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Article

Twenty-Two Years of GPS Monitoring at Rabaul Caldera, a Narrative History

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Abstract: It has long been recognised that volcanoes deform as fluids migrate, or change pressure in fractures and reservoirs within the volcano or in the crust below and around them. Calderas in particular have been shown to deform in complex and often major ways. The Rabaul Caldera is a type example of a caldera that undergoes complex and occasionally rapid deformation. This was first recognised by visual observations, and by the 1970s these movements were being monitored by traditional surveying techniques. Between 1972 and 1994, the centre of the caldera was uplifted by approximately 2 m. Following the 1994 eruption, it was indirectly found that parts of the caldera were uplifted ~6 m in the final hours before the eruption. It was realized that 'real-time' monitoring of the uplift may have given a better warning that an eruption was imminent. Traditional surveying techniques are time consuming; in the late 1990s, the only option for real-time monitoring was a Global Positioning System (GPS). By early 2000, a real-time GPS system was working at Rabaul Volcanological Observatory (RVO). Twenty-two years of continually recording differential GPS or Global Navigational Satellite System (GNSS) has proven the technique to be of immense importance. Often it has been the only parameter showing that unrest is happening. At times, inflation and deflation have warned of impending activity or recorded the emptying of the system; at other times, patterns of deformation have been more difficult to interpret. The technique has proven its worth in monitoring the status or general 'health' of the caldera, but for more precise forecasts it can only form part of an integrated monitoring system. Current testing of much cheaper receivers and improvements in telemetry mean the technique may soon be available for the more remote volcanoes of Papua New Guinea.

Keywords: volcano deformation; volcano monitoring; GPS/GNSS monitoring; Rabaul Caldera

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1. Introduction

It has long been recognized that volcanoes deform due to many factors. Most simply, as magma rises from the depths it intrudes into shallower parts of the Earth's crust, so the volume of the intruded area must increase to accommodate it, usually leading to some form of measurable surface deformation (Figures 1–4). These intrusions may be driven by buoyancy or magma pressurization. Some form of 'conduit' must be used if a viscous fluid is to move through the solid lithosphere; pressurized magma can itself initiate new cracks, intrude existing cracks (faults/joints) or inflate, or leave, existing bodies of older magma. Magma bodies can also auto-expand or contract due to bubble nucleation and growth, or bubble collapse; cooling magma will contract, and crystallizing magma can expand as fluids (including volatiles) are expelled from crystal lattices. Steam can be produced, either as exsolving magmatic (juvenile) water or by the boiling of ground water in the surrounding rocks. Steam production increases hydrostatic pressures and can cause significant deformation at the surface. Many volcanoes are located in tectonically active areas, and tectonic stress can compress (potentially leading to surface up-doming) or extend fluid bodies of magma (leading to surface subsidence). These multiple factors can make the interpretation of volcano deformation complex, with very few models truly incorporating all possible contributing factors and variables. As such, volcanologists need to remain flexible in their interpretations and expectations.

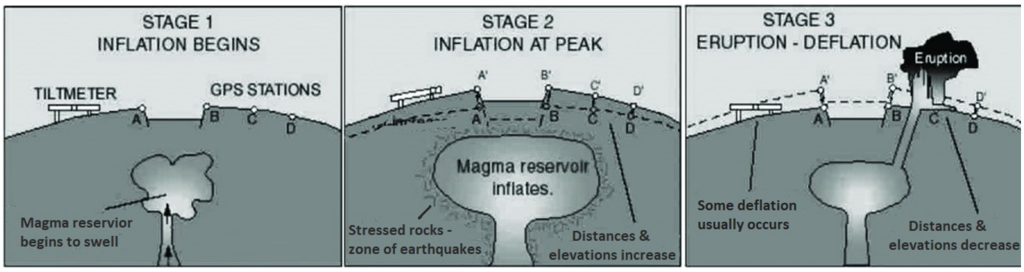


Figure 1. Adaption of a well-known figure of an inflation-to-deflation cycle (courtesy of USGS). Left and centre images: pressurization of a deep magma chamber usually leads to broad and reasonably slow inflation, usually on the time scale of months to multiple years. Magma rise is constrained by the overburden and high lithostatic pressures; as such, the magma body can inflate with no eruption occurring, either stalling or deflating. For magma to reach the surface, it needs a 'conduit', usually accomplished by intruding existing cracks or forming new ones. Once the gas-rich magma approaches the surface, lithostatic confining pressure falls and vesiculation (bubbling) will occur, causing a massive increase in pressure and buoyancy; as such, the intrusion can accelerate. This can cause rapid and localized deformation and may culminate in eruptions with short lead times.

Rabaul Caldera shows ample evidence of past and contemporary deformation (e.g., [1–9]).

At Rabaul two types of deformation can be generally recognized:

Broad and slow or episodic—indicating a deep-seated source, which can be thought of as showing the general 'health' of the volcano.

Detailed and rapid—more detailed deformation may start to be observed with areas of uplift and discrete areas of relative subsidence, indicating that magma is at shallower levels and may erupt.

From the available geophysical and geochemical data, many models of varying complexities have been produced to try to define the 'plumbing' of the Rabaul Caldera (e.g., Figure 2 & refs. [6,10–13], etc.). Here, however, we will concentrate on the 'simple': the ability of the Rabaul Volcano Observatory to answer, at any given time, the often asked and heartfelt question 'What is the volcano doing now and when will it erupt?'. Figures 3 and 4 show images of deformation obvious to the general public, which have become part of popular culture and tradition.

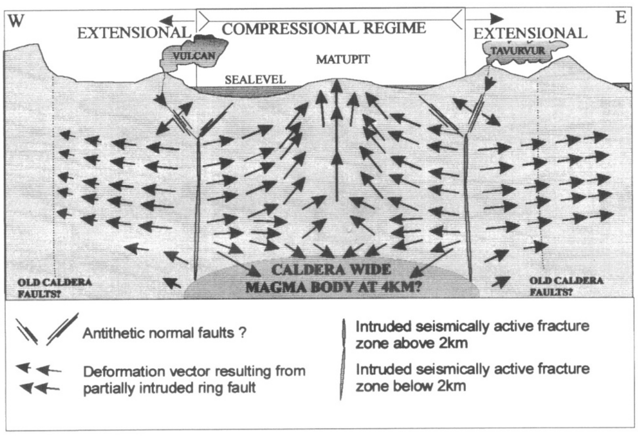


Figure 2. An illustration of one model [6] that used 2D finite element modelling to reconcile recorded deformation (areas of relative subsidence around the central uplift) and pre-1992 seismicity at Rabaul, with the classic caldera model of Smith and Bailey (1968) [14].

