8

Eruptions of 1994–2014

8.1. ‘Twin’ Eruptions, 19 September – 2 October 1994

Rabaul Volcanological Observatory (RVO) volcanologists undertook a helicopter-borne inspection of the changes taking place in Simpson Harbour at dawn on Monday 19 September 1994. They were over the general area of the Greet Geothermal Field when a convoluting ash cloud began emerging slowly from the 1937 crater of Tavurvur (GVP 1994b; Lauer 1995; McKee et al. 2018). The ash was then blown by south-east winds towards Lakunai Airfield and near-deserted Rabaul town. An Air Niugini F28 managed to take off from the airstrip just as the eruption started.

The eruptions increased in intensity over the next several hours (Figure 8.1), and the eruption columns above Tavurvur grew in height over the next few days, eventually reaching a maximum height about 6 kilometres above sea level. These eruptions were vulcanian and they deposited large amounts of ash to the north-west, covering the airport, stranding aircraft and causing numerous roof collapses, especially in the southern part of Rabaul town including Malaytown (Blong and McKee 1995). The first-deposited tephras consisted of dark-brown ash as well as a wet, mud-like, blue-grey ash strongly reminiscent of the ‘blue gummy mud’ that had been produced by Tavurvur in May 1937. The Tavurvur eruptions were again disrupting the clay- and sulphide-rich, geothermally altered interior of the volcano, and were, therefore, at this stage, technically of ‘hydrovolcanic’ origin.

Figure 8.1. Double-layer ash cloud from Tavurvur on 19 September 1994.

Ash clouds from Tavurvur volcano are here seen spreading across the eastern part of Rabaul town on Monday 19 September 1994, as photographed from Observatory Ridge at 7.30 am. The lower of the two layers of volcanic cloud represents the earlier, less intensive phase of the initial eruption, whereas the upper one is from the higher, stronger eruption column seen rising from Tavurvur. Vulcan had by this time started its activity on the other side of the harbour (off the photograph to the right) but its ash had not yet drifted over Rabaul. This digitally enhanced copy was provided courtesy of the photographer, Nick Lauer (Lauer 1995, 15).

RVO volcanologists on Observatory Ridge also observed—and photographed—the beginning of the eruption at Vulcan at 7.17 am on 19 September (Lauer 1995). The eruptions began low at the northern foot of the 1937 cone and appeared for a while to be 'phreatomagmatic', caused by the interaction of new magma with seawater in the harbour, much as had happened at the start of the Vulcan eruption in 1937. Pyroclastic flows or surges were produced, some extending out over the harbour floor and later creating tsunamis (Nishimura et al. 2005). New craters opened further upslope and a full plinian eruption began to develop. A conduit high on the 1937 cone was inclined, as seen by the prominent slant of a jetting ash column (Figure 8.2).

Figure 8.2. Initial explosive eruptions from Vulcan as seen from the south on 19 September 1994.

Vulcan is seen from the south jetting pumice, ash and water vapour out from an inclined vent shortly after 7.30 am on 19 September 1994. Pyroclastic flows are being emitted, moving to the north-west and north, and to the north-east across the waters of Rabaul Harbour. The water surface in the foreground is calm but would soon become disturbed after further pyroclastic flows began crashing down onto the water, generating volcanic tsunamis. The green vegetation seen here would also soon be destroyed by further eruptions. Accreditation: M. Phillips, B. Alexander and S. McGrade, Rabaul.

The plinian column grew higher, dumping pumice and ash to the west and north-west, but for a while its pyroclastic materials were carried north-east over Rabaul, adding to the loads from Tavurvur, much as had happened in 1937. Visibility deteriorated on Observatory Ridge as a result of this north-west drift and RVO volcanologists could no longer make good observations—a reflection on the unsuitability of the observatory's location during actual eruptions, at least in the south-east season. Forked lightning was seen in the developing Vulcan cloud, much as had appeared in 1937. Four more plinian or strong explosive eruptions took place at Vulcan over the following two days, but their strength declined by 22 September (Figure 8.3). This short duration is similar to that for the plinian phase at Vulcan in May 1937, although the lesser eruptions at Vulcan in 1994 lasted until 2 October. Floating pumice covered Simpson Harbour extensively in both 1937 and 1994, hindering ships and boats, until it dispersed in the following north-west season.

Figure 8.3. Vulcan and Tavurvur in double eruption on 22 September 1994.
The 'twin' eruption at Rabaul is seen in this photograph taken by Torsten Blackwood (Agence France-Presse) from the south on Thursday 22 September 1994 (see also front cover). Pyroclastic flows are being emitted by a vulcanian eruption on Vulcan (left). The well-established vulcanian cloud at Tavurvur is seen on the right still depositing ash on Rabaul town.

News of the 'twin' eruptions and volcanic disaster at Rabaul soon spread beyond East New Britain. There was full daily coverage by the Port Moresby–based *Papua New Guinea Post-Courier*, *National* and *Times* newspapers during the first two weeks, beginning on Tuesday 20 September and including articles, photographs and commentary on many aspects of the disaster. These covered the immediate disaster-relief arrangements and—almost inevitably—discussion on the future of Rabaul. The news spread also via radio and television to Australia and globally as many other international media outlets carried the story. Reporters, photographers and disaster specialists all started arriving in the province.

