Erupting Neighbors—At Last

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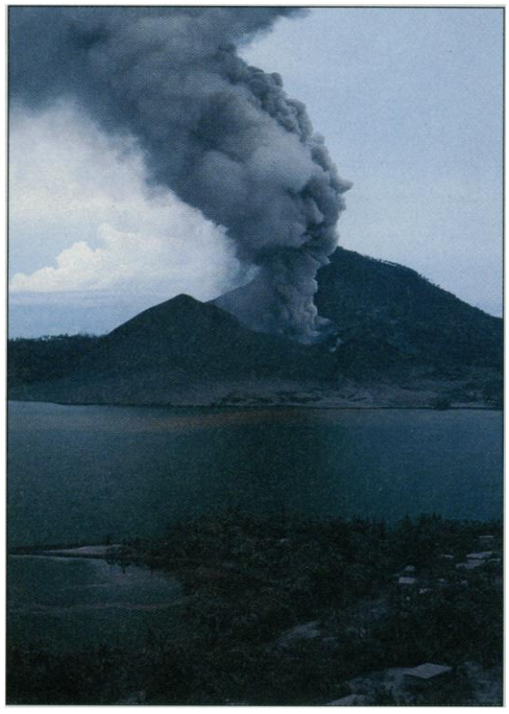
The Mount St. Helens volcano eruption of 18 May 1980 sparked worldwide volcano curiosity because it was so well covered by the press. However, an event 1 week later really made the volcanologists take note—powerful earthquakes near Long Valley caldera in California. The eruption that produced this caldera 700,000 years ago had discharged 500 km^3 of ash, not the 1 km^3 of Mount St. Helens. With the California event, three calderas around the world were all showing signs of being in unrest—Rabaul (Papua New Guinea) had been restless for 9 years, and Campi Flegrei (Italy) for more than 1 year. Finally, on 19 September 1994, Rabaul had the first eruption of these giants.

James Mori, who had worked in Rabaul for 3 years, had warned us just 2 weeks before the eruption that the volcanic activity had never declined to levels like those before 1971 and one could not be surprised by an eruption at any time. Although not huge, the Rabaul eruptions were from a pair of volcanoes situated opposite one another on the edge of the caldera. Vulcan and Tavurvur (see diagram) had erupted together once before, back in 1937 (*1*), and since 1971 had been pressure cooker vents on the big structure that was showing more activity.

PNG, as it is known by the few of us who have worked there, is a very special place for a volcano crisis. Its people speak about 700 languages (not dialects) and live in widely different cultural settings. Rabaul is an economic center because the calderas (actually two or more interwoven with one another) form a deep, sheltered harbor on the Bismarck Sea. The 1937 eruption had killed about 500 people, and since then the population has grown substantially. This disaster led to the creation of the Rabaul Volcano Observatory. In the 1994 eruption, however, fewer than a dozen people died and more than 50,000 evacuated, almost by themselves, because of the science and emergency simulations organized by the observatory over the past decade.

The events of Rabaul have taught some important lessons. A crisis began on 25 September 1983 as 1500 earthquakes were felt and the ground deformation accelerated. By April 1984, uplift of Matupit Island (close to the center of the caldera) reached 4 mm per day, which was almost exactly the same as that detected at Campi Flegrei and Long Valley. The Rabaul Volcano Observatory staff rushed to improve the network of seismic and deformation stations, assess the recent geologic evolution of the caldera, and educate the population in hazard mitigation (*2*). Seismicity was recorded with sufficient quality to allow resolution of an elliptical annulus of 10 by 4 km, marking the outward dipping structural boundary of a magma body. The annulus appeared to be quite similar in position and shape to the caldera that erupted 1400 years ago, with magma reaching to within 4 km of the surface (*3*).



Restless giant. A recent view of the Rabaul volcano.