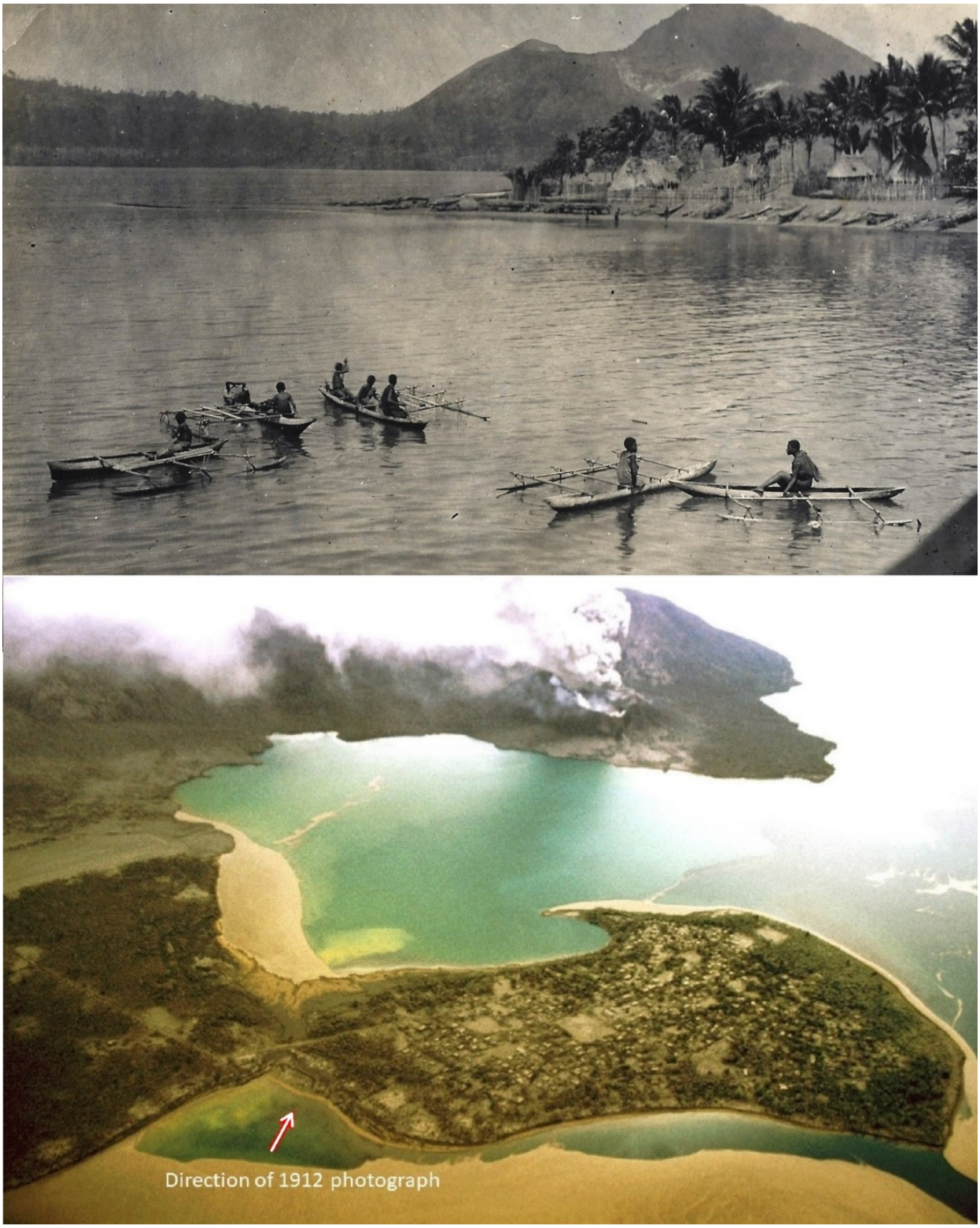


Figure 3. Two images showing the broad long-term and episodic (the time period encompassed by the two photos includes the 1937–1943 eruption and the initial 1994 eruption) uplift of the centre of the Rabaul Caldera. The top image, from 1912, is a view from a boat looking eastwards towards Tavurvur volcano across the northern point of Matupit Island. The lower picture is an aerial view of Matupit in 1994, a few days after the initial eruption. The approximate view direction of the 1912 photograph is shown by an arrow. The broad uplift, which has caused the island to become a peninsula, is obvious. The coastal cliffs in the bay formed by the uplifted causeway can be seen to record a complex history of wave-cut terraces, indicating that the uplift was episodic (Photos—RVO collection).

Figure 4. The brown tongue of land is uplifted seabed that occurred at Vulcan in the hours before the 1994 eruption. A tide-gauge pylon can be seen in the embayed part; from it, uplift was estimated to have been over 6 m. The eruption of Vulcan commenced a few minutes after this picture was taken. It was realized that being able to identify such an acceleration of deformation in realtime would have been a powerful tool in short-term interpretation (Photo:Nick Lauer).

As can be seen in Figure 5, that broad, slow, sometimes episodic deformation that had occurred in the decades before the 1994 eruption had been well constrained by traditional surveying techniques. However, these traditional techniques usually involve the mobilization of field parties to occupy a number of bench marks over a broad area, often taking several days to collect and process the data. As such the rapid and large magnitudes of deformation that occurred in the hours before the 1994 eruption at Vulcan, and to a lesser extent at Tavurvur (see Figure 6 for locations), could not have been monitored with such techniques. It was realized that if the rapid movements during the night of 18–19 September 1994 could have been seen in realtime, a much better understanding of the situation would have resulted.

In the 1990s, few options were available for real-time deformation monitoring. Electronic tilt meters and tide gauges were in theory able to transmit data in realtime, but both had problems with very noisy data and the relatively unreliable telemetry of the time. The infrastructure for tide gauges is extremely expensive; three had been installed at Rabaul in the 1980s but were unserviceable within a few years (instrumental drift and the extremely high cost of maintenance). Tide gauge location is of course also dictated by bathymetry. Tiltmeters are of limited value as they do not show the magnitude of uplift or horizontal movement, only whether a patch of ground on which the instrument is situated has tilted. The noisiness of electronic tilt data is the result of such things as fluctuating temperatures and local ground disturbances, including biological and cultural. Some of these issues can be overcome by having an array of tiltmeters across a volcanic area, but then maintenance and logistics become an issue.

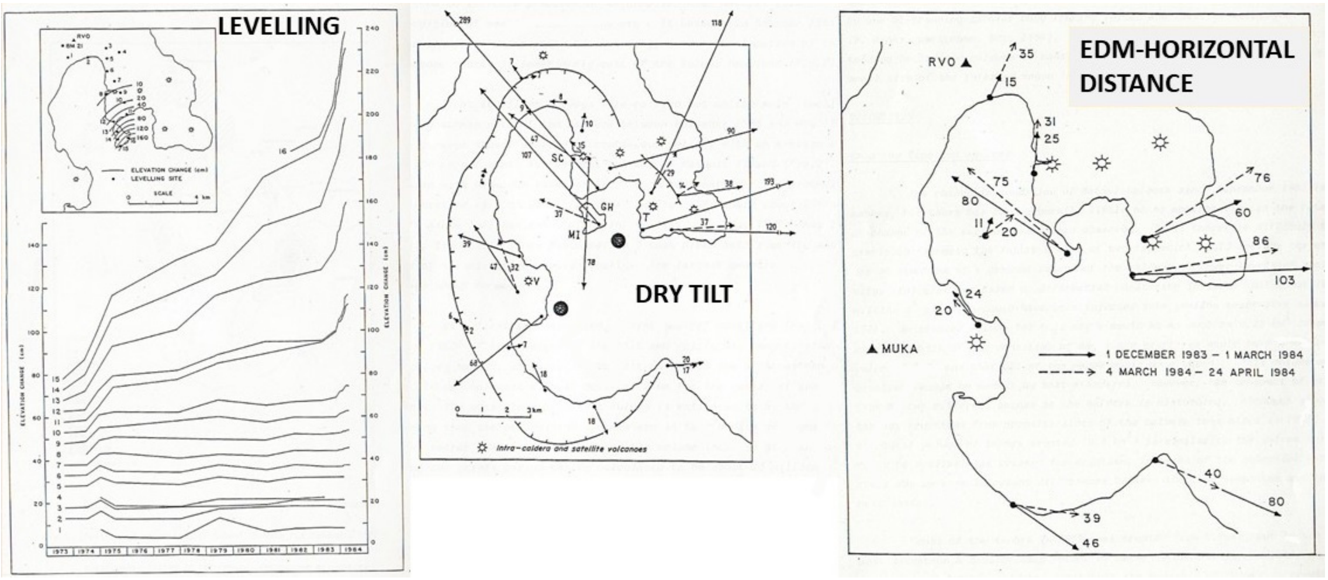


Figure 5. The broadscale movements had been satisfactorily measured with traditional surveying techniques since the early 1970s. Shown are examples of published results from levelling, dry tilt and EDM (Horizontal Distance Meter) surveys in the early 1980s [4], see that reference for better clearity.

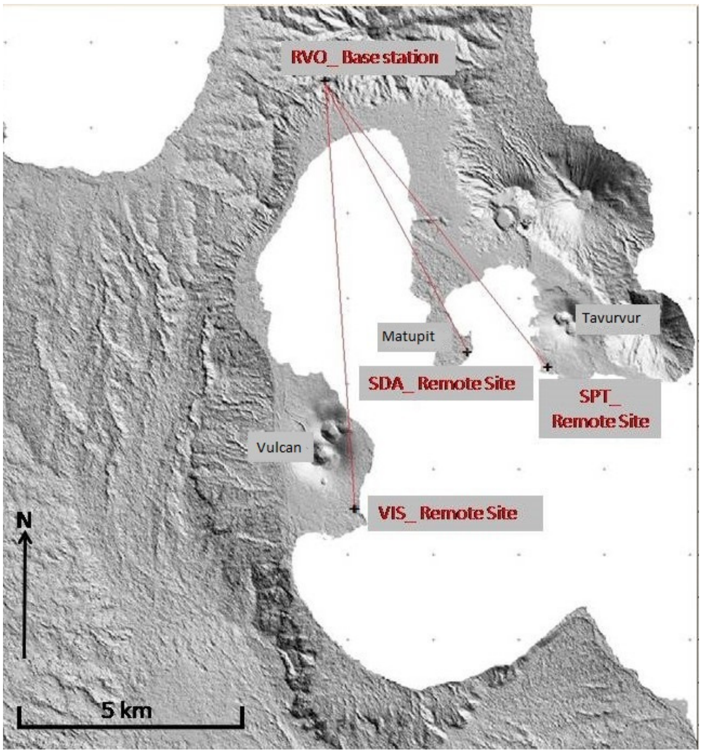


Figure 6. Location map and 1996 infrastructure put in place for the SAGEM system. Rabaul Caldera Real-Time/CORS GPS Sites in red. The infrastructure, with modifications, has been in existence since 1996–1997. Since Jan. 2000 both RVO and SDA have been in almost constant operation. VIS_ and SPT_ have suffered from theft/vandalism on occasions and have long gaps in their data. VIS_ is today still operating; SPT, however, succumbed to coastal erosion in 2021.

An instrumental technique that was coming into maturity at that time was the Global Positioning System (GPS). Several volcanoes around the world were by the mid-1990s being monitored by campaign-style Static GPS surveys of benchmarks, such as on Mount Etna, Italy, e.g., [15], Piton de la Fournaise, Reunion Island, e.g., [16], Hawaii, e.g., [17] and Japan, e.g., [18] and several other places.

A particularly interesting GPS monitoring system working during that period (mid-1990s) was on Augustine Volcano in the Aleutian Islands, e.g., [19]. After 4 years of experimentation, a successful low-power, low-cost, remote system was developed. It consisted of three permanent L1-only GPS receivers (Ashtec SCA-12), with telemetry. Once a week, these receivers were polled from an office in Homer (~150 km away) and approximately an hour of data was downloaded. This was in turn sent by modem via phone-line to the Cascades Volcano Observatory for processing using Ashtec's PRISM software. The routinely produced weekly positions enabled a general idea of how the volcano was deforming, and at times of interest more frequent data polling could be initiated. (NB. Elliot Endo recommended this type of system to RVO in 1996, but procurement of a real-time system had already commenced).

