Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

The Insar Data Detect Shallow Dyke Intrusion at the Rabaul Volcano, Papua New Guinea - Potential Site for Caldera Geothermal Field

Manoj Mukhopadhyay and Suame Ampana

Department of Applied Physics, PNG University of Technology, Lae, Morobe Province, Papua New Guinea

Correspondence: suame.ampana@pnguot.ac.pg; manoj.mukhopadhyay@pnguot.ac.pg

Keywords: Rabaul Volcano Complex, twin-crater eruptions, elliptical seismic zone, InSAR data interpretation, shallow dike intrusion

ABSTRACT

The Rabaul Volcano Complex (RVC) is composed of twin calderas, namely; the Tavurvur and Vulcan, in the New Britain Island, Papua New Guinea. This is developed as an elliptical volcanic complex of 9 x 14 km^2 within the Bismarck Volcanic Arc. Central part of the RVC is breached by sea-water, causing inundation, between the eruptive centers. Consequently it produced a series of caldera collapse structures and a group of basalt–andesite volcanic centers. After a major twin eruption in 1994, Vulcan has ceased activity while Tavurvur has continued intermittent eruptions with last major eruption in 2014. Local seismicity is monitored by the Rabaul Volcanology Observatory (RVO) that is operational since 1937. The Rabaul seismic zone is elliptical ~5 x 9 km^2 oriented NNE/SSW, extending from near surface to a depth of 4 km. This corresponds to the walls of eventual caldera collapse, leading to outward-dipping ring-fault structure. Such gross pattern is also corroborated by 3-D seismic tomography which reveal low velocity zone underneath. Two popular models are advocated in literature to explain its current deformation: (i) Point pressure source, called the Mogi model and (ii) Radial dike intrusions along the caldera wall, leading to outward-dipping ring-fault structure. Here we make use of the conventional geodetic data as well as the Interferometric Synthetic Aperture Radar (InSAR) data to detect ground deformation to further constrain the possible pressure sources (Mukhopadhyay et al., 2018). Using ALOS PALSAR and GPS datasets, we model a shallow dike intrusion at 1 km depth to explain the localized deformation observed on the NE-edge of the Tavurvur cone and a 4 km deep Mogi source model at the center of the caldera just south of Matupit. Finally, the shallow dike intrusion is interpreted here to represent the root plumbing system beneath the RVC at this specific locality. Large, young calderas and associated volcanic rocks are indicators of potentially immense geothermal resources. It is envisaged that for every km^3 of material erupted, between 3 and 9 km^3 of partly molten rock resides below the volcanic field, most likely within the upper 10 km of crust. The geothermal resource beneath a caldera exists as long as eruptive activity continues; what appears to be the most likely case for RVC. Here we infer that the interpreted dike intrusion model bear significant potential for geothermal resource. RVC hydrothermal systems are likely to be confined to caldera ring fractures and caldera-crossing faults, which form zones of fracture permeability. Further studies are however, warranted in this direction to establish its nature.

1. INTRODUCTION

The Rabaul caldera belonging to RVC is a low lying, 14 x 9 km^2 elliptical volcano complex located on the north-eastern end of the island of New Britain, Papua New Guinea (Figure 1). Current intra-caldera eruption centers, Tavurvur and Vulcan, are located approximately east-west on the caldera rim. Eruptions in RVC have occurred roughly once every 30-60 years. RVC is considered a high risk volcano due to large population that inhibits the town of Rabaul, located within the caldera to the northwest. The eastern side of the caldera is widely breached on the sea and therefore most of the caldera is submerged under water thereby critically limiting the available deformation data. RVC is considered the deadliest volcano in SW Pacific, having one of many explosive volcanoes located within the collision zone of the Pacific and India-Australia Plates in PNG region (Figure 2). Convergence of the two plates in this region is buffered by a collision zone which is characterized by high level of seismicity and volcanism and rapid evolution of micro-plate boundaries that define its complex tectonic regime. The dominant interaction in the buffer zone is the rapid subduction of Solomon Sea Plate north-northwestwards beneath New Britain Island front of the South Bismarck Plate along the New Britain Trench at the rate of 150mm/year (Tregoning et al., 1999). This subduction gives rise to a string of destructive volcanoes stretched along the Bismarck Arc.

Monitoring of ground deformation at active volcanoes is considered the most effective tool in elucidating pressure changes in the magma system and its migration. Inversion of geodetic data can provide information on the location, depth and volume change of magma source. In this study, we analyzed geodetic dataset from space-based techniques namely; Differential Interferometric Synthetic Aperture Radar (DInSAR) and Global Positioning System (GPS) to assess ground deformation related to volcanic activity at RVC after the October 2006 eruption. We pay particular attention to significant post-eruptive subsidence of the caldera detected by GPS network, especially SDA and VIS, beginning from late 2007 to end of 2009, to model pressure sources and discuss the caldera activity in light of these results.

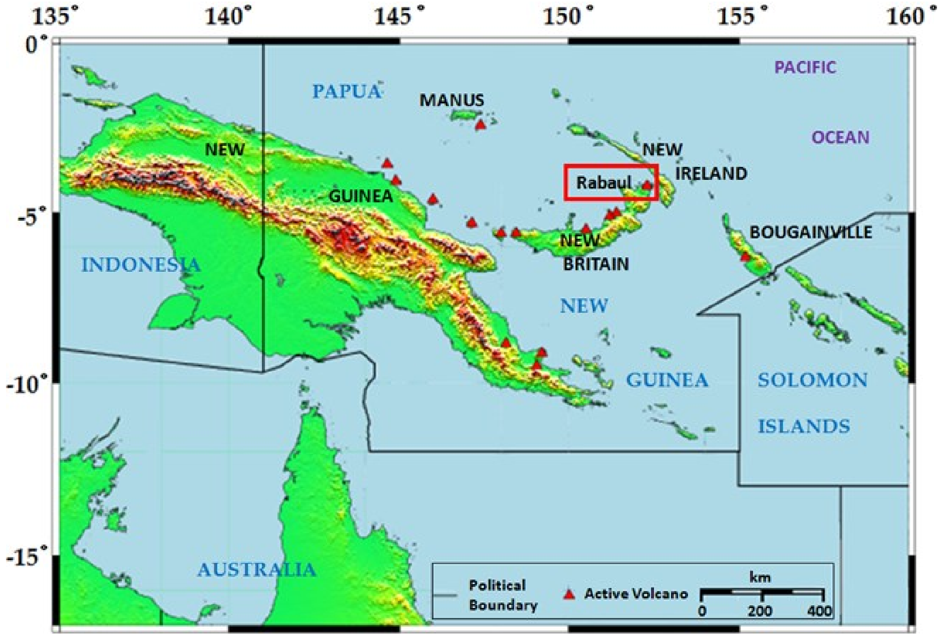


Figure 1: Location map of the study area. Active volcanoes in PNG are shown as red triangles. Rabaul volcano is located on the northeastern end of the island of New Britain.

