Twenty-two years of GPS monitoring at Rabaul Caldera.

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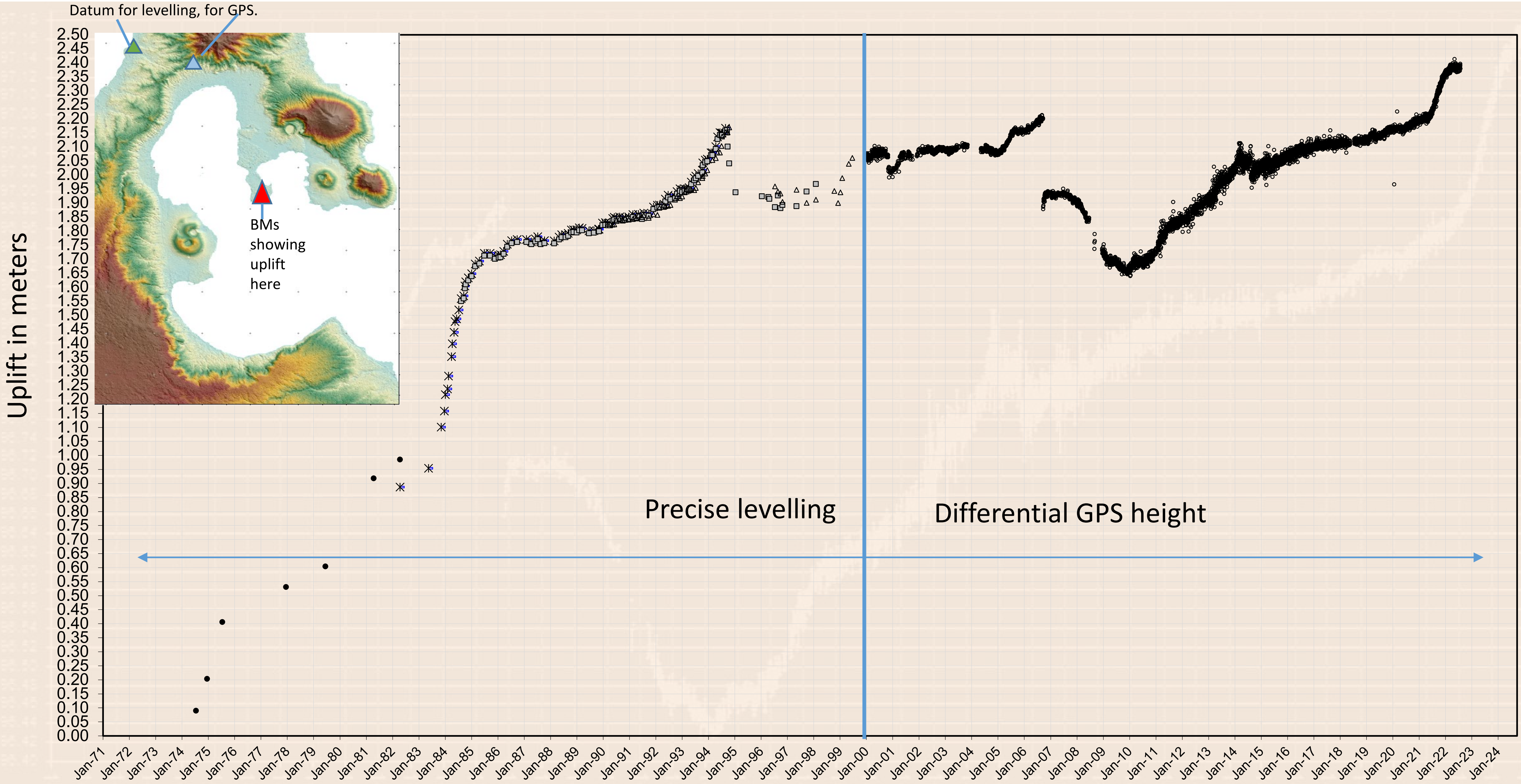
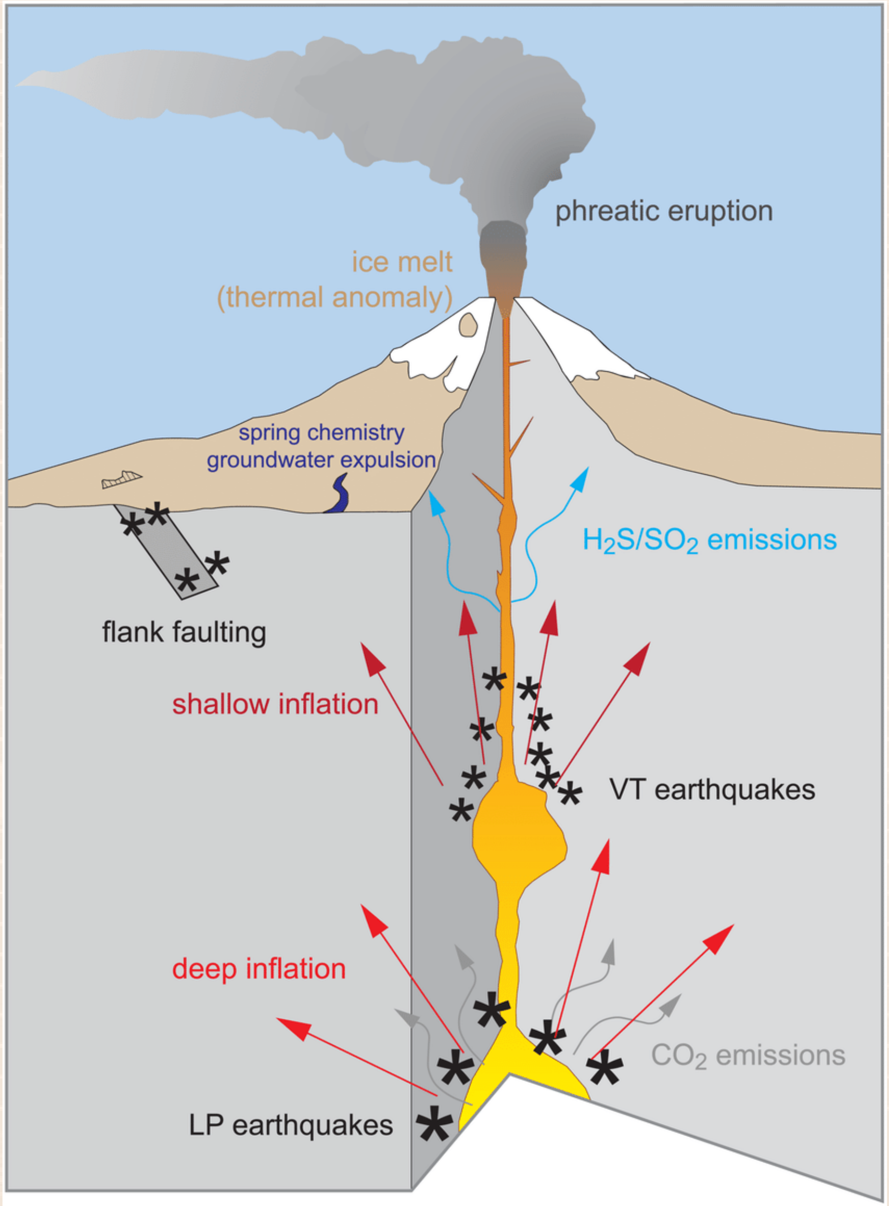
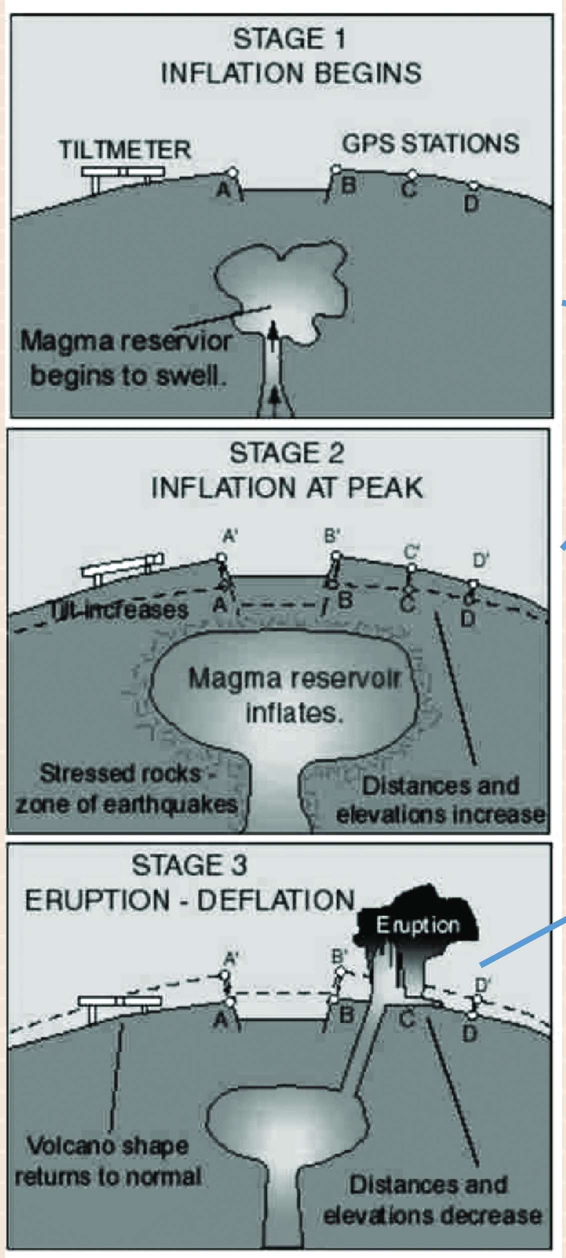


Uplift for various BMs at the south of Matupit from1972 to now. Before Jan 2000 measured by levelling, since 2000 by differential GPS. Rabaul Caldera does indeed deform!

Volcanoes deform due to many factors.

- Most simply as magma rises from depth it intrudes shallower parts of the earth's crust = earthquakes + deformation.
- Magma can initiate new cracks, intrude existing cracks or inflate existing bodies of older magma.
- The magma bodies can expand or contract due to bubbles forming or collapsing.
- Steam can be produced causing hydrostatic pressure in the surrounding rocks.
- Cooling magma can contract; crystalizing magma can expand.
- Many volcanoes are located in tectonically active areas. Tectonic stress can compress or extend fluid bodies of magma.





Simple model of an inflation-deflation cycle

Top two images, deep magma chamber, inflation will be broad and reasonably slow – years to months. It is constrained by the overburden and high lithostatic pressures. As such it can inflate and deflate with no eruption occurring.

