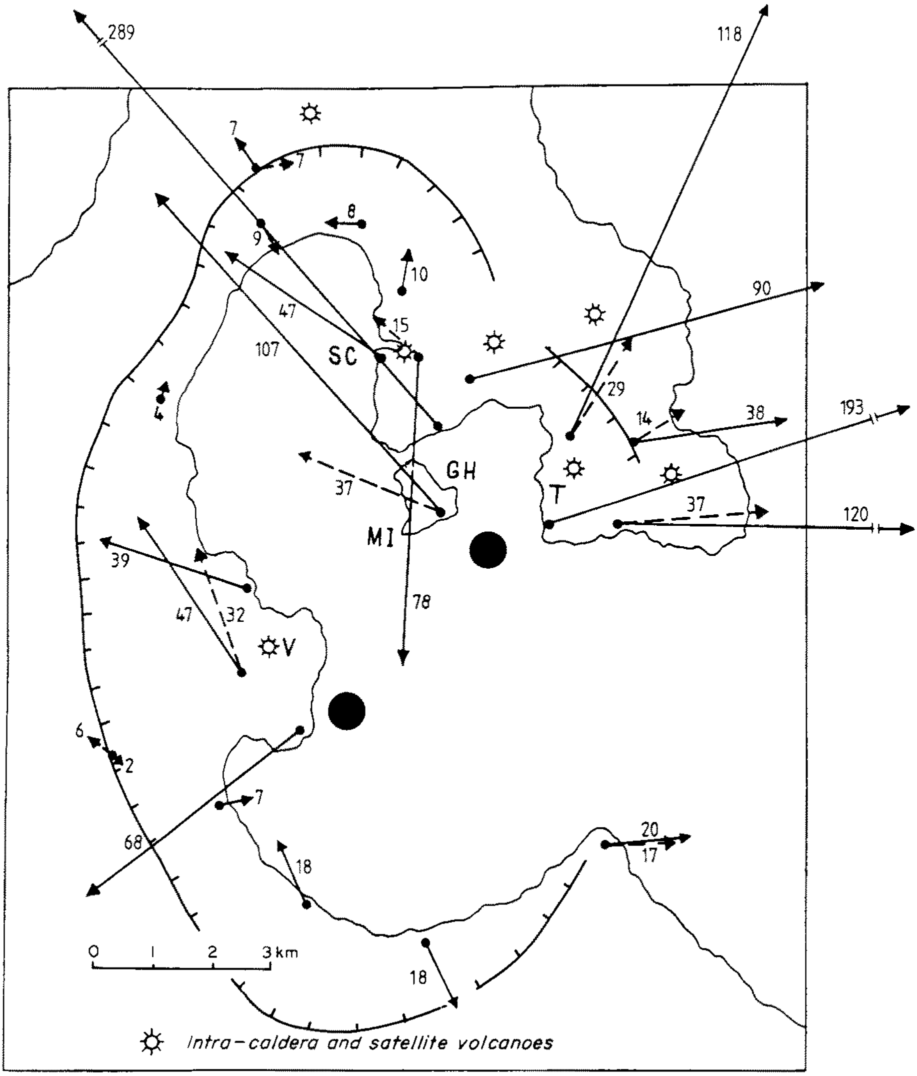

FIG. 7 - Tilt vectors (microradians) in Rabaul Caldera for the periods (i) January-30 September 1983 (broken arrows), and (ii) 1 October 1983-31 May 1984 (solid arrows). Inflation centres are shown as large filled circles. The striking south-trending tilt vector (78 microradians) at the head of Sulphur Creek inlet was associated with local subsidence initiated by the major crisis of 22 April 1984.

volume change. A calculation of the volume change at the Vulcan source is not possible as the time of its reactivation since the last eruption is unknown. However, on the basis of similar volume changes at both sources in the current crisis period, if the Vulcan source was also active since 1971, about 50 million m^3 of magma may have been stored there also.

Gravity

Gravimetric changes measured on a network of about 40 stations in and around the caldera appear to be closely correlated with uplift in the caldera since measurements began in 1973. The greatest measured change between September 1973 and August 1983 was about - 250 microgals at the southern coast of Matupit Island. Between September 1983 and May 1984 the change at the same location was about - 100 microgals. These changes can be fully explained by the measured uplift if a density of about 1.9 $g \cdot cm^{-3}$ is assumed in the Bouguer plate corrections. Such a density value is appropriate for near surface lithology within the caldera.

