9

Aftermath of the 1994 Twin Eruptions

9.1. Relief Measures, 1994–95

The disaster-management responses to the 1994 eruptions were very different to those in 1937 when Rabaul was still the capital of the Territory of New Guinea and the administration was accountable to the Australian Government in Canberra. The official responses in 1994 were considered initially by the national government in Port Moresby, the capital of independent Papua New Guinea (PNG), and a state of emergency in East New Britain Province was soon declared. Prime Minister Sir Julius Chan, on Monday 19 September, flew from Port Moresby to East New Britain and saw the eruptions and devastation for himself, as portrayed famously in the artwork of John Siune (Figure 9.1). Chan had a family home in Malaytown that was destroyed by the eruption.

Provincial and national government support for relief and then recovery assistance was soon provided, aided by donations from other parts of PNG. Australia was the first to respond from outside the country, when the Royal Australian Air Force began flying C120 Hercules aircraft into Tokua Airport with the first of several deliveries of relief supplies. Other major participants were the international development-assistance agencies of Australia, Japan, the European Union and the US; international development banks, such as the World Bank; agencies of the United Nations, including the World Health Organization and the Department of Humanitarian Affairs; and non-governmental organisations such as Red Cross and World Vision. The United Nations Development Program already had an office in Port

Figure 9.1. John Siune painting of Prime Minister Chan's helicopter visit over Rabaul.

'Dispela helekopta kisim Praim Minista bilong PNG igo lukim volkenu pairap long Rabaul': John Siune, 1996, acrylic on paper mounted on board. R.W.J. Collection. Intellectual property rights are held by the artist.

Moresby. This international participation is illustrative of a much more globalised and interconnected world than existed in 1937 and, thus, one more able to rally to a disaster-relief effort. The UN was evidently more effective in this regard than the League of Nations had been before WWII.

Disaster-relief activities in the province itself focused on a program called 'Operation Unity' that was managed from headquarters set up at Ralum Golf Club, Kokopo, where the controller was Brigadier-General Rochus I. Lokinap. The controller provided the national government in Port Moresby with a series of progress reports over the next several months that, together with local newspaper and other reports, provide a valuable source of disaster-management information about the relief phase. There were many disaster-relief issues to be addressed before the state of emergency could be called off and a 'Gazelle Restoration Authority' established to undertake and manage eventual resettlement in the province. Hugh Davies, professor of geology at the University of Papua New Guinea in Port Moresby, returned to the area to engage in liaison work between Operation Unity, the Rabaul Volcanological Observatory (RVO) and overseas visitors (Davies 1995a, 1995b, 1995c). Kokopo-based exploration geologist David Lindley spent four weeks assisting the Provincial Disaster Committee (PDC), briefing residents in care centres on aspects of the eruptions and hosting refugees in his own home. Lindley provided an insightful summary of his observations and experiences during the relief phase (Lindley 1995). In October, the PDC released an information newsletter for the community entitled *Tephra Tok: The Voice of the Rabaul Volcanoes.*

The priority for Operation Unity was ensuring that the tens of thousands of displaced people in the province were well cared for until resettlement could begin. Their health and safety were paramount. Law and order also had to be maintained, particularly as looters and armed gangs were roaming the Rabaul area. Non-Tolai Papua New Guineans, perhaps as many as 15,000 of them, were provided free passage back to their home provinces. A damage assessment was soon made of Rabaul town by provincial government staff, who prepared a coloured map (Lokinap 1995; Figure 9.2). The bright-green areas on the map refer to total damage (e.g. north of Lakunai Airfield, Malaytown, and most of the central business district of eastern Rabaul), whereas the maroon and light-blue colours signal areas that were relatively unharmed (e.g. Malaguna Road).