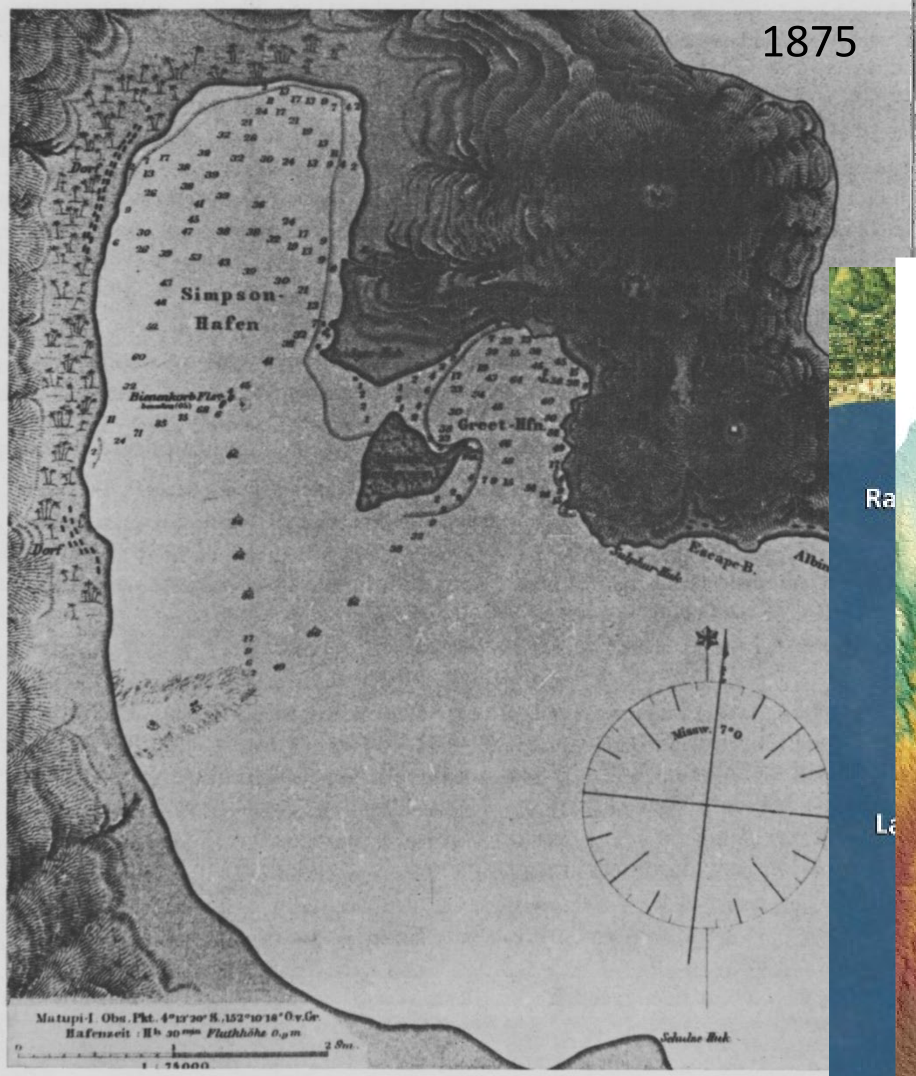
For magma to reach the surface, if no conduit exists, it has to intrude existing cracks or make it's own cracks. As gas rich magma approaches the surface lithostatic confining pressure falls, vesiculation (bubbling) will occur and the intrusion can become rapid. Leading to fast and localized deformation.

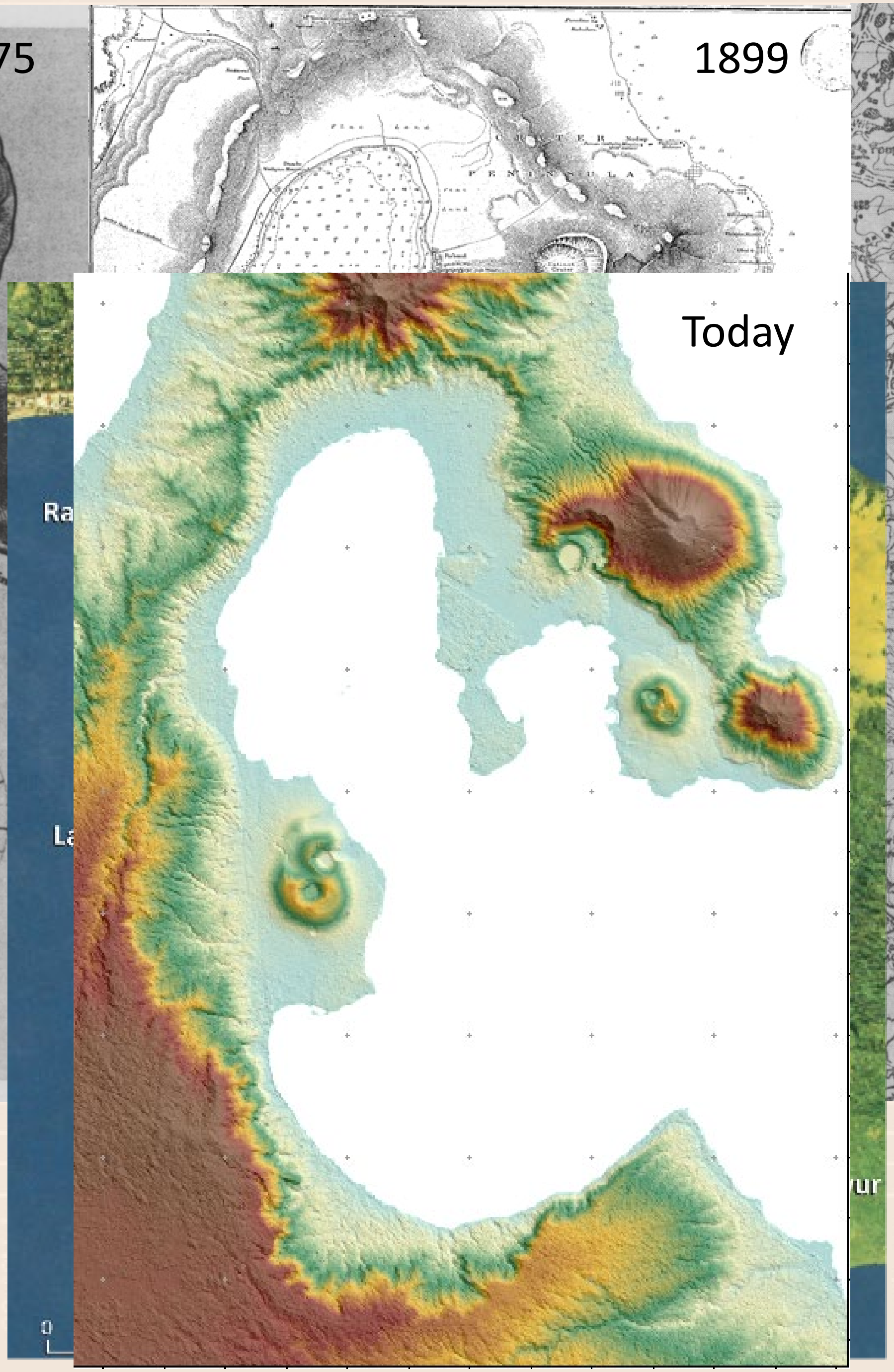
Rabaul shows two types of deformation.

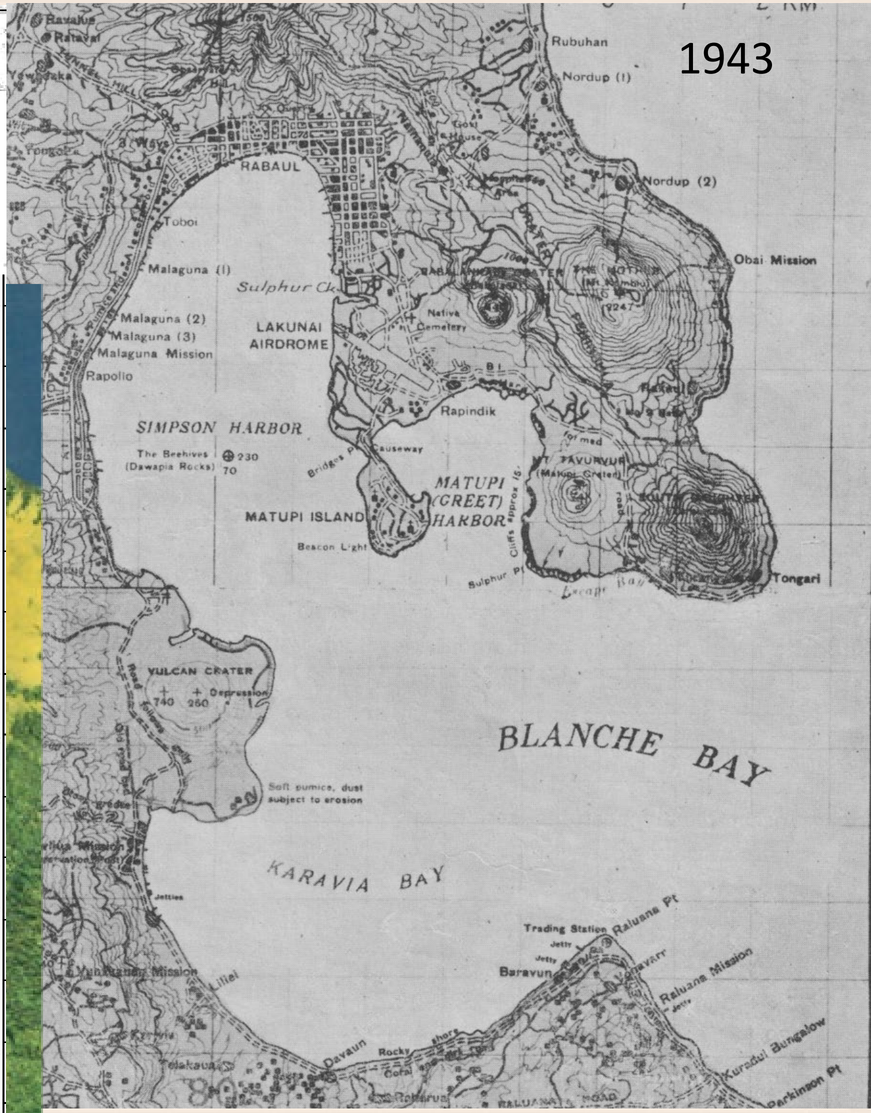
Broad and slow – Deep-seated source. Showing general 'health' of volcano.

Detailed and rapid – Showing magma is at shallow levels and may erupt.

