High-resolution gravity survey: Investigation of subsurface structures at Poás volcano, Costa Rica

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Received 6 May 2004; accepted 8 July 2004; published 3 August 2004.

[1] Bouguer gravity surveys have long been used to investigate sub-surface density contrasts. The main sources of error in previous surveys have been the determination of relative elevations of stations and the effect of topography (removed via the terrain correction). The availability of high precision Kinematic GPS data now facilitates generation of high-resolution Digital Elevation Models that can help to improve the accuracy of relative elevation determination and the terrain correction. Here we describe a high-resolution gravity survey at Poás volcano, Costa Rica. Our gravity modelling (i) identifies small pockets of magma at shallow depths which relate to successive magma intrusion through time and (ii) shows that the persistent degassing in the eastern part of the crater is related to local deformation at the top of the volcano and changes in the fracture network, rather than to the presence of a shallow magma intrusion. *INDEX TERMS:* 0920 Exploration Geophysics: Gravity methods; 8434 Volcanology: Magma migration; 8499 Volcanology: General or miscellaneous. **Citation:** Fournier, N., H. Rymer, G. Williams-Jones, and J. Brenes (2004), High-resolution gravity survey: Investigation of subsurface structures at Poás volcano, Costa Rica, *Geophys. Res. Lett.*, *31*, L15602, doi:10.1029/2004GL020563.

1. Introduction

[2] Static gravity surveys investigate the spatial heterogeneity of the gravity field at the surface of the Earth in order to retrieve density distribution underground. They are carried out measuring and comparing gravity values at several stations, with various corrections applied to the data. In addition to Earth Tides, latitude, free-air and Bouguer corrections, one must determine the local effect of the surrounding topography on the gravity field. A relatively easy way of calculating this effect is by representing the local topography around each station by a succession of cylinders of different heights and radius, centred on the station [*Nowell*, 1999]. Each cylinder is given a density and is divided into sectors for a better approximation of the topography [*Hammer*, 1939; *Krohn*, 1976]. The cumulated effect of all the cylinders on the gravity field is then calculated for each gravity station. Finally, once the data corrected, the remaining gravity anomaly can be interpreted in terms of heterogeneous density distribution underground. Structural studies on volcanoes using gravity surveys are typically carried out on a large, whole volcano scale, [e.g., *Locke et al.*, 1993] with a view to determining the general plumbing system within and below the edifice [*Locke et al.*, 1981; *Thorpe et al.*, 1981] or the general structure of calderas [*Campos-Enriquez and Arredondo-Fragosso*, 1992]. More detailed surveys would not only require a greater number of measurements but also the confidence that the various corrections needed for data processing are accurate enough to allow comparison of small gravity differences between close stations. In topographically severe places such as volcanoes, the main source of errors in the corrections lies in the poor knowledge of topography within about 100 m of each measurement point (station). Improved accuracy of topographic models would reduce the errors in terrain corrections used for gravity surveys. Smaller gravity differences between stations could then be investigated with high precision topographic models and so surveys could become more accurate.

[3] Development of new technology (e.g., real-time kinematic Global Positioning System) now allows 3D coordinates to be recorded in the field in a matter of seconds and therefore allows the generation of precise Digital Elevation Models that can be used to calculate terrain correction around the gravity stations.

[4] Previous gravity surveys have been carried out at Poás volcano to investigate the structure of the whole edifice [*Thorpe et al.*, 1981; *Brown et al.*, 1987]. However, while these studies provide information about the main features of the edifice, they do not have the resolution to detect small sub-surface bodies and it is these features (e.g., shallow magma intrusions) which are important for micro-gravity monitoring as they are likely to be the cause of micro-gravity changes through time.

[5] Here we present the results of a new high-resolution gravity survey carried out at the top of Poás volcano, which provides new insights into the structure of the active crater at Poás.

2. Data Collection and Reduction

[6] A 0.17 km^2 network of 33 stations was established on the crater floor of Poás in February 2002. Station coordinates were determined by differential GPS with a precision of 3 cm or better for most stations. Gravity data were collected at every station with a Lacoste & Romberg® G-meter (s.n. G-403) and measurements were repeated as often as possible (up to 4 times per day per station) to quantify the instrument drift.