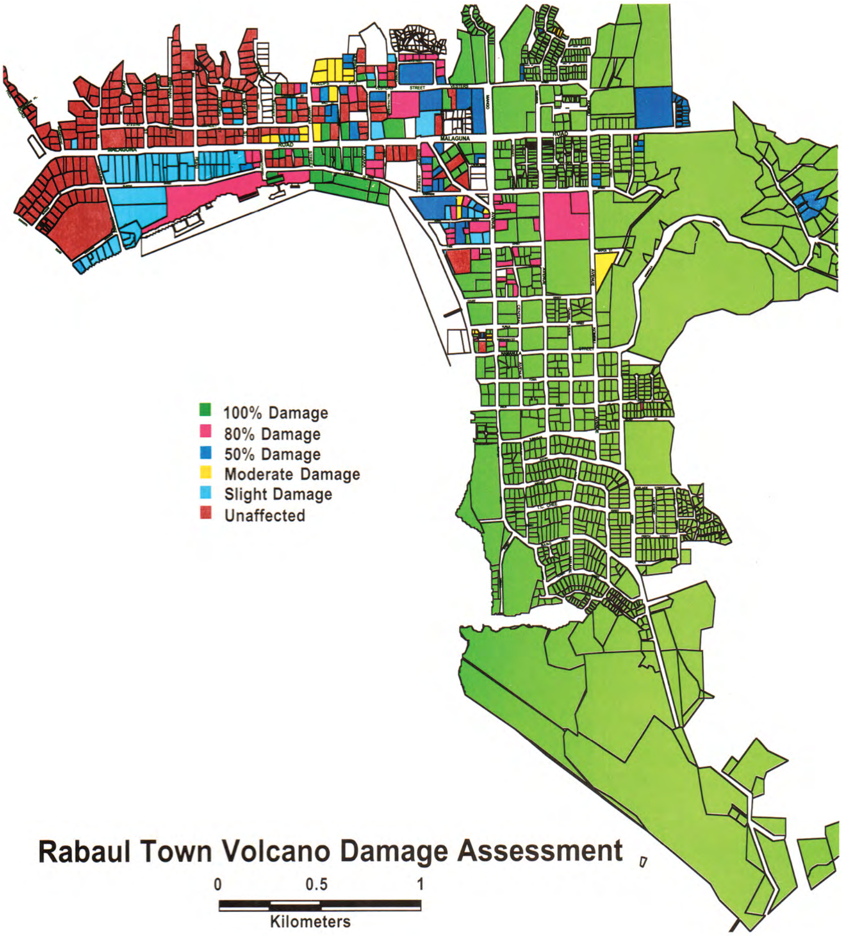

Figure 9.2. Map of damage assessment results for Rabaul town.

Officers of the East New Britain Provincial Administration produced this map of relative ash damage in Rabaul town. This is the front-cover illustration of a report by Lokinap (1995).

The Australian International Development Assistance Bureau (AIDAB, later AusAID) supported a 'Rabaul Volcanic Disaster Needs Assessment Mission' that was undertaken by external consultants (AIDAB 1994). Seventeen recommendations were listed, the first being that an urgent program of support be provided to upgrade the capacity of the RVO. Support was expressed also for the prevailing view that Kokopo should become the island's regional centre and the provincial capital for East New Britain, and what was left of Rabaul town in the north-west, including the wharves, should be partially redeveloped and remain as support for the

region. The Insurance Underwriters Association of PNG funded a damage assessment from an insurance point of view, leading to a comprehensive and well-illustrated account of the 1994 eruption (Blong and McKee 1995).

These early damage assessments were undertaken towards the end of the dry season and so could not consider the impacts in the following wet seasons of flooding and mudflows in areas stripped of vegetation by the eruption as well as erosion and the redistribution of new ash and pumice, much as had happened in 1937. Hazard maps for mudflows and flooding were distributed in the community, including for Rabaul town, that showed places where mudflows and floods from the steep caldera walls to the north and east might impact on the remaining part of Rabaul town (Davies 1995a, Figures 17–18; Brown and Tutton c. 1994–95). Flooding and mudflow damage would lead to extra costs, and Department of Works staff were kept busy clearing debris from streets in Rabaul town, and from affected roads in general. Neumann (1996) concluded that the overall cost of the 1994–95 disaster was probably in excess of K300 million; this included the cost of caring for thousands of refugees, restoring electricity and telecommunications, short-term assistance to the education sector and looting, but did not include government-building losses (AIDAB 1994) and private losses (Blong and McKee 1995).

9.2. Recovery and Resettlement, 1995–2013

Widespread sadness was felt for old Rabaul as a result of the destructive eruption of 19 September 1994, as well as feelings of nostalgia—as articulated in the titles of both a song and a book, *Rabaul Yu Swit Moa Yet* or 'Rabaul you are so sweet' (Neumann 1996, 1997). Papua New Guinean author Grace Maribu wrote in 1994:

> The Premier and I were discussing Rabaul [at the Rabaul Disaster Control Centre at Ralum], the once beautiful, and peaceful town which was the pride of the Tolais in particular, and Papua New Guineans in general. The destruction of Rabaul and the surrounding villages was enormous, but the Premier was telling me how he was not going to abandon Rabaul, how his government was going to do everything in its power so that Rabaul would be back better than it was ever before …

> Rabaul was a special place, not just because of its picturesque setting and colourful history—it was a living monument of a people's pride. It was home to the East New Britain men and women—the Tolai, the Baining, the Sulka and the Tomoip, the Taulil and Mengen, the Kol, Makolkol, Nakanai and the Mumusi. (cited in Maribu 2021)

Self-organised resettlement took place over the next few years, even in the knowledge that the places to which people were returning were at risk of future volcanic eruptions. Major restoration and relocation were the two main goals of the Gazelle Restoration Program created by the PNG national government. The program was supported by the major international funders AusAID and the World Bank, together with the Japanese International Cooperation Agency (JICA), which concentrated on construction works at Tokua Airport. The Gazelle Restoration Authority (GRA) was established in early 1995. Its overall objectives were relocation of urban services, infrastructure and population to the Kokopo area; relocation of rural populations away from the high-risk eruption zone; and restoration of economic and social linkages, including roads (Scales 2010). However, given the importance for regional development of both the wharf area on Simpson Harbour and the trunk-road link from the wharves to Kokopo, what was left of Rabaul would not be totally abandoned.