Being able to identify the acceleration of deformation can be a powerful tool in predicting eruptions in the short time







Maps showing the changing land and sea scape at Rabaul, due to ground deformation and volcanic activity

The Rabaul caldera has always been known for its deformation; with the 500m offshore Matupit Island rising, hence expanding enabling first a bridge and then a Causeway to be built to the mainland. Vulcan was known slowly to rise and fall as were the Dawapia Rocks (the Bee Hives).

In 1937 a quaritine station was to be built on Vulcan Island. On a series of site inspections it was realized the land was sinking. Above a cartoon of what might happen if it were built.

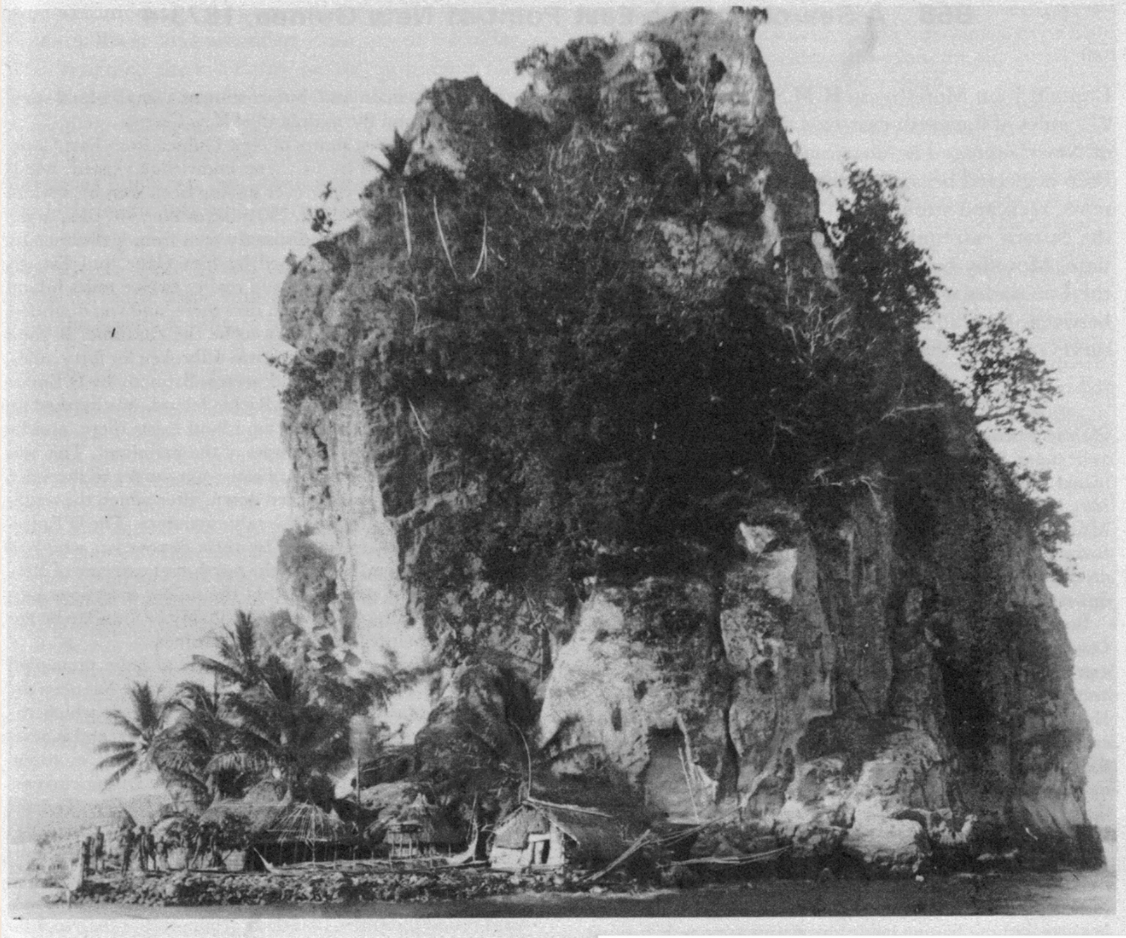


PLATE 33: The Beehive Rock, Blanche Bay, New Britain, 1883.

The Dawapia Rocks in 1883. Higher than now, with houses and trees at its base, notice raised wave cut notch at right.

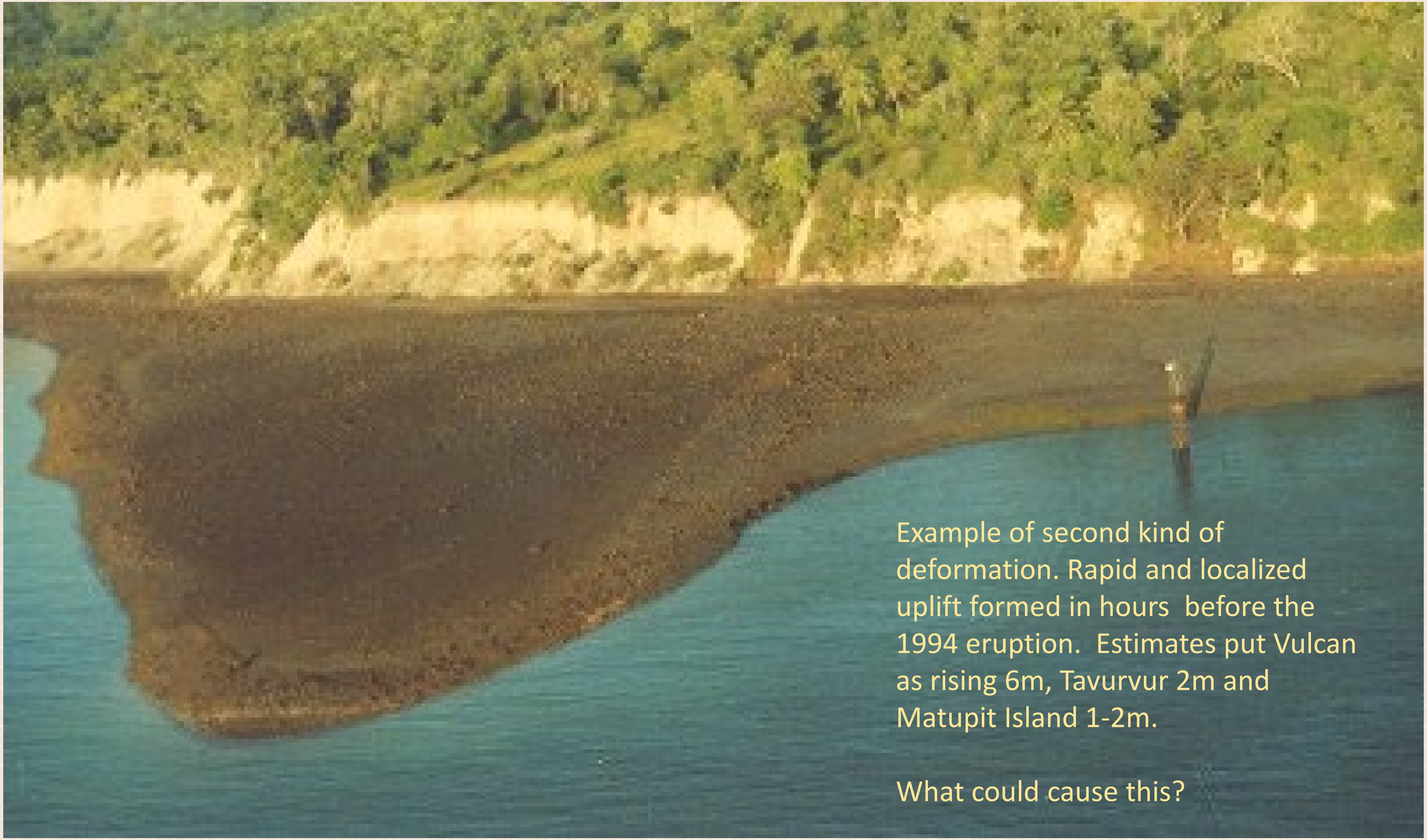
Example of Broad Uplift in Center of Caldera

Matupit Island's transition to 'Matupit Peninsular'

1912, view looking towards Tavurvur across the north point of Matupit 'Island'.

Matupit, 1994. The view direction of the 1912 photo is shown. The coastal cliffs in the bay formed by the uplifted causeway can be seen to record a complex history of wave cut terraces.


1966
Example of first kind of deformation. Broad and relatively slow.


Example of second kind of deformation. Rapid and localized uplift formed in hours before the 1994 eruption. Estimates put Vulcan as rising 6m, Tavurvur 2m and Matupit Island 1-2m.
What could cause this?

View from inside Palangiangia, behind Rabalanakia. The walls of the Palangiangia cone are cut by numerous sub-vertical thin intrusions in cracks, called 'dykes'. As they are thin the magma must have been quite fluid, probably basalt.

Magma moves primarily through the crust in cracks. Cracks widen, can inflate in certain locations, or be eroded by preferential flow to produce conduits etc., they can coalesce and melt surrounding rock to form huge intrusions.

Shallow intrusions lead to eruptions when they intersect the surface

Thick intrusions in the Eastern Wall of Rabaul Caldera. Their intrusion at such shallow levels would have produced significant and localized deformation at the time.

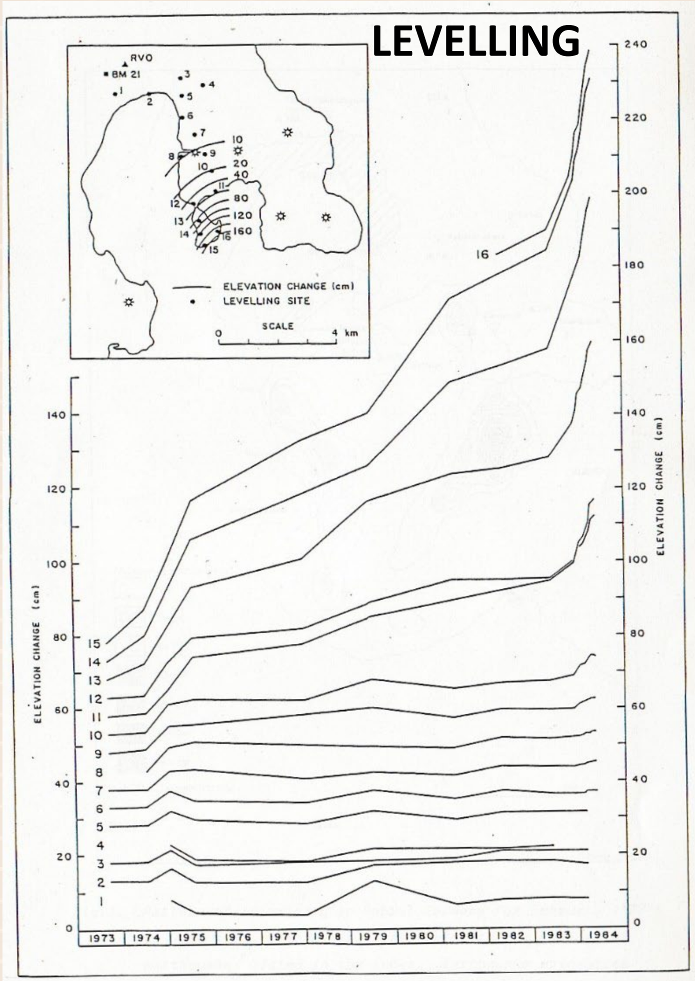
These large thick intrusions (predominantly dacite) would have been viscous magma, which would not easily flow up thin cracks. They seem to have wedged open the 1400 BP caldera fracture system here?