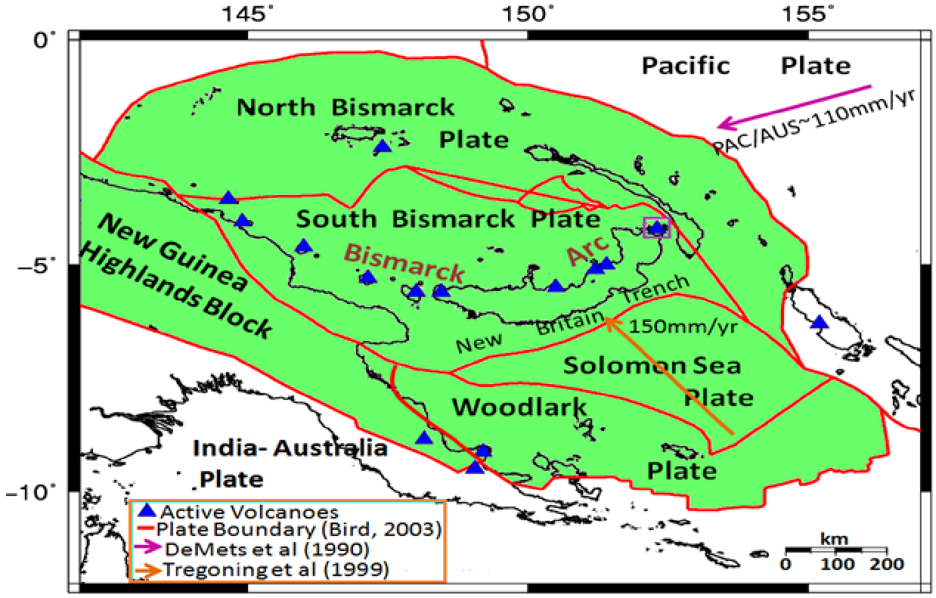


Figure 2: Tectonics Setting of PNG region. The Pacific and India-Australia Plates collision zone is highlighted in green.

2. RABAUL VOLCANO HISTORY

2.1 Deformation, Seismicity and Eruptive History

Most now accept that the RVC formed by a series of caldera collapse structures. It was formed ~3500 years ago in a collapse event and modified by two more major eruptions, the most recent of which was 1400 years ago (Walker et al., 1981). Within the caldera, subsequent eruptions have produced a field of volcanic cones from east to north of the caldera and Vulcan cone to the west (Figure 3). Recorded eruptive history of RVC dates back to 1878. The largest and fatal twin eruptions occurred respectively under Tavurvur and Vulcan in 1937 and 1994, having casualties of 500 by the former. The latter eruption destroyed about two thirds of Rabaul town, caused major infrastructural damage and displaced about 25,000 people; however, the low death toll is attributed to increased monitoring, strategic planning and evacuation.

After 1943 the caldera experienced a period of quiescence until November 1973 when the onset of unrest and progressive change in uplift and tilting began. This resurgence in activity was attributed to changes in stress regime of RVC possibly initiated by two tectonic earthquakes of Mw=8.0 below Solomon sea, 200-300km to the southeast in July 1971. Slow evolving situation gave way to a dramatic increase in seismicity and deformation that began in September 1983. It has been suggested that this intensified activity could have been the result of much higher rate of magma injection induced by a nearby tectonic earthquake (M7.6) 200km east of Rabaul in March 1983. The crisis period lasted for 9 months. Notably, the Matupit Island structure uplifted more than 50 cm and monthly seismicity peaked at over 13,000 events in April 1984 during the crisis period (Mckee et al., 1984). Hypocentral distribution of recorded seismicity during the crisis period delineated a NNE/SSW trending ellipse extending from near surface to a depth of 4 km (Figures 4a and 4b) and indicated an outward-dipping normal fault system interpreted to be the fault structure along which cauldron subsidence occurred 1400 years ago (Mori and Mckee, 1987).

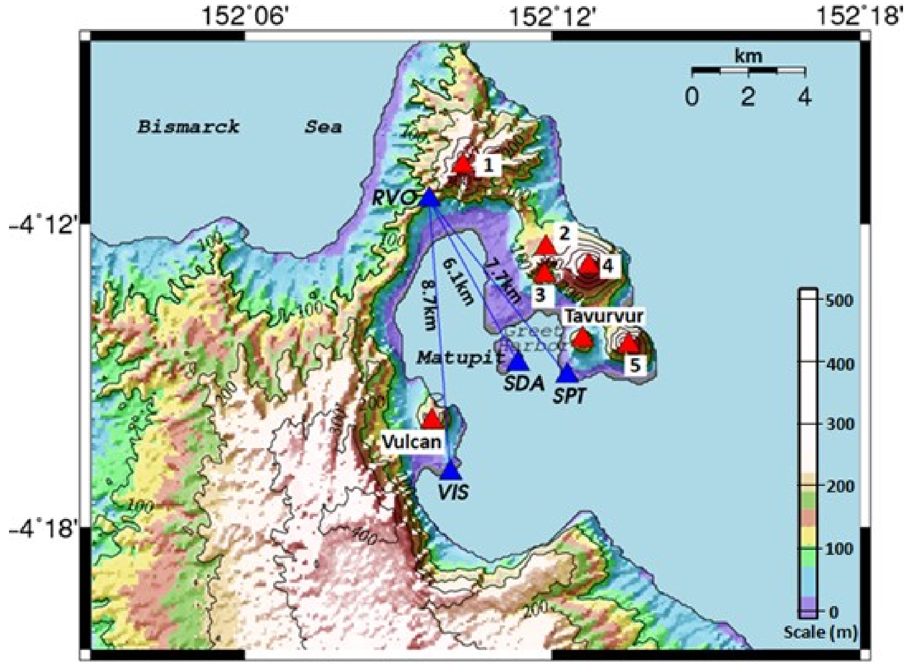


Figure 3: Location of GPS stations operated by RVO (base) and active volcanoes in and around Rabaul caldera. Blue and red triangles indicate GPS stations and active volcanoes respectively. Numbered craters are; 1) Tovanambatir, 2) Palangiagia, 3) Rabalanakaia, 4) Kebiu and 5) Turanangunan