At RVO, it was reasoned that if permanently recording GPS receivers were installed around the caldera at strategic points and data continually transmitted to a processing centre, a real-time deformation monitoring system could be constructed, and the large-scale and rapid deformation that occurred in the hours before the 1994 eruption could have been seen and interpreted.

Unfortunately, the notion of getting a real-time GPS deformation monitoring array at Rabaul had one problem: none existed at that time.

2. A Time-Line of Early GPS Work at RVO

Early in 1994, RVO's Nick Lauer had discussions with Rod Little and Russell Jackson, of the Papau New Guinea University of Technology (Unitech), Lae, about setting up a GPS-based deformation monitoring network at Rabaul. Planning reached a level where implementation would have been practical. But lack of funding and resources at Unitech and RVO put the plan on hold. When the September 1994 eruption occurred, RVO's resources were immediately dedicated to trying to replace equipment that had been destroyed. In early 1995, however, Unitech's surveying facility received funding to purchase a number of GPS receivers, three of which would be dual-frequency. RVO was able to provide funding for a Unitech trip to Rabaul in June 1995. During that field season, Russell Jackson, working with Nick Lauer and Alois Gawisa, established:

- A local control GPS baseline.
- 12 benchmarks (BM), with baseline GPS coordinates observed.
- Connections to existing benchmarks and longer baselines to BMs outside the caldera; (these were stated to be to get away from volcanic deformation and to have some BMs survive in a cataclysmic eruption!).

In July 1995, Little, Lauer, Jackson and Ananga presented a paper at the SE Asian and Australian Survey Congress, entitled 'Volcanic Deformation Monitoring, Rabaul, Papua New Guinea'. Other presentations were given that year with the lead author rotating. These papers detailed their achievements and aspirations. All this, however, was still aimed at periodic occupations of benchmarks with GPS equipment, with static results being produced periodically.

In the meantime, Chris Rizos, of the University of New South Wales, a correspondent and nascent collaborator with RVO, had put in a proposal to the Australian Research Council in February 1995 entitled 'Develop, Test and Deploy a GPS Receiver Array System for Continuous, Automated, Real-Time Geodetic Monitoring of Active Volcanoes'. The work was in collaboration with Rod Little at Unitech and academics in Germany. The recipient of the system would be RVO. The date envisaged for the deployment of this Real-Time GPS System at Rabaul was around 1998.

Meanwhile, in response to the damage caused by the 1994 eruption, (which had severely compromised RVO's ability to operate) the Australian Geological Survey Organization (AGSO) produced a PNG-Volcanology PDD (Program Design Document). This PNG-Australia collaborative plan was to restore and extend RVO's ability to monitor not only Rabaul, but all the volcanoes of PNG. It was produced by a team lead by Wally Johnson and was submitted to AusAid in November 1995. It was subsequently adopted by AusAid and funded. (For almost two decades, in different manifestations, this project was a major source of resources, inspiration and encouragement for RVO and still continues today in an important but residual form).

2.1. The SAGEM System (1996)

The RVO-Unitech drive of 1994–1945 to develop GPS capabilities at Rabaul was encouraged by the new RVO-AGSO partnership. However, in mid-1995 it became apparent that the private sector was claiming to have developed centimetre accuracy, and real-time GPS monitoring capabilities. SAGEM Australia Pty. Ltd. had presented at the 'Satellite Navigation Conference', Brisbane, June 1995, a paper entitled 'Robust Real-Time Centimeter GPS Positioning—Considerations and Results'(Stephan Harwin and Rod MacLoad). Within a few weeks of this presentation, the RVO-AGSO team had contacted the SAGEM authors.

After discussions with RVO and AGSO, SAGEM produced a document including a detailed description and a quote for an 'Off the Shelf' system. The system was based on Ashtech Z12R (base) and three Z12 (remotes), linked by a Bel S103 radio telemetry system (in use at the time by electricity companies in Australia to remotely poll domestic meters). The supplied kit was to include a roving receiver and peripherals to survey off the volcano and run small local campaign surveys.

This Ashtech Real-time Kinemtric (RTK) system used an Ashtec DBEN message sent from the Base Station (located at RVO) to resolve ambiguities at the remote receivers, using Ashtec Z-tracking and PNAV algorithms. This internal GPS receiver processing (or 'onboard')at the remote site would produce an accurate carrier-phase differential position (CDP) for itself. This CPD solution would in turn be sent from the remote sites to RVO for collection, storage and plotting on a PC for interpretation by volcanologists. The RVO-AGSO project purchased the system, and it was received mid-1996.

The first author came on the scene at this point and was charged with putting this off-the-shelf system together. It did not work. Russell Jackson was flown from Unitech to help troubleshoot. It was found that, although the system would start to acquire satellites and put out DBEN singles and the remotes would start sending back CPD solutions, the system would soon lockup. It appears the internal processor struggled to provide ambiguity resolutions when more than nine satellites were acquired. It also seemed that the telemetry system would crash when larger packet sizes were produced. Another fault, or oversight, was that the system came with no user interface; RVO was expected to simply take the raw CPD results and write a program to plot them on graphs. Even if the system worked, the raw CPD results would have been very noisy, as there was no filtering. Also, the remote sites were purchased with no memory as a cost-cutting measure, so post-processing was impossible unless a laptop was left on site to record data (1996) laptops were expensive and in short supply). Various remedial schemes were tried, and much toing-and-froing ensued, led by AGSO's Canberra-based Project Manager, Shane Nancarrow. It eventually was found that the problem was an intrinsic one to the system's design. By 1999, it was realized that a complete reworking was needed.

Robust site infrastructure was, however, successfully designed and built by RVO, under the supervision of Jack Pittar, seconded to Rabaul during the early years of the project, (see Figures 6 and 7)

Figure 7. The Remote site at Vulcan (VIS) in 1999. A concrete bunker to house the receiver, telemetry, power, etc., is in the centre. Left, a choke-ring antenna is being placed on a 6 m pole (to avoid rapid tree growth). Right, a solar panel mast, with telemetry yagi antennas. The opportunity was taken to co-host seismometers in the bunkers. (Photo by author.).

2.2. The 'Hydra' System (2000)

Fortuitously, an Astech-based Real-Time GPS system had been developed in collaboration with the USGS at Long Valley, California in the late 1990s [20]. Their system, especially the software, was a success. Elliot Endo of the USGS, an existing collaborator with RVO, having worked on the 1994 eruption response, and having provided advice on the post-eruption GPS plans, was contacted and the problems explained.

As part of a collaborative effort between RVO-AGSO-USGS, this aspect was funded by the U.S. Office of Foreign Disaster Assistance, and a project was started mid-October 1999. It was decided that much of the existing infrastructure would remain, and the Ashtech Z12s would form the basis of the new system.

An important component of the new system would be an epoch-by-epoch real-time GPS positioning program called HYDRA (renamed '3d Tracker' in 2001), a product of 'XYZ's of GPS' and 'Condor Earth Technologies, Inc., (Sonora, CA, USA)'. This needed a purpose-made dual-processor Pentium III NT Work Station at the base (it was 1999 and stock computers were not fast or powerful enough), to run Magellan/Ashtech'Geodetic Base Station Software' (GBSS V. 3) (Santa Clara, CA, USA), for collecting carrier-phase data as defined by the user and provide that data in a usable form to other programs (i.e., HYDRA/3d Tracker). Spread-spectrum radio-modems by 'Freewave Technologies, (Boulder, CO, USA)' were provided for communications and data transfer between the various receivers. The problem of unreliable power at RVO was also addressed with line conditioners, surge protectors and large UPSs [21].

This new system worked almost perfectly, was user friendly and gave good results. Best of all, the system was relatively simple and robust. Figure 8 is an example of actual real-time visual output showing vertical deformation at the SDA_RT site during the hours before, during and after the violent phase of the 7 October 2006 eruption of Tavurvur.