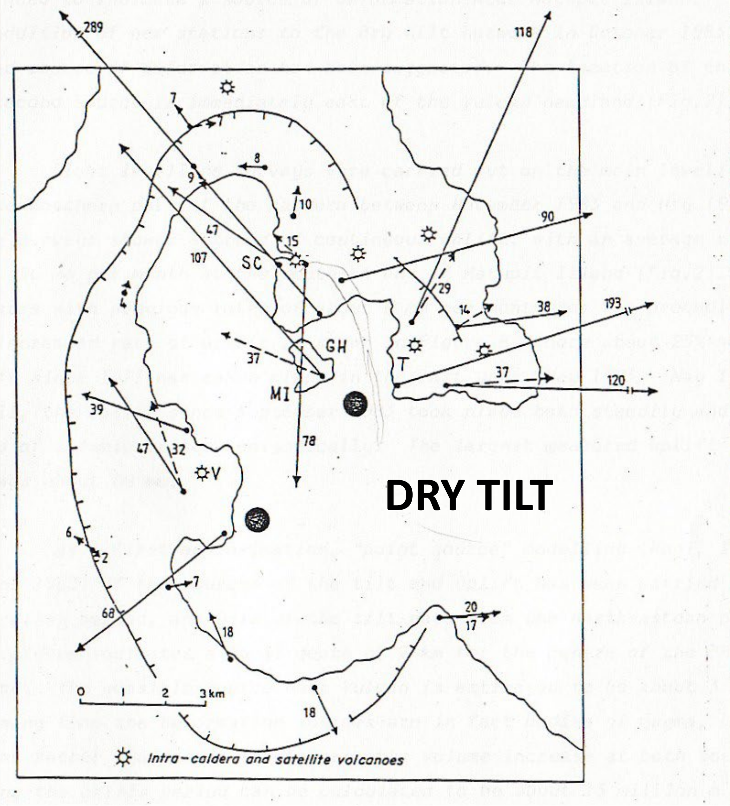
N.B. Lack of exposure due to thick vegetation before the bush was stripped by volcanic activity, lead to these Intrusions being called the 'East Wall Lavas'.

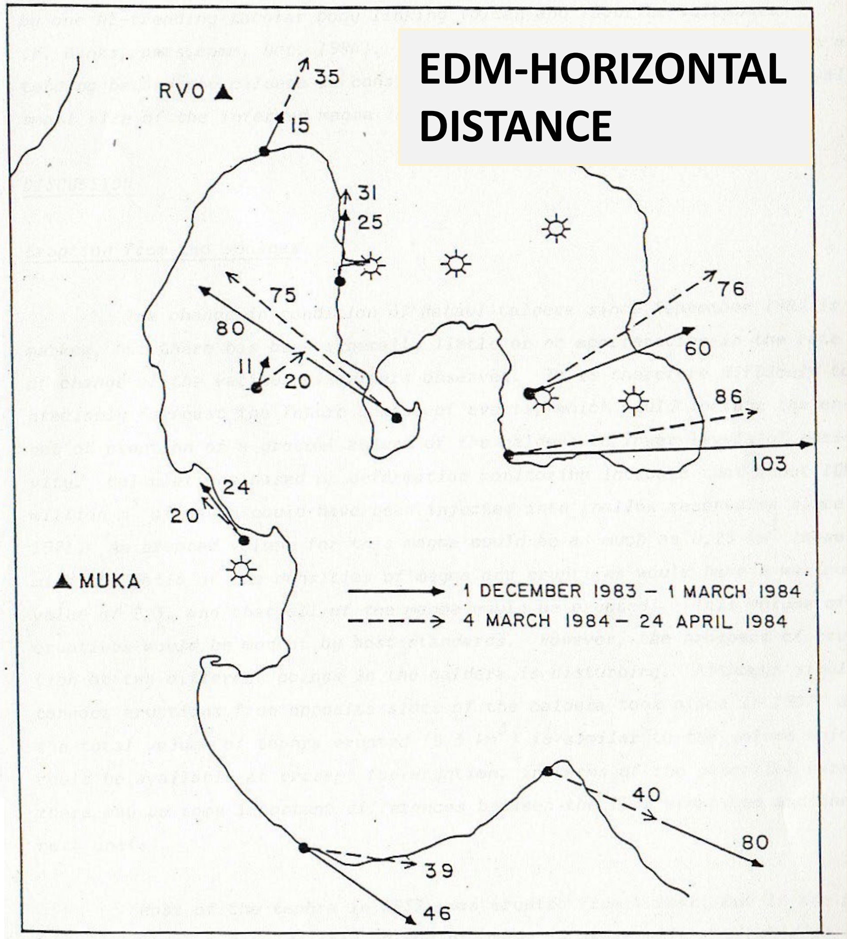
Rapid deformation of ~6m at the Vulcan Tide Gauge, just before the Vulcan eruption. Caused by a shallow intrusion of relatively viscous magma in caldera fractures below Vulcan?

??Could the lesser deformation estimates at Tavurur in the hours before the eruption be due to thinner fluid basaltic dykes intruding there??

The broad scale movements had been satisfactorily measured with traditional surveying techniques since the early 1970s leveling, and dry tilt and EDM Horizontal Distance changes - from early 1980s.







As can be seen in the former slide the broad and steady deformation that had occurred in the previous decades had been well constrained by traditional surveying techniques.

The large magnitude and rapid deformation that occurred in the hours before the 1994 eruption at Vulcan, and to a lesser extent Tavurvur lead to the conclusion that if these rapid movements during the night of 18-19th September 1994 could have been seen in real-time a much better forecast of an eruption could have been made.

In the 1990s few options were open for real-time deformation monitoring.

Electronic tilt meters and tide gauges were in theory able to transmit data in real-time, but both had problems with reliable telemetry. Tide gauges were extremely expensive, three that had been installed in the 1980s but were un-serviceable within a few years; and their location was of course limited by bathymetry. Tiltmeters are of limited value as they do not show the magnitude of uplift or horizontal movement, just whether a 20cm patch of ground had tilted. Electronic Tilt meters were also very noisy, responding to fluctuating temperatures and local disturbances.

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

Several volcanoes around the world were monitored by campaign style Static GPS surveys of benchmarks. Such as on Mount Etna, Italy; Piton de la Fournaise, Reunion Island, Hawaii, Japan and several others places. And as laid out below a GPS Network had just been installed and measure at Rabaul in 1995.

An interesting GPS monitoring system working at this time (1996) was on Augustine Volcano on the Aleutian Islands. After 4 years of experimentation a successful low power, low cost, remote system was developed. 3 permanent L1 only GPS receivers (Ashtec SCA-12) were installed. Once a week they were polled from an office in Homer 150 km away and around an hour of data was downloaded. This was in turn sent to the Cascades Volcano Observatory for processing using PRISM software. The weekly positions enabled a general idea of how the volcano was deforming and at times of interest more frequent data polling could be initiated.

Elliot Endo recommended this type of system to RVO in 1996, but procurement of a Real-time System had already commenced.

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 University of Technology, Lae, (Unitech) 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.

- The September 1994 eruption occurred. RVO's resources were now dedicated to trying to replace equipment that had been destroyed.

- In early 1995 Unitech's surveying facility received funding to purchase a number of GPS receivers, 3 were dual frequency.

- RVO was able to provide funding for a Unitech trip to Rabaul in June, 1995. Russell Jackson, working with Nick Lauer and Alois Gawisa established ---
  - A local control baseline.
  - 12 benchmarks, with base coordinates observed.
  - Connections to existing marks and longer baselines to BMs outside the caldera; 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 changing. Detailing their achievements and aspirations.

- All this however was still aimed at periodic occupations of benchmarks with GPS equipment, with static results weekly or monthly.

- 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 Feb. 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 several German academics. The recipient of the system would be RVO. The date envisaged for the deployment of this Real-Time GPS System at Rabaul was however ~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 ~ two decades, in different manifestations, the project was a major source of resources, inspiration and encouragement for RVO (Thank you Wally!), and still continues today in an important but residual form).*

The SAGEM System (1996)

- The RVO-PNG academia drive of 1994-5 to develop GPS capabilities at Rabaul was encouraged by the new AGSO-RVO partnership. However, in mid-1995 it became apparent that the private sector was claiming to have developed centimeter, 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 Malcolm Somerville of AGSO had contacted them.