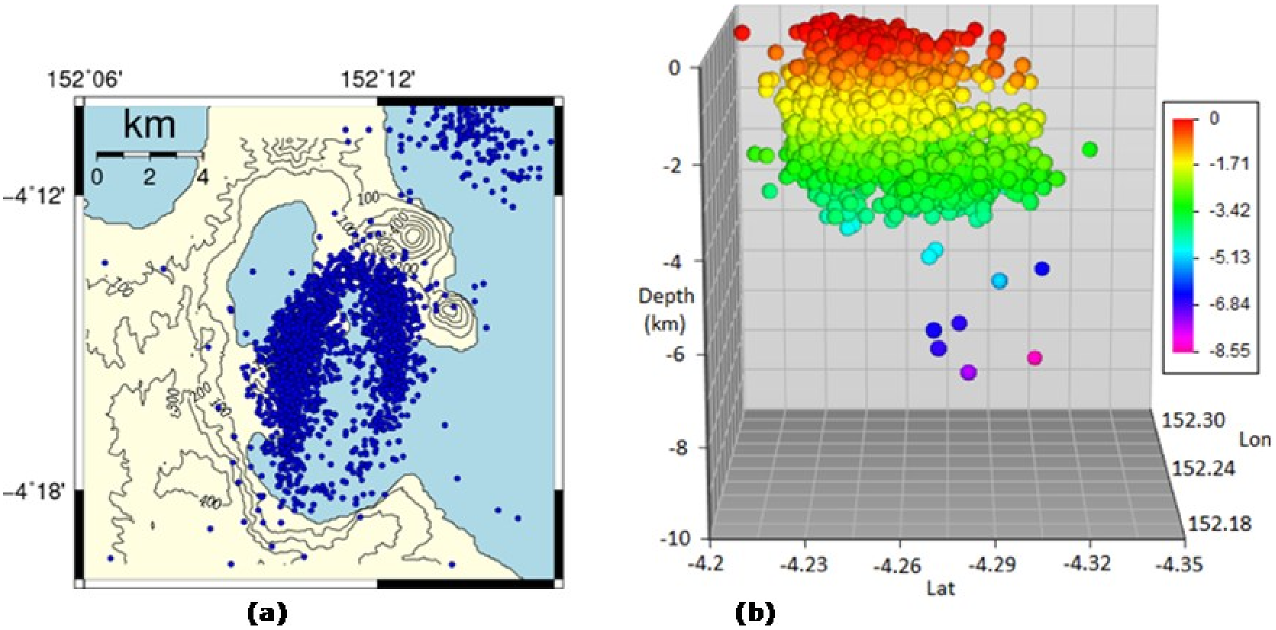


Figure 4: (a) Epicenter distribution map of Rabaul caldera in the period from 1980 to 1984; modified from Mori and Mckee (1987). (b) Hypocenter distribution of seismicity beneath Rabaul caldera in the same period in (a), viewing from the west.

Activity soon returned to pre-crisis levels without an eruption. The anticipated eruption occurred ten years later on 19th September 1994. Post 1994 eruption, seismicity and deformation patterns clearly vouch for a restless caldera. The unrest at the caldera has continued to the present with intermittent eruptions in 1995, 2002, 2005, a significant eruption in 2006, 2010, and 2011 and most recently in 2014, all from Tavurvur, except for the 1995 eruption. Eruptions at RVC are generally characterized by explosive, central vent and phreatic eruptions and pyroclastic and lava flows. According to RVO reports, a sub-Plinian eruption occurred from Tavurvur on the morning of 7October 2006 and continued into the afternoon. The ejected ash plume rose to a height of about 18 km. Moderate ash fall of 3cm fell on Rabaul town. The eruptions were characterized by frequent explosions accompanied by shockwaves and rhythmic air blasts that were felt in Rabaul town. By 28 October, the eruption had died down only with occasional ash emissions and rare explosions. No casualties and damages were reported.

2.1 Source models applicable to Rabaul Volcanic Complex

Two spherical pressure sources are identified: one near Greet Harbor with an estimated depth ranging from 1.5-2 km and the other near the Vulcan headland at a depth of 3 km by analyzing tilt and leveling data obtained during the seismo-deformational crisis period shown in Figure 5 (McKee et al., 1984). Archbold et al., (1988) also estimated a point source near southeast of Matupit at a depth of 1.2 km based on EDM and leveling data. Complexity of the observed caldera-wide deformation suggests that larger or more complex intrusions may be involved (De Natale and Pingue, 1993). By taking annular seismicity under RVC as evidence, Saunders (2001) envisioned magma intrusions into fracture systems what magma utilizes to ascend. This relate to the deformation of the caldera structure to stress caused from a 4- to 5- km deep magma source. Seismic tomography studies are undertaken using regional and local earthquakes and explosive seismic sources to map the caldera sub-surface structure (Finlayson et al., (2002); Bai and Greenhalgh (2005) and Itikarai et al., (2006). These studies have identified two low velocity regions in the center of the caldera that are likely magma reservoirs; a shallow region at a depth of ~4 km and deeper region at depths of 10 to 12 km. A third low velocity region has also been identified to the east of the caldera.

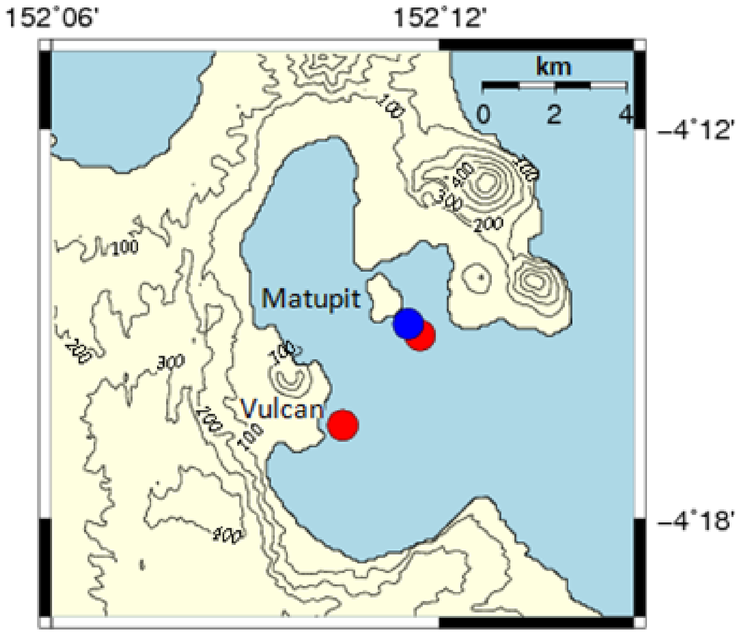


Figure 5: Spherical sources modeled in previous studies. Red and blue circles are Mckee et al., (1984) and Archbold et al., (1988), respectively.

3. INSAR DATA ANALYSIS METHODOLOGY

3.1 InSAR Data for Rabaul Volcanic Complex

InSAR and GPS geodetic dataset are analyzed in the present study to constrain pressure source at the RVC. A total of 12 PALSAR scenes, all in ascending mode, of Rabaul spanning from February 2007 to September 2009 were obtained from Japan Aerospace Exploration Agency (JAXA). Suitable pairings were selected for analysis after testing all possible pairings with consideration for de-correlation effect, Zebker and Villasenor (1992) associated with longer spatial and temporal baselines. The pairings used for deformation analysis are shown in Figures 9 and 10. All interferometric processing were performed using GAMMA SAR processor, Werner and Wegmuller (1997) a SAR/InSAR processing software package. Final interferograms show vertical components of satellite-line-of sight (LOS) displacements.

Additionally, we also obtained post-processed GPS data from RVO for deformation analysis in conjunction with InSAR data. At the present, RVO operates a Continuous GPS network comprising of 4 stations; RVO the base station and SDA, VIS and SPT the remote stations located on the caldera (Figure 3). Station SPT was not operational until end of December 2008 due to technical problems. Moreover, available GPS data at SDA and VIS are discontinuous in some periods.

3.2 InSAR and GPS Data Analysis for Rabaul Volcanic Complex

Post 2006 eruption, the GPS network indicated subsidence of the caldera toward the end of Oct- 2007 (Figure 6). By Dec-2009, the caldera had subsided significantly. SDA and VIS deflated about 29 and 16 cm respectively (Figures 7 and 8). Corresponding horizontal displacements were 7 and 15 cm respectively and indicated a deflating source south east of Matupit. SPT began operational again in October 2008. By Dec-2009, it had subsided 7cm and was horizontally displaced ~8cm to the east-northeast notably inconsistent with the trend indicated by SDA and VIS in the corresponding period (Figure 7b).