Volcanologists arrived too from overseas, most of them (but not all) invited by the RVO to assist in re-establishing instrumental monitoring at Rabaul, assessing the ongoing eruptions at Tavurvur and Vulcan, and—in the longer term—undertaking new scientific research support projects. International volcanological research interest in Rabaul and in other 'restless' calderas globally was high again, after the crisis periods of the mid-1980s. 'Erupting Neighbours—At Last' was the title of one article in the popular international

journal *Science* (Williams 1995). However, the much-anticipated Rabaul eruption at Vulcan and Tavurvur was not the large-magnitude, caldera-forming event that some had thought might take place—and no eruptions at all took place at Campi Flegrei (Italy) and Long Valley (US), the other two restless volcanic areas of concern in the 1980s.

Interest in Rabaul has lasted up to the present day. There has been extensive reporting of all kinds since 1994, ranging widely from personal accounts and collections of colour photographs of the eruptions and their effects, through to specialised disaster-management and scientific articles, including major contributions from RVO staff and presentations at international conferences. There is now much more information on the 1994–2014 period than there is for 1937–43—easily enough for a comprehensive volume of its own. Accounts have been provided for the 1994–95 period from a community perspective—including from schoolchildren and students—by ANU historian Klaus Neumann (Neumann 1995, 1996; see also Neumann 2014, 2017; Matupit 2003); from a disaster-management perspective (Tomblin and Chung 1995; Davies 1995a, 1995b, 1995c; Lindley 1995; McKee, Itikarai and Davies 2018); and from a mainly volcanological standpoint by RVO staff led by Chris McKee (McKee et al. 2018). The US-based Global Volcanism Program (GVP) at the Smithsonian Institution, Washington, DC, played an important scientific role internationally in compiling reports on the Rabaul eruptions of 1994–2014 in their globally distributed *Bulletin of the Global Volcanism Network* (see, in particular, GVP 1994a, 1994b, 1994c, 2006, 2014, 2017).

Summaries of most of the 1994–2014 period are also provided by us in our earlier books (Threlfall 2012; Johnson 2013) and we draw on these here, concentrating on how the 1937–43 events compare with those of 1994–2014. We have been highly selective in the topics we discuss in the remainder of this final chapter and in the bibliographic sources we quote.

8.2. Pyroclastic Deposits, Damage and Deaths

Space technologies were not available in 1937 but they certainly were in 1994. The Vulcan plinian column and eruption cloud were clearly visible on 19 September 1994 from the Space Shuttle *Discovery* (Figure 8.4). The Vulcan cloud was seen as a well-defined fan that had an east–west

axis consistent with the known direction of high-level winds, its fan-shape having been caused by wind shearing. Much information on satellite imagery of Rabaul eruptions was provided to the GVP, including from US agencies such as the National Oceanic and Atmospheric Administration (NOAA) and the National Aeronautics and Space Administration (NASA). The *Bulletin of the Global Volcanism Network*, therefore, contains valuable images of the Rabaul eruptions as seen from space. Tracking clouds using satellite imagery and distributing the results promptly also assist aviation authorities. There were no encounters between international jets and the drifting ash clouds from Rabaul in 1994, but airline companies sustained additional fuel costs because of aircraft diversions on longer routes.

Figure 8.4. Space shuttle image of Vulcan and Tavurvur eruption clouds.

Eruption clouds from both Vulcan and Tavurvur were photographed on 19 September 1994 by space shuttle astronauts. The larger, higher Vulcan cloud is seen spreading, fan-like, westwards across the Bismarck Sea, caused by shearing of winds at different levels. The lower and less pronounced cloud mainly from Tavurvur — indicated by the two arrows — extends north-westwards. Normal atmospheric weather cloud covers much of New Ireland in the foreground. This image was published in the *Bulletin of the Global Volcanism Network* (GVP 1994a, Figure 17) and credited to NASA (reference code STS064-116-064).

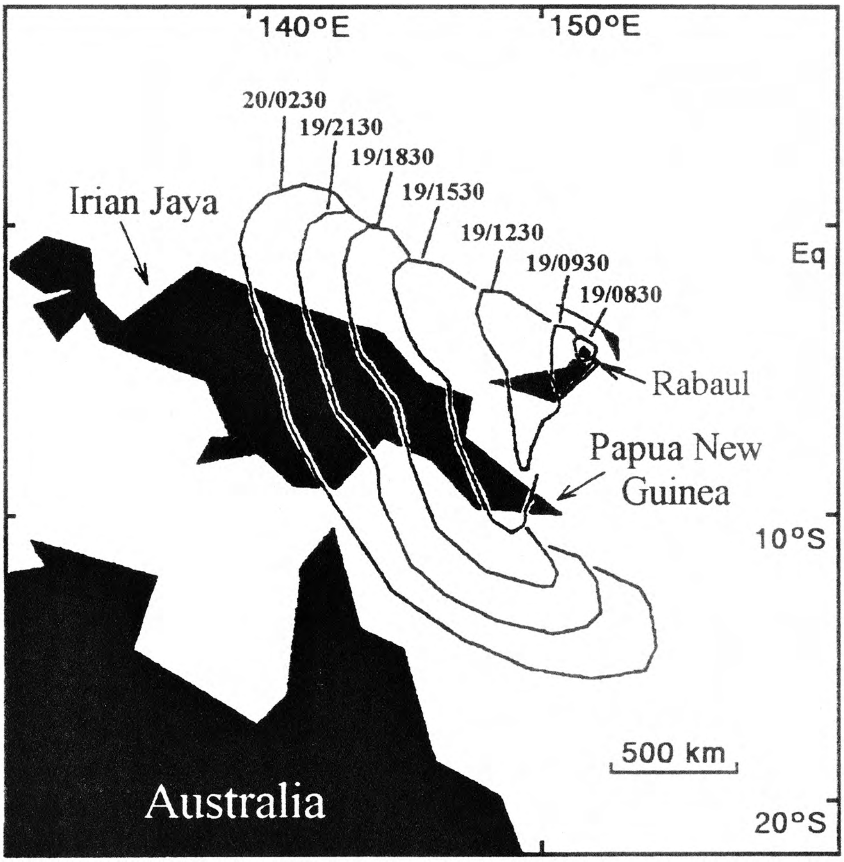

Figure 8.5. Vulcan ash cloud positions tracked by NOAA satellite at different times.