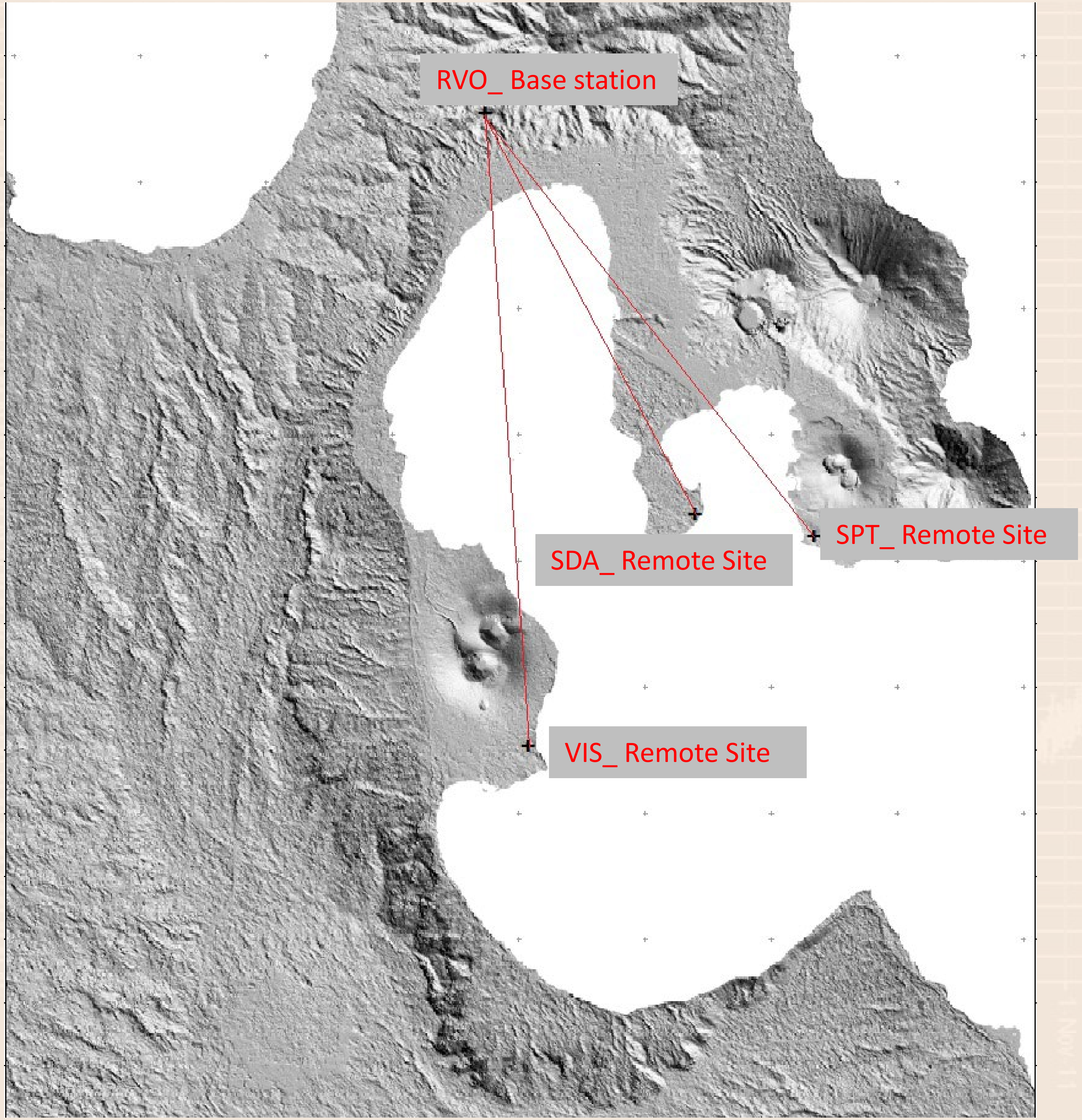
- After discussions with AGSO and Nick Lauer at RVO, SAGEM produced a document including a detailed description and a quote for an 'Off the Shelf' system. Including a 'roving' receiver and peripherals to survey off the volcano and run small local campaign surveys.

- The system was based on Ashtech Z12R (Base) and three Z12 (Remotes), linked by a Bel S103 radio telemetry system (at the time in use by electricity companies in Australia to remotely pole domestic meters!)

- The Ashtech Real-time Kinemtric (RTZ) system, used an Ashtec DBEN message sent from the Base Station (located at RVO) to resolve ambiguities at the Remote receiver, using Ashtec Z-tracking and PNAV algorithms. This internal GPS receiver (or 'onboard') processing at the Remote site produced 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.

- I came on the scene at this point. And was charged with putting this 'off the shelf' system together.
- It didn't work…
- First bet was that it was me!... So Russell Jackson was flown from Unitech. Although it 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 9 satellites were acquired. Also it 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 with 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 in short supply).
- Various remedial schemes were tried, and much toing-and-froing, lead by AGSO's Projects Manager, the inexhaustible - Shane Nancarrow. It eventually was found that the problem was an intrinsic one to the system's design. By 1999 it was realized a complete reworking was needed.
- Robust site infrastructure was, however, successfully designed and built.



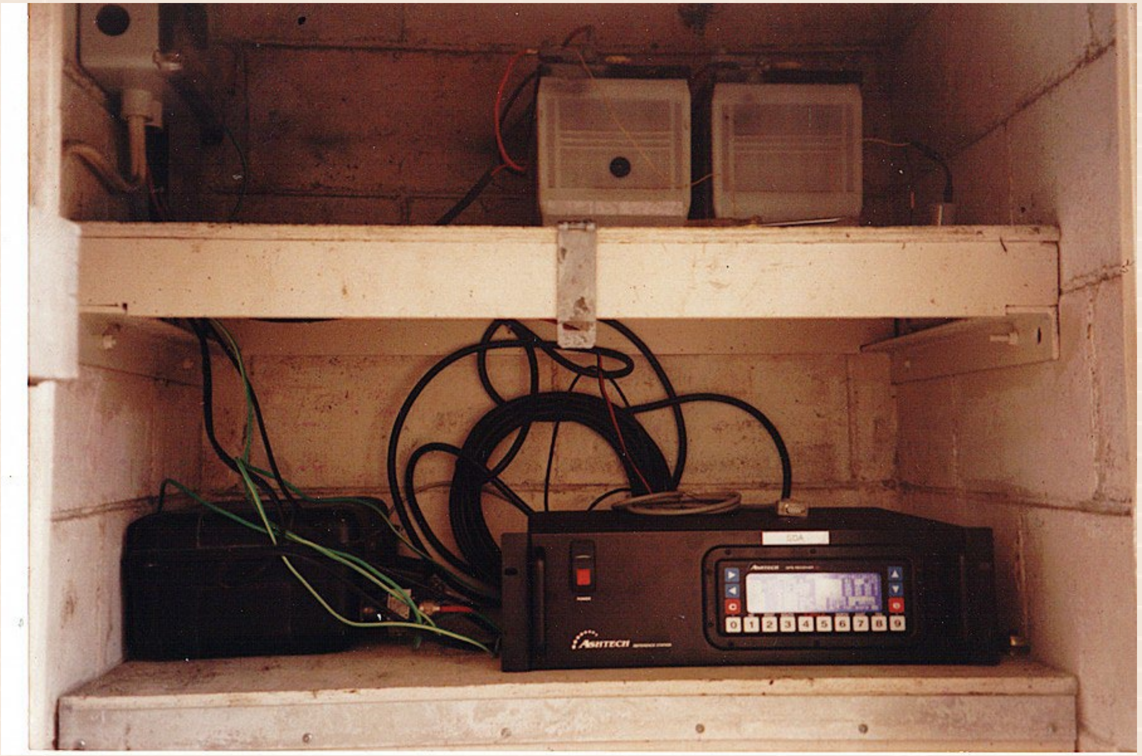
Rabaul Caldera Real-Time/CORS GPS Sites.

The infrastructure, with modifications has been in existence since 1996-97. Since Jan. 2000 both RVO_ and SDA_ have been in almost constant operation. VIS_ and SPT_ have suffered from vandalism on occasions and have long gaps in their data. VIS_ is today still operating, SPT_ however succumbed to coastal erosion in 2021.

1996 infrastructure put in place for the SAGEM system.

The Remote site at Vulcan Island South (VIS). A concrete bunker to house the receiver, telemetry, power etc. At left the choke ring antenna is being placed on a 6 m pole. At right a solar panel mast, with the telemetry yagi antennas. The masts are so high so as to avoid being over taken by tree growth. The opportunity was taken to co-host seismometers in the bunkers.

Elliot Endo inspects a bunker (1999), the Ashtech rack mount, housing the Z12 and Bel S103 radio can just be made out.



A Z12 housed in the SDA Church bell tower at ↑ Matupit. The receiver and original Bel S103 were housed in the rack mountable box. Box at left is electronics for a tilt meter and seismometer.

The Base Receiver at RVO, a very noisy trace can just be made out on the computer screen. At the right is the backpack for carrying the ‘roving receiver’, PRISM Astech ↓ post processing manuals can be seen in center.

The 'Hydra' System (2000)

- Fortuitously an Astech based system had been developed in collaboration with the USGS at Long Valley California in the late 1990's (Endo and Iwatsubo, 2000). 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.

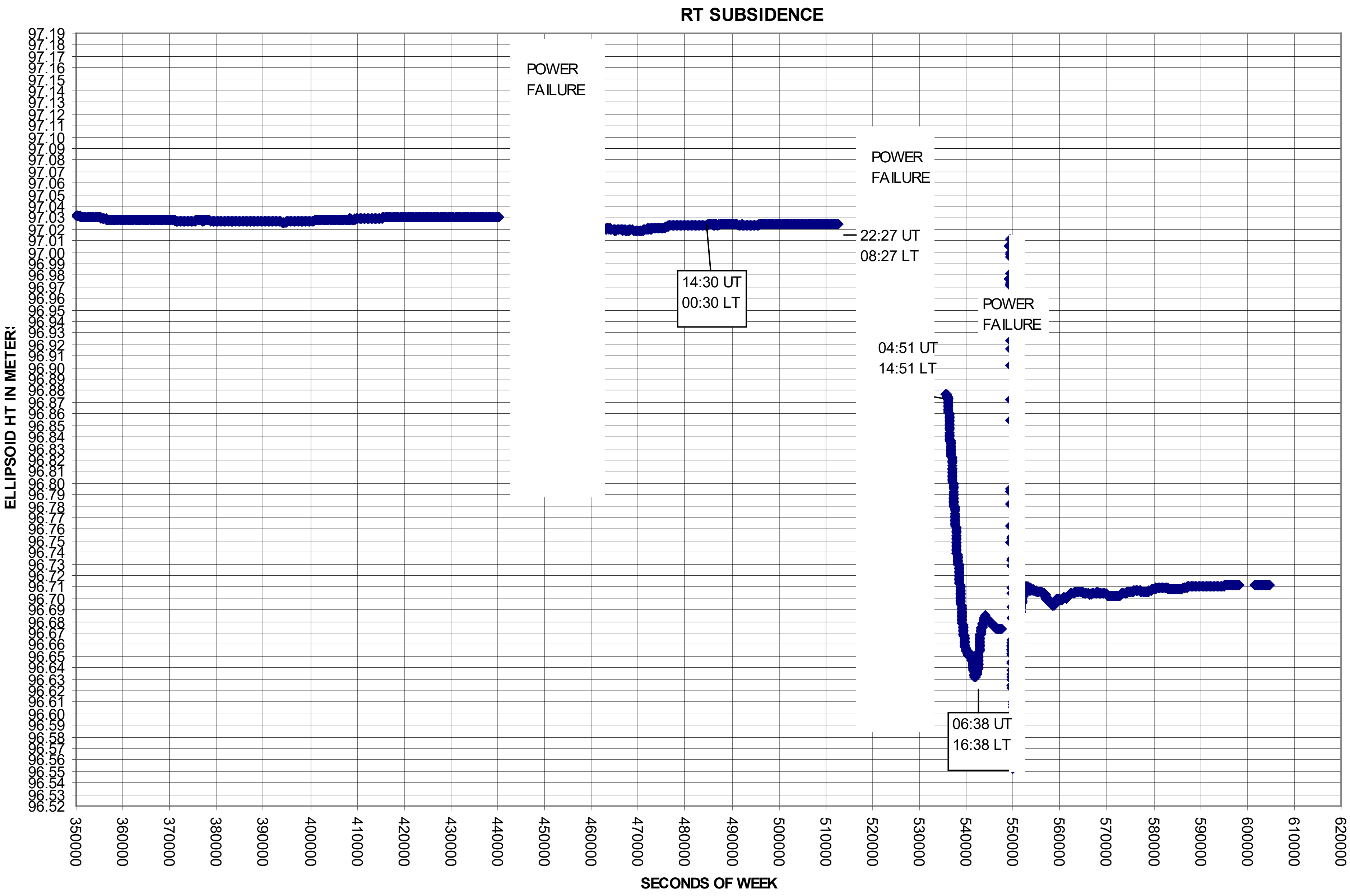
- As part of a collaborative effort between RVO-AGSO-USGS, this aspect was funded by the U.S. Office of Foreign Disaster Assistance, a project was started mid-October 1999.