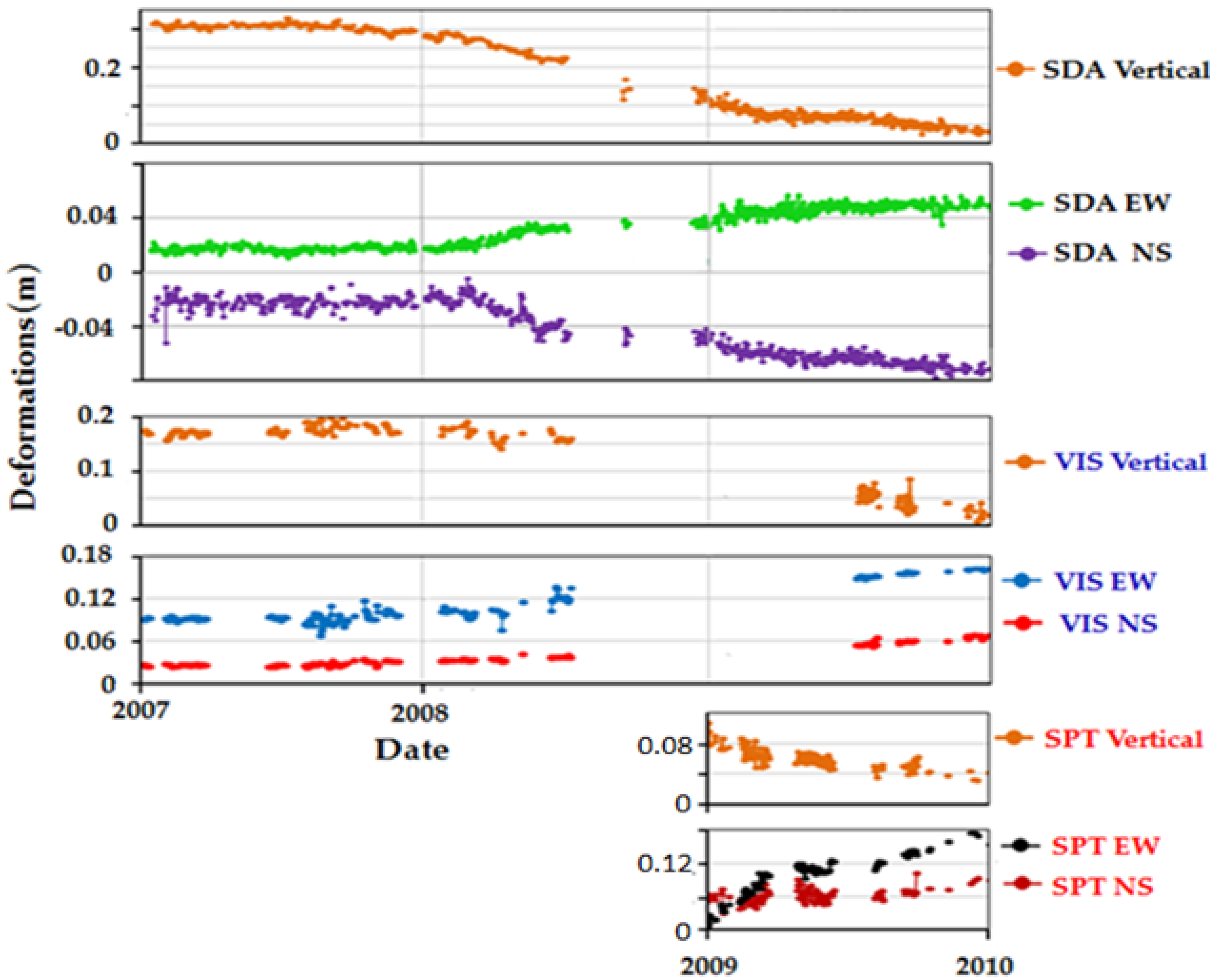


Figure 6: Time series of station velocities at three GPS sites; SDA, VIS and SPT relative to station RVO. SPT became operational again at the end of 2008.

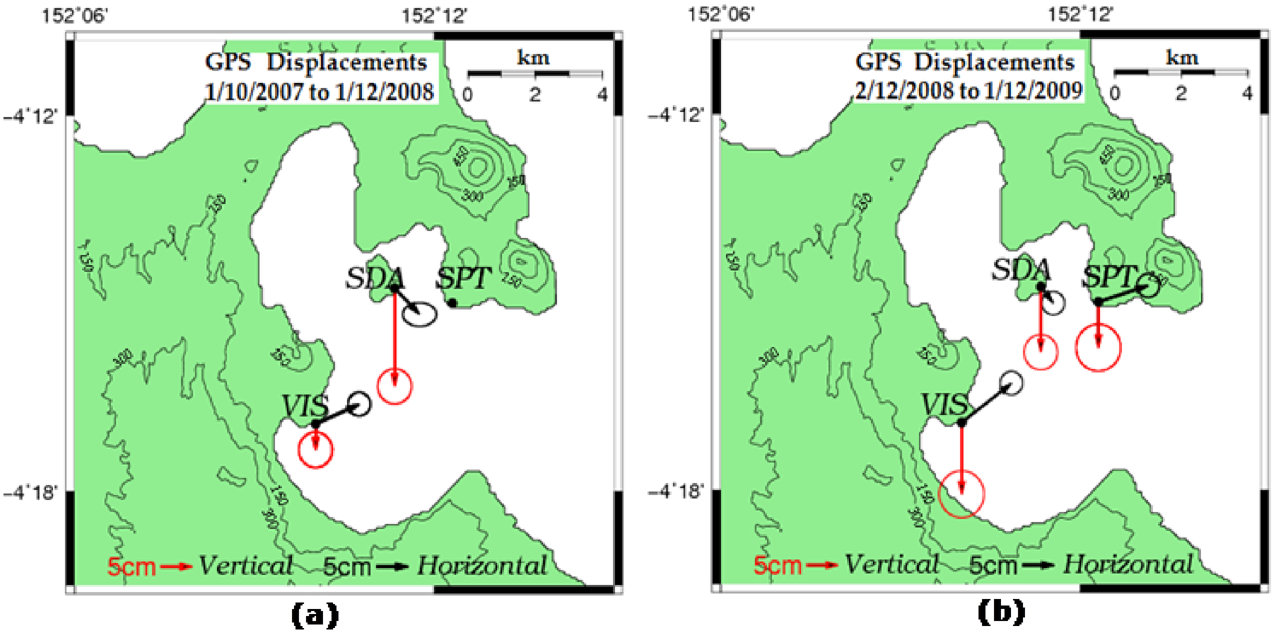


Figure 7: GPS Displacements for the periods (a) from October 2007 to December 2008; SPT was not operating in this period; (b) from Dec-2008 to Dec-2009 after SPT was re-installed; SPT subsidence was inconsistent with the trend indicated by SDA and VIS.