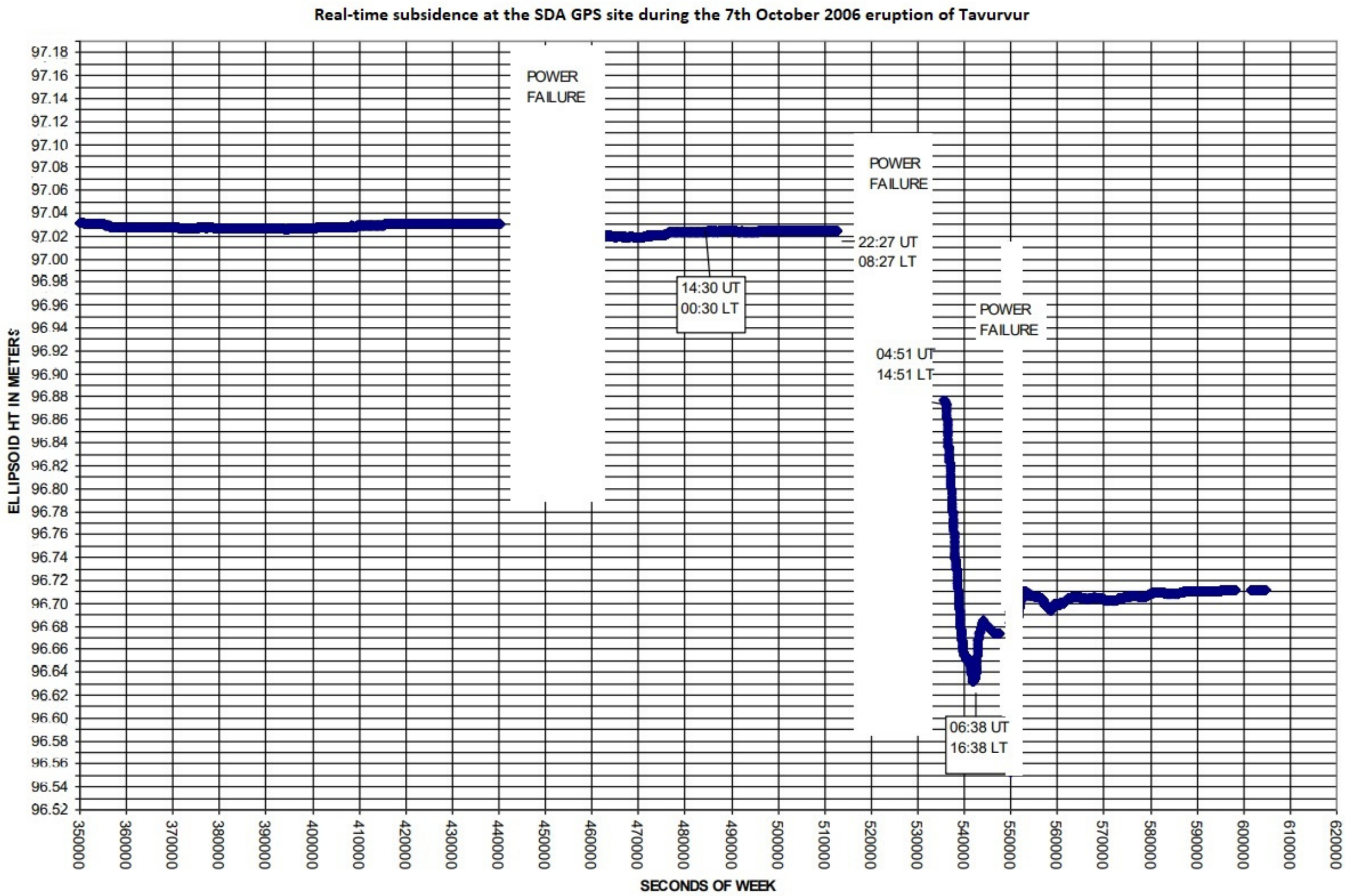


Figure 8. The most spectacular real-time response recorded is shown here, (a 2006 screen grab, hence low resolution). At 08:45LT 7 October 2006, with little warning, a sub-plinian eruption began at Tavurvur. The eruptive column forcefully reached 18km in height and shockwaves broke plate-glass windows more than 10 km away. The GPS site at SDA on Matupit showed in Real-Time a subsidence of ~30 cm in ~6 h. The subsidence stopped at 16:38 local time. Even though the volcano was obscured, debris was still falling and the eruption was still producing deafening explosions, RVO were able to inform the community that the worst was over.

2.3. The Trimble System (2008)

In 2008, it was thought necessary to change the system due to Ashtec ceasing to trade in this sort of technology. With this departure of Ashtech from the GPS field, tenders went out in early 2008 for a replacement Real-Time GPS system. Now, a number of companies offered such systems. After normal tendering and cost-benefit analysis, a Trimble system was chosen. All stations would use Trimble NetRS receivers with choke-ring antennas. Although originally slated to have MOXA AWK-1100 WLAN for communication, the final system was delivered with COMPEX WPE53G WLAN modules. Software would be Trimble Integrity Manager (TIM) run, again, on a specially built high-speed 'RAID' type computer.

Again, there were start-up problems as the COMPEX WPE53G WLAN modules appeared to be on the edge of their range. RVO itself corrected this by replacing them with Intuicom, EB-6 plus, Long Range Ethernet Bridge radio modems. Also, the TIM suite of modules proved complex, with numerous points of potential conflict and system failure. Unlike 3dTracker, many crashes of TIM required phone calls to Singapore (Trimble's Regional Centre). Even though the system was fragile, it ran until 2013, when the computer failed. Being a specialist computer, replacement was difficult and expensive, as were licenses and upgrades for the commercial software.

2.4. Operating as a Continuously Operating Reference Stations (CORS) System (2013 to Present)

As mentioned above, RVO has had a problem in affording updates and licenses for commercial RT-GPS/GNSS software. As such, alternative methods of GNSS monitoring have been sought.

Since 2013, raw GNSS data (TrimbleT02 files) have been collected daily via FileZilla and then processed using Trimble Business Center (TBC. V. 5.0) software with daily averaged Latitude, Longitude and Height plotted on an Excel spreadsheet.

Working as a simple CORS, the 24 h data, recorded on the receivers at 10 s epochs, are easily retrieved, and when specific events occur, such as an earthquake or significant volcanic events, the data can be examined in more detail, epoch by epoch if necessary. RVO has used Geosciences Australia's AUSPOS internet GNSS processing facility, and Richard Stanaway of Quickclose Pty Ltd, Carlton, VIC, Australia, has helped greatly in running RVO's data against the 'Regional Reference Frame' when geophysical phenomena occur.

Note: this was a solution—remotely downloading data from CORS (Continually Operating Reference Stations) and post-processing those data—that Elliot Endo had recommended for RVO in 1996!

Due to the original SAGEM system being purchased without internal memory in the remote sites, between 2000 and 2008, the daily plot was constructed by taking Ashtech Q files (list of RT epoch-by-epoch solutions) and taking the 24 h average of those positions.

This CORS system has proved to be a simple and robust option. A spreadsheet started on 26 January 2000 now has over 8500 daily average points for the three components, leading to the growth of an impressive data set. L2 observations were missing for SDA, SPT and VIS after 2015, due to a defect in the choke-ring antennas; these were replaced by Trimble in 2020.

3. Results

3.1. A Brief Description of the Vertical Deformation Data

As shown in Figure 5, from the early 1970s onwards the vertical deformation of benchmarks was monitored using traditional levelling techniques. A detailed description of the deformation seen before the 1994 eruption can be found in [9]. During the 1994 and subsequent eruptions, heavy ashfall and frequent mud flows, leading to accumulations of up to 3–4 m in places (a recurring problem until at least 2017), led to many levelling benchmarks being lost or destroyed and made replacement impossible. Civil clean-ups also led to numerous benchmarks being destroyed or disturbed when roads and associated drainages were dugout or graded.

CORS GNSS monitoring of the Matupit SDA_ site has been ongoing since the year of 2000. Figure 9 shows the two vertical surveying techniques' data for Matupit combined on one graph. Periods of uplift, subsidence and relative stability can be seen, and deformational events that can be related to various geophysical events are shown on the graph.

A notable feature of the GNSS data is that they are continuous and show that deformation is often steady. The periodic nature of the previous levelling surveys lead to the possibility that many movements may have been episodic; the CORS data, however, show that near-instantaneous episodic movements are indeed seen, during the onset of large eruptions or regional earthquakes, but the majority of the uplift has been the result of comparatively steady deformation, with month- to year-long periods of relatively uniform rates and trends, e.g., 2010–2014, 2014–2021.