- It was decided that much of the existing infrastructure would remain, the Ashtech Z12s would form the basis of the new system.

- An important component of the new system was 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'.

- 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). Including Magellan/Ashtech 'Geodetic Base Station Software' (GBSS), 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’ were provided for communications and data transfer between the various receivers.
- The problem of power at RVO was also addressed with line conditioners, surge protectors and large UPS’s.
- It worked almost perfectly, was user friendly and gave good results. Best of all the system was relatively simple and robust.



The most spectacular real-time response is shown here.

At 08:45LT 7th October 2006 with little warning a sub-plinian eruption began at Tavurvur, the eruptive column forcefully reached 18km in height and broke plate glass windows more than 10km away.

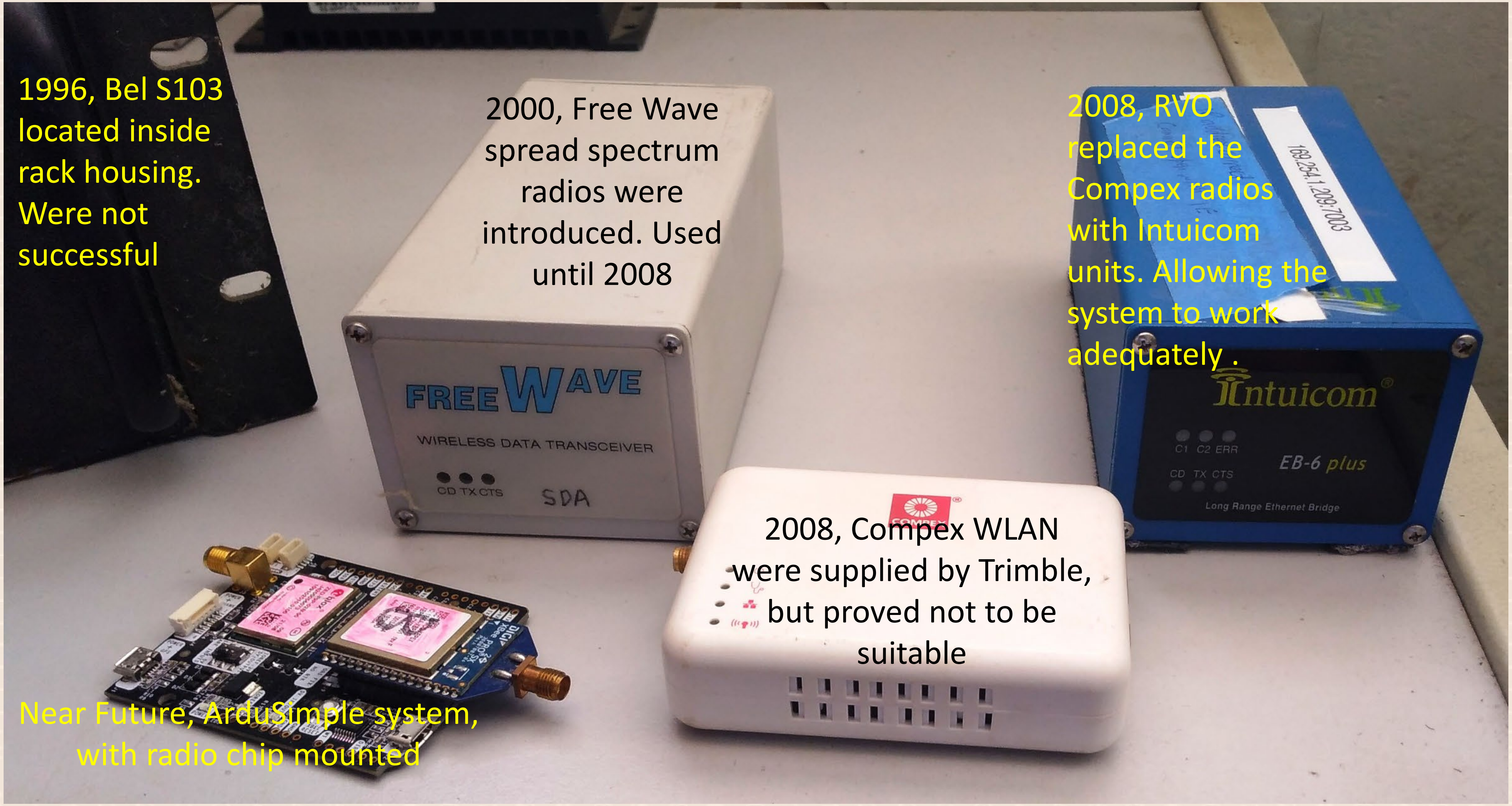
The RT site at SDA on Matupit showed in real-time subsidence of ~30 cm in ~6 hours. The subsidence stopped at 16:38 local time. Even though the volcano was obscured, debris still falling and the eruption still producing deafening explosions, we were able to say the worst was over.

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 the 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.
- 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 teething 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 3d-Tracker many crashes of TIM required phone calls to Singapore.
- Even though the system was fragile it ran until 2013, when the computer failed. Being a specialist computer, replacement was difficult and expensive.

Real-Time, or CORS Receivers used since 1996 at RVO

The Radio-Modems used at RVO for GPS data transfer or CPDs



Operating as a Continuously Operating Reference Stations (CORS) system 2013-

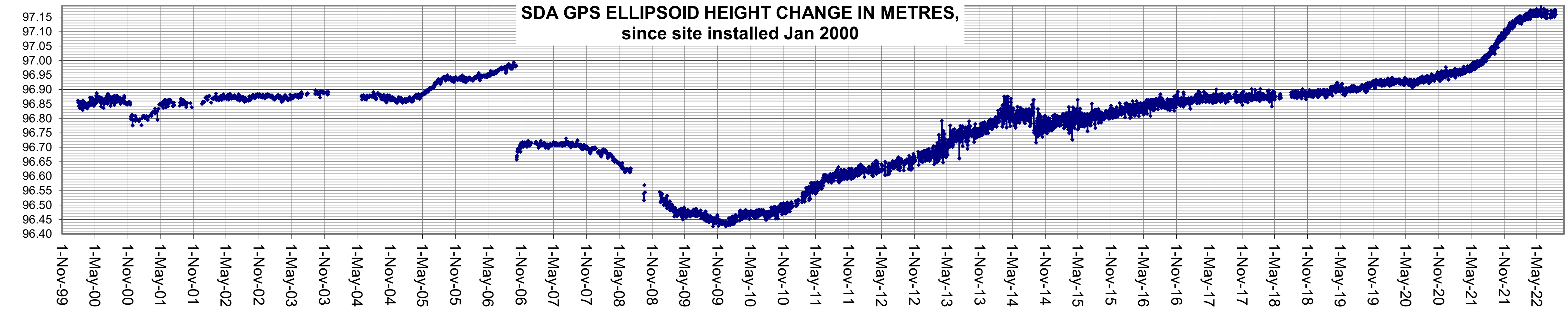
- Since 2013 raw data has been collected daily via ‘FileZilla’ (Trimble *.T02 files), and ‘Trimble Business Center’ (TBC) software used for post processing and Northing, Easting and Height (XYZ) plotted on an Excel spreadsheet.

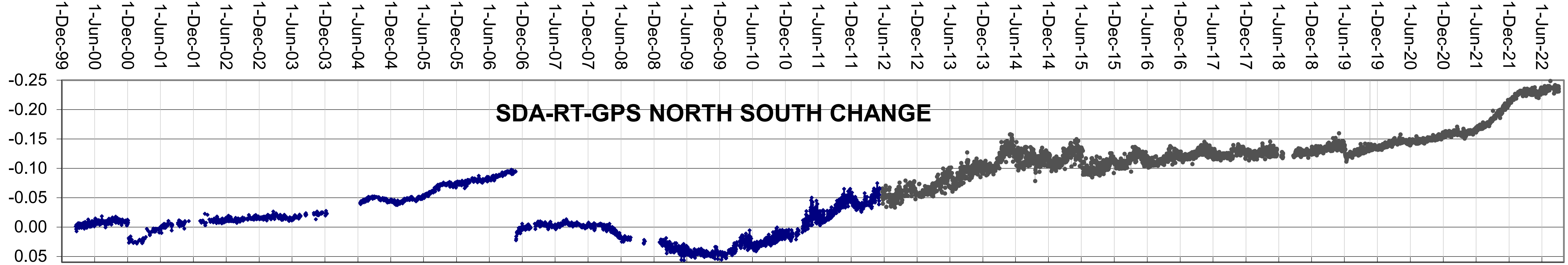
- Due to the original SAGEM system being purchased without internal memory in the Remotes, between 2000 and 2008, the daily plot was constructed by taking Ashtech Q files (list of RT epoch by epoch solutions) and taking the 24 hours average of those positions.

