Shallow structure beneath the Central Volcanic Complex of Tenerife from new gravity data: Implications for its evolution and recent reactivation

J. Gottsmann[1], A.G. Camacho[2], J. Martí[3], L. Wooller[4], J. Fernández[2], A. García[5], H. Rymer[4]

[1] Department of Earth Sciences, University of Bristol, Wills Memorial Building, Queens Road, Bristol BS8 1RJ, United Kingdom

[2] Instituto de Astronomia y Geodesia (CSIC-UCM), Ciudad Universitaria, Pza. de Ciencias, 3, 28040 Madrid, Spain

[3] Institute of Earth Sciences "Jaume Almera", CSIC, Lluís Solé Sabarís s/n, Barcelona 08028, Spain

[4] Department of Earth and Environmental Sciences, The Open University, Walton Hall, Milton Keynes, MK7 6AA, United Kingdom

[5]Department of Volcanology, Museo Nacional de Ciencias Naturales, CSIC, C/ José Gutiérrez Abascal, 2, 28006 Madrid, Spain

Abstract

We present a new local Bouguer anomaly map of the Central Volcanic Complex (CVC) of Tenerife, Spain, constructed from the amalgamation of 323 new high precision gravity measurements with existing gravity data from 361 observations. The new anomaly map images the high-density core of the CVC and the pronounced gravity low centred in the Las Cañadas caldera in greater detail than previously available. Mathematical construction of a subsurface model from the local anomaly data, employing a 3-D inversion based on "growing" the subsurface density distribution via the aggregation of cells, enables mapping of the shallow structure beneath the complex, giving unprecedented insights into the sub-surface architecture. We find the resultant density distribution in agreement with geological and other geophysical data. The modelled subsurface structure supports a vertical collapse origin of the caldera, and maps the headwall of the ca. 180ka Icod landslide, which appears to lie buried beneath the Pico Viejo – Pico Teide stratovolcanic complex. The results allow us to put into context the recorded ground deformation and gravity changes at the CVC during its reactivation in spring 2004 in relation to its dominant structural building blocks. For example, the areas undergoing the most significant changes at depth in recent years are underlain by low-density material and are aligned along long-standing structural entities, which have shaped this volcanic ocean island over the past few million years.

1. Introduction

The Central Volcanic Complex (CVC) of Tenerife (Canary Islands, Spain)), which includes the 16 x 9 km wide Las Cañadas caldera (LCC, Figure 1), reactivated after an almost century-long period of quiescence in spring 2004, with increased seismicity (including felt earthquakes) and subsurface mass addition into its north-western and western portions (García et al., 2006; Tárraga et al., 2006; Gottsmann et al., 2006; Almendros et al., 2007). It has been speculated that earthquake locations and density changes during the reactivation may be controlled by the internal structure of the CVC (Martí et al., 2008a). However, the available geophysical information on its sub-surface architecture is mainly based on rather crude surveys highlighting large wavelength anomalies such as from aero-magnetic data (Araña et al., 2000; García et al., 2007) or gravimetric data with substantial uncertainties (Araña et al., 2000). A detailed assessment of structural controls on the spatio-temporal variations in geophysical parameters during the recent reactivation thus remains ambiguous. At other collapse calderas (e.g. Long Valley, Valles, Toba, Campi Flegrei) geophysical imaging has provided important insights into their internal architecture including the identification of potential magma and hydrothermal reservoirs (e.g. Sanders et al., 1995; Aprea et al., 2002 Guidarelli et al., 2002; Masturyono et al., 2001). Such reservoirs may play an important role during post-collapse processes, including episodes of unrest (see Martí et al., 2008b for a recent review). In light of the recent unrest, knowledge about the shallow subsurface beneath the CVC is of great importance, and provided the motivation for this study. This work also aims to contribute to the discussion as to the origin of the Las Cañadas Caldera (LCC): lateral collapse due to edifice instability (Cantagrel et al., 1999) or vertical collapse due to explosive volcanism (Martí and Gudmundsson, 2000) having been proposed.

We present results from a new series of gravity measurements performed at the CVC over the past few years, which, combined with existing gravimetric data, enable us to image its shallow sub-surface density distribution at a higher resolution than previously possible.

