Deformation source modelling of a probable magma intrusion in the Fogo/Congro area (S. Miguel Island, Azores)

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BIOGRAPHIES

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ABSTRACT

GPS is nowadays an essential tool for understanding crustal deformation in volcanic regions. The monitoring of volcanic activity is particularly important in populated regions, such as the Azores islands. As the result of such monitoring in the S. Miguel Island, we present a case study of a probable siliceous magma intrusion, inferred from the velocity field obtained from the analysis of GPS data spanning the period 2000.0 – 2007.7. The magma inflow has contributed to an important 3D deformation pattern over the central of S. Miguel Island (Azores), in the vicinity of the Fogo composite volcano. The horizontal deformation shows a clear outward radial pattern whereas the vertical component shows stepwise inflation/deflation episodes along the intrusion processes. The best simple source deformation modelling of the 3D displacement field points out for a cigar-like shape intruded magma body, with a 110 m radius and a depth of 600 m (height of top and bottom of 1800 m and 2400 m, respectively). This intrusion has contributed to a widespread seismic swarm, correlated in magnitude, time, and space with the deformation field. The very high ratio of the seismic moment (calculated based on the seismic magnitude of registered events) to the magma injection geodetic moment (based on the volume change estimations using the Mogi model) give evidences of an important stress regime prior to the onset of the intrusion, afterwards triggered by the uprising magma. Moreover, underestimation of intrusion volume and very high magma viscosity could also be considered as causes for the high moment ratio. These results give important clues for understanding of the source mechanisms of magma intrusion for the Azores volcanic systems and contribute for risk mitigation in S. Miguel Island, far significant for society.

INTRODUCTION

The Azores region was built by the accretion of volcanic products in the framework of the triple plate junction where North America, Eurasia, and Nubia plates meet. The interplay between volcanoes deformation and tectonics for the Azores imposes a widespread analysis of deformation. The present-day volcanic activity is confirmed by the 30 historical eruptions witnessed by local inhabitants from 1439 to nowadays (Trota, 2008). Thus, efforts on volcanic surveillance, aiming the prediction and monitoring of volcanic unrest, is very important for risk analysis.

Eruption activity is a matter of concern for society as it poses threat to human life and risk of property losses. Since 1993 active Azorean volcanoes have being monitored aiming the understanding of volcanic plumbing systems by using GPS (Sigmundsson *et al.*, 1995). Densification of geodetic networks and continuous data acquisition are giving chance to precisely measure the deformation in time and space domains (Trota, 2008).

Sete Cidades, Fogo, and Furnas volcanoes are the most outstanding features of S. Miguel landscape. These central polygenetic volcanoes with remarkable craters, expression of voluminous eruptions that ended with collapse episodes, presents a geological record of several intracaldera explosive eruptions. Ankaramites, alkali olivine basalts, hawaiites, mugearites, tristanites, along with trachyte domes, flows, and pyroclastic deposits constitute the outcrops of volcanic products which resulted from a range of low Hawaiian to highly explosive Plinian activity.

In order to measure the deformation in S. Miguel Island we installed a dense GPS network with almost 130 markers (around 1 per square km). GPS data set on S. Miguel was gathered from episodic, continuous to semi-continuous data acquisition spanning 2000.0-2007.7. Seven summer time campaigns were carried out in S. Miguel Island (SMIG2000, SMIG2002, SMIG2003, SMIG2004, SMIG2005, SMIG2006, and SMIG2007). All the GPS data was previously validated and small pieces of data were disregarded.

In the processing of GPS data and estimation of station coordinates and velocities we used GAMIT/GLOBK, a software package developed at MIT, the Harvard-Smithsonian Center for Astrophysics, and the Scripps Institution of Oceanography (Herring *et al.*, 2006a, 2006b). In addition to our campaign and continuous data, we also included data from 158 global stations from the International GNSS Service (IGS) network. We used precise orbits from SIO (final orbits) and estimated 25 atmospheric zenith delay parameters per 24-hour sessions using the GMF mapping functions (Boehm *et al.*, 2006). Final daily positions are based on the ionospheric-free linear combination. Using GLOBK, we combined our daily solutions with independent four global IGS subnetworks processed by SOPAC (University of California, San Diego), designated as IGS1, IGS2, IGS3, and EURA. For the final velocity field estimation we used all the cleaned monthly-combined h-files for the period 1999.9-2007.7 and tied the network in the ITRF2000 reference frame.

DISCUSSION

Step analysis of the time series of station coordinates allowed the identification of three deformation periods which were correlated in time with seismic events. The velocity field based on the full data set showed a clear outward radial shape. The height component presented a more complex behaviour, with intermittent periods of inflation followed by deflation.