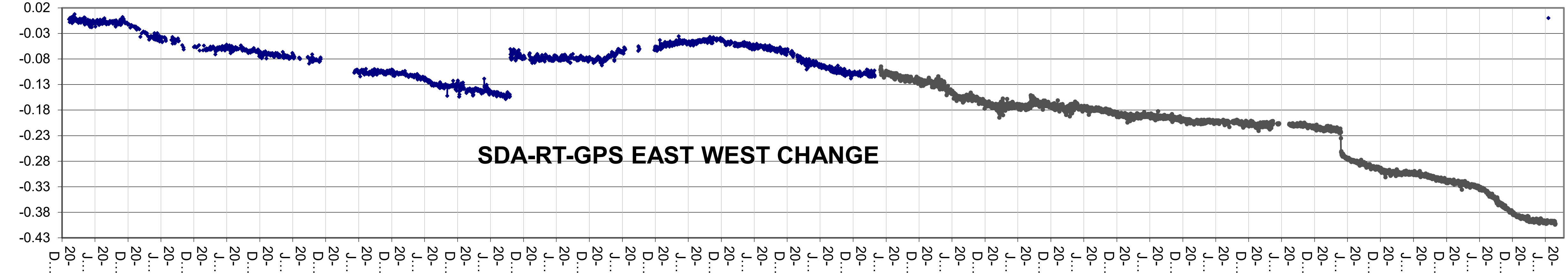
- The data, recorded on the receivers at 10 sec epochs is easily retrieved and when specific events occur, such as an earthquake or significant eruption can be examined in more detail, epoch by epoch if necessary. (Richard Stanaway has helped greatly running this data against the ‘Regional Reference Frame’ when geophysical phenomena occur)

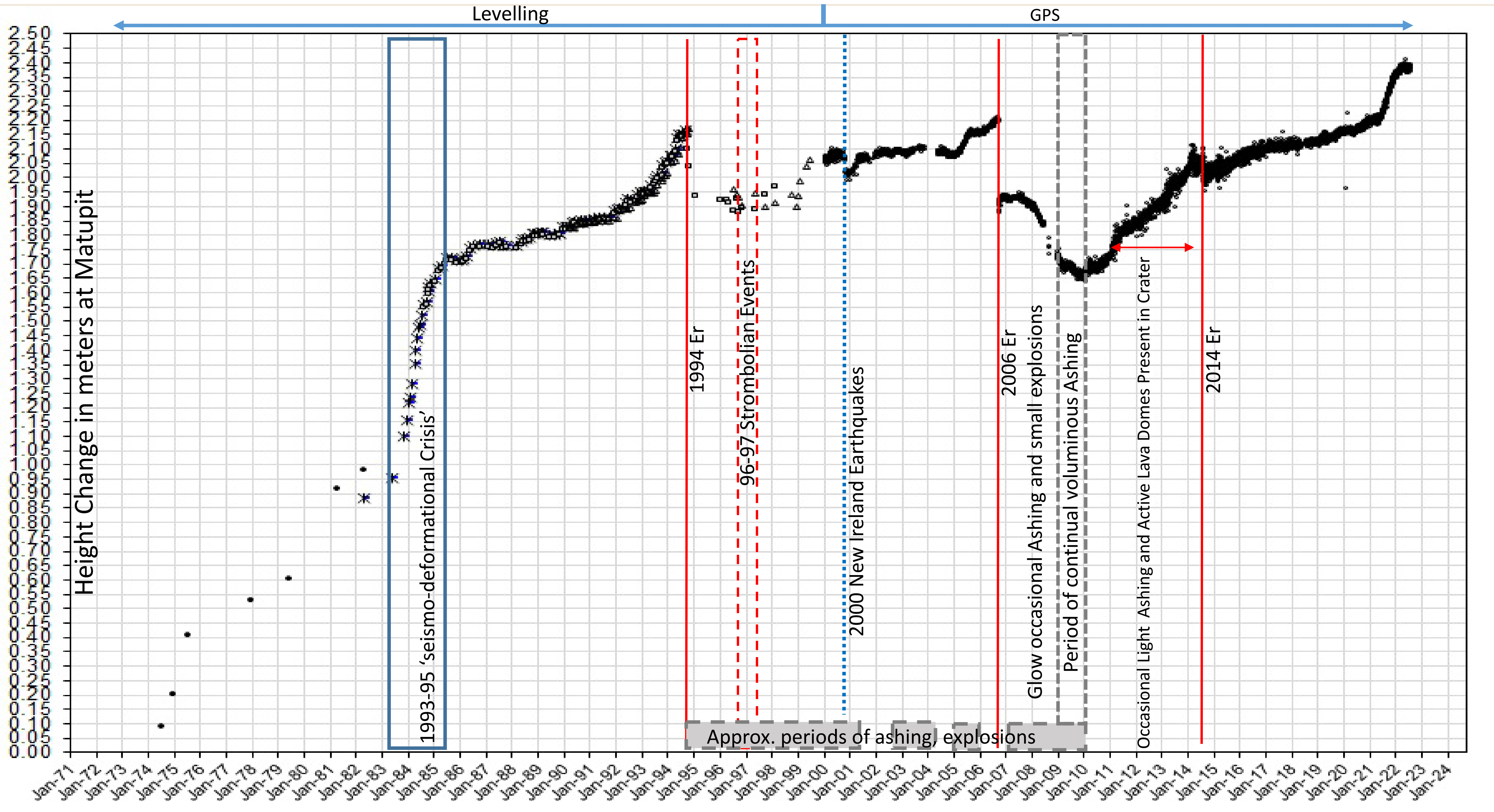
- Note, this was a solution - remotely downloading data form CORS and post processing - is what Elliot Endo recommended for RVO in 1996!

- This has proved a simple and robust option. A spread sheet started 26 January 2000 now has over 8000 daily average points for the 3 components added leading to the growth of an impressive data set.