Geological mapping, aimed at assessment of nature, volume, and frequency of eruptions, improved the general picture of these big eruptions, but quantitative models were difficult because few good samples of charcoal fragments in rock deposits were available and absolute ages were rarely obtained (*4*). Recent uplift of the caldera was especially obvious because it brought well-developed reefs out of the water and produced "bath tub rings" visible over large areas of the harbor. Research by staff at the observatory revealed that the rings represented inflation that had begun after the 1937 eruption and provided a potentially quantitative measure of the rates at which magma was arriving at shallow levels within the caldera over decades or centuries (*5*). The fundamental question remained—what scale eruption may happen? Studies of the gases emitted from hot springs and volcanic fumaroles in the caldera and individual volcanoes showed that the $^3H/^4He$ ratios and carbon isotopes were consistent with magma from predominantly mantle sources (*6*). Gases from Campi Flegrei caldera have never had a clear mantle signature (*7*), and Long Valley has, interestingly, gone through two different gas periods, with the changes of the last few years showing more significant mantle input to the activity (*8*).

International volcanologists expected "the big eruption" to take place in Rabaul at any time, with the observatory alert system in stage 2—that is, an eruption likely within the next few weeks to months of the mid-1980s. The potential for eruptions of Rabaul, Long Valley, and Campi Flegrei focused attention on how poorly we understood precursors of big caldera-scale eruptions. Newhall and Dzurisin (*9*) put together a collection of information on how 138 large Quaternary calderas have shown 1299 historic episodes of unrest. Well-documented unrest had taken place at 94 calderas, which had erupted within the past 30 years, and of these 45 culminated in eruptions. On the basis of threatening activity at those calderas with no eruptions within the past 100 years, only 10 of the 60 examples had led to eruptions.

Despite the uncertainties of when and how big, the Rabaul Volcano Observatory was able to educate the local population. Maps, published in three different languages and widely distributed, depicted hazards in a simple format. Chalk boards were put on store fronts and frequently updated messages of "volcano information" were distributed, along with privately published news sheets, to minimize confusion of residents or sensationalism by the media. Evacuations were simulated, as tests and plans were upgraded (*10*).

For the eruption, Rabaul behaved as it should, and proved capable of surprises. Deformation and seismicity did not change over the last months. In retrospect, one can see that the last 27 hours before the eruptions began were unusual. However, after the 18 September earthquake, the shoreline around Vulcan was observed to uplift by (nearly) 6 m in the final hours before the eruption. The historic eruption of Campi Flegrei, in 1538, was preceded by almost exactly the same intensely rapid and

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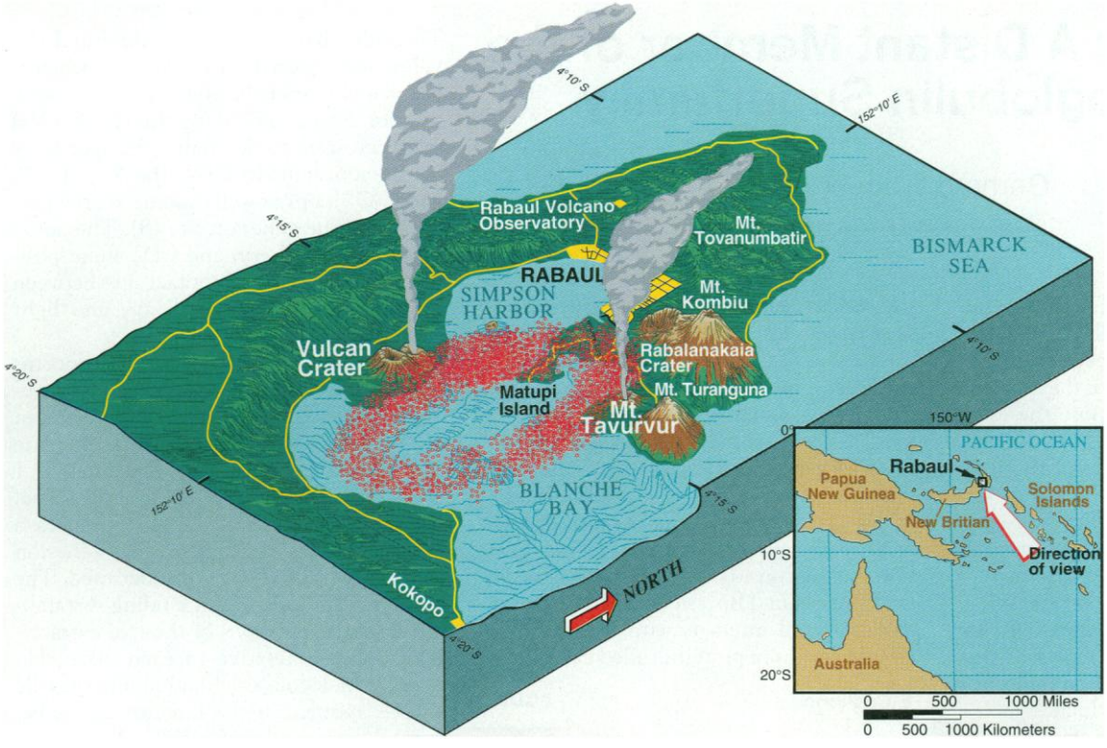