A Development Rezoning Plan for Rabaul was released in 1997. It described 'a town more limited in extent than previously … [starting in the western part] and extending sufficiently eastwards to include urgently needed community facilities, such as market and sportsground' (Steering Committee 1997, 3 and 2.10). People and businesses would return to the now smaller town area. The provincial government headquarters, which was previously located in Rabaul, would be re-established in the new capital, Kokopo, but RVO headquarters would remain on Observatory Ridge. The Rabaul–Kokopo Road was repaired and sealed, except for a dusty segment immediately west of the new Vulcan cone. Other parts of the road would remain susceptible in the years ahead to flooding and landslips from the devastated inland areas.

Resettlement of displaced communities to safer places was encouraged by the provincial government through the GRA. New land for resettlement was made available towards the Warangoi River well south of Blanche Bay, and services provided, including roads that connected the new settlements to the slowly developing Kokopo area (Scales 2010). A new suburb, Kenabot, was built at Kokopo, as well as a new satellite town at Baliora.

The resettlements at Sikut, Clifton, Warena and Gelagela did not evolve as planned, many displaced villagers facing practical difficulties, as described elsewhere (Neumann 1996). Many villagers were drawn back to the coastal areas of their traditional lands where their homes, gardens, cemeteries and fishing practices had long been established. Two Australian environmental researchers supplemented a growing body of information about the resettlement by conducting comparative botanical field surveys in 1997 and 1999, interviewing affected people and reporting on the 1994 eruptions and their impact (Lentfer and Boyd 2001).

Assessing future risk and achieving disaster-risk reduction were a key part of the challenge of resettlement in the north-eastern Gazelle Peninsula. This was addressed in two main studies funded by AusAID. Both studies examined risk throughout East New Britain Province for a range of geological hazards, not just volcanic threats. Their aim was to solve the simple but challenging 'risk equation' (exposure x vulnerability x hazard). These studies were driven in part by the 1990s being declared the International Decade of Natural Disaster Reduction, and in part by a devastating tsunami that killed at least 2,200 people at Aitape on the north coast of mainland New Guinea on 17 July 1998 (Davies 2017).

The first of the two studies was a community-based hazard and risk assessment conducted in the province in April–December 2001 in close association with the staff of the GRA, the provincial administration and communities. The leader and coordinator was Dr Isolde Macatol, a contracted disaster-risk advisor from AusAID's PNG Advisory Support Facility Project (Macatol 2002). Four PNG staff from the RVO were involved, each writing chapters for one of the final reports on geological hazards: Jonathan Kuduon considered volcanic hazards; Ima Itikarai, now head of the RVO, dealt with earthquakes; Felix Taranu discussed landslides; and tsunamis were considered by Kila Mulina. Luke Sendo from Kerevat National High School presented a chapter entitled 'Vulnerability Due to Geology'. A highlight of the compilation was a collection of 119 maps of geological-hazard impact throughout the province, together with population data for specific areas likely to be affected. Two other reports by Macatol and delivered to the GRA, the provincial administration and AusAID covered (1) an assessment of vulnerability and capability, and (2) community-risk perceptions.

The second study was even more ambitious. It aimed to be more quantitative than the Macatol study had been, concentrating on the collection of available geospatial digital data for the whole province. The data were then analysed mainly in a geographical information system (GIS) environment, much as had been pioneered by Ken Granger (1988, 2000) in Rabaul in the context of 'Risk-GIS', as referred to above. The work was part of a larger AusAID-funded activity called 'Strengthening Natural Hazard Risk Assessment Capacity in Papua New Guinea'. In 2010–13, in East New Britain, it involved the integration of natural-hazard and exposure information but only for the three hazards of earthquakes, tsunamis and volcanic ash. The volcanic-hazard methodology included a 'regional probabilistic assessment' based on computational modelling using a sophisticated volcanic ash dispersal model.

The final, highly technical report had 15 authors, 10 of them from Geoscience Australia in Canberra (Bear-Crozier et al. 2013). The authors were clear in identifying the limitations of their report, emphasising that it contributed only partly to the risk-analysis component of a full risk assessment. Spatial data needed to be accurate and constantly updated, something that might be achievable in some developed countries but not necessarily in provinces like East New Britain. Two of the authors, both spatial-data specialists, were clear on this point in one of the chapters:

> A plan for the ongoing maintenance and improvement of exposure information for East New Britain Province has not been developed, but future risk analysis activities would benefit from improvements to the input datasets that have been used to develop the exposure information, particularly for the themes identified [in this chapter]. (Jakab and Pirit 2013, 71)

Future planning in East New Britain can find value in continuing the approaches identified in both of these reports, even though many of the concepts were driven by outside expertise. Constantly updating digital data sources can be challenging and costly, and good GIS technical skills must remain and be valued in the province if the concepts are to survive. The concepts are an obvious reminder, too, that GIS technology—like earth-orbiting satellites—were not available before 1937–43.