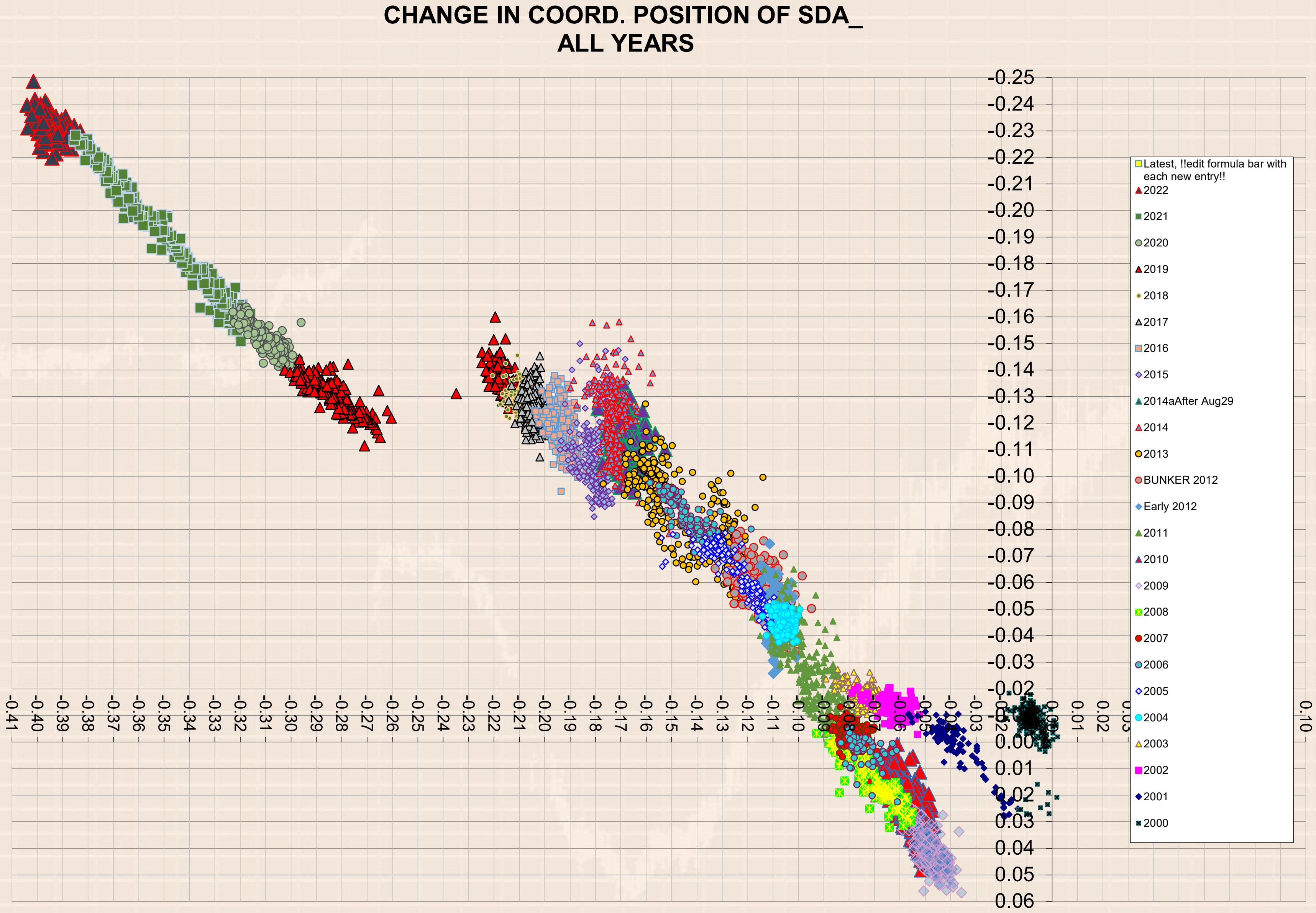

SDA GPS ELLIPSOID HEIGHT CHANGE IN METRES,
since site installed Jan 2000


SDA-RT-GPS NORTH SOUTH CHANGE

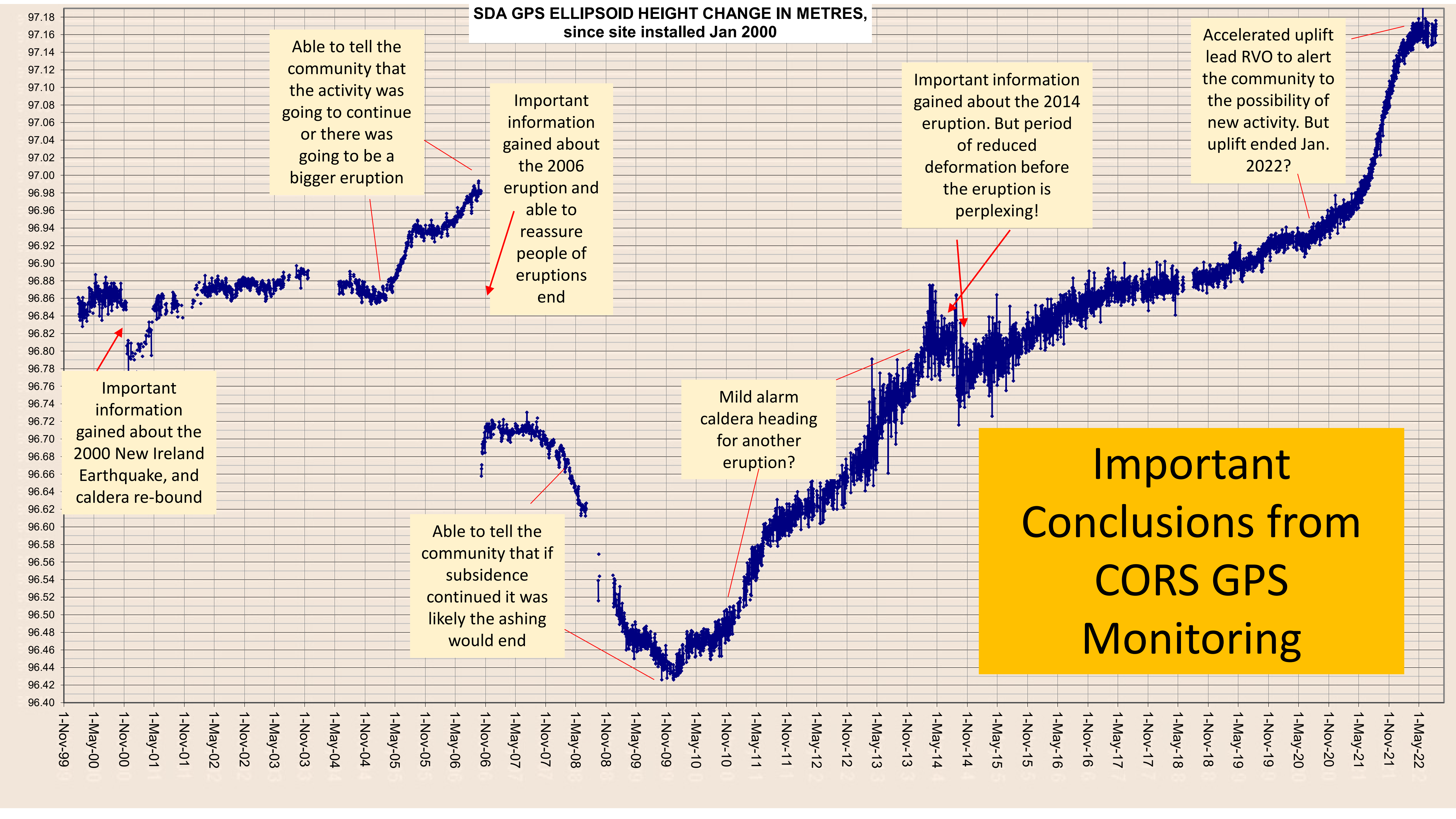

SDA-RT-GPS EAST WEST CHANGE



Levelling
GPS
Height Change in meters at Matupit
1993-95 'seismo-deformational Crisis'
1994 Er
96-97 Strombolian Events
2000 New Ireland Earthquakes
2006 Er
Glow occasional Ashing and small explosions
Period of continual voluminous Ashing
Occasional Light Ashing and Active Lava Domes Present in Crater
2014 Er
Approx. periods of ashing, explosions



An XY-plot of horizontal movements since 2000, many of the events recorded in the vertical plots can be seen here, but a detailed discussion of this, the other CORS and ‘Rover’ sites would add a few hours to this talk!


SDA GPS ELLIPSOID HEIGHT CHANGE IN METRES,
since site installed Jan 2000
Able to tell the community that the activity was going to continue or there was going to be a bigger eruption
Important information gained about the 2006 eruption and able to reassure people of eruptions end
Important information gained about the 2014 eruption. But period of reduced deformation before the eruption is perplexing!
Accelerated uplift lead RVO to alert the community to the possibility of new activity. But uplift ended Jan. 2022?
Important information gained about the 2000 New Ireland Earthquake, and caldera re-bound
Able to tell the community that if subsidence continued it was likely the ashing would end
Mild alarm caldera heading for another eruption?
Important Conclusions from CORS GPS Monitoring
97.18
97.16
97.14
97.12
97.10
97.08
97.06
97.04
97.02
97.00
96.98
96.96
96.94
96.92
96.90
96.88
96.86
96.84
96.82
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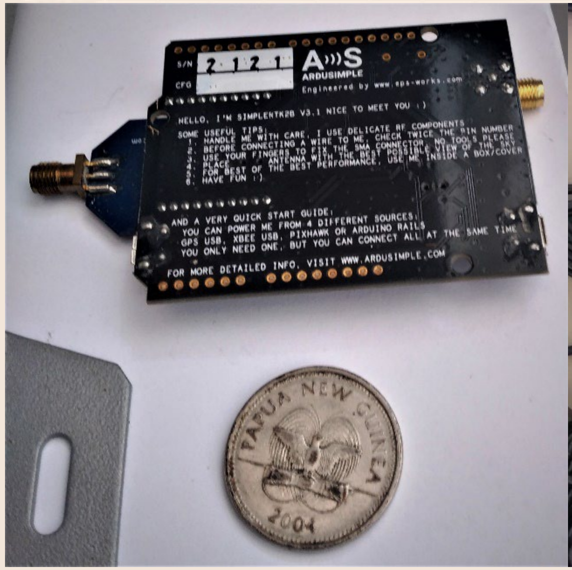
The Future?

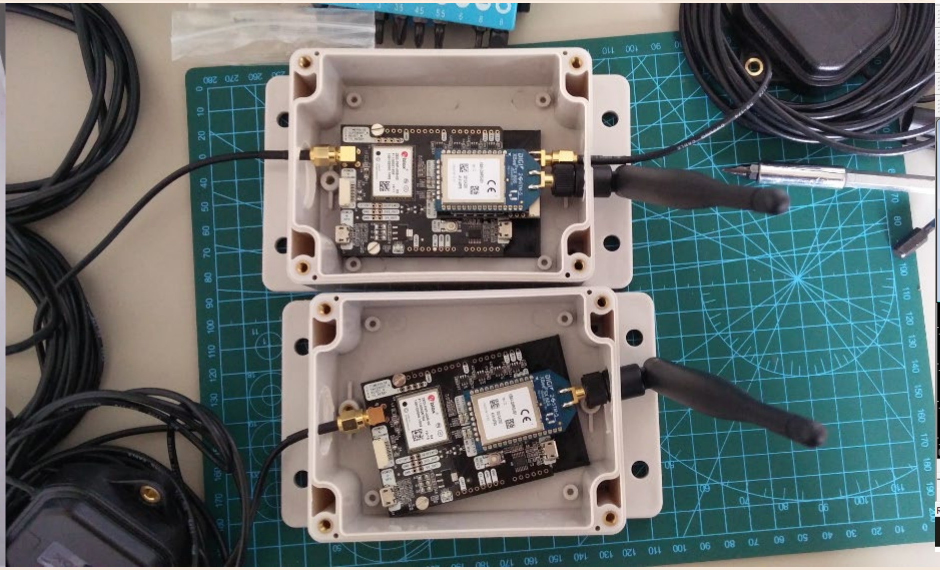
As already alluded too, very cheap differential GPS (GNSS) systems are now available. Hundreds of dollars rather than thousands.

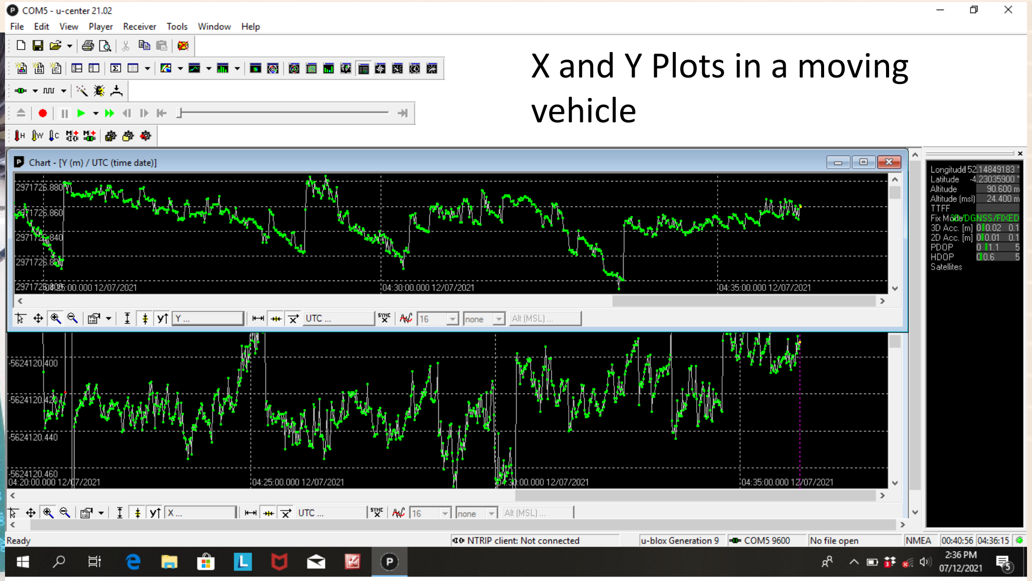
At present RVO is evaluating ArduSimple's duel frequency system, it uses the U-Blox ZED F9P chip. Utilizing GPS, GLONASS, Galileo and BeiDou to produce RTK solutions. These measurements, combined with corrections from a local base station, allow the receiver to solve carrier ambiguities and provide centimeter-level accurate position of the Rover/Remote.

So far our tests , in collaboration with Richard Stanaway (Quickclose Pty Ltd), have been very promising. The receivers do everything promised of them and the limiting factor for accuracy is the quality of the antenna.

A pair of Ardusimple receivers when configured as Base and Remote, when turned on the Base will automatically start sending corrections to the Remote. Using the 'Free U-Center' software on a Lap top or PC connected to the Remote, centimeter Real-Time solutions will start to be plotted, for up to ~15 km if line of sight. And of course, connected to a data logger (Laptop etc) they record high quality GNSS data usable by surveyors…   **Any interested individual in PNG could have their own CORS!**







Conclusions

- RVO was perhaps over optimistic in 1996 wanting a Real-Time GPS monitoring system
- But when actually operating the Real-Time system was of great use during times of crisis
- Using the network as **Continuously Operating Reference Stations (**CORS) with daily, or more frequent post processing, has proved a powerful tool and has produced a scientifically important data set.
- Patterns of deformation have been recognized at Rabaul that have helped in understanding the geodynamics (volcanological and tectonic) and has help in forecasting the waxing and waning of eruptions.
- Of course deformation itself cannot provide a clear understanding of a volcanic system. It is only a part of an integrated monitoring strategy including seismology and geochemistry etc.
- The extreme cost of equipment has always been a problem and manufactures over confidence or over complicated solutions have sometimes hampered RVOs use of GNSS.
- It looks like finally precise Real-Time and CORS systems are going to be within the price range of none specialists.
- RVO hopes to utilize the new cheap GNSS systems to monitor not only Rabaul, but other volcanoes of PNG.
- In PNG interested parties can now perhaps help in setting up CORS across the country; where-ever there is power, internet access and a willing operator; to add to the tracking and understanding of PNG’s ‘Crustal Motion’?