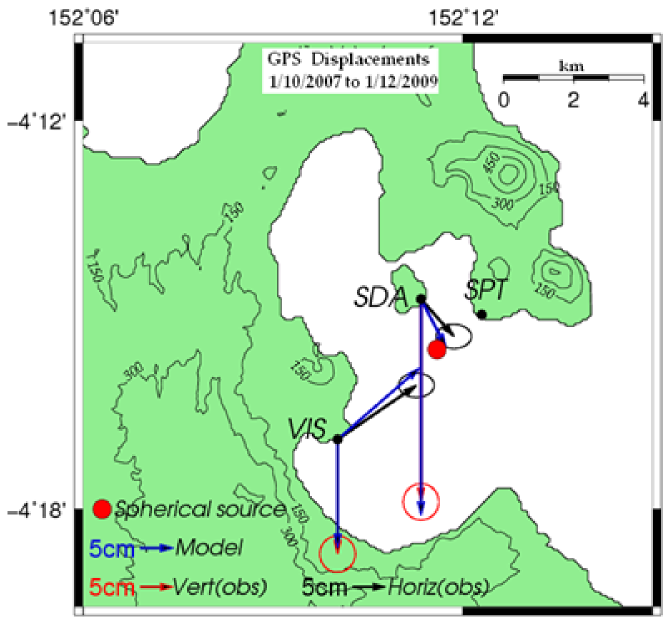


Figure 8: Mogi model predicted vertical and horizontal displacements (blue arrows). Black (horizontal) and red (vertical) vectors are observed displacements. Surface location of the modeled spherical source is ~1.3 km south-southeast of SDA and is indicated by red filled circle. Depth of the source is 4 km.

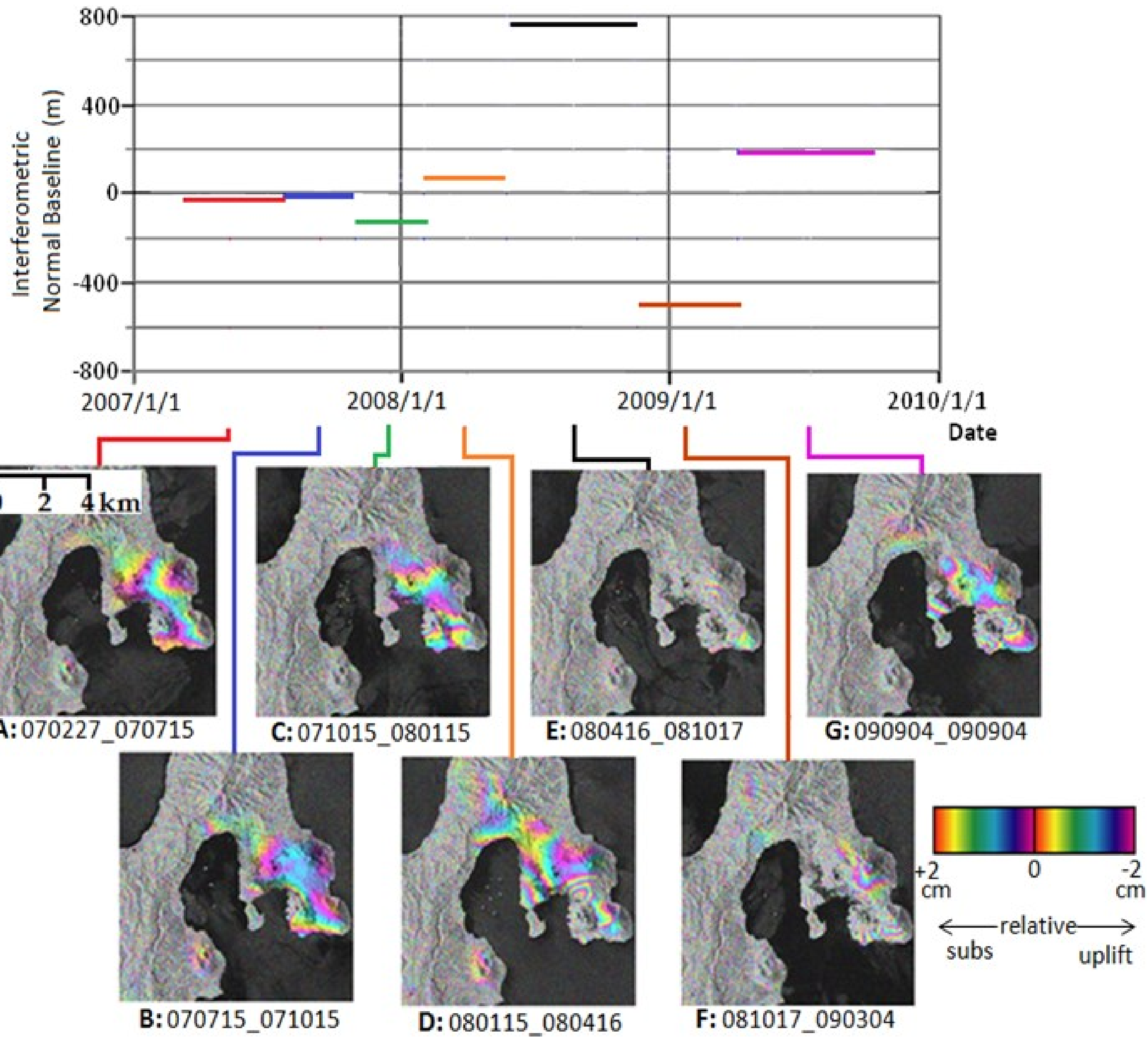


Figure 9: Interferograms generated for this study identified with dates for each inteferometric pair. Interferometric and temporal baselines are indicated above. Large interferometric baselines resulted in degraded coherence (Eg; interferogram E with Bn=760m).

From InSAR results in Figure 10, interferograms A and B (periods Feb-2007 to Jul-2007 and Jul-2007 to Oct-2007) showed ~2 cm uplift and ~2 cm subsidence respectively around Greet Harbor area. In period Oct-2007 to Jan-2008 represented by interferogram C, a marked uplift of ~8cm was detected to the northwest flank of Tavurvur. About 4 cm of subsidence was detected to the north of Tavurvur in interferogram D in the period Jan-2008 to Apr-2008. Interferogram E for period Apr-2008 to Oct-2008 suffered from poor coherence which was attributed to large interferometric baseline. Interferogram F (period Oct-2008 to Mar-2009) detected more than 2 cm of uplift east of Tavurvur and ~8 cm of subsidence north of Matupit. This subsidence was consistent with SDA which subsided more than 10 cm in the corresponding period. In interferogram G (Mar-2009 to Sep-2009), more than 4cm of localized subsidence was observed east of Tavurvur.

Upon comparison of GPS and InSAR results, we noted the following. First, the inconsistency in SDA and VIS station velocities to that of SPT after re-installation. Second, localized deformations observed around Tavurvur in interferograms C, D and G and third, SPT subsidence confirmed InSAR detected deformation east of Tavurvur. Based on these observations, we modeled the observed deformations as follow; 1) SDA and VIS subsidence from Oct-2007 to Dec-2009 and 2) InSAR data based on interferograms C, D and G. It is assumed that SPT subsidence was responding to the source of deformation detected in interferogram G east of Tavurvur.