9.3. Scientific Responses and New Insights, 1994–2022

There were also strong responses in 1994 from overseas geoscientists, most of them volcanologists who had been invited by the RVO to participate in assisting the ongoing post-disaster work of the observatory. Their number was well in excess of the three geologists who investigated the 1937 disaster—C.E. Stehn, W.G. Woolnough and N.H. Fisher. The most important immediate response came from the Volcanic Disaster Assistance Program (VDAP) of the United States Geological Survey (USGS), which arrived in the second week of the eruption, funded by the US Agency for International Development (USAID). VDAP was based at the Cascades Volcano Observatory in Vancouver, Washington State, near Mount St Helens, which had been in eruption in 1980. The volcanologists there had developed a suite of portable monitoring instruments that could be deployed quickly at volcanoes that seemed to be reawakening (Ewert et al. 1997). VDAP was created in response to the disastrous eruption at Nevado del Ruiz volcano, Colombia, in 1985 when more than 23,000 people were killed by fast-moving mudflows. Three VDAP volcanologists arrived at Rabaul at the end of September 1994 with about 40 crates of new monitoring equipment for the RVO—seismometers, tiltmeters and computers—which had lost monitoring capacity through eruption damage and vandalism. The earlier visit of USGS volcanologist Norm Banks in 1983, bringing in electronic distance-measuring equipment, had also been funded by USAID. All of this USGS technical capability was greatly in excess of that portrayed comically in Figure 3.65.

Two academics from the University of Arizona arrived at the same time. They brought a 'correlation spectrometer' to measure, remotely from the air, the amount of volcanic sulphur dioxide gas being emitted from Tavurvur, and they collected samples of the recently erupted ash and pumice for geochemical study, leading to early publications on the 1994 eruption in the international literature (Williams 1995; Roggensack et al. 1996).

Canberra-based staff from Geoscience Australia (GA), which in 1992 had changed its name from the Australian Geological Survey Organisation (AGSO, formerly BMR), arrived at Rabaul in October 1994. Their role was to provide initial support to the RVO in conjunction with VDAP staff and to organise additional technical-assistance support for the observatory. Rock samples were collected and brought back to Canberra, where petrologists

and geochemists at The Australian National University provided mineral and whole-rock analyses. These early results were consistent with the view that the rocks were actually 'mixtures' of two different magma types that had mingled with one another: basalt and dacite (Johnson et al. 1995).

Discussions at the RVO in October 1994 led to a comprehensive AusAID initiative, the 'Papua New Guinea Volcanological Service Support (VSS) Project', which carried a total budget of A$6.8 million and ran from 1995 until 2000 as a joint project between RVO and GA staff. The VSS Project was multifaceted and its overall aim was to strengthen the technical and scientific capabilities of the national volcanological service based at the RVO. Ben Talai and Chris McKee exchanged roles at the end of 1994, meaning that Talai became the first Papua New Guinean to lead the RVO and thus to represent the RVO during the first years of the VSS Project. This VSS work also formed the basis for a subsequent, lower-budget 'RVO Twinning Program' between the RVO and GA that ran until 2015 (Nancarrow and Johnson 2015). AusAID during this time provided financial support for postgraduate studies by RVO volcanologists Herman Patia and Ima Itikarai at The Australian National University in Canberra, leading to the award of masters' degrees (Patia 2004; Itikarai 2008). Herman Patia's research was petrological and geochemical and included the study of 1937–43 samples among others.

There have been numerous laboratory studies of the volcanic rocks produced by the historical eruptions at Tavurvur and Vulcan. A dominant interpretation in these studies is that high-temperature basaltic magma has mixed or mingled with a cooler dacitic magma believed to occupy a Harbour low-velocity anomaly (LVA; see below). Petrologists who have analysed the constituent minerals of the rock samples, using electron-microprobes, repeatedly draw attention to the fact that the common rock-forming minerals of feldspar and pyroxene have 'bimodal' compositions—that is, one mineral mode corresponding to the basalt, the other to the dacite (Johnson et al. 1995; Patia 2004; Patia et al. 2017). The basalt component is more prevalent in the samples from Tavurvur than in those from Vulcan, particularly in the well-studied rocks produced during the 1994–2014 eruptive period. Herman Patia studied samples from the 1878 and 1937 eruptions of both volcanoes and confirmed the mixed/mingled character of some of them. There were also 'micropillows' of basaltic material with crenulate margins that had chilled against the cooler dacite (Figure 9.3).

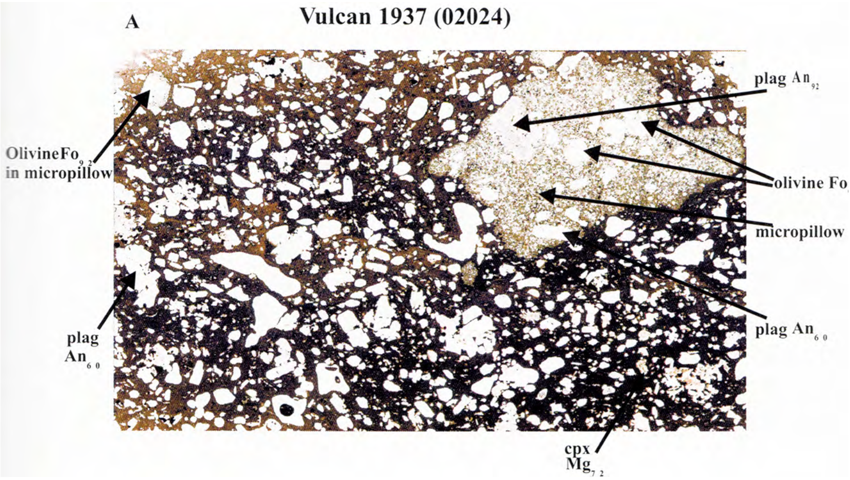

Figure 9.3. Vulcan 1937 sample as photographed through a microscope.