2. Previous geophysical work

While the surface geology of the CVC (Fig. 1) has been a target in the past (e.g. Martí et al., 1994; Ablay et al., 1998; Ablay and Martí, 2000), the complex's internal structure remains rather enigmatic. Previous geophysical studies have focused on obtaining sub-surface images based on large wavelength (>> 1 km) anomalies (MacFarlane and Ridley, 1968; Ablay and Kearey, 2000; Watts et al., 1997; Araña et al., 2000) but have not provided information on the shallow structure beneath the CVC, including the caldera itself. Ablay and Kearey (2000), provided a coherent interpretation of the magmatic and structural evolution of Tenerife from gravity data predominantly collected in the 1980s and 90s by members of the Instituto de Astronomia (CSIC-UCM) and the Instituto Geografico Nacional (Camacho et al., 1991; Araña et al., 2000). Ablay and Kearey's emphasis lay in the integration of a rich petrological data set with the existing gravimetric data. The original gravity data suffered from significant uncertainties stemming from both terrain correction methods and control of benchmark elevation using topographic maps and barometers, which resulted in uncertainties in the Bouguer anomalies on the order of 5 mGal (1 mGal=10^{-5}m/s^{-2}) (Ablay and Kearey, 2000). One of the first high-resolution geophysical images to a depth of approximately 1500 m beneath the LCC floor was provided by the audiomagnetotelluric study of Coppo et al. (2008), which enabled the identification of three adjacent bowl-shaped depressions consistent with a multiple-event vertical collapse origin of the LCC.

3. Geological background

The geological and tectonic evolution of the triangular island of Tenerife and the CVC was described in recent papers (Martí et al., 1994; Martí et al., 1998; Araña et al., 2000) and we therefore only provide a short summary. The Canary Islands form a volcanic archipelago with a long-standing history of volcanic activity that began more than 40 million years ago (Araña and Ortíz, 1991). More than a dozen eruptions have occurred on the islands of Tenerife, Lanzarote, and La Palma since the 16^{th} century. Tenerife, the largest of the Canary Islands, has an eruptive history of over 12 million years, including a shield building phase and the construction of a central volcanic structure, the Las Cañadas edifice (LCE) from 3.5 Ma onwards (Martí et al., 1994). Table 1 provides a stratigraphic scheme of the island, and highlights the main constructive and destructive episodes during its formation. The LCE is composed of a mafic post-shield Lower Group (>3.5 Ma – 1.57 Ma), overlain by the Upper Group comprising three felsic formations (1.57 Ma -0.179 Ma).

The evolution of the LCE comprises both constructive and destructive phases, including vertical and lateral collapses with volumes on the orders of several to tens of km^3 (Martí et al., 1997). Martí et al. (1994) propose at least three vertical collapses during Upper Group times, which resulted in the formation of the LCC (Table 1). High walls nowadays bound the LCC to the southwest, south, east and northeast.

Over the past 170-190 ka, the prominent Pico Viejo - Pico Teide (PV—PT) volcanic complex was emplaced inside the caldera depression during predominantly effusive but also explosive activity (Ablay and Martí, 2000; Edgar et al., 2007). The PV-PT complex appears to be fed by both shallow-level (< 5 km) phonolitic magma reservoirs and deeper-seated basaltic magma patches (Ablay and Hürlimann, 2000; Ablay and Martí, 2000). Recent (< 2 ka) volcanic activity was located both on the PV—PT complex (explosive and effusive phonolitic eruptions) and along two extensional structural lineaments referred to as the NW—SE oriented Santiago Rift, and the SW-NE striking Dorsal Ridge (both rifts are dominated by monogenetic mafic eruptions). Historic eruptions at these centres were fed by mafic magmas and occurred in 1704, 1706, 1798, and 1909. To the north of the CVC lie the valleys of Icod and Orotava, which are interpreted to represent scars from large lateral collapses (landslides). The absence of a visible caldera wall to the North has led some workers to infer a lateral collapse origin of the LCC (Cantagrel et al., 1999; Ancochea et al., 1999). Others see clear evidence for vertical collapse origin of the LCC based on the abundance and nature of pyroclastic deposits consistent with explosive caldera formation (Martí et al., 1998; Bryan et al., 1998; Ablay and Hürlimann, 2000; Martí and Gudmundsson, 2000; Brown and Branney, 2004).