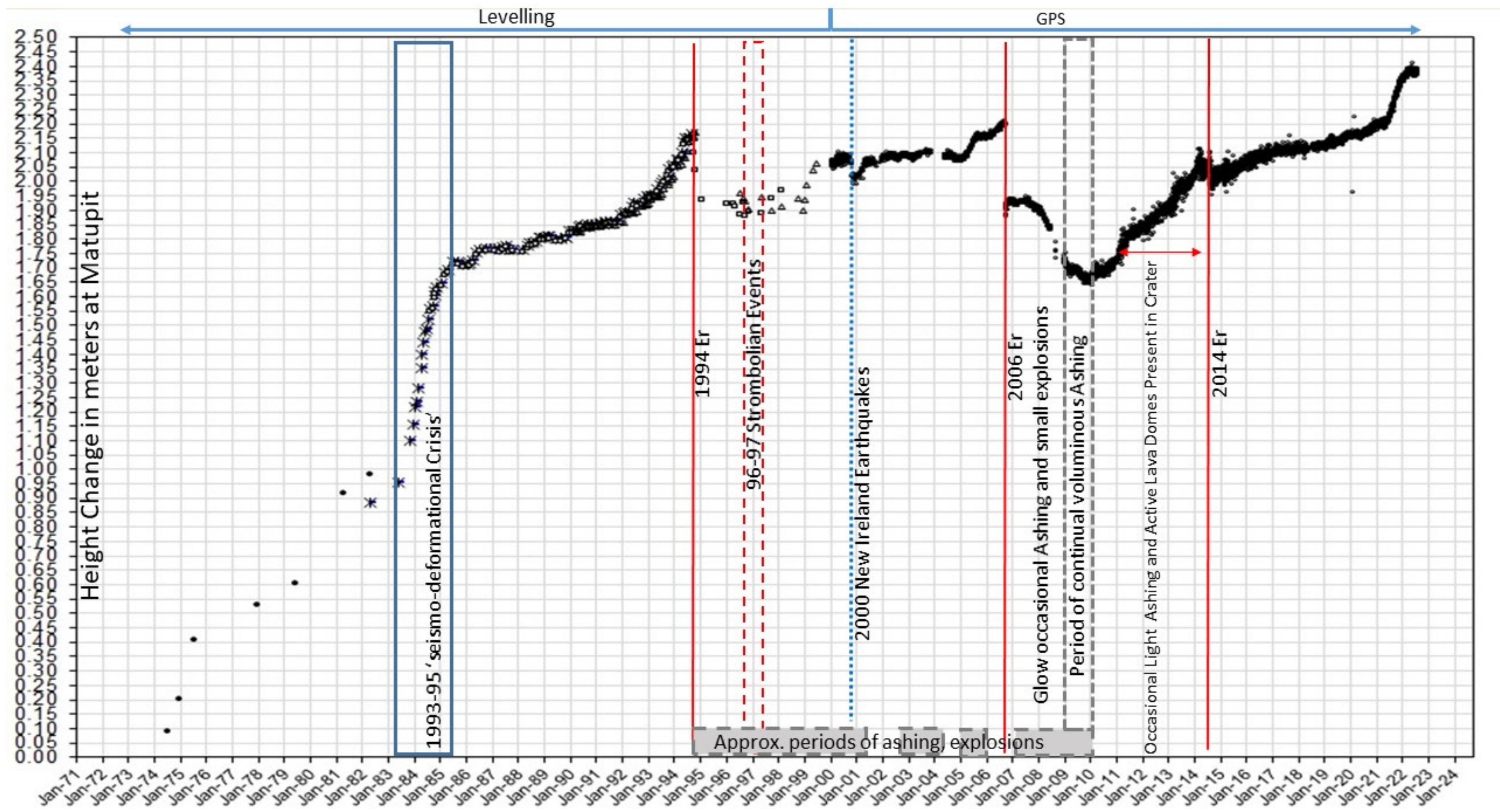


Figure 9. A composite of traditional levelling data (left of tick mark at top of graph) and CORS GNSS data (right of tick mark at top of graph) of height change at the centre of the caldera (BMs in south part of Matupit) since 1970. Recognised geological events/phenomena are shown. (Due to benchmark loss data from several BMs are shown at left, hence variety of markers, to avoid large gaps in data).

3.2. A Brief Description of the Horizontal Deformation Data

As well as the vertical movements, horizontal deformation is also recorded by CORS GNSS and used in the intuitive or numerical modelling of subsurface processes. In Figure 10, acoordinate wander plot of all the recorded datais shown. A complex pattern of predominantly north-westward deformation, generally corresponding to the periods of uplift seen in the vertical data, with south-eastward movements, which can be related to the periods of subsidence seen in the vertical data. The cumulative wander plot shows many overlapping data points, leading to a very complex graph; certain periods of deformation can be recognised and separate time period plots are available from RVO, but for the sake of brevity are not included here.

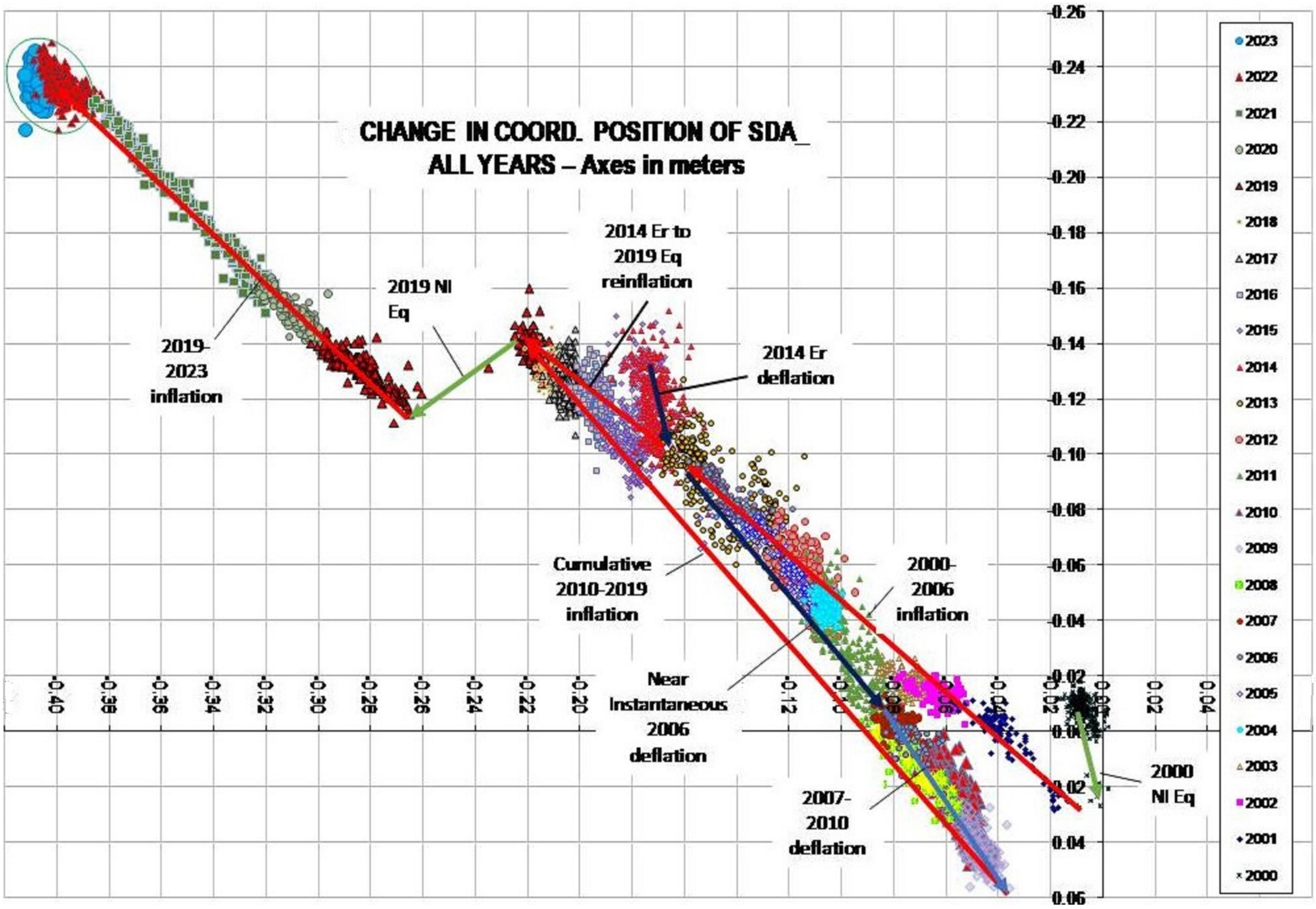


Figure 10. Lat-Lon coordinate wander plot for the SDA GNSS site (2000 to 2023) at the centre of the Rabaul Caldera (movements relative to the RVO Base station). A generally northwestern movement is the norm (red arrows), but with periods of acceleration and periods of relative stability. A near-instantaneous reversal during the 2006 eruption, followed by a near-year-long period of stability, and then a slow SE movement between 2007–2010 (dark and light blue arrows) occurred during a period of sustained ashing, after which the NW movements recommenced. A smaller syn-eruption deflation occurred during the 2014 eruption (dark blue arrow). Marked near-instantaneous offsets can also be seen, caused by the large 2000 and 2019 regional 'New Ireland earthquakes' (NI Eq) (green arrows). It is particularly clear that the 2019 regional NI Eq led to a period of accelerating deformation (inflation) starting immediately after the earthquake, and becoming alarming during 2021, with corresponding uplift. In early 2022, stability returned and continues to the date of writing (green ellipse top left).

3.3. Some Comments on Possible Causes of the Observed Deformation

As mentioned in the introduction, the causes of surface deformation in volcanic areas are multiple and diverse, e.g., [22,23]. Calderas typically have long geological histories, leading to complex plumbing systems (bodies of magma of varying geometries, ages and composition; hydrostatically linked with others or as isolated pockets) and structures (suites of faults, including both those tectonically derived and those volcanically induced (circumferential, radial, etc.)). These fractures may or may not be intruded, with some acting as potential magma storage areas or conduits, and some may act as slip surfaces or as stress-focusing or attenuating discontinuities. As such analytical modelling of deformation data will always involve gross oversimplifications, this should be born in mind when trying to predict or explain the behavior of a volcano.

Rabaul in particular has multiple potential stress sources. Seismic tomography has shown three low-velocity anomalies (LVA) to be present [7,12]. These are the Harbour LVA, Mid-Crustal LVA and Rabuana LVA. Numerous eruptions have been recorded above the caldera's ring-faults, indicating that these are regularly intruded, acting as conduits and potentially providing locations for shallow magma storage. The top of the Harbour LVA is at about 3 km depth, at which lithospheric pressure may allow quasi-stable bubble nucleation and re-absorption if local conditions vary, leading to the possibility of complex volume changes at the top of the resident chamber. Also, the hydrological system at Rabaul appears unusual; the caldera block mainly consists of pumice, with much of its surface flooded by the sea. Investigations into the hydrological and geothermal system led to the need for a ship-based vibro-coring project in the early 1990s [24]. This study showed that the caldera floor is porous, resulting in seawater convection cells forming in the pumice, with areas of upwelling warm waters and areas of cold seawater down-draw. This porosity may actually reduce potential deformation due to stream production, as pressure is unable to build up under an impermeable cap.