The westward progress of the Vulcan eruption cloud was tracked by NOAA using infrared imagery from the polar-orbiting NOAA-12 satellite. The notation '19/0830' refers to 8.30 am on 19 September 1994 and so on (GVP 1994b, Figure 19). The map was supplied by J. Lynch, NOAA.

The maximum height of the original plume from Vulcan was estimated to be 21–30 kilometres—that is, well into the stratosphere. This is much higher than the figure of about 8 kilometres for the Vulcan plume in 1937, which was estimated from the ground at an unspecified time and probably in limiting circumstances. The northern part of the space-imaged cloud in 1994 had stalled and was dissipating, leaving its more active south-western part to move across New Britain, then southwards and south-eastwards (Figure 8.5). This denser plume of ash and aerosols apparently did not

remain in the upper atmosphere for long. Ice was detected in satellite images, the result of seawater thrown up by the eruptive activity evidently freezing on ash particles (Rose et al. 1995). The solid pyroclastic and ice particles may then have fallen out of the atmosphere fairly quickly, and mainly to the south-west just downwind from the volcano. Sulphur dioxide gas in the cloud was not detected from space on this occasion, possibly because it was caught up in the freezing process or, more likely, the amounts were very small to start with, at least compared with the amounts that would be detected later from Tavurvur eruptions.

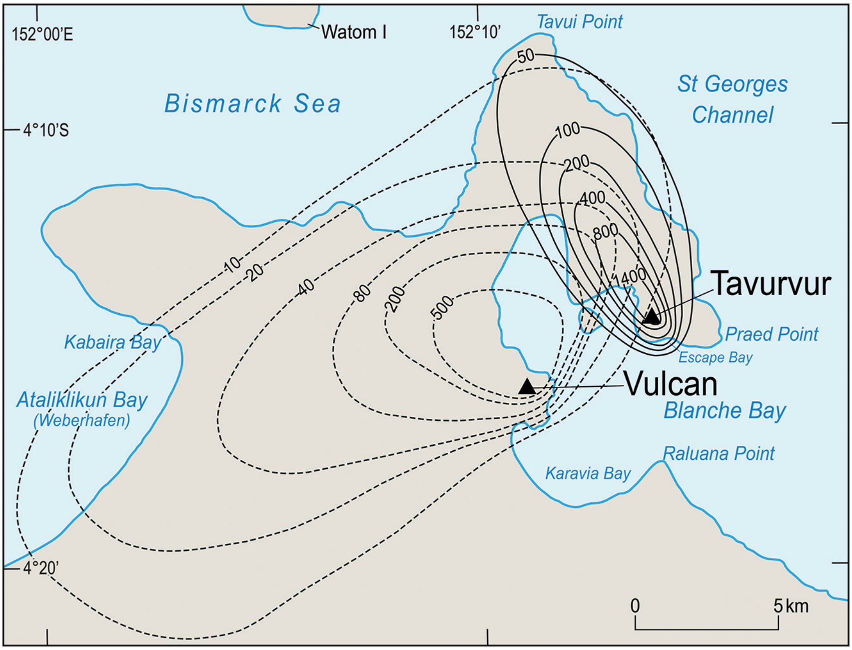

Figure 8.6. Thicknesses of 1994 ash from Vulcan and Tavurvur plotted as isopachs.

Distribution (isopachs) of air fall tephras (given in millimetres) for Vulcan and Tavurvur and deposited up to the end of September 1994 (Blong and McKee 1995, Figures 12 and 13; McKee et al. 2018, Figure 15). Thicknesses of pyroclastic-flow deposits near the volcanoes — especially those of Vulcan — are excluded. Compare these isopach patterns with those for 1937 in Figure 4.9 where pyroclastic-flow deposits must have been included in the thickness measurements.

The thicknesses of ash deposited from Vulcan and Tavurvur in 1994 were later mapped and 'isopachs' constructed for them (Figure 8.6) in much the same way as had been undertaken following the 1937 eruption (Figure 4.9). The patterns for Tavurvur in 1937 and 1994 are rather similar. Their respective isopachs trend roughly north-westwards, reflecting the low-level winds of the south-east seasons of both years, although the 1994 isopachs trend a little more northerly. The main difference, however, is in the much greater amount of ash deposited from Tavurvur in 1994—estimated to be one order of magnitude more voluminous (0.04 cubic kilometres) compared with the minimal Tavurvur deposits of 1937 (Blong and McKee 1995). Most of the main central business district of deserted Rabaul town was destroyed (Figures 8.7–8.8) and looting of the abandoned town began almost immediately until eventually brought under control by police and the military. The wet ash from Tavurvur flowed into buildings, probably enhanced by rain that fell on Rabaul that night (Blong and McKee 1995). Lakunai Airfield was made inoperable, stranded aircraft receiving heavy loads of ash, and Tokua Airport came into almost full use from thereon (Figure 8.9).