[7] Raw data were corrected for Earth Tides [*Broucke et al.*, 1972] and then for instrumental drift, which was

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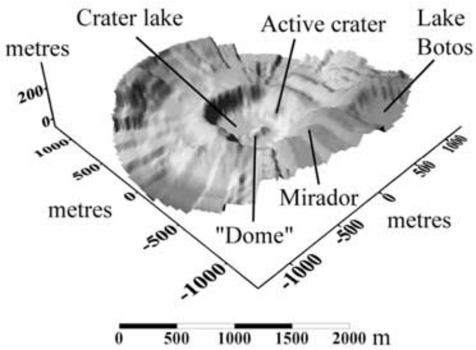

Figure 1. Example of topography estimate for Terrain Correction Hammer zones at one gravity station. Hammer zones are divided in 64 sectors and the accuracy of the topography increases dramatically close to the station where the influence of surrounding topography is greater. Axes represent the distance from the station.

typically 80 μGal day^{-1}. The standard latitude, elevation and Bouguer corrections were also made, using GPS data and a 2.4×10^3 kg m^{-3} density [*Brown et al.*, 1987].

2.1. Terrain Correction

[8] Errors in terrain correction are thought to be the main source of inaccuracy in Bouguer Surveys [*Nowell*, 1999] and therefore great care must be taken to minimize any error. This is especially the case here as this gravity network is very small and so too is the gravity difference between stations. Consequently, errors in terrain correction could easily exceed the actual gravity differences between stations. Causes of these errors are mainly a poor knowledge of the topography around the stations and of the density of the material involved. Therefore a specific protocol had to be designed to reduce the uncertainty of such parameters.

[9] For large scale (several square km) surveys, terrain corrections are usually carried out using digitised maps at the scale of 1:50000 or better. The effect of local topography (within a few tens of metres) is sometimes ignored, or at best estimated crudely (e.g., assuming a regularly shaped topography around the station). Given that this work considers sample points spacing of 15–30 m to complete a spatially detailed survey, it was vital to obtain accurate corrections since terrain effects would be large.

[10] Obviously, the influence of topography is greatest close to the station and this influence decreases with distance from the station. There is therefore a threshold distance, beyond which the terrain correction for different stations will tend to be the same. We determined this maximum distance by comparing resulting terrain corrections between stations and when the difference between stations becomes negligible compared to the instrument noise (i.e., 15 μGal), the zones taken into account for the terrain correction do not need to extend any further. Due to the limited extension of this high-resolution network, we found that terrain corrections converge for all stations from 1290 m thus we defined 1295 m as the outer radius of concern for this study.

[11] The highest resolution maps available for the Poás crater are 1:50000 maps which are not sufficient for this study. Therefore, a precise topographic campaign was carried out in February 2002 using RTK Leica® GPS receivers. The RTK GPS allows measurements of coordinates with a precision better than 3 cm in less than 10 seconds. An extensive survey was carried out at Poás with precise 3D coordinates measured for 2670 points along crests (i.e., crater rim, and 'dome' crest), bases of slopes (i.e., limits of the crater bottom) and around the edge of the acid lake. The static Base receiver was located at the 'mirador' viewpoint (on the southern rim of the crater) during the whole survey in order to keep direct sight with the mobile Rover. Elevation of the acid lake has also been measured (2330.41 m a.s.l.) and the elevation of the surface of the lake (area within the measured edge) has been fitted with this value. From these topographic data, we generated a high-resolution Digital Elevation Model (DEM) with resolution of less than 5 m^2 horizontally.

[12] We designed an automated gravity terrain correction using this DEM based on 260 "Hammer" zones [*Hammer*, 1939]. Each zone annulus was 5 m thick for zones inside the crater and 10 m for zones outside the crater where topographic effects are less. Each "Hammer" zone was divided into 64 equal sectors. Tests for each gravity station, using successively 8, 16, 32 and 64 sectors for each Hammer zone, show that the resulting terrain corrections tend to converge at 32 sectors per Hammer zone. The results shown here were achieved by using 64 sectors (Figure 1) and a measured density of 2.4×10^3 kg m^{-3}.

2.2. Lake Correction

[13] As density of the lake water (1.0×10^3 kg m^{-3}) greatly differs from that of the substratum (2.4×10^3 kg m^{-3}), the effect of the lake on the gravity field on the crater floor must be taken into account. Lake bathymetry [*Martinez et al.*, 2000] was combined with our RTK GPS survey to estimate the shape of the lake. To a first approximation, Poás lake 3D geometry can be represented as an asymmetric inverted flat-bottomed cone. The lake bottom is circular with a radius of 80 m while the contours of the lake are ellipsoidal. Slope of the lake wall is assumed here to be constant from the surface to the bottom.