Saunders 2001 [6], commenting on the pre-1994 analytical modelling of Rabaul, states: 'The broader pattern of intra-caldera up-doming has been modelled as being caused by one- or two-point sources at shallow levels within the caldera block (McKee et al., 1984 [4]; Mori et al., 1986 [25]; McKee et al., 1987 [26]; Archbold et al., 1988 [27]). Archbold et al., (1988) [27], however, he goes on to state that the deformation is complex and may not be related to a simple point-source model. McKee et al., (1985 [28], 1987 [26]) also suggest that, in order to explain some aspects of the observed deformation pattern, larger or more complex intrusions may be involved. De Natale and Pingue (1993) [29] relate the deformation to a response of the caldera structure to the stresses from a 4- to 5-km deep magma source. Newhall and Dzurisin (1988) [30] suggest that the new structural context provided by Greene et al., (1986) [3] allowed for a re-interpretation of the causes of the unrest, noting the alignment of the central anticlinal features and their associated faults with the long axis of the seismic ellipse. Graham et al., (1993) [24] also suggest a re-interpretation of the point-source models based on the hydrothermal regime, as does Saunders (1999) [31], who also suggests inconsistencies with the structural geology and surface strain patterns. Saunders (2001) [6] went on to produce simple two-dimensional FEM models based on the traditional plumbing model of calderas and was able to produce scenarios, which approximated the measured deformation patterns at Rabaul, and provided mechanisms to explain the significant temporal changes seen in the observed deformation pattern.

In the following discussion of the 2000s to the present, CORS GNSS data results from three modelling projects are included; two [13,32] use data from the same time period but use differing methodology. The project authors arrive at least three different models of the pressure sources, with volume discrepancies of ~40%. These projects were, however, attempting different things. While [13] was using a relatively new technique, FEM-based linear inversion of InSAR data capable of estimating the extended, arbitrary distribution of mass and pressure changes within the integration domain of FEM models'to try to constrain a realistic multiparameter plumbing system; Ref. [32] however, was developing a simple modelling strategy, based on 'Mogi sources' to give rapid first approximations of depth, location and volume of pressure sources. This technique was intended for use as a reasonably simple algorithm to apply to deformation data in house at institutions with limited resources.

The third project mentioned in the following section is another state-of-the-art attempt to produce geologically realistic results [33]. RVO is to collaborate with this team on a project entitled 'Volcano physical-chemical source dynamics constrained by non-linear geodetic time series', which proposes '. . .to develop a family of thermo-chemical mechanical models for a coupled conduit-magma reservoir system and constrain them with geodetic time series'; a technique which will attempt to produce geologically realistic detailed results, but which will remain as a specialist tool for the foreseeable future.

What follows is a narrative description of the possible causes of deformation defined by the GNSS data presented in this paper and refers to Figure 9 and Figure 14. Note there are numerous small events, changes of a few centimetres or minor changes of trend; here, only large or obvious deformations are discussed.

1. First Data Point to September 2000 New Ireland Earthquake and Related Deformation (Jan 2000–May 2001)

During early 2000, when this data set starts, Tavurvur was experiencing periodic periods of small vulcanian activity and occasional strombolian events. As such, the slight fluctuations in the deformation signal may be weak but real changes related to stresses increasing and releasing due to volatile build-up before and during discrete eruptions, respectively.

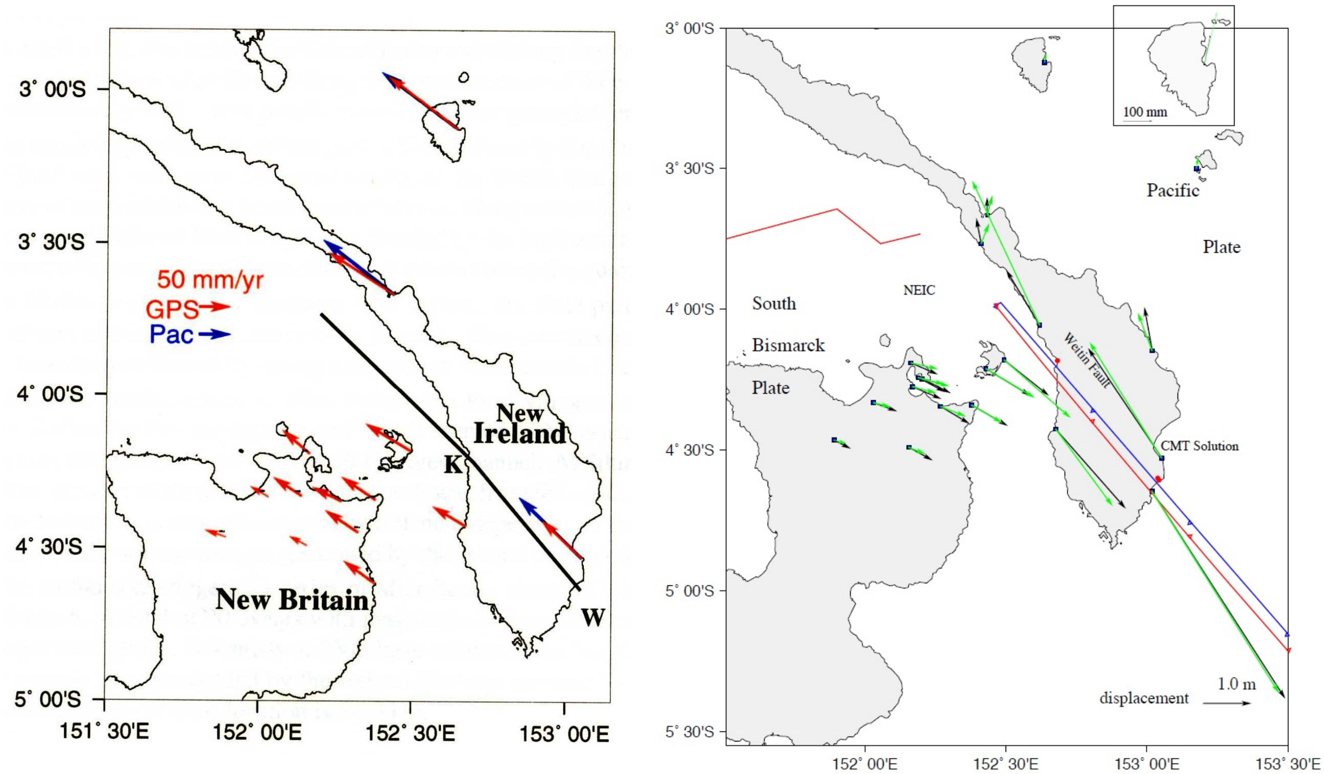
In November 2000, two very large earthquakes occurred on the Weitin fault [34] (see location in Figure 11a). The first earthquake caused tens of centimetres to metres of extension across the Gazelle Peninsula [35], perpendicular to the Nengmukta–Tavui Zone of Late Miocene-to-recent volcanoes (see [7] for location of NTZ and description). Rabaul Caldera's centre (SDA GNSS site), near-instantaneously subsided by 7–8 cm relative to the base station at RVO. This subsidence was possibly due to the NW–SE extensional stretching increasing the E–W dimensions of the chamber while the magma volume initially stayed the same, causing the roof to sag. Alternatively, the extension of peripheral faults may have allowed passive intrusion of magma away from the reservoir, causing slight drainage. The instantaneous nature of the subsidence, however, would favour the first mechanism. If the chamber is simply modelled as an elliptical container, with an arbitrarily NNE–SSW profile of 5 km by 3 km top to bottom, if it was perpendicularly stretched by 10 cm the volume increase would be in the order of a ~1.2×10^6 m^3 (simply modelled as the introduction of a 5000 m $\times$ 3000 m $\times$ 0.1 m elliptical cylinder). This near-instantaneous increase in the volume of the container would have decompressed the magma body, possibly causing some vesiculation throughout the resident dacite and the smaller volumes of recent basalt. This may have lowered rheologies, potentially increasing the mobility of the resident magma. This mechanism may have an important bearing on the subsequent intrusive and eruptive history of Rabaul, with Tavurvur's largest historical eruptions being recorded in 2006 and 2014 (e.g., [36], see their Figure 2).

The recorded subsidence had substantially recovered by June 2001, even though slow post-seismic extension continued (Tregoning, personal communication.). The relatively rapid (months) recovery may imply that new magma intruded the chamber, or that vesiculation occurred, returning the volume of resident magma to an ambient lithospheric pressure.