The Deformation Phase One (from 2000 until beginning of 2005) corresponded to a sustained uplift probably caused by a spheroid prolate-like magma body installed between the 1800 m and 2400 m depths (Bonnaccorso and Davies, 1999). This modelled source body remained almost constant with respect to depth over the deformation period. The Deformation Phase Two corresponded to a rapid deflation/inflation period which ended with a strong seismic swarm by late September 2005, with the most prominent energy released for all the unrest period. The vertical component of deformation showed strong deflation over the south sector in opposition to a small inflation over the north. The deformation Phase Three, which started October 2005, showed a decrease in the deformation rate and widespread deflation processes, giving evidences of a probable magma migration, namely downward.

The pressure source modelling showed a differentiated deformation strain rates for the three phases, with maximum registered for the Deformation Phase Two. For all the deformation phases there was a clear spatial relationship between event location and deformation source location thus indicating a similar cause for both deformation and earthquakes. By using all the deformation phase data for a 7.83 yr period, and performing an analysis of source with the Mogi model, we calculated a total volume change of the order of 0.089 km^3 (Trota, 2008). This volume estimate did not represent the magma injection due to the lack of magma compressibility estimates. Nevertheless it can give an order of magnitude for possible moving magma for the unrest period. This estimated volume closes dense-rock equivalent volumes estimations for some historical eruptions that took place in S. Miguel, as 0.087 km^3 for the Furnas 1630 AD eruption (Duncan *et al.*, 1999).

Based on the seismic magnitude of registered events we calculated the approximate seismic moment ratio as 1.3×10^{23} Nm. Taking into consideration the volume change estimations by using the Mogi model (0.089 km^3) we estimated the geodetic moment as 8.8×10^{18} Nm. The very high ratio of the seismic moment to the geodetic moment give evidences of an important stress regime prior to the onset of the intrusion, triggered afterwards by the uprising magma. Nevertheless, in the computations we must considered the probable underestimation of intrusion volume and very high magma viscosity as causes for that high moment ratio.

The FCA is close to the Fogo Caldera, where several intra and outer caldera eruptions have taken place in the last 4600 yr B.P., most of them of trachyte magma composition which requires shallow deep seated reservoirs (magma chambers) to evolve from parent basaltic magmas (Trota, 2008). The deformation that took place in the Fogo/Congro area is here interpreted as a dome-like siliceous magma intrusion from shallow sited magma chamber.

CONCLUSION

GPS technique made possible the detection of important long-term volcanic deformation unrest in Fogo/Congro area (S. Miguel Island, Azores) from 2000.0 to 2007.7. Based on simple deformation modelling (Mogi and Prolate Spheroid Model), seismic, and geologic data we interpreted this phenomena as an uprising of a stepwise siliceous magma body which stayed around 2100 m depth. This intrusion gave rise to a long term complex deformation pattern, with inflation and deflation periods space, magnitude, and time correlated with seismic energy release. Great discrepancies between seismic and geodetic moments points out for the probable high stress regime over the area prior the onset deformation which ultimately could be linked to the stress transfer between Nubia and Eurasia tectonic plates for the Azores.

Active volcanoes on the Azores must be geodetic monitoring aiming the surveillance of future magma intrusions giving chances for eruption prediction, important for volcanic risk analysis and significance for society.

REFERENCES

Boehm, J., A. Niell, P. Tregoning, and H. Schuh (2006). Global Mapping Function (GMF): A new empirical mapping function based on numerical weather model data, *Geophysical Research Letters*, 33, L07304, doi:10.1029/2005GL025546.

Bonaccorso, A., and Davis, P.M. (1999). “Models of ground deformation from vertical volcanic conduits with application to eruptions of Mount St. Helens and Mount Etna.” *Journal of Geophysical Research*, Vol. 104, No.B5, pp. 10531-10542.

Duncan, A.M., Gaspar, J.L., Guest, J.E., and Wilson, L. (Eds) (1999). Furnas volcano, São Miguel, Azores. Journal of Volcanology and Geothermal Research, Special issue, pp. 214.

Herring, T.A., King, W.R. and McClusky, S.C. (2006a). “GPS Analysis at MIT, Gamit Reference Manual, Release 10.3.” Department of Earth, Atmospheric, and Planetary Sciences Massachussetts Institute of Technology, Cambridge.

Herring, T.A., King, W.R. and McClusky, S.C. (2006b). “Global Kalman filter VLBI and GPS analysis program, Globk Reference Manual, Release 10.3.” Department of Earth, Atmospheric, and Planetary Sciences Massachussetts Institute of Technology, Cambridge.

Sigmundsson, F., Tryggvason, E., Alves, M.M., Alves, J.L., Palsson, K., and Olafsson, H. (1995). “Slow inflation of the Furnas volcano, Sao Miguel, Azores, suggested from initial leveling and Global Positioning System measurements.” *Geophysical Research Letters*, Vol. 22, pp. 1681-1684.

Trota, A. (2008). “Crustal deformation studies in S. Miguel and Terceira Islands (Azores). Volcanic unrest evaluation in Fogo/Congro area (S. Miguel).” PhD Thesis. Universidade dos Açores.