The Vulcan air fall–distribution patterns for 1937 and 1994 are different to each other (Figures 4.9 and 8.6). Those for 1994 are elongated north-east–south-west, whereas those for 1937 trend more to the north-north-west. The presence of a south-western limb for the 1994 isopachs is consistent with the satellite observations that the main part of the high-level eruption cloud trended in that same direction, but the explanation for the 1937 pattern is less clear. This apparent discrepancy may relate to the different heights reached by the two eruption columns: the 1937 pattern overall is the result of a lower column height (8 kilometres) and greater influence of the lower-level winds from the south-east. However, the north-eastern parts of both Vulcan patterns over Rabaul town are similar, apparently indicating that, in both 1937 and 1994, there were temporary, ephemeral changes in wind vectors in the early stages of column growth that permitted the ash clouds to drift over Rabaul for a relatively short time, adding to the ash load being produced by Tavurvur.

Figure 8.7. Aerial view of ash damage in northern part of Rabaul town.

The extent of damage to buildings and vegetation in the northern part of Rabaul town is seen in this aerial view in October 1994. The roofs of ash-covered houses have collapsed or buckled. Trees have been stripped of foliage, including those that once shaded the central strip of Malaguna Road, running left–right across the photograph. Graders by this time had cleared roadways and streets, leaving ash piled in ridges on either side of their tracks. Photograph by R.W.J.

Figure 8.8. Close-up aerial view of roof and tree damage in Rabaul town.

Roof collapses on houses and water tanks can be seen in this aerial photograph of damage in the southern part of Rabaul town. The leaves of coconut palm trees are folded back caused by ash loading. Photograph taken by R.W.J. in October 1994.

Figure 8.9. Lakunai Airfield damage including ash-covered aircraft.

The buildings at Lakunai Airfield were destroyed by the eruption and aircraft were left stranded. The rotor blades of helicopters were bowed down by the ash loading. Photograph courtesy of H.L. Davies.

The 1937 Vulcan cone grew in size as a result of the 1994 eruption. Much of that growth was caused by ash deposition from the pyroclastic flows that, as in 1937, were relatively limited in lateral extent. The maximum height of the cone grew only by about 20 metres, but the new craters greatly altered the cone's configuration (McKee et al. 2018). The eastern shore at Vulcan was extended into Simpson Harbour, and settlements and the Rabaul–Kokopo Road to the west were buried. These included the now deserted villages of Tavana and Valaur where there had been so many casualties in 1937, as well as the memorial at Tavana to those killed by the 1937 eruption.

People stranded by the twin eruptions of 19 September 1994 were rescued over the following few days by sea and land, including from coastal areas in the north and east outside the harbour area, such as the beach at Nodup where thousands of people had assembled and been evacuated in 1937. They joined evacuees, eventually numbering in the tens of thousands, who had already moved mainly southwards to safer places, including hastily erected camps. Nonga Hospital on the north coast was affected by ash fallout from the eruptions and about 400 patients had to be evacuated over the next two to three days to the safety of Vunapope Hospital, to other health centres or to the homes of relatives (Dent et al. 1995). Vunapope, therefore, undertook a role similar to the one it had adopted so successfully in 1937.

Ten fatalities were recorded by medical authorities, although there could have been more. Deaths were from several causes including traffic accidents, a lightning strike and entrapment in houses that had collapsed under ash loadings. This death total of about 10 is much lower than the total of more than 500 recorded in 1937, mainly in the villages near Vulcan.

How 'big' were the explosive eruptions at Rabaul in 1994 compared with those in 1937? Volcanologists measure the size or 'bigness' of such eruptions by estimating the total volume of expelled pyroclastic material (tephra) and by using the volcanic explosivity index (VEI) scheme devised by Newhall and Self (1982). The VEI is used in the Smithsonian Institution's definitive GVP database, and is a simple 0–8 index of increasing explosivity, each interval representing a tenfold increase in volume. The Rabaul eruptions of 1937 and 1994 are both indexed in the database as '4?' and represent the sum of the volumes for both Tavurvur and Vulcan combined (Siebert, Simkin and Kimberly 2010, 79). The question mark, presumably, acknowledges the difficulty of estimating the volumes at Rabaul, especially for Vulcan, where so much pyroclastic material is lost at sea or is deposited in distant places where any tephra would be poorly preserved in the tropical environment. VEI 4 is said to represent a 'large' eruption; however, it is considerably smaller than, say, the VEI 6 value for an eruption such as Krakatau in 1883. Estimates for the different volumes in cubic kilometres for both volcanoes in both years are as follows.

	Tavurvur	**Vulcan**	**Total**
1937 (Fisher 1939a)	0.003	0.3	0.30
1994 (Blong and McKee 1995)	0.04	(0.26)	0.30

Thus, the volumes for Vulcan in both 1937 and 1994 are much greater than those for Tavurvur. The two volumes for Tavurvur alone in 1937 and 1994 correspond to VEIs of much less than VEI 4 and, somewhat remarkably bearing in mind the uncertainties of measurements made at different times, the two final totals are the same. Further, the volume for Tavurvur in 1994 is much greater than it was in 1937. Therefore, the Australian administration in Rabaul in 1937 would have had a much greater recovery problem had Tavurvur produced an eruption of the same scale as it did in 1994.