The apparent absence of a gravity anomaly associated with the inferred magma body beneath the entrance to Great Harbour is possibly due to lack of density contrast between the intruded magma and its surroundings. This suggests that the combined effects of hydrostatic head and buoyancy have allowed the magma to rise to a level at which its density matches its surroundings. At the estimated depth of the magma body (about 2 km), a density of

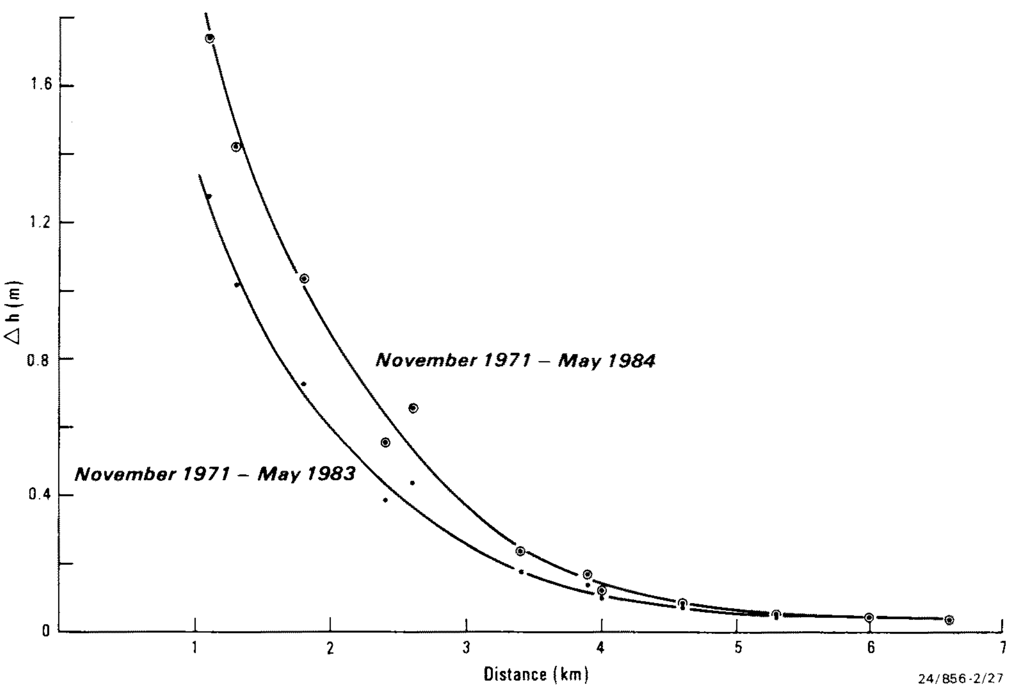

FIG. 8 – Uplift versus distance from the inflation centre near Matupit Island. After MCKEE *et al.* (1985).

2.5 g.cm^{-3} can be derived (GARDNER *et al.*, 1974) for the crustal rocks from their seismic velocity of about 4.5 km·sec^{-1} (average of values from CIFALI *et al.*, 1969; FURUMOTO *et al.*, 1970; FINLAYSON and CULL, 1973; COOKE, 1977; ALMOND and MCKEE, 1982). This value of density would be appropriate for a hydrous, intermediate magma (about 3% H_2O and 60% SiO_2) at a pressure of about 1 kbar (KUSHIRO, 1978).

Horizontal Deformation

Horizontal deformation measurements using a laser EDM instrument commenced in December 1983. All distances measured within the caldera showed evidence of dilatational strain (Fig. 9), while base line measurements outside the caldera did not show any significant changes. Horizontal strains were most pronounced in the Greet Harbour area. Fairly steady, radially-symmetrical expansion of about 25 microstrain per month was observed at the mouth of the harbour. However, rapid changes of about 30-40 microstrain accompanied seismic crises of 3 March and 22 April 1984. Substantial horizontal deformation also took place in the southern part of the caldera. This lends support to the suggestion of a second inflationary source in this region, although the overall pattern of horizontal strain vectors could perhaps be modelled