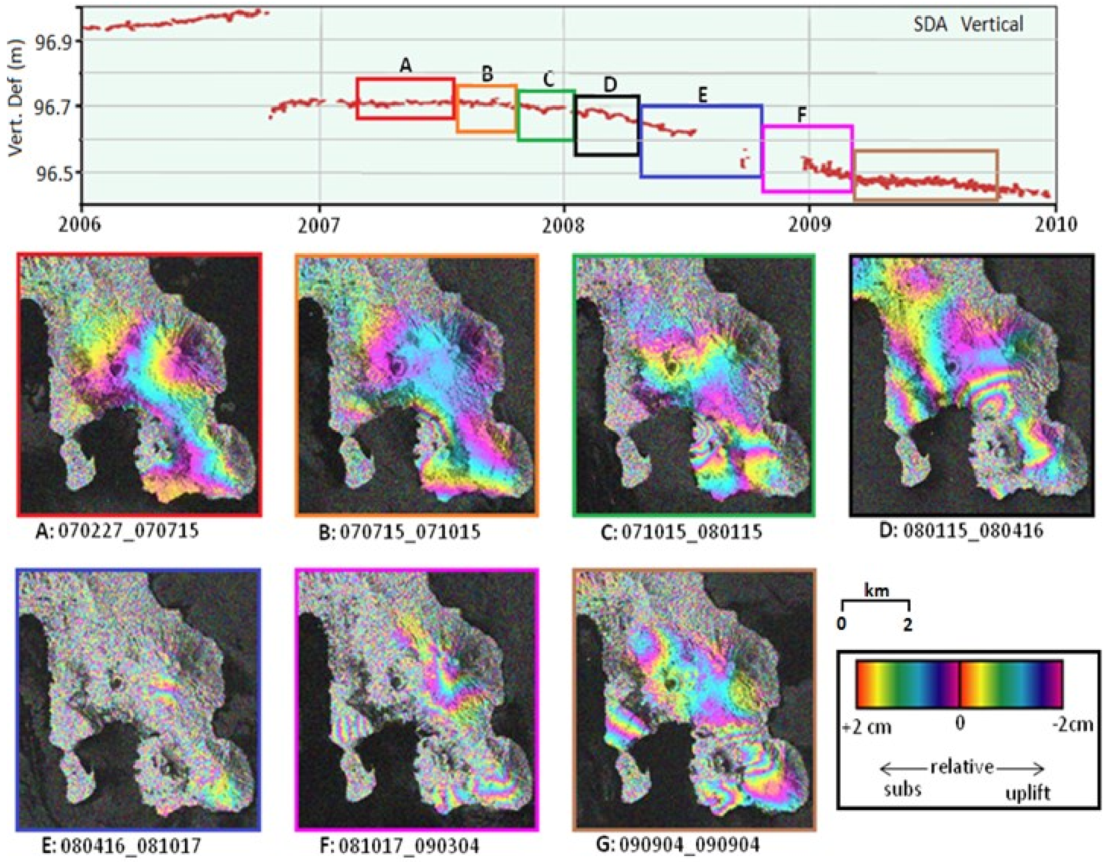


Figure 10: Displacement interferograms cropped for Greet Harbor area where coherence is maintained at considerable levels. SDA vertical displacement time series is shown above for corresponding periods.

4. DEFORMATION AND PRESSURE SOURCE MODEL FOR RABAUL VOLCANIC COMPLEX

Based on SDA and VIS data, two possible scenarios were contemplated. First, a deeper larger point source at the mouth of Greet harbor could be responsible for the observed deformations. Alternatively, taking into consideration previous study of McKee et al., (1984), there is a possibility that two shallow localized magma bodies maybe involved. The second possibility could not be explored further for two reasons; i) insufficient GPS stations and ii) poor coherence in InSAR images around Vulcan area. Consequently, the first scenario was followed for modeling.

In our modeling strategy we tested spherical and sill- like chambers by generating predicted surface displacements from these sources placed at same depths. Upon comparison with observed data, it was noted that a sill-like chamber produced large vertical displacements near and directly above the source and did not correlate well with the observed data. In contrast, a spherical source yielded reasonable fit to the observed data and was subsequently applied in modeling. On the basis of Mogi model calculations, we modeled a deflated spherical pressure source in the middle of the caldera located roughly south-southeast of Matupit Island.

The depth was estimated at the depth of 4 km, about 1.3 km from SDA and ~3.8 km northwest from VIS (Figure 8). Assuming that the subsidence was due to volume decrease at the source, the magnitude of this volume change was calculated to be about -2.45 x 10^7 m^3. The depth of the source modeled here is consistent with the depth of low velocity region (4-5 km) identified at the center of Rabaul caldera by various seismic tomography studies alluded to earlier.

4.1 InSAR Deformation Modeling

The uplift observed in interferogram C was attributed to a localized dyke intrusion. Various depths were assessed based on rectangular fault and dislocation parameters defined by Feigl and Dupre (1999) using the formulations by Okada (1985). Accordingly, the source depth was estimated at 0.9km. The volume change was calculated to be 2.1 x 10^4 m^3 (Table 1 and Figure 11). It deflated to the north of Tavurvur in the succeeding period (D) at a depth of 1.1 km with an estimated volume change of -1.0 x 10^4 m^3.

In interferogram G, ~6 cm of subsidence was detected to the east of Tavurvur. We estimated the depth and volume change of this deflated dike to be 1.2 km and -1.3 x 10^4 m^3 respectively (Table 1 and Figure 11). We noted that the inconsistent subsidence trend observed at SPT was likely responding to this source. The summary of the sources estimated in this study are indicated in Table 2 and Figure 12.

Rectangular Fault Dislocation Parameters	Interferogram		
	C	D	G
L (m)	870	820	1300
W (m)	300	300	200
Depth (m)	900	1100	1200
Dip (Deg)	30	20	0
Strike (Deg)	85	230	254
Rake (Deg)	0	0	0
U1 (m)	0	0	0
U2 (m)	0	0	0
U3 (m)	0.8	-0.9	-1.1
Volume Change, ΔV ($x10^4 m^3$)	2.1	-1.0	-1.3

Table 1: Rectangular dislocation parameters for dike intrusions in interferograms C, D and G

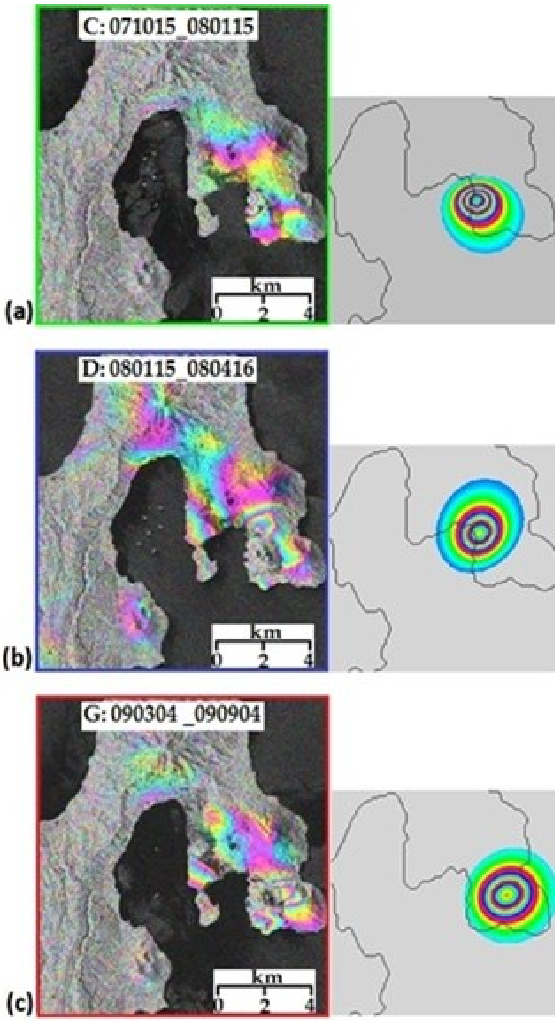
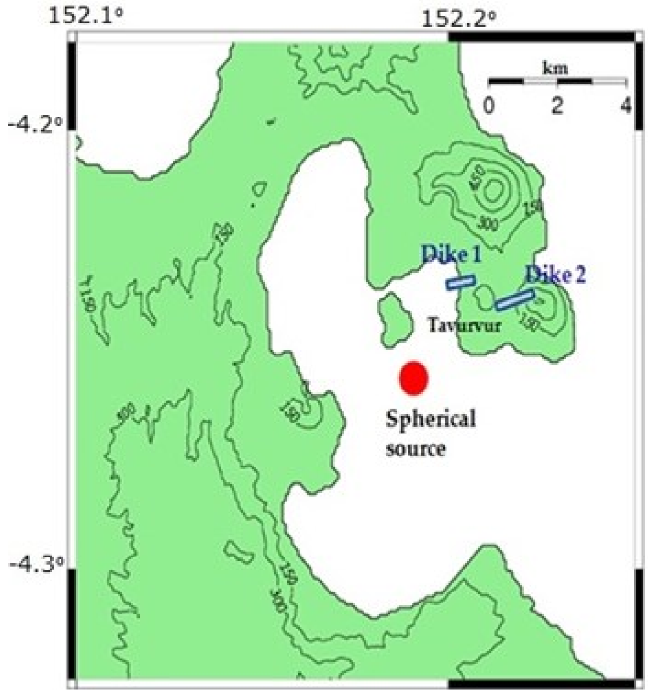