8.3. Comparing the Timing of the May 1937 and September 1994 Outbreaks and Their Precursors

An initial and perhaps obvious point of emphasis concerns the quite remarkable similarities between the explosive eruptions that broke out in Blanche Bay in May 1937 and September 1994—as well as in January 1878. Vulcan and Tavurvur in these three years were the only two volcanoes in eruption, and they were in simultaneous activity—although for a fairly short time: less than a week in 1878, less than a day in 1937 and for two weeks in 1994. Both volcanoes in 1937 and 1994 produced what turned out to be immediately damaging explosive eruptions during the south-east season, meaning that Rabaul town did not escape the volcanic fallout, as might have been the case during a north-west or monsoon season—as in 1878, before Rabaul had been built.

A second similarity between the two eruptive periods of 1937–43 and 1994–2014 is that the eruptions at Tavurvur, in both cases, lasted much longer than those at Vulcan, although they later (in both cases) became interspersed with periods of inactivity lasting from weeks to years, while Vulcan remained totally inactive, as discussed further below.

A third notable point is the duration of the time gaps between the initial outbreaks of the three eruptions. The gap between January 1878 and May 1937 is 59 years and four months, and between May 1937 and September 1994 is 57 years and four months. This could suggest that the Rabaul volcanoes are active periodically—say, every 60 years or so—but this speculation would have be treated with caution as it is based on the durations of only two time gaps. The concept, therefore, cannot be used with confidence for any future disaster-planning purposes.

Perhaps the most striking similarity from an eruption-forecasting perspective is the 27-hour precursory lead-up time to eruptions in both May 1937 and September 1994. Strong harbour earthquakes were felt near the two volcanoes in both years, heralding 27 hours of near-constant and alarming ground-shaking that was considered different to the earthquakes of the ‘swarms’ recorded by the RVO in 1971–94.

1937 Earthquake at about 1.20 pm, Friday 28 May

1937 First eruption at about 4.15 pm, Saturday 29 May, **27 hours later**

1994 Earthquake at 2.51 am, Sunday 18 September

1994 First eruption at 6.06 am, Monday 19 September, **about 27 hours later**

Earthquakes were not recorded instrumentally in the lead-up to the 1937 eruption so considerable care must be taken in suggesting that the earthquake activity in both 1937 and 1994 was similar before the start of these 27-hour periods. Further, there is no evidence that the 1878 outbreak was necessarily preceded by the same 27 hours of strong seismic activity as in 1937 and 1994. However, 27 hours is hardly much comfort to disaster managers who require longer times for early warnings and for the effective evacuation and relocation of displaced people. In addition, there is no available evidence that a seismic 'annulus' of the type recorded in the 1970s–90s existed before 1937, nor is there evidence of a clearly defined 'seismo-deformational crisis' between 1919 and 1937, like the one in 1983–85. These points are discussed further below.

An enduring theme in global volcanology, including in Papua New Guinea, is that some volcanic eruptions may be caused or 'triggered' by strong earlier earthquakes of tectonic origin that can take place either nearby or distant to the volcano being considered (e.g. Hill, Pollitz and Newhall 2002; Marzocchi 2002; Bebbington and Marzocchi 2011). This theme was dealt with in the 1950s by Tony Taylor and colleagues (e.g. Taylor 1955, 1958, 1960). Further, the two magnitude 7.9 earthquakes of July 1971 have been interpreted as 'destabilising' events for the start of the Rabaul Harbour seismic swarms four months later, leading up to the eruptions 23 years later (McKee et al. 2018). This is not the place to discuss the volcanological significance of the regional seismic-energy release hypothesis in detail—including statistical arguments and in the modern context of plate tectonics—but a few comments can be offered in the case of Rabaul.

The lead-in times of the six large-magnitude earthquakes that took place in the twentieth century in the New Britain area (Figure 6.9), and prior to the Rabaul eruptions in 1937 and 1994, are fairly similar to one another—about 20–30 years.

1937 minus 1906 = 31 years
1937 minus 1910 = 27 years
1937 minus 1916 = 21 years
1937 minus 1919 = 18 years
1994 minus 1971(2) = 23 years

Kizawa (1951) appears to have identified the 1906 earthquake as the tectonic precursor to the 1937 eruption—the one whose effects in Rabaul had been described by Pullen-Burry (1909) in German times. Further, Fisher (1939a) listed the strong earthquakes of 1910 (February), 1916 and especially 1919, just before his description of the immediate (late May) precursors to the May 1937 eruption. He seems to have been cautious, however, about the tectonic 'eruption-triggering' interpretation in general, and did not state specifically that the 1919 earthquake was the actual precursory 'trigger' for the 1937 eruption. Fisher (1941) was also critical of W.G. Woolnough, who suggested that the tectonic earthquake of January 1941 near Rabaul was a precursor to an outbreak of eruptions at Tavurvur (see Section 5.1).

Do the earthquake/eruption lead-in times of about 20–30 years have any geophysical significance? A key factor in answering this difficult but significant question may be understanding the timing of when magmas first form in the earth's mantle above the subduction zone beneath Rabaul, and how long they take to reach the surface and create a volcanic eruption. This complex process may be related in the first instance to a new period of northward subduction of the Solomon Sea plate and to dehydration or melting of the down-going plate, as referred to in Section 6 (see Figure 6.11). The newly formed 'primary' magmas in the deep mantle rise buoyantly towards the surface and begin crystallising. They may cool against and interact with solid conduit-wall rocks, and mix or mingle with any resident magmas that have preceded them. Their upward movement may be arrested at times, particularly when they reach the base of the lower-density earth's crust. Other factors are the volume and other physical properties (gas content, viscosity and so forth), and how effectively they are stored in reservoirs immediately beneath the volcano 'ready' for eruption.