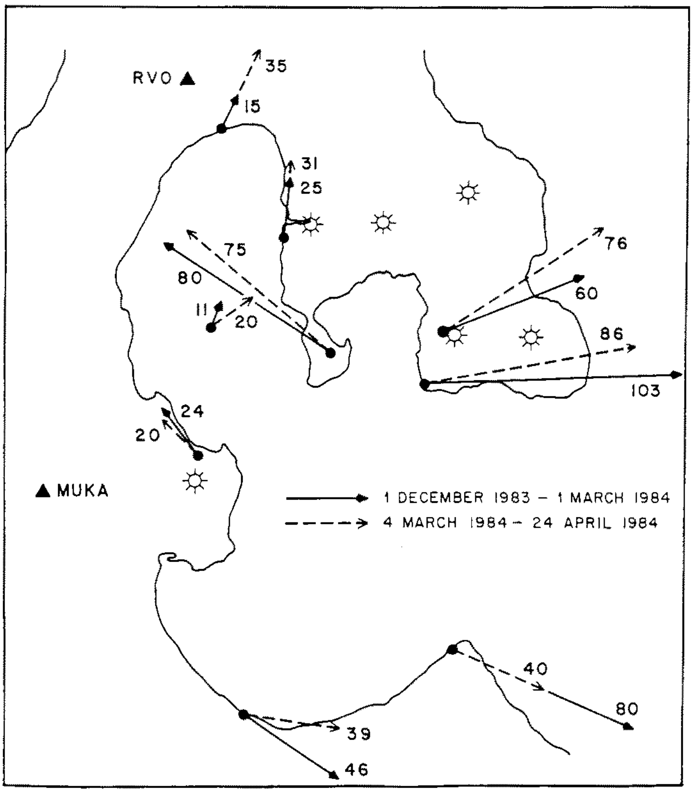

FIG. 9 – Horizonal distance changes (mm) in Rabaul Caldera for the periods 1 December 1983-1 March 1984 and 4 March-24 April 1984. Base stations RVO and MUKA are shown.

by one NE-trending tabular body linking Vulcan and Tavurvur volcanoes (N. BANKS, pers. comm., Oct. 1984). The apparent lack of broad deformation extending beyond the caldera is consistent with the shallowness and relatively small size of the inferred magma intrusions.

DISCUSSION

Eruption from Two Sources

The change in condition of Rabaul Caldera since September 1983 is marked, but there has been generally little or no acceleration in the rate of change of the various parameters observed. It is therefore difficult to precisely forecast the future course of events, which could include the onset of eruption or a gradual return of the caldera to lower levels of activity. Calculations based on deformation monitoring indicate that about 100 million m^3 of magma could have been injected into shallow reservoirs since 1971. An erupted volume for this magma could be as much as 0.25 km^3 (assuming the ratio of the densities of magma and eruptives would have a maximum value of 2.5, and that all of the magma would be erupted). This volume of eruptives would be modest by most standards. However, the prospect of eruption at two different points in the caldera is disturbing. Although simultaneous eruptions from opposite sides of the caldera took place in 1937, and the total volume of tephra erupted (0.3 km^3) is similar to the volume which could be available at present for eruption, in terms of the potential hazards, there may be some important differences between the 1937 eruptions and the next one(s).

Most of the tephra in 1937, was erupted from Vulcan, but in the present situation a considerable volume of magma is apparently available on the opposite side of the caldera. This puts the township of Rabaul in greater danger. A second consideration is that the Matupit magma body is in a region covered by a greater depth of water than was the eruption focus of Vulcan in 1937. This implies that a longer period of potentially very dangerous phreatomagmatic activity could occur in the early stage of the next eruption if a vent was established directly above the magma body. However, as most of the post-caldera eruptives have emerged from vents developed on the caldera bounding faults, it is possible that magma may be channelled to nearby existing sub-aerial volcanoes.

Dacitic Magmatism and Seismic Precursors

On grounds of uniformitarianism, the predominance of dacitic rocks in the volcanic sequence at Rabaul suggests that future eruptives are also likely to be of dacitic composition. The apparently slow evolution of the current unrest may well be consistent with the movement of viscous dacitic magma. The causes of the unrest and its recent intensification are not known, but it is interesting to note a possible connection with preceding strong regional earthquakes. It could be that activity in the period November 1971 - August 1983 was triggered by the nearby major tectonic earthquakes in July 1971 and represented slow, steady accumulation of magma at a shallow level beneath the caldera. The intensification since September 1983 could be the result of a much higher rate of magma injection which may have been induced by the nearby major tectonic earthquake of March 1983.