Figure 11: Observed and synthetic interferograms; (a) period C, (b) period D and (c) period G. Corresponding synthetic interferograms were generated based on rectangular fault dislocation parameters given in Table 1.



Pressure Source	Depth (km)	Volume Change ΔV (m^3)
Spherical	4	-2.45 x 10^7
Dike 1	0.9	2.1 x 10^4
Dike 2	1.2	-1.3 x 10^4

Table 2:

Summary of pressure sources modeled in this study

Figure 12: Pressure sources modeled in this study. See full text for explanation.

5. DISCUSSIONS

From the results, the volcanic activity at RVC can be summarized as a time-dependent activity as depicted in Figure 13. Prior to the Oct-2006 eruption, magma was transported from deeper reservoir to the 4 km chamber as evidenced by the observed uplift prior to the sub-Plinian eruption from Tavurvur on 7-Oct-2006. Marked subsidence observed at SDA immediately after the eruption corresponded to chamber deflation as a result of eruption and lava flow.

Analysis of data reveal that the chamber re-inflated and the post eruptive period comprising of diffused Strombolian and phreatic eruptions, explosions, lava flows and ash fall followed sub-continuously for the next 12 months to the end of 2007. In this period, it is apparent from the data that no significant deformation occurred. We suggest that there was a balance in magma intrusion into the chamber and magma extrusion at the surface.

The caldera wide subsidence that began at the end of 2007 to March 2009 indicated chamber deflation due to magma drain back. A slight uplift after March 2009 that lasted for 3 months indicated that the chamber was supported temporarily and continued to deflate again in Jul-2009 until Dec-2009. Based on GPS data in this period (Dec-2007 to Dec-2009), we modeled a spherical pressure source in the middle of the caldera at a depth of 4 km. Volume decrease was estimated to be -2.45 x 10^7 m^3.

At the beginning of caldera subsidence towards the end of 2007 (Phase 4 in Figure 13), dike 1 inflated at the northwest flank of Tavurvur. The depth and volume change of this source were estimated to be 0.9 km and 2.1 x $10^4 m^3$ respectively. Between Jan- and Apr-2008, this dike deflated to the north of Tavurvur at a depth of 1.1km with an estimated volume change of -1.0 x 10^4 m^3. Another dike (dike 2 in Figure 13) deflated east of Tavurvur during Mar- to Sep-2009 period. We estimated the depth and volume change of 1.2 km and -1.3 x 10^4 m^3 respectively for this deflation source.

From InSAR data processing and analysis of Rabaul volcano, it is obvious that conventional InSAR technique was unable to mitigate the problem of coherence loss in the broad caldera area. Possible causes of low coherence could be due to; first the changing vegetation cover and its effect on scattering behavior and second increasing interferometric baselines resulting in temporal and spatial decorrelation. This problem could be addressed by utilizing advanced InSAR techniques such as the PSInSAR analysis (Hooper et al., 2004) which identifies and analyses phase response from coherent pixels only to attain good degree of coherence.

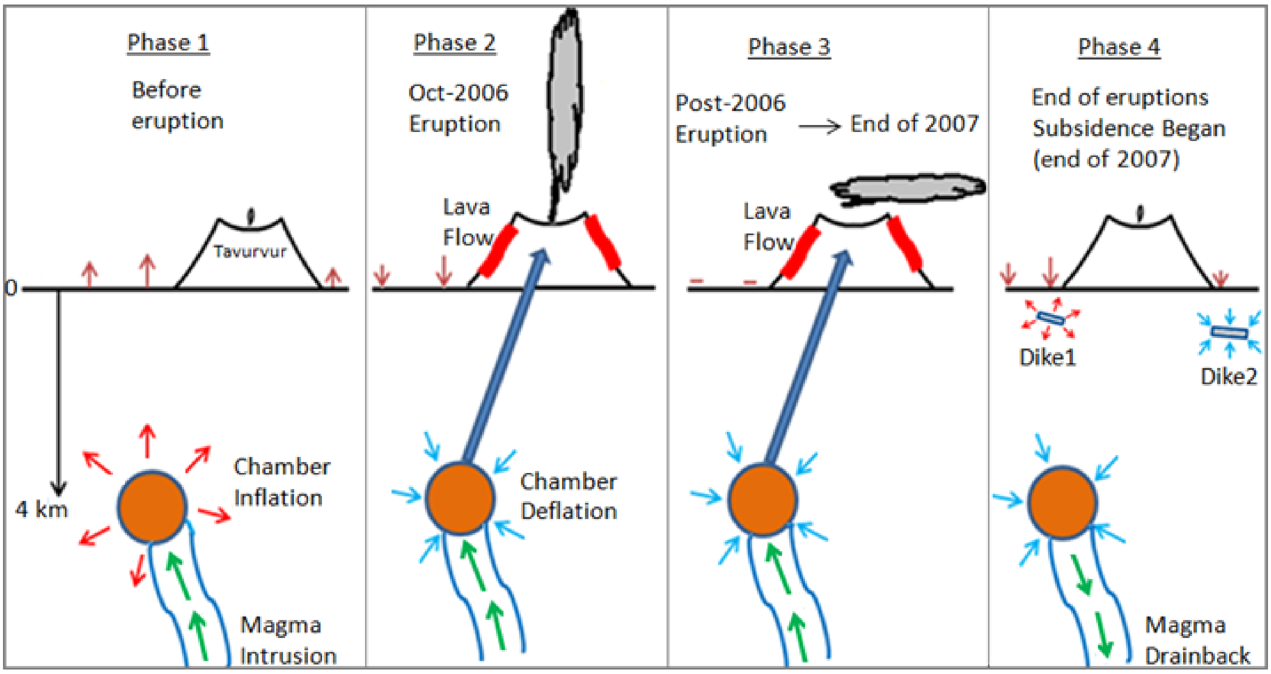


Figure 13: Eruption process at Rabaul volcano. *Phase 1:* Inflation before eruption. *Phase 2:* Oct-2006 eruption. *Phase 3:* Post-eruptive period to end of 2007 comprising of frequent Strombolian eruptions. *Phase 4:* Caldera subsidence; End of 2007 to Dec-2009. During phase 4, dike 1 inflated on the NW flank of Tavurvur. Dike 2 deflated east of Tavurvur in this phase.