2. June 2001 to the 16 October 2006 eruption.

Following the re-inflation that occurred following the 2000 regional earthquake and related subsidence, a period of relative deformational stability occurred until February 2005. During this period, Tavurvur had long periods of quiescence, with no activity from mid-2001 to September 2002; activity recommenced at this point and consisted of regular vulcanian events. These ceased February 2004, resulting in about 8 months of inactivity. Starting in January 2005, a period of sub-continuous vulcanian activity and periods of billowing ash emissions began (see [37] for a geochemical-based interpretation of Tavurvur's plumbing in this period). Contrary to customary logic, this period of renewed activity coincided with the start of a period of relatively rapid uplift. At the time, it was suggested that this was a response to a deeper intrusion 'pushing older shallower material out'. This relatively rapid uplift continued until the major sub-plinian eruption of

16 October 2006. This period of rapid uplift between the start of 2005 and the 2006 eruption involved a two-part pattern or 'doublet'; (1) a steady, near-linear 6–7-month rapid inflation during the initial stages of the resumption of eruptive activity, followed by (2) a short period of relative stability which began to accelerate to another phase of steady and rapid uplift (although not as rapid as the initial phase). This acceleration of uplift continued until the start of the sub-plinian event. Looking at Figure 9, it can be seen this pattern of uplift is similar to the uplift pattern of the early 1980s to 1994, a 'doublet' of rapid near-liner uplift; then an abrupt deceleration, mid-1985, followed by a gradual acceleration of uplift, giving a concaved curve, which led up to the 1994 eruption. The 2005–2006 'doublet' is, however, of a much smaller scale.



(**a**) (**b**)

Figure 11. (**a**,**b**) Measured compression and extension perpendicular to the direction of tectonic convergence, from [35]. (**a**) Within the South Bismarck Plate (SBP), the drag of the locked boundary of the Pacific Plate (PP) caused a slow NW compression to be observed 1998–2000 (blue arrows show modelled PP velocities if the boundary was not locked). (**b**) On 16 November 2000, the Weitin Fault ruptured (black line in (**a**)), and major extensional movements were observed (black arrows = GPS measured displacement, green = modelled displacements, using ruptured dipping fault plane shown by parallel v-hachured lines (red bottom, blue top of modelled fault)). Note that in (**a**), deformation is plotted in millimetres and years, whereas in (**b**) the scale of deformation is in metres and the time scale (for the RVO site at least) was less than one minute. It is assumed that this compression–extension process is cyclic with a reoccurrence period for large earthquakes in this sector of about 20 years.

The 2006 sub-plinian eruption led to a near-instantaneous subsidence of ~32 cm in ~6 h. The deformation then shows that a rapid rebound took place of ~5–6 cm over the next 26 days, with half of the recovery occurring in just the first 6–7 days. This rapid rebound has been attributed to a simple 'bounce', resulting from the several-billion-ton caldera roof accelerating downwards ~32 cm in ~6 h; its momentum may have taken it past the systems point of equilibrium, hence the readjustment.

3. Post-2006 Eruption to the end of 2009.

After this post-eruption rebound, a period of deformational stability lasted until Sep. 2007, when a period of prolonged subsidence commenced. The subsidence coincided with the start of, at first periodic, then billowing ash emissions; from the start of ~2008, these billowing emissions became almost continuous until the end of 2009. From early- to mid-2009, glowing lava domes began to be observed within the crater; see Figure 12.

Figure 12. At left, an active lava dome present in the SW sector of Tavurvur's crater in May 2009. At right, the same feature in 2013 now appears as a plug due to continued collapse of the crater floor. An active debris-covered dome can be seen on the floor to the left of the plug. The plug was destroyed not long after this image was taken due to collapse, possibly during explosive activity.

The cause of this more than 2-year period of sustained subsidence may be related to the size and nature of the 2006 eruption. The 2006 eruption was unusual for Tavurvur, being larger than previous historical events.

Reference [8], using a joint inversion using this GNSS data, plus InSAR data, arrived at a volume lost of ~1×10^7 m^3 between February 2008 and November 2009. Using the InSAR data alone, the lost volume was modelled as ~3.5×10^7 m^3. Also, their method resulted in two source depths being of almost equal fit: one of 6.5 km depth southwest of the SDA site and northeast of VIS, and a second source of 1.5 km depth south of SPT. Reference [13] estimates a total volume loss of 119×10^6 m^3 between February 2007 and December 2010, from 'two main pressure sources at opposite sides of the caldera and connected at depth'. These variations in lost-volume estimates, location and geometry of sources arrived at by analytical modelling for a similar time period, highlight the uncertainties inherent in modelling caldera systems using deformation data alone.

4. End of the subsidence to the 2014 eruption (December 2009 to August 2014)

In December 2009, the sub-continuous billowing eruptions came to an end; with the cessation of eruptive activity, re-inflation immediately commenced. An intuitive reason for this was that the 2006 eruption had reamed out the conduit to depth, allowing the passive degassing of the main caldera magma body. As gas pressure ultimately began to fall, the upper conduit again became blocked by debris. Gas pressure was then able to again build up, leading to the re-inflation. During the deflation and ashing, it appears that viscous magma was intruding the conduit, with active domes present by early 2009 (see Figure 12), indicating some of the deflation was due to relatively degassed magma leaving the main chamber without significant replenishment.

Initial visits to the crater in 2010 revealed a sealed vent, with no emissions other than fumaroles. By early 2011, small high-pressure vents were present which became incandescent by mid-year. A debris-covered dome was present by 2013 (Figure 12). By early 2014, the large dome present in previous visits no longer existed, but smaller uncovered domes were present in a deep hollow where the previous dome had been; these would sometimes lead to an observable night-time glow if low cloud was present. Sub-continuous degassing from the interface of these domes/plugs with the vent material resulted in small dark grey ash emissions being produced, often only noticeable from a distance as a light haze above the vent. Occasional dome disruption would produce heavier ash emissions. This basic pattern of activity during the period of uplift continued until early March 2014, at which point the uplift ceased and a period of stability occurred (visits to the summit showed no real change with small incandescent domes present with ash being winnowed from its interface with the crater floor). The deformational stability remained until the eruption of 29 August, although there was a very slight (~2 cm uplift starting from mid-August). Even though the sub-plinian eruption was powerful, with an ash plume forcefully ejected to a height of 18 km, and large explosions that threw several-meter diameter cow-pat bombs more than a kilometre from the vent, the total subsidence as measured at SDA was only 6–7 cm. Occasional strong explosions continued to 30 August, after which activity reduced to occasional ashing and final cessation. No eruptive activity has taken place at Rabaul since. The huge difference in the scale of deformation between the large 2006 and 2014 eruptions seems to indicate that in 2006 the main chamber was involved, whereas the 2014 eruption may have been just the conduit plug explosively disintegrating, the main chamber by this time being relativity degassed.

5. Post-2014 eruption to present.

Immediately following the 2014 eruption, a gradual uplift began, totalling 10 cm by March 2017, after which a period of stability occurred from mid-February 2019 until the 14 May 2019 New Ireland earthquake, which immediately initiated a period of accelerated deformation, which was most notable in the horizontal data. This deformation became alarming from the start of April 2021, with 20 cm of uplift occurring by the end of March 2022, after which stability returned.

Modelling in [33] uses both GNSS and InSAR data for this period of rapid deformation; the authors propose a NNE–SSW sill-like body at 2.5–3 km depth, running from the mouth of Greet Harbour south to about 1 km NW of Ralauana point (See Figure 13).

This period of alarming uplift was near linear, similar to the linear part of the early 1980s to 1994 ‘doublet’ of uplift and that of the 2005 to 2006 ‘doublet’. The modelling by [33] describing a deep-seated source may indicate that the linear part of the earlier ‘doublets’ were also a response to deeper intrusion. The later-accelerating, or curved uplift pattern, which make up the second part of the earlier ‘doublets’, may represent an upward migration or shallowing of the intrusion [6], or be a geochemical response to the magma’s new environment after emplacement, or be a response of the caldera structure to the stress of emplacement of the deep intrusion, incrementally weakening structures/potential pathways and allowing the final rise of the magma.

The deformational stability of the Rabaul Caldera that commenced in early 2022 has continued to the present (July 2023).

The lead author has argued elsewhere (unpublished) that the volcanism in the Gazelle Peninsula, the Nengmukta-Tavui Zone of Late Miocene-to-recentvolcanoes, owes its origins and behavior to induced extensional tectonics, as the SE corner of the South Bismarck Plate rotates into the uniquely configured area of the Pacific-Solomon-South Bismarck Plate Triple Junction; ill defined, but assumed to be just south of New Ireland. This periodic (typically decades apart), rapid and strongly induced SE–SSE extension (e.g., Figure 11) which is seen during large seismic events in the area of the triple junction and on the strike slip South Bismarck Plate/Pacific Plate boundary, may be instrumental in controlling the timing and behavior of volcanism at Rabaul.

Other calderas around the world have experienced similar deformation to that which ledup to the 1994 eruption at Rabaul. Space does not permit an in-depth discussion of these other calderas, but the behavior of Rabaul may serve as a cautionary example; after large inflation events, eruptions can occur with very short lead-up times. The unique nature of Rabaul’s tectonic relationship mentioned above may mean that its behavior cannot be compared to other large, deforming calderas that are in quite different tectonic environments.