The source of the dacitic magma is uncertain, but it is possible that the 1400 yr B.P. eruption left a large residual body of dacitic magma beneath the caldera and that the observed deformation and seismicity were caused by leaks of still-liquid magma which fed shallow reservoirs above the larger, deeper, crystallizing magma body. Some support for the possible existence of active residual magma from the latest major eruption lies in the striking chemical similarity of eruptives from some of the post-caldera volcanoes and the tephra of the 1400 yr B.P. eruption (HEMING, 1974), and the presence of a nearly aseismic zone in the centre of the caldera. It could be argued that, periodically, batches of magma have become available from the residuum of the 1400 yr B.P. magma body and that their eruption has resulted in the development of the Vulcan headland, Davapia Rocks (The Beehives), and Matupit Island (Fig. 1). Some tephra from Tavurvur and Sulphur Creek also have chemical similarities with these rocks.

Role of Mafic Magmatism

Mafic rocks are also present in the post-caldera volcanic sequence at Rabaul. This diversity of magma chemistry thus leads to the speculation that more than one body of magma exist beneath Rabaul Caldera. Mafic magmas are probably of mantle origin, whereas, felsic magmas have probably evolved in higher levels of the crust over long periods of time. There is now evidence (JOHNSON *et al.*, 1985) to suggest that some eruptions result from the mixing of chemically different magmas (SPARKS *et al.*, 1977), and indications of this phenomenon are present in the deposits from several Rabaul eruptions (WALKER *et al.*, 1981).

Mafic magmatism could affect Rabaul Caldera in a variety of ways. Assuming that a residual body of dacite is present beneath the caldera, the rise from depth of relatively cool, volatile-poor and therefore sluggish mafic magmas could terminate at the base of the dacite because of greater buoyancy of the latter. However, if a batch of mafic magma was particularly hot, rich in volatiles and therefore more mobile, it could force its way through the dacite and erupt at the surface. These extreme cases and all intermediate scenarios would, however, cause come disruption to the body of dacite. The transfer of heat to the dacite or any significant degree of magma mixing could culminate in eruption from the body of dacite. The fact that an eruption has not already taken place at Rabaul (since the commencement of the current unrest in 1971), suggests that, if mafic magma is involved, it has not been sufficiently mobile to break through the assumed body of dacite, or the disturbance to the dacite by mixing of mafic magma has not been sufficiently extensive to cause the kind of exponential disruption which would lead directly to an eruption.

If the current unrest at Rabaul Caldera is the result of activation of pre-existing dacitic magma caused by inter-mixing with mafic magma, the following scenario could be envisaged. Following a major seismic disturbance, an initial small injection from depth of mafic magma into a body of dacitic magma may have triggered convective overturn and expansion of the dacite which resulted in magma migrations (beginning in 1971) into reservoirs at a shallow level beneath the caldera. Because of continued supply of dacitic magma, these shallow reservoirs expanded slowly. After another strong earthquake, a new injection of mafic magma may have caused the intensification of the unrest (starting in 1983) by inducing a higher degree of agitation of the dacitic magma and an increased rate of magma migration into the shallow magma reservoirs.

Caldera Formation

Deformation surveillance results are consistent with small, shallow intrusions, but it remains possible that the existence of a large active magma body at greater depth is being missed by current surveillance. A rather forbidding scenario is that if simultaneous eruptions were to begin at several places in the caldera, rapid decompression of the postulated large dacitic magma body could result in vesiculation of large quantities of magma and lead to an escalation of activity to the scale of a major eruption. In this context, the elliptical pattern of seismicity (Figs. 3 and 6) could be of great significance, as it probably marks the caldera bounding faults, and the role of these faults in channelling magma to be erupted at the post-caldera volcanoes has in past eruptions been of major importance.

An unresolved question at this time is whether the elliptical pattern of seismicity is an indication of a process of de-coupling along the caldera faults which could lead to further caldera collapse.

ADDENDUM

Activity at Rabual Caldera declined from June to December 1984, although a brief resurgence took place in October which included a crisis on the 18th involving a M_L 4.9 earthquake, and measured deformation of 100 mm uplift and 90 microradians tilt at the entrance to Greet Harbour. At the close of 1984, background seismicity was about 60 events per day, and rates of ground deformation were about 1-2 times pre-crisis levels.

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REFERENCES

ALMOND, R.A., and MCKEE, C.O., 1982, *Location of Volcano-Tectonic Earthquakes within the Rabaul Caldera.* Geol. Surv. Papua Guinea Rep., *82/19,* 10 pp.