4. Gravity data

a) New gravity survey

All 323 new gravity measurements were performed by the same operator (JG) at the CVC between May 2004 and November 2006 using LaCoste&Romberg gravimeter G-403 (Fig. 1). The accuracy of individual readings was maintained through regular reoccupation of each station and the reference station. The reference was conveniently located in the caldera depression at 340088.27m Easting and 3124255.73m Northing, at an ellipsoidal elevation of 2223.83 m. The reference was occupied between 4 and 8 times per day depending on the design of measurement loops to check for instrument drift and tares. At each benchmark the reading was derived by the averaging of between 5-10 manual readings taken over a few minutes, depending on benchmark stability and ambient noise. The error on the raw readings is less than 0.02 mGal. Location and elevation data were provided by differential GPS measurements (operated by LW), conducted at the same time as the gravity measurements. Leica System 530 receivers and AT502 antennas were used, with data sampling at 1 Hz. A reference station was established (with matching occupation frequency of 1 Hz running for a total of more than 250 hrs), for which absolute WGS84 co-ordinates were derived. A rover GPS receiver, mounted on a 1.9 m-high staff, was placed at the measurement point and recorded for periods of between 60 and 180 seconds, depending upon satellite visibility and the distance to the reference. Post-processing of the GPS data was carried out using Leica Geosystems' Ski-Pro software. 2σ errors for most positions were generally under 5 cm in the Z axis and better than 4 cm in the X and Y axes. Fig. 2 shows the location of the new gravity/GPS benchmarks which provide coverage of the LCC, the PV-PT complex and the Santiago Rift. An additional 361 gravity data (from a total set of 975 covering the entire island) obtained earlier are used for investigating the wider area surrounding the CVC (Camacho et al., 1991, Araña et al., 2000). These earlier gravity readings are reported with an uncertainty of 1.2 mGal. The significantly larger error in the earlier gravity data compared to the new data is due to uncertainties in benchmark elevation.

b. Terrain density

The terrain density is among the most critical parameters for gravimetric data reduction and choosing the 'right', i.e., realistic, terrain density for a whole island (with bimodal magmatism/volcanism spanning several million years and the associated variety in eruptive products) is prone to errors. Terrain effects are significant on Tenerife as the CVC represents the top of a volcanic edifice rising to more than 3.7 km elevation within 12 km from the northern shoreline, and extending more than 3.5 km below sea level. Despite these complexities, it is possible to deduce an optimal value for terrain density from both gravity and elevation data. According to a general assumption (Nettleton, 1939), a suitable density value must produce a minimum correlation between gravity anomaly ($\boldsymbol{\Delta g}$) and elevation ($\boldsymbol{h}$). However, this approach can lead to erroneous density estimates, for example if long wavelength components of both gravity and topography are correlated due to deep structural features. The general terrain on Tenerife follows a convex geometry common to all volcanic islands related to the intrusive and extrusive nature of ocean island building, and thus the gravity anomaly will also follow this pattern. A more realistic value for the terrain density can be obtained by looking for the minimum correlation between the shortest wavelength components of both gravity and topography.

For each benchmark P_i, we therefore calculate the short wavelength values $\Delta\tilde{g}_i$ and $\Delta\tilde{h}_i$ for the gravity anomaly and elevation, respectively, by removing regional values determined as mean values between P_i and surrounding benchmarks P_j up to a radius r:

$$\Delta\tilde{g}_i = \Delta g_i - \frac{1}{n_i}\sum_J \Delta g_j \,, \qquad \Delta\tilde{h}_i = \Delta h_i - \frac{1}{n_i}\sum_J \Delta h_j$$

where distance (Pi, Pj) ≤ r.

The optimal theoretical terrain density ρ_t corresponds to the minimum correlation between the resulting $\Delta\tilde{g}_i$ and $\Delta\tilde{h}_i$ values. Fig. 3 gives terrain densities (kg/m^3) as a function of *r*. However, we choose a terrain density accounting for both theoretical constraints and measured densities of exposed lithologies of the CVC. Ablay and Kearey (2000) report more