Perspective view of region, with sea floor and subaerial topography shown schematically. The two simultaneously erupting volcanoes, Vulcan and Tavurvur, are shown with the new crater that was produced by the eruption on Vulcan. Rabaul town, with approximately 30,000 residents, lies at the northern edge of the harbor, which is about 11 km from north to south. Red open symbols are earthquake hypocenters, which were used to annulus of magma body. [Adapted from T. R. Alpha and H. G. Greene (*16*) and J. J. Mori and C. O. McKee (*3*)]

short-period deformation after years of premonitory signs (*11*). Tavurvur, the Rabaul volcano to the east, began an ash eruption of possibly andesitic composition which lasted several weeks; while an hour and a half later, Vulcan, on the western margin of the caldera, erupted dacitic pumice for more than 1 hour to form a 20-km-tall column, with minor activity for about three more days (*12*). McKee *et al.* (*13*) recognized the shift in deformation from Vulcan toward Tavurvur after the 1937 eruption, and suggested that this might be a warning of the more energetic eruptions occurring on the east margin of the caldera. Furthermore, they suspected that the renewed activity of 1971 to present might well have been caused by emplacement of a new mafic magma into the older dacitic body, which is likely to be a remnant of the caldera-forming eruption of 1400 years ago.

Images from TOMS, the satellite measuring ozone and, coincidentally, SO_2 emissions from eruptions, found that Rabaul emitted a maximum of 80,000 ± 50,000 metric tons on 20 September. Another surprise—after the 20 million tons emitted by Pinatubo in 1991, we have grown to expect much greater output from a caldera eruption. Further SO_2 data obtained from airborne use of a COSPEC (correlation spectrometer), which began on 29 September 1991, showed around 30,000 tons per day and a decline to about 3000 tons per day 8 days later. This is quite a challenge to expectations of gas emissions dropping exponentially over hours and days after the most important emission during the explosive eruptions.

Long Valley has never had a modern eruption on the scale of Rabaul, but it is also not quiescent. Deformation and seismicity climbed and slowed irregularly and at about the same rate and time as Rabaul. Recently, however, a volcano-dome complex on the edge of the caldera showed helium isotopic signatures of an increased deep magma intrusive event in 1980 to 1992 (*8*). Now trees are dying from increased CO_2 content of soil gases and long-period earthquakes are occurring (*14*). Both have been recognized as related to magma movement at active volcanoes. The Lander earthquake of 28 June 1992, which was 400 km south of Rabaul, seems to have produced clear signs of excitable magma lurking at shallow depth. Seismicity and deformation of Long Valley increased significantly within 4 or 5 days of the major tectonic earthquake and it has been argued that these could be reflecting movement of bubbles within the magma body (*15*). Tectonic waves passing through a magma body may shake loose bubbles generated by crystallization processes.

Interestingly, pilots operating in PNG reported observing an increased gas plume from Ulawun volcano, which is 120 km west of Rabaul, within about 1 week of the Rabaul earthquake and eruption. Our measurements confirmed an increase of about an order of magnitude in SO_2 gas release, as compared to our measurements in 1983 and 1989. So, Rabaul's earthquakes, which triggered the eruption, may have shaken bubbles in an open and persistently active but distant basaltic volcano that caused it to emit a much greater flux of gases, which can move more freely than those in Long Valley, an old and very viscous rhyolitic magma body. The implication is that very active volcanoes can be easily pushed over the edge into eruptive activity because of simple triggers. Calderas are huge, and because we have little direct experience with premonitory activity associated with the large-volume eruptions, it is not easy to write off the hazards.

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17. I thank the National Science Foundation for supporting my research in PNG during 1983 and 1989 and the emergency response to the 1994 eruption; the staff of the Rabaul Volcano Observatory for supportive collaboration, despite the difficult time associated with the disaster; and S. Selkirk for preparation of the figure.