BROWN, G., 1878, *Journal of the Rev. G. Brown, 1860-1902* (11 volumes). Mitchell Library, Sydney, Aust.

CIFALI, G., D'ADDARIO, G.W., POLAK, E.J., and WIEBENGA, W.A., 1969, *Rabaul Preliminary Crustal Seismic Test, New Britain 1966.* Bur. Miner. Resour. Aust. Rec., *1969/125,* 14 pp.

COOKE, R.J.S., 1977, *Rabaul Volcanological Observatory and Geophysical Surveillance of the Rabaul Volcano.* The Australian Physicist, Feb. 1977, p. 27-30.

EATON, J.P., 1962, *Crustal Structure and Volcanism in Hawaii.* Am. Geophys. Union Monogr., *6,* p. 13-29.

EVERINGHAM, I.B., 1975, *Faulting Associated with the Major North Solomon Sea Earthquakes of 14 and 26 July 1971.* J. Geol. Soc. Aust., *22,* p. 61-70.

FINLAYSON, D.M., and CULL, J.P., 1973, *Time-Term Analysis of New Britain/New Ireland Island Arc Structures.* Bur. Miner. Resour. Aust. Rec., *1973/21,* 20 pp.

FISHER, N.H., 1939, *Geology and Vulcanology of Blanche Bay, and the Surrounding Area, New Britain.* Territory of New Guinea, Geol. Bull., *1,* 68 pp.

FURUMOTO, A.S., HUSSONG, D.M., CAMPBELL, J.F., SUTTON, G.H., MALAHOFF, A., ROSE, J.C., and WOOLLARD, G.P., 1970, *Crustal and Upper Mantle Structure of the Solomon Islands as Revealed by Seismic Refraction Survey of November-December 1966.* Pacific Science, *24, (3),* p. 315-332.

GARDNER, G.H.F., GARDNER, L.W., and GREGORY, A.R., 1974, *Formation Velocity and Density – the Diagnostic Basics for Stratigraphic Traps.* Geophysics, *39, (6),* p. 770-780.

HEMING, R.F., 1874, *Geology and Petrology of Rabaul Caldera, Papua New Guinea.* Geol. Soc. Am. Bull., *85,* p. 1253-1264.

JOHNSON, R.W., JAQUES, A.L., HICKEY, R.L., MCKEE, C.O., and CHAPPELL, B.W., 1985, *Manam Island, Papua New Guinea: Petrology and Geochemistry of a Low-TiO_2 Basaltic Island-Arc Volcano.* J. Pet., in press.

KUSHIRO, I., 1978, *Density and Viscosity of Hydrous Calc-Alkalic Andesite Magma at High Pressures.* Carnegie Inst., Washington, Year Book, *77,* p. 675-677.

McKee, C.O., 1982, *Rabaul Caldera, New Britain*. SEAN Bull., *7, (8)*, p. 9-13.

———, Johnson, R.W., Lowenstein, P.L., Riley, S.J., Blong, R.J., de Saint Ours, P., and Talai, B., 1985, *Rabaul Caldera, Papua New Guinea: Volcanic Hazards, Surveillance, and Eruption Contingency Planning*. J. Volc. Geotherm. Res., *23*, in press.

Mogi, K., 1958, *Relations Between the Eruptions of Various Volcanoes and the Deformations of the Ground Surface Around Them*. Bull. Earthq. Res. Inst., *36*, p. 94-134.

Sapper, K., 1910, *Beitraege zur Kenntnis Neupommerns und des Kaiser-Wilhelms-Land* (in German). Petermanns Mitteilungen, *56*, p. 189-193, 255-256.

Scholz, C.H., 1968, *The Frequency-Magnitude Relation of Microfracturing in Rock and its Relation to Earthquakes*. Bull. Seism. Soc. Am., *58, (1)*, p. 399-415.

Sparks, R.S.J., Sigurdsson, H., and Wilson, L., 1977, *Magma Mixing: a Mechanism for Triggering Acid Explosive Eruptions*. Nature, *267*, p. 315-318.

Walker, G.P.L., Heming, R.F., Sprod, T.J., and Walker, H.R., 1981, *Latest Major Eruptions of Rabaul Volcano*. In: R.W. Johnson (Editor), *Cooke-Ravian Volume of Volcanological Papers*, Geol. Surv. Papua New Guinea, Mem., *10*, p. 181-193.

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