Note also that the lead-in times to the eruptions in 1937 and 1994 reduce to 18–23 years where only the nearby 1916–19 and 1971 tectonic earthquakes are considered. Speculatively, therefore, values in the range 18–23 years could be indicative of the times taken for primary magmas, newly formed above the down-going subducted plate, to rise, evolve and reach the surface in eruption at Rabaul in both 1937 and 1994, as discussed further in Section 9.4.

Subduction, therefore, can be regarded as the primary kinetic driving force that produces *both* deep magma-formation and tectonic stress release. Occasions where a large nearby tectonic earthquake may trigger an eruption from an already 'charged-up' magma reservoir—by, say, breaking its roof rocks or opening old conduits—are possible but cannot always be established confidently. Furthermore, tectonic earthquakes caused by the same period of plate subduction might take place at any time during this overall magmatic process and at different depths and distances from Rabaul. In addition, there are many tectonic earthquakes that are not obviously triggers of volcanic eruptions and there are eruptions that seem to take place without tectonic triggering.

The 1937 and 1994 'twin' eruptions—and the 1878 one too—may have had similar geotectonic origins, but there were notable differences in the way that the 1937–43 and 1994–2014 eruptive periods developed, including their damaging effects on Rabaul town and the surrounding area.

8.4. Tavurvur Eruptive Activity, 1994–2014

Tavurvur ceased its eruptive activity in 1937 less than a day after the 'twin' outbreak of 30–31 May and it remained inactive for the next four years. While there were more vulcanian eruptions between June 1941 and into early 1942 when the Japanese invaded Rabaul, Takashi Kizawa witnessed only one eruption from Tavurvur during his four years there (1942–46)—the final one of the series in December 1943. This pattern has some similarities to the one at Tavurvur between 1994 and 2014—notably the intermittent nature of the eruptions, periods of non-eruption lasting up to months or years, and eruptions taking place in both the north-west (monsoon) and south-east (trade winds) seasons. Such a long period of intermittency, however, does not seem to apply in the case of the 1878 eruptions.

Strombolian eruptions took place at Tavurvur in eight separate phases between May 1996 and August 1997 (McKee et al. 2018; Figure 8.11). This type of explosive eruption tends to be less energetic than vulcanian explosions, producing less fine ash and tending to have lower VEI values, although distinguishing between the two is not always straightforward. The names 'strombolian' and 'vulcanian' both derive from those of historically active volcanic islands in the Mediterranean. The most distinctive feature of strombolian eruptions is the explosive ejection of incandescent lumps of lava on parabolic trajectories from magma that has

risen into the active craters. The explosions produce spectacular sprays that are especially impressive on clear nights. Lava flows can also be produced by strombolian eruptions. Almost four months of quiescence followed the strombolian phases at Tavurvur, until a period of intensified vulcanian activity began again on 7 December 1997 lasting throughout 1998 (McKee et al. 2018). Intermittent vulcanian eruptions of different intensities continued into the new millennium, as reported in some of the monthly bulletins of the Global Volcanism Network (GVN) for 1999–2006.

Figure 8.10. Small Tavurvur eruption and general view along the Turagunan–Watom Island line.

A small vulcanian eruption from Tavurvur is seen near the left-hand edge of this aerial photograph taken on 2 or 3 January 1996 from the south-east. Greet Harbour, old Lakunai Airfield, Matupit Island and Dawapia Rocks are seen behind Tavurvur. Note especially the alignment of the four major stratovolcanoes of Turagunan (bottom left), through Kabiu and Tovanumbatir (overlooking Rabaul) to Watom Island in the distance. The photograph was taken on a commercial aerial survey and was supplied courtesy of the Gazelle Restoration Authority, East New Britain Province.

Figure 8.11. Night-time incandescent strombolian eruption at Tavurvur.

Strombolian activity at Tavurvur on 14 March 1997 is seen in this photograph taken by Steve Saunders (RVO) from Kaputin Point on Matupit Island. Note the expulsion of incandescent lava particles on parabolic trajectories. A new lava flow is moving down the southern slopes of the volcano to the right. A cloud of finer ash particles is being blown by the north-west winds of the monsoon season away from Rabaul.

This pattern for Tavurvur contrasts sharply with notably brief periods of eruption for Vulcan in 1878, 1937 and 1994. Further, there were significant differences between the 1937–43 and 1994–2014 periods, notably in two styles of explosive eruptive activity—'strombolian' and 'sub-plinian'—that had not been reported for Tavurvur for either 1878 or 1937–43. These two eruption styles were in addition to the 'normal', but intermittent, vulcanian eruptions that took place throughout 1994–2014 (Figure 8.10).

Local earthquakes continued to be recorded by the RVO after deployment of the Volcanic Disaster Assistance Program equipment in 1994 and were found to have a distribution quite unlike that of the 'seismic annulus' identified prior to the 1994 twin eruption. Instead, most local earthquakes after the twin eruption defined a broad linear zone that extended north-eastwards from the vicinity of Kabiu volcano into St Georges Channel (Itikarai 2008; Figure 8.12). Further, there appeared to be a relationship between the occurrence of some of these so-called north-east earthquakes and the timing of the vulcanian eruptions taking place at Tavurvur. The earthquakes apparently defined a major radial-fault zone running out from the caldera

area, thus adding further complexity to what was known about the structure of the Rabaul and Tavui area. Some north-east earthquakes, in fact, had been recognised in May 1992, and even during the 1983–85 crisis period. However, they could not be well mapped owing to the limitations of the recording network at the time, meaning their possible significance remained unexplored. 'North-east' earthquakes, as expected, had not been recognised during or before 1937–43 owing to the total absence of seismographs in the area at that time.