This photomicrograph is an image as seen through a petrographic microscope of a thin slice of a glassy sample taken from the 1937 deposits of Vulcan and described by Herman Patia in his master's thesis (Patia 2004, Figure 4.3a). The width of the image is about 20 millimetres, and the minerals are olivine, plagioclase feldspar (plag) and clinopyroxene (cpx). Note especially the two areas labelled 'micropillows'. These are of basaltic material containing olivine, a typical basaltic mineral.

New Zealand Government volcanologists Ian Nairn and B.J. 'Brad' Scott visited Rabaul in May 1995 as part of a fact-finding mission (Finnimore et al. 1995; Nairn and Scott 1995). Nairn knew Rabaul well from earlier visits when, with RVO staff, he produced a modern geological map and report on the area (Nairn et al. 1989). Geological mapping of the Rabaul area remained an important element of the RVO's work, much of it undertaken by Chris McKee, Herman Patia and Jonathan Kuduon. This work eventually led to major reviews being printed in locally produced reports (McKee et al. 2018, 2020; McKee 2021), the results of which place the 1937–43 eruptions in a strong geological context, as discussed further below. John Tomlin was another well-known visiting volcanologist who came to Rabaul in early 1995 accompanied by disaster-management specialist Joe Chung, both from the UN Department of Humanitarian Affairs (Tomblin and Chung 1995). Their visit was an investigative one aimed at identifying 'lessons learnt' as a basis for future disaster-mitigation planning internationally.

A major component of the VSS Project was a multinational geophysical survey of the Rabaul area, the 'Rabaul Earthquake Location and Caldera Structure' (RELACS) program (Gudmundsson et al. 1999). It was led by Doug Finlayson (AGSO) and Oli Gudmundsson (ANU) and was funded jointly by AusAID and JICA. RELACS was a modern rerun of a survey undertaken in the late 1960s in the Rabaul area that had seen artificial explosions detonated and the shock waves recorded at numerous stations (Brooks 1971; Finlayson 1972). The recording stations for RELACS in 1997–98 included not only instruments on land but also ocean-bottom seismometers provided by the University of Hokkaido, Japan. RELACS results form the basis for new interpretations of the nature of the deep interior of the Rabaul volcanic complex. Magma bodies were detected and mapped at depth by the technique known as 'seismic tomography' and results were reported in the international scientific literature (Finlayson et al. 2003; Gudmundsson et al. 2004; Bai and Greenhalgh 2005).

A major discovery of the RELACS geophysical survey was that parts of the crust beneath the Rabaul region were found to transmit earthquake waves so slowly that the transmitting material was inferred to be molten or at least partly so. Two such 'low-velocity anomalies or LVAs' were mapped by this 'seismic tomography' method, as seen in the 5-kilometre-deep horizontal 'slice' shown in Figure 9.4. The elongated 'Harbour LVA' in the south-west coincides with the northern seismic ellipse shown in Figure 7.9, whereas 'Rabuana LVA' is more circular and underlies both the shoreline between the Watom–Turagunan Zone and St Georges Channel, and the trend of the North-East Earthquake Zone. A third LVA was also detected below the Harbour LVA at depths of about 12–18 kilometres. It has been called the mid-crustal anomaly, but how it links with the two shallower anomalies is very unclear on current lines of evidence.

Satellite-borne radar imaging studies of the Rabaul area were also introduced to the RVO in the new millennium by GA through the RVO Twinning Program (Hutchinson and Dawson 2009; Romeyn and Garthwaite 2012; Garthwaite et al. 2015). These involved the precise measurement to the nearest centimetre of the distance between the satellite and the ground, comparing radar images of volcanic areas, including Rabaul, obtained from successive overpasses of the satellite and then constructing maps of changes to the elevation of the land surface. A multinational group of researchers combined satellite-radar results with RELACS data using geophysical finite-element modelling (Ronchin et al. 2017). Radar images can also be used in association with the results of ground-based stations of the GPS for accurate

determination of locations and the measurements of relative plate motions (Tregoning et al. 2000). GPS data had been adopted widely in Papua New Guinea by this time by surveyors and geodesists in general, including at Rabaul, where four GPS stations had been installed in 1998 providing real-time geodetic monitoring of the harbour area by the RVO (Stanaway 2004). The sophisticated level of all these investigations was a measure of the strong local and international interest that had been generated in the nature of Rabaul volcano after 1994—something that certainly did not exist in Rabaul in 1937–43.