3. Gravity Modelling

[14] The reduced gravity data show a positive Bouguer anomaly inside the active crater, centred on the south side of the lake, with a relative maximum amplitude of 2.5 mGal (Figure 2a).

[15] We modelled this anomaly using 2.5D gravity modelling software GravMag [*Pedley et al.*, 1997]. The modelling is not strictly three-dimensional because although it allows control of the third dimension, the modelled bodies must be centred on the studied profile. As the extent of the gravity network is relatively small, the zone investigated by the Bouguer survey remains relatively shallow and we do not expect to investigate structures deeper than a kilometre below the crater floor.

[16] We modelled two perpendicular profiles across the crater floor and compared model gravity anomalies with actual gravity data along the profiles. The final best-fit model was achieved when the mean residual between data and model fell below 15 μGal which is the estimated instrument noise (the maximum residual at gravity stations did not exceed 80 μGal; Figure 2b). The model comprises a quasi-vertical structure with a density contrast of $+0.4 \times 10^3$ kg m^{-3} with the surroundings, extending from 500 m

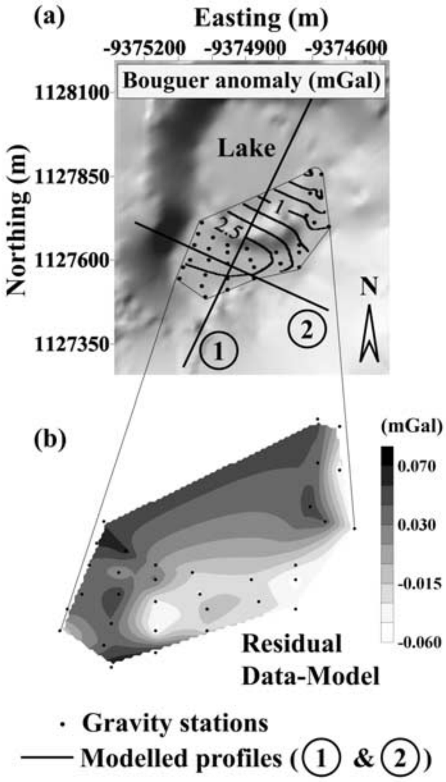

Figure 2. (a) Map of Bouguer anomaly in mGal. Contours are 0.50 mGal. Points on the map indicate stations for the high-resolution gravity network and lines indicate the two perpendicular profiles along which gravity anomaly was modelled. (b) Residual gravity anomaly in mGal between data and model. Mean residual gravity station is 15 μGal which is the estimated noise for the gravity meter.

below the crater floor (i.e., ~1800 m a.s.l.), up to only a few metres below the crater floor. It is centred on the maximum gravity anomaly, south of the so-called "dome" on the south side of the lake, and has a horizontal cross-section of ~300 × 340 m (Figure 3).

[17] The top of Poás volcano is mainly made of light vesiculated material, with a measured density of 2.4×10^3 kg m^{-3}. This is similar to the values used in previous studies [*Brown et al.*, 1987; *Rymer et al.*, 2000]. If we take this as the background density for our models, it gives a density of 2.8×10^3 kg m^{-3} for the vertical structure responsible for the observed high-resolution Bouguer anomaly. Because of its vertical elongated shape and especially its density, this body is thought to be crystallised magma, rooted to the upper reservoir at ~1800 m a.s.l. [*Thorpe et al.*, 1981; *Rymer et al.*, 2000]. The closest analogue to a magma body located at shallow depth under the crater floor is the degassed lava flows located on the inner eastern crater wall. Measurements on these lava flows give an average density of 2.8×10^3 kg m^{-3}, which fits well with the inferred density from the Bouguer survey for a cooled magma body under the crater floor. At such shallow depths, volatile solubility in magmas is almost nil [*Burnham*, 1994], therefore magma so close to the surface is expected to be almost entirely degassed [*Fournier*, 2003]. High-temperature fumaroles (960°C) on the "dome" in 1981 [*Casertano et al.*, 1987] indicated the presence of a hot magma body at the time, only a few metres below the surface. The presently low temperatures at the fumaroles on the "dome" (i.e., <100C) are not compatible with hot magma just underneath the surface, so the shallow magma body has now to be mostly crystallised. It is this frozen magma that we have identified and modelled using the high-resolution gravity survey.