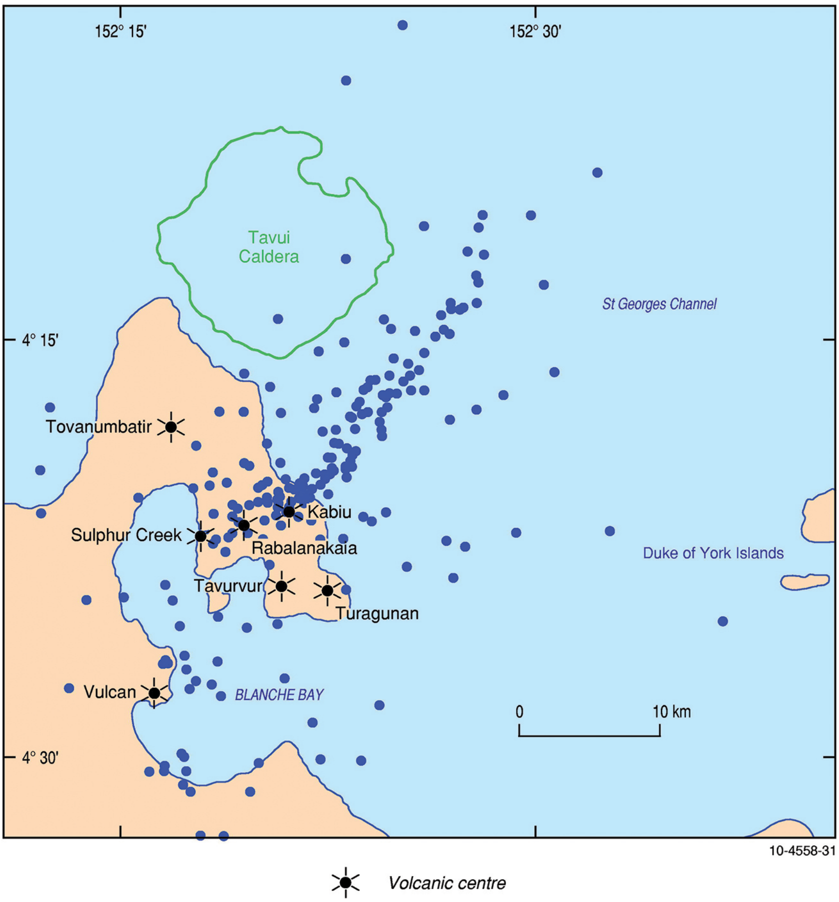

Figure 8.12. Plot of 'north-east' earthquake epicentres for 1994–98.

This map of earthquake epicentres for the period October 1994 – December 1998 is adapted from the map of 'relocated' earthquakes presented by Itikarai (2008, Figure 5.10a). The distribution is scattered except for the zone of earthquakes running north-east from the vicinity of Rabalanakaia and Kabiu volcanoes into St Georges Channel and parallel to the south-eastern margin of Tavui caldera. These form the North-East Earthquake Zone.

Unexpected explosions started at about 8.45 am on 7 October 2006, producing air blasts that caused doors to slam and windows to rattle in Rabaul town (GVP 2006; McCue 2007; Saunders 2008). These were the beginning of a sub-plinian eruption that continued into the early afternoon, the height of its column reaching 18 kilometres (Figure 8.13). This volcanic activity was the first time such an eruption had been recorded at Tavurvur, including in 1937–43. It had some similarities to the longer-lasting sub-plinian eruptions at Vulcan in both 1937 and 1994 but was shorter in duration and less voluminous (about 0.2 cubic kilometres) although the same VEI value of '4?' was assigned to it (Siebert, Simkin and Kimberly 2010). A sector of the west-north-west side of the cone collapsed, creating tsunamis and making parts of Greet Harbour shallower (Saunders 2008). Ash and pumice from the eruption covered Rabaul and Blanche Bay, reaching further south to Kokopo, Tokua and beyond. People evacuated from the Rabaul area, and Tokua Airport was closed to aircraft. A small pumice raft accumulated in Greet Harbour where the pumice was still drifting about several weeks later. Images of the sub-plinian cloud were obtained from both satellites and nearby in-flight aircraft.

Figure 8.13. October 2006 Tavurvur eruption as seen from the south.

This photograph was taken by Julie McLean at 9.57 am on 7 October 2006 from the south-east at Takubar, near Kokopo. The nearly vertical western side of the eruption column at Tavurvur can be seen clearly on the left, but the cloud has already risen to greater heights towards the west or south-west.

The cloud seen from space was roughly fan-shaped, as the Vulcan cloud had been in 1994, and most of it drifted south-westwards over central New Britain, as in 1994. The Tavurvur cloud in 2006, however, was seen to contain significant amounts of the volcanic gas sulphur dioxide, as deduced by results using a spectroradiometer on board NASA's Aqua satellite (GVP 2006). The nature of the eruption changed to strombolian at 2.25 pm but, by 5.30 pm, the eruption began to subside and smaller ash explosions resumed. An inspection on the following morning, 8 October, revealed that lava flows had been emplaced down the western and northern flanks of Tavurvur. Herman Patia noted that the eruption had declined by 28 October and that there were only occasional ash emissions accompanied by rare explosions (GVP 2006).

The last week of October 2006 was memorable for another reason: 97-year-old Dr N.H. 'Doc' Fisher visited RVO headquarters, almost 70 years after he began his studies of Rabaul volcano in 1937 (Saunders 2007; Figure 8.14).