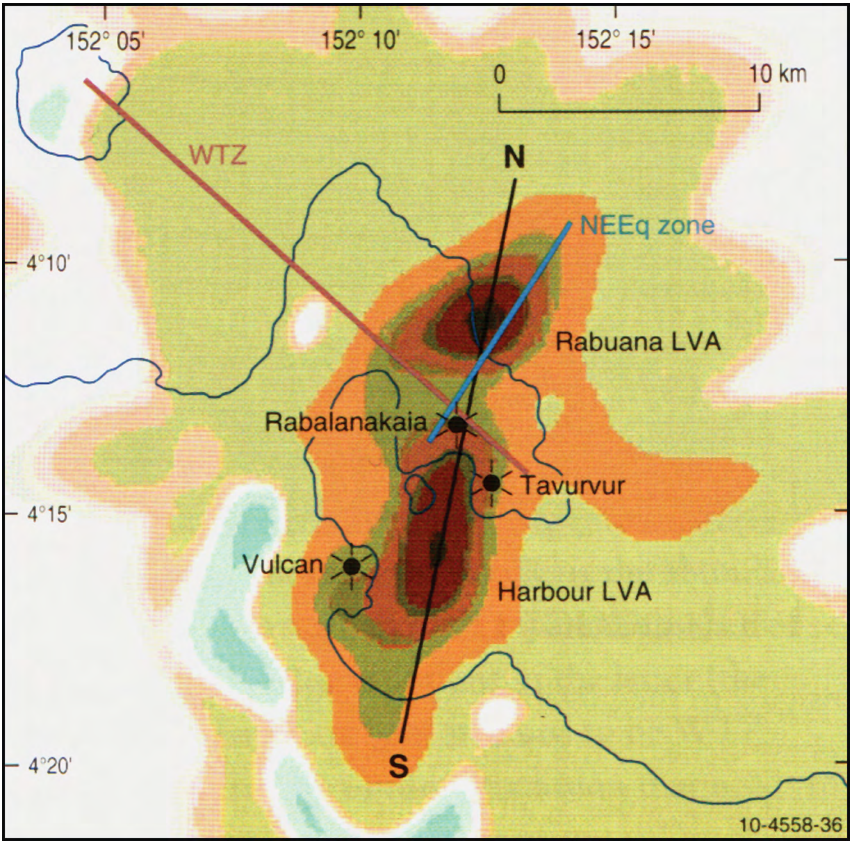

Figure 9.4. Seismic tomography of the north-eastern Gazelle Peninsula area.

Different seismic velocities (kilometres per second) are plotted here for a 5-kilometre-deep horizontal slice showing the Harbour LVA and the Rabuana LVA (adapted from Itikarai 2008, Figure 6.3a). The lowest velocity is shown in dark brown, grading up to olive green. WTZ signifies the Watom–Turagunan Zone, NEEq the general trend of the North-East Earthquake Zone shown in Figure 8.12, and N-S is the approximate line of the cross-section shown diagrammatically in Figure 9.6.

Ben Talai left the RVO in 1999 at the age of 51 and returned to his home in the Duke of York Islands. Ima Itikarai from Central Province, a physics graduate from the University of Papua New Guinea, took over as head of the RVO, a position he holds to the present day. Chris McKee transferred to Port Moresby, taking charge of the geophysical observatory there but maintaining a strong interest in Rabaul volcanology before his retirement and return to Australia.

9.4. Model for the 1937–43 Eruptions at Rabaul

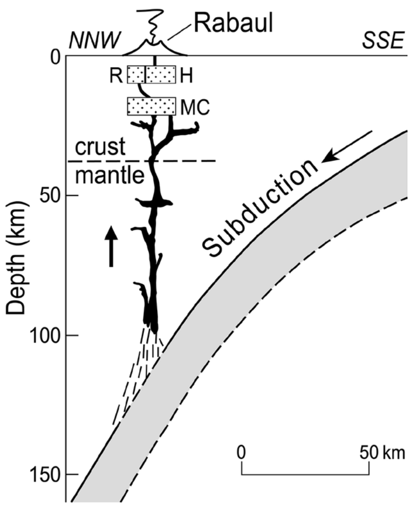

Figure 9.5. Subduction and magma-formation cross-section.

Magmas that were eventually erupted in both 1937 and 1994 at Rabaul may have had a similarly deep origin, as represented highly schematically in this cartoon adapted from Figure 7.2. The shaded subduction zone represents only the seismically active upper part of the down-going Solomon Sea plate as mapped by Everingham (1975) for the July 1971 earthquakes. R, H and MC refer to the Rabuana, Harbour and Mid-Crustal LVAs, respectively.

We are now faced with the challenge of summarising, from the wealth of specialist and scientific information available, what may have happened deep beneath the northern Gazelle Peninsula before and during the 1937–43 period. We attempt to achieve this by adapting relevant results from the better known 1994–2014 period. We emphasise, however, that our conclusions are not only, in part, speculative, but also greatly simplified, as seen in the cartoons in Figures 9.5 and 9.6.

Four sequential points can be made with reference to Figure 9.5:

1. First, the large-magnitude tectonic earthquakes of 1916 and especially 1919, plus any related aftershocks, are taken to correspond to a downward surge in subduction of the Solomon Sea plate. These earthquakes are equivalent to the two magnitude 7.9 earthquakes of July 1971 that preceded the 1994 eruption.