4. Discussion

[18] The total mass of intruded magma responsible for the observed positive gravity anomaly is $\sim 149 \times 10^9$ kg. This is a minimum estimate as part of the crater floor has not been investigated for this Bouguer survey (i.e., crater lake). However, stations on the eastern side of the lake do not show the higher gravity values that would be expected if there was shallow magma close to the eastern fumarolic field. Indeed, even very small shallow magma intrusions below the north and west of the crater floor would affect the gravity field at the present stations and dramatically decrease the horizontal gradient of gravity between the stations. We are therefore confident that the underestimate, if any, is minimum.

[19] This overall mass of magma represents more than 5 times the total mass of magma intruded during the last crisis in 1986–89 (i.e., $\sim 27 \times 10^9$ kg [*Fournier*, 2003]). At least two episodes of magma intrusions at the summit of Poás volcano are thus necessary to account for the observed Bouguer anomaly. While this high-resolution Bouguer survey cannot discriminate between the different intrusions, it clearly shows that the greatest part of the magma intruded at the top of Poás is localised on the southern side of the crater lake. The present degassing seen on the crater walls, especially on the eastern side, is therefore related to fractures going deep below the crater floor rather than the presence of magma immediately underneath.

[20] The presence of a group of solidified, high level bodies below Poás active crater has two major consequences. Firstly, it may prevent the magmatic gas to rise up through the zone where the intrusions emplaced and thus play a role in the location of fumaroles in the active crater. This would explain why fumaroles are now located on the eastern side of the crater and not at the south. Fumaroles at the south were present 20 years ago. This may indicate

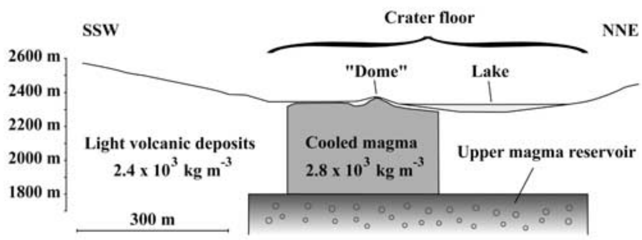

Figure 3. Schematic cross-section along profile 2 (see Figure 2a) of the active crater at Poás volcano inferred from high-resolution gravity survey. Different material densities are indicated in kg m^{-3}. The cooled magma body is off-centred with the actual crater lake.

that, at the time, some magma was still hot enough to heat the hydrothermal system in its vicinity.

[21] Secondly, the presence of frozen intrusions above the upper magma reservoir raises the general issue of the increase of density of volcanoes summit zones. Indeed, when frozen magma is much denser than the surrounding material (e.g., volcano-clastic deposits), the cumulated mass of magma intrusions tends to increase the overall density of the area above the upper magma reservoir. Persistent gas circulation in fractures around these intrusions invariably leads to sustained hydrothermal alternation and deposition of clay-rich minerals, as observed at Poás. Consequently, circular slip surfaces may develop around the intrusions, close to the crater walls and we suspect the combination of these slip surfaces with the added weight of frozen magma intrusions above the magma reservoir to be an aggravating factor for ground subsidence at the top of many volcanoes. At Poás, the lack of ground deformation in the active crater [*Rymer et al.*, 2000] seems to show that subsidence is not a gradual process. However, in case of a pressure decrease in the upper magma reservoir (i.e., drainage of part of the magma), the reservoir roof may not be able to support the added weight of frozen intrusions above it anymore. Catastrophic subsidence and formation of pit-craters may then occur.

[22] As high-resolution gravity surveys allow a detailed assessment of density distribution at volcanoes summit zones, we believe that similar studies should be applied to other volcanoes in order to investigate the occurrence of shallow magma intrusions on different types of edifice.

[23] **Acknowledgments.** This work was supported by the Open University, NERC, NASA-EOS/IDS (NAG5-10640) programs and the Royal Society. We are grateful to the staff of OVSICORI and the Parque Nacional del volcan Poás, Costa Rica, for the logistical support. The manuscript was greatly improved thanks to helpful comments from Andrew Harris and an anonymous reviewer. Thanks also to Dave Rothery, Anna Ksienzyk and "Mula" for their help in the field.

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