Figure 8.14. Visitors to the RVO recording room in October 2006.

Dr N.H. and Mrs Molly Fisher are seen here on a visit to the RVO recording room on 25 October 2006. Herman Patia is on the left and Jonathan Kuduon, now retired, is behind him. Dr Fisher died in 2007 and Mr Patia in 2012. The photograph was supplied by Steve Saunders.

The October 2006 eruption at Tavurvur was short-lived but is of interest for other reasons. First, it appears to have been part of a 'time-cluster' of volcanoes in eruption in 2002–06, mainly in the eastern part of the Bismarck Volcanic Arc, as summarised elsewhere (Johnson 2013, Table 8). The cluster included volcanoes that had not been in eruption in historical time (Garbuna), or had unexpected gas emissions but no eruption (Likuruanga) or showed signs of magma having been intruded beneath the volcano but not leading to actual eruption (Sulu Range). In October 2006, Ritter Island had its first-reported eruptions since 1997, and both Ulawun and Langila had had mild ash eruptions during the 2002–06 period, the ones at Ulawun following an especially large eruption at the volcano on 28 September 2000.

Further, a remarkable sequence of tectonic earthquakes was recorded in the New Britain and New Ireland area in late 2000 (Anton and McKee 2005). A magnitude 6.8 earthquake along the New Britain submarine trench on 29 October 2000 started the sequence, followed on 16 November by a magnitude 8.2 earthquake along the Weitin Fault in southern New Ireland, and on 16 and 17 November by two more large earthquakes (magnitudes 7.8 and 8.2, respectively) along the New Britain trench (Park and Mori 2007). The earthquake on 16 November had an epicentre remarkably close to that of the major earthquake of 26 July 1971. The earthquake pattern in October–November 2000 seemed like a seismic chain of reaction of related releases of tectonic stress, and potentially may have been a 'trigger' for the 2002–06 volcano time-cluster. Note, however, that the large eruption at Ulawun in September 2000 preceded the earthquake sequence, leading to some questions. First, was the Ulawun eruption of late September 2000 an indication of crustal stress release and perhaps a precursor of the tectonic-earthquake sequence that would follow in October–November? Also, but even more uncertainly, was the large eruption at Ulawun in January 1970 a similar precursory signal of the two major earthquakes of July 1971? Both questions remain unanswered.

The 2006 eruption, and Rabaul volcanology in general, attracted research scientists from the Earth Observatory of Singapore to Rabaul in the new millennium. They and their co-workers published internationally on their petrological, geochemical and petrophysical findings, thus adding to the growing mountain of data and concepts that had arisen since 1994 (Bouvet de Maisonneuve et al. 2015; Bernard and Bouvet de Maisonneuve 2020; Fabbro et al. 2020; Bernard et al. 2022). Among their findings was confirmation that different magmas of basaltic and dacitic composition had mixed or mingled at least over the past few centuries, including in the pre-1937–43 period.

Tavurvur continued to produce intermittent vulcanian explosive eruptions after the October 2006 eruptions (Figure 8.15), as reported in the *Bulletin of the Global Volcanism Network,* but there were only four GVN reports between December 2009 and July 2014. Further, the southern end of Matupit Island had been subsiding since the 2006 eruption, as indicated by both local global positioning system (GPS) measurements undertaken by the RVO and by time series images from satellite-radar surveys (Garthwaite et al. 2015). Two phenomena were indicative of new changes taking place. The first was a resurgence of uplift of Matupit starting in about January 2010. The second was a series of tectonic earthquakes between 14 July and 1 August 2014 in a well-defined zone extending west-north-westwards from Cape Lambert on the north-western tip of the Gazelle Peninsula and in line with the north-western part of the Baining Fault west of Rabaul (Taranu and Herry 2015).

Figure 8.15. Distant incandescent explosive eruption at Tavurvur at night.

The lights of Rabaul town, shipping and wharves in the foreground, and of the Kokopo–Tokua area in the right background, are seen in this photograph taken on 16 April 2008 from Observatory Ridge (compare this view with that in Figure 6.7). Incandescent explosive activity is taking place at Tavurvur. Small, glowing pyroclastic flows appear to be moving down the upper northern flank of the volcano, and there is apparently some lava fountaining within the crater itself. The activity appears to be somewhere on the borderline between vulcanian and strombolian. Ash is drifting south-eastwards towards Tokua, caused by monsoonal winds. The photograph is reproduced here courtesy of Simon V. Hohl, who was working at the RVO at the time.

A large eruption from Tavurvur broke out on 29 August 2014 (GVP 2014, 2017). It included more strombolian activity, before another towering eruption cloud formed that is thought to have risen 18 kilometres and was imaged from space. The Darwin Volcanic Ash Advisory Centre issued warnings to aviation and a sulphur dioxide plume was again mapped by the spectroradiometer on board NASA's Aqua satellite. Analysed rocks from the eruption again retained evidence for magma mixing (Fabbro et al. 2020). The Cape Lambert earthquakes preceded the Tavurvur eruption, but the geodetic information for ground inflation at Matupit was an indication of magmatic unrest before both the earthquakes and the actual eruption of 29 August, which was maintained strongly only until the next day.

Tavurvur became inactive after August 2014, a condition that it has maintained up to the time of writing.

The amount of new scientific and disaster-management information that has emerged since 1994 is nothing less than prodigious, if not overwhelming, and we have had to be selective—and hopefully not too prejudicial—in the bibliographic sources we have chosen to reference so far and in the final Chapter 9.

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