6. CONCLUSIONS

We utilized GPS and InSAR dataset in the present study to estimate sources of deformations at RVC following the October 2006 eruption. Main conclusions derived from the study are the followings:

Twelve months after the eruption, the caldera started subsiding in late 2007. By the end of 2009, the GPS displacements at SDA and VIS detected a marked subsidence of 29 and 17 cm and corresponding horizontal movements of 7 and 15 cm respectively. InSAR detected deformations did not correlate with GPS (SDA and VIS) data. Furthermore, SPT displacement after re-installation in Oct-2008 to Dec-2009 was inconsistent with the other GPS station displacements. It subsided to the east-northeast direction. We therefore modeled GPS (SDA and VIS) and InSAR dataset separately.

Based on SDA and VIS data and Mogi model calculations, the depth of the spherical pressure source was estimated at 4 km with an associated volume decrease of -2.45 x 10^7 m^3. This source is consistent with the depth of low velocity zone identified by seismic tomography studies. There is a possibility of two point sources; though, it could not be confirmed due to insufficient data.

InSAR data was modeled based on fault dislocation parameters defined by Feigl and Dupre (1999). We modeled dike inflation beneath northwest flank of Tavurvur at a depth of 0.9 km based on interferogram C with a volume change of 2.1x10^4 m^3. It deflated to the north in interferogram D to a depth of 1.1 km with an associated volume change of -1.0 x 10^4 m^3. Based on InSAR detected subsidence east of Tavurvur in interferogram G, we estimated a deflated dike at a depth of 1.2 km and a volume change of -1.3 x 10^4 m^3. The subsidence detected by SPT confirmed this pressure source.

Interferometric coherence in the broad caldera area is poorly maintained in conventional InSAR technique, thereby making it insufficient for deformation detection at RVC. Advanced techniques that retain phase stability to improve coherence such as PSInSAR method (Hooper et al., 2004) may help in such situations.

7. ACKNOWLEDGEMENT

We acknowledge Steve Saunders of Rabaul Volcanology Observatory for providing the GPS data and JAXA through AUIG for providing ALOS PALSAR scenes of Rabaul volcano for interferometric processing.

8. REFERENCES

Archbold, M.J., McKee, C.O., Talai, B., Mori, J., and Desaintours, P.: Electronic distance measuring network monitoring during the Rabaul seismicity deformational crisis of 1983-1985. J. Geophys. Res., 93(B10), (1988), 12123-12136.

Bai, C., and Greenhalgh, S.: 3D multi-step travel time tomography: Imaging the local, deep velocity structure of Rabaul volcano, Papua New Guinea,Phys. Earth Planet. Interiors, 151, (2005), 259-275.

Bamler, R., and Hartl, P.: Synthetic aperture radar interferometry, Inverse Problems, no. 14, (1998), pp. R1-R54.

Bird, P.: An updated digital model of plate boundaries. Geochem. Geophys. Geosyst., 4(3), (2003), 1-52.

DeMets, C., Gordon, R.G., Argus, D.F. and Stein, S.: Current plate motions, Geophs. J. Int., 101, (1990), 425– 478.

Denatale, G., and Pingue, F.: Ground deformations in collapsed caldera structures. J. Volcanol., 57, (1993), 19-38.

Endo, E.: The Rabaul Volcano Observatory Real-Time GPS Upgrade. Open-File Report (2006), 1232.

Finlayson, D.M., Gudmundsson, O., Itikarai, I., Nishimura, Y., Shimamura, H., and Johnson, R. W.: Rabaul Volcano, Papua New Guinea: island arc structural architecture and seismic tomography imaging of an active volcanic caldera. J.Volcanol. Geotherm. Res., 124, (2003), 53-171.

Hooper, A., Zebker, H., Segall, P., and Kampes, B.: A new method for measuring deformation on volcanoes and other natural terrains using InSAR persistent scatterers, Geophys. Res. Lett., 31(23), 5, (2004), doi: 10.1029/2004GL021737.

Luis, J.F.: Mirone: A Multi-Purpose Tool for Exploring Grid Data. Computers and Geosci., 33(1), 2007, 31-41.

Massonnet, D., Rosd, M., Carmona, C., Adragrra, F., Peltzer,G.,Feigl, K., and Rabaute, T.: The displacement field of the Landers earthquake mapped by radar interferometry, Nature, 364, (1993), 133142.

Massonnet, D., and Feigl, K.: Radar interferometry and its application to changes in the Earth's surface, Rev. Geophys., 36, (1998), 441-500.

McKee, C.O., Lowenstein, P.L., de Saint Ours, P. and Talai, B.: Seismic and deformation crises at Rabaul Caldera--prelude to an eruption? Bull. Volcanol., 47(2), 1984, 397-410.

Mogi, K.: Relations between the eruptions of various volcanoes and the deformations of the ground surface around them, Bull. Earthquake Res. Inst. Univ. Tokyo, 36, (1958), 99– 134.

Mori, J., and McKee, C.: Outward-dipping ring-fault structure at Rabaul caldera as shown by earthquake locations. Science, 235 (1987), 193-195.

Okada, Y.: Surface Deformation Due to Shear and Tensile Faults in a Half-Space.Bull. Seismol. Soc. Am., 75, (1985): 1135-1154.

Patia, H.: Petrology and Geochemistry of the recent eruptive history at Rabaul Caldera, Papua New Guinea: implications for magmatic processes and recurring volcanic activity, M. Phil. Thesis, (2003), Australian National University.

Rosen, P. A., Hensley, S., Zebker, H. A., Webb, F. H. and Fielding E. J.: Surface deformation and coherence measurements of Kilauea Volcano, Hawaii, from SIR-C radar interferometry. J. Geophys. Res., (1996), 101(E10):23109-23125.

Saunders, S.J.: The shallow plumbing system of Rabaul caldera: a partially intruded ring fault? Bull. Volcanol., (1999), 63:406–420. DOI 10.1007/s004450100159

Tregoning, P., Jackson, R., McQueen, H., Lambeck, K., Stevens, C., Little, R., Curley, R. and Rosa, R: Motion of the South Bismarck Plate, Papua New Guinea, *Geophys. Res. Lett.,***26, (1999),** 3517-3520.

Walker, G.P.L., Heming, R.F., Sprod, T.J. and Walker, H.R.: Latest major eruptions of Rabaul volcano, in R.W. Johnson, ed., Cooke-Ravian volume of volcanological papers. Geol. Surv. Papua New Guinea Memoir 10, (1981), 181-193.

Wegmuller, U., and Werner, C: Gamma SAR Processor and Interferometry Software, 3rd ERS Symposium, Florence (1997).

Zebker, H.A., and Villasenor, J: Decorrelation in interferometric radar echoes, IEEE Trans. Geosci. Remote Sens.,30, (1992), 950–959.