2. Fluids rise from the surface of the dehydrating and possibly melting subducting slab at depths of about 100–150 kilometres, into the overlying mantle causing partial melting and the creation of new 'primary' basaltic magma. The new magma is buoyant. It rises, recharging and rejuvenating the complex conduit and channel system used by earlier magmas that had been created by earlier subduction. The new, rising hot magma interacts with wall rocks and mixes or mingles with any stalled magma still residing in the conduit system.
3. Magma reaches the top of the earth's upper mantle, intruding on the 30–35-kilometre-thick crust beneath the Rabaul area (Finlayson et al. 1972). The structure of this crust is poorly known but the three LVAs referred to in the previous section are shown schematically in Figure 9.5 by the stippled boxes in the upper and middle crust. There may be more than three such LVA systems beneath Rabaul and how they are all connected remains unknown.
4. Much research has been accomplished globally on the nature of possible magma bodies directly beneath active volcanoes, and the notion of a shallow single crustal 'chamber' of magma—that is, completely molten material—has been sidelined to a large extent. A consensus now seems to have been reached that several systems may exist at different depths and that, as a whole, they are vertically extensive, unstable and some possibly connected (Cashman, Sparks and Blundel 2017). Further, the materials contained in such systems include magma, and also crystals of different compositions from different sources, some in such abundance that the name 'mush' is used for cases where the crystals form a continuous framework through which melt is distributed. Magma and crystals are stored during and after a long, and probably complex, process of magma ascent, magma and crystal mixing, and incorporation of wall rocks.

The Watom–Turagunan Zone is regarded as the primary, controlling geological feature of the three volcanic systems at Rabaul shown in Figure 7.12, at least during recent times encompassing the 1878, 1937 and 1994 eruptions. Basaltic magma derived from a long course of ascent and petrological evolution from the earth's upper mantle rises up into the Rabuana LVA but then moves obliquely into the Harbour LVA where it mixes with dacite magma. This magma mixing or mingling takes place beneath the general area of the Greet Geothermal Field, which includes the historically active volcanoes of Tavurvur, Rabalanakaia and Sulphur Creek. The sideways entry of the basaltic magma from the Rabuana LVA is regarded as the process by which the Harbour LVA has been replenished

in modern times, not that other entry points can be excluded (see e.g. the question mark in Figure 9.6). The mixed magmas eventually also reach that part of the reservoir beneath Vulcan, although by this time they have lost much, but not all, of their basaltic component (Figure 9.3).

The Harbour and Rabuana LVAs are the two shallowest of the three LVAs detected beneath Rabaul. They are believed to be connected laterally, as shown diagrammatically in the cross-section in Figure 9.6. The section corresponds roughly to the N-S line in Figure 9.4, which runs through the two LVAs, both of which are seen to be roughly lenticular, based on the RELACS results. More exact shapes cannot be mapped for the two inferred magma- and mush-containing reservoirs, as the outer, cooler zones of both may contain more solid material than the hotter, more liquid central parts. One suggestion is that the Harbour LVA could correspond to a flat magma reservoir only 500 metres in thickness, or even less (Patia et al. 2017). Similarly, the width of the Harbour LVA shown in Figure 9.4 could correspond in reality to a much narrower reservoir of hotter magma, in which case the reservoir would be shaped more like a horizontal tube or cylinder.

Magmas in the Harbour LVA, comprising different mixed proportions of crystals, melt and mushes, rise up the ring fault or seismic annulus (Figure 9.6). This is a phenomenon that could not be recorded in either 1937 or 1994 but which could be modelled computationally, taking into consideration the geodetic and earthquake data that had been collected in the Rabaul area in the 23 years or so prior to the 1994 eruption (Saunders 2001; Robertson and Kilburn 2016; Figure 7.11). The notion that magma can be emplaced into a ring-like structure is well known from the geology of old volcanoes such as Glen Coe and Mull in Scotland, where 'ring dyke' intrusions had been mapped more than a century ago. The concept of dyke-formation had been discussed at the RVO, for example, when USGS volcanologist Norm Banks visited Rabaul in 1983. The fact that magma was erupted from Tavurvur and Vulcan in 1994, both of them close to the seismic annulus, is strong evidence that magma at some stage had indeed risen in conduits from the same 4–5-kilometre-deep magma reservoir identified beneath the northern ellipse and the Harbour LVA (Figure 7.9). More uncertain, however, was how much of other parts of the annulus were emplaced by magma; a complete ring dyke may not have formed. Also, when did the intrusions beneath Vulcan and Tavurvur actually start, and why did the other young volcanoes not form around the northern ellipse?