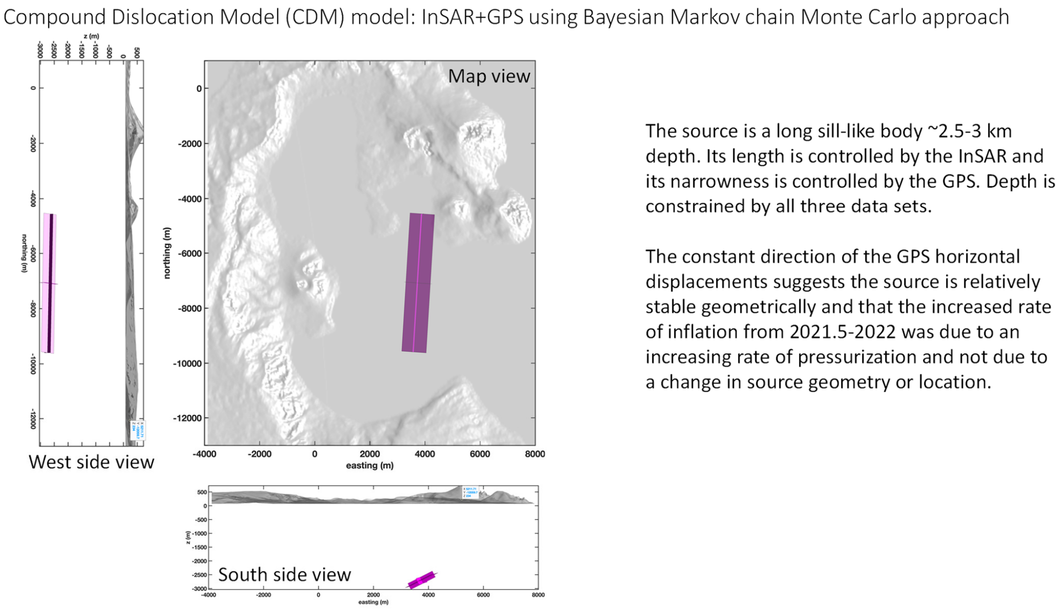


Figure 13. A model of a possible inflation source (purple) causing the 2021 to 2022 inflation, derived from the GNSS data, combined with InSAR data, using Bayesian Markov chain Monte Carlo approach [33]. A slide from a talk given at the 'Cities on Volcanoes 11' conference, Crete, Greece, 2022.

4. The Future?

As already alluded to, very cheap differential GPS (GNSS) systems are now available. These cost hundreds of dollars rather than tens of thousands. At present, RVO is evaluating ArduSimple's dual-frequency system, which uses the U-Blox ZED F9P chip, utilizing GPS, GLONASS, Galileo and Bei Dou constellations to produce RTK solutions. Corrections sent from a local base station allow the remote receiver to solve carrier ambiguities and provide centimetre-level-accurate positions. Using the Free U-Center software on a Laptop or PC connected to the remote, centimetre real-time solutions will start to be recorded/plotted for sites up to ~15 km distant from the base, if there is a line of sight. An example of a currently operating short-baseline dam monitoring system using low-cost instruments (U-Blox NEO-M8T GNSS), linked to an automated alert system, is outlined in [38].

So far, our tests on baselines, which for volcano monitoring must be from relatively stable areas to the potentially deforming part of a volcano, must typically be around 10 km in length and often involve many hundreds of metres of elevation, have been promising. Like most systems, however, the claimed accuracies are compromised in real life by such things as local radio interference and impediments to the quality of the broad line of sight (Fresnel zone). Even though the system appears not to be quite as precise as more expensive systems it is thought that they will provide useful data where deformation monitoring would otherwise be prohibitively expensive.

Like more expensive receivers, if connected to a data logger, individual U-Blox ZED F9P units will record high-quality GNSS data usable for post-processing in local or regional networks.

5. Discussion

This paper has been written as a narrative history of the use of GPS/GNSS at Rabaul Volcano Observatory, rather than as an in-depth analysis of the data and its systematic application to analytical modelling; to a certain extent, this has been done elsewhere (e.g., [8,13,32,33]). In this narrative context, Figure 14 shows the practical way in which the Observatory has been able to use data produced by this technique to address community questions in realtime. The technique enables simple easily understood answers to be given at any particular point in time, even when other parameters are absent, such as during times of aseismicity and periods of stable gas and thermal readings.

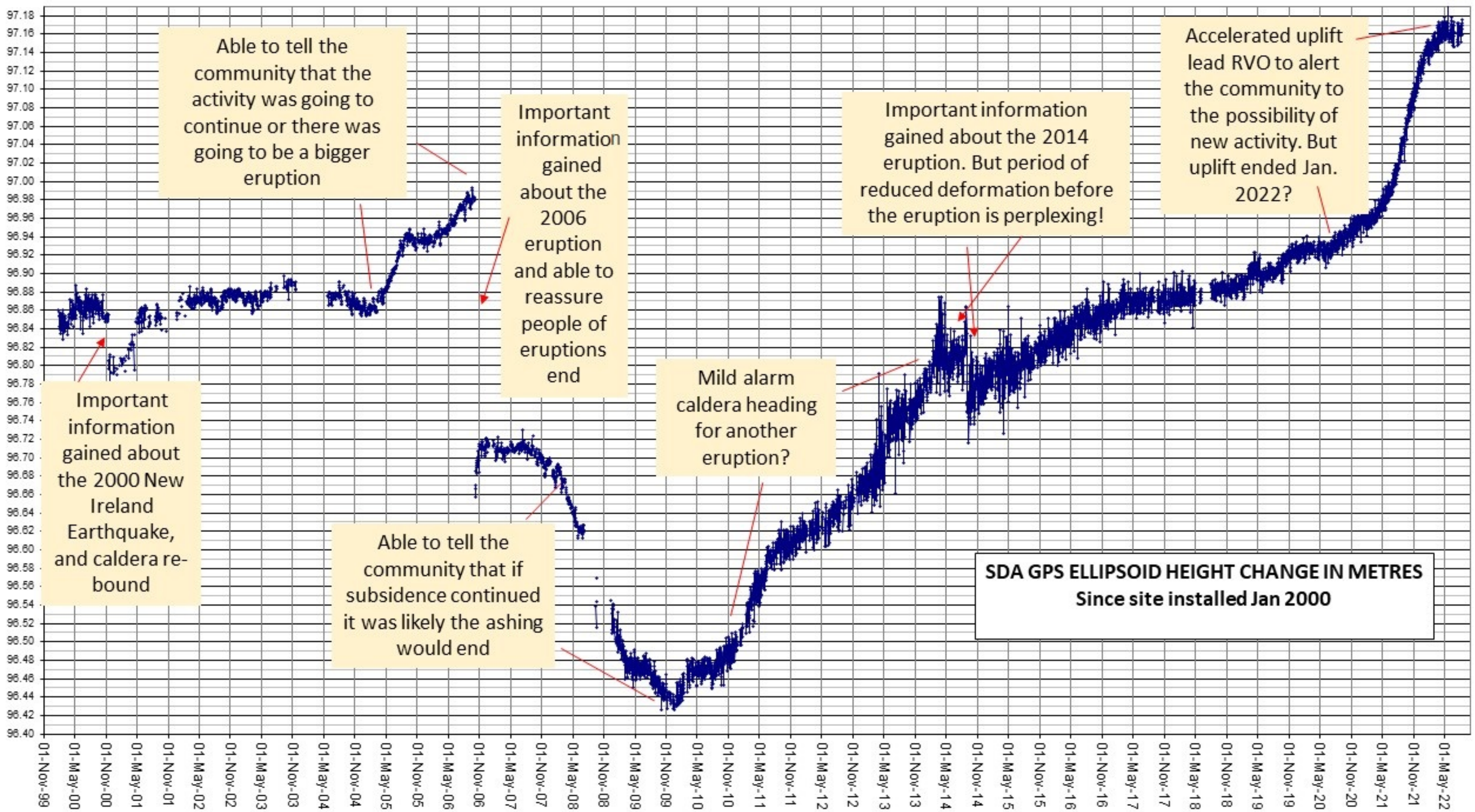


Figure 14. Important conclusions from CORS GNSS at Rabaul. As mentioned above, geophysical data is often used to model complex subsurface plumbing and processes. The bottom line for an observatory, however, is to be able to respond to questions from the local communities in realtime. The Rabaul CORS system has sometimes enabled this; above are examples of simple messages the Observatory was able to relay to the community during certain periods based on this data set.

The technique has proved itself to be extremely useful, and with the emergence of much cheaper systems hopefully the technique will be expanded to other volcanoes of PNG.

6. Conclusions

RVO was perhaps overly optimistic in 1996 in wanting a Real-Time GPS monitoring system. When actually operating, however, the Real-Time system was of great use during times of crisis.

Operating GPS/GNSS receivers as a CORS network has proved to be more sustainable and affordable than a Real-Time System. Using the network as CORS with daily or more frequent post-processing has proven to be a powerful tool, producing a scientifically important data set; but most importantly, it has provided a near-continuous insight into the state of the volcano, one that is easily understood by the general public(see Figure 14).

Patterns of deformation have been recognized at Rabaul that have helped in understanding the geodynamics (volcanological and tectonic [39]) and in forecasting the waxing and waning of eruptions. Often, it has been the only perimeter showing unrest or stability, especially during times of near-aseismicity, as occurred once the volcanic system became open after the initial 1994 eruption.

Of course, deformation itself cannot provide a complete understanding of a volcanic system, it being only one part of an integrated monitoring strategy, which may include seismology, geochemistry (solid, aqueous and gas), thermometry and various remotely sensed parameters, etc.

The extreme cost of GNSS equipment has always been a problem for RVO and manufacturers' over confidence or over complicated solutions have sometimes hampered RVO's use of it. But recently precise Real-Time and CORS systems are coming within the price range of modestly funded institutions. RVO hopes to utilize the new cheap GNSS systems to monitor not only Rabaul, but other volcanoes of PNG. Their wide geographic spread will also add to our understanding of PNG's tectonism and Crustal Motion.

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