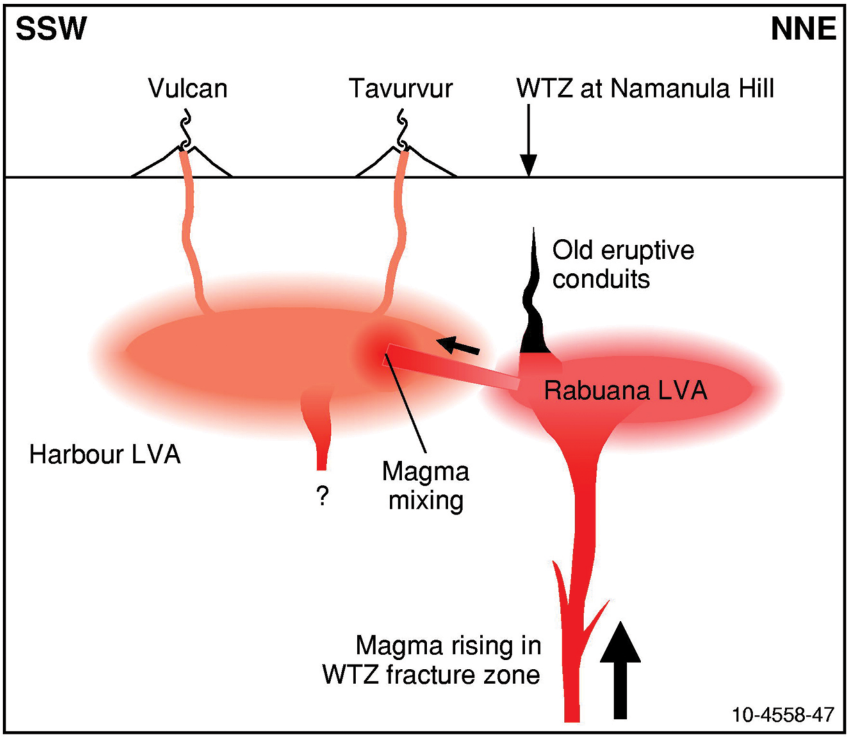

Figure 9.6. Magma mixing and low-velocity anomalies.

A zone of magma mixing beneath Tavurvur and the Greet Geothermal Field is shown in this schematic cross-section using RELACS seismic-velocity results for the two LVAs at Rabaul. Vulcan and Tavurvur are about 6 kilometres apart.

Eruptions at Tavurvur in 1878 and 1994–2014 were longer lasting than those at Vulcan in 1937–43, but even in 1941, after four years of inactivity, the recurrence of explosive eruptions at Tavurvur was consistent with the known longevity of Tavurvur eruptions—maintained within the Greet Geothermal Field—compared with those at Vulcan. Eruptions at Vulcan, including those in 1937, evidently require the underlying magma reservoir to be recharged relatively quickly, a process that may not be efficient or even possible as long as Tavurvur remains in eruptive activity.

The small size of the short-lived Tavurvur eruption in May 1937 can be considered from two other perspectives. First, the colonial administration in Rabaul and mainly expatriate townspeople were much more concerned, at least initially, by the impact of the ash fall on Rabaul town than they were about the much larger eruption at Vulcan where more than 500 village people had been killed. The much larger volume of deadly Vulcan pumice and ash did not become fully obvious until later, and particularly after volcanologist Norm Fisher calculated the amounts that had been erupted (Figure 4.9). Second, the dominance of the Vulcan eruption in 1937 is striking because the volcano is several kilometres from Tavurvur, below which basalt intrusion, magma mixing and reservoir recharge are thought to have taken place. Mixed magma in May 1937 (Figure 9.3) had reached places in the reservoir directly beneath Vulcan, and conduits beneath that volcano were evidently more effective in delivering the mixed magma to the surface than those at Tavurvur (Figures 9.5 and 9.6).

The basalts carried up in the WTZ have components that become volatile during eruptions and afterwards. These include the volcanic gases of sulphur dioxide and carbon dioxide, as well as water vapour, all of which are of interest to petrologists and geochemists as they can be detected and measured in microscopic pieces of glass trapped in pre-eruption crystals. Sulphur dioxide gas from the Tavurvur eruption of 2006 had been imaged in the large fan-like cloud seen from space (GVP 2006) and measured in 1994 by airborne spectrometers operating in Rabaul (Roggensack et al. 1996). Sulphur dioxide issuing from Tavurvur can be smelled locally, particularly during eruptions, as well as hydrogen sulphide, which is recognisable by its sulphuretted or 'bad-egg' smell when Tavurvur is quiescent. The magma between the zone of magma mixing and the roots of Tavurvur (Figure 9.6) is what keeps the Greet Geothermal Field active, its long-lived heat and volatiles chemically altering the volcanic rocks and deposits making up the cone of Tavurvur. This geothermally altered material was erupted hydro-explosively early in the eruptions of Tavurvur in both 1937 and 1994, as sticky blue-grey sulphide-bearing mud. Vulcan, by comparison, is different. It does not seem to be a major sulphur producer, or else the amounts are very small, and no geothermal activity survives for long after the explosive eruptions. The volatile element chlorine has been detected in Vulcan deposits from 1994; however, this is probably the result of seawater influence that is absent at Tavurvur.

The interpretations presented above are oversimplified, reflecting ongoing uncertainties over what actually happens beneath Blanche Bay in both a physical and a chemical sense. What are the amounts and rates at which the WTZ basalt reaches the Rabuana LVA and then the mixing zone and over what time frame? How much basalt or mixed magma remains in the Harbour LVA after any one eruption for involvement in later eruptions? How does the mixed magma beneath Tavurvur move laterally several kilometres to places beneath Vulcan? What happens in the deeper parts of crust and mantle below the levels shown in Figure 9.6? Also, can the interpretation be used to assess the chance of eruptions taking place that are substantially larger than those of 1878, 1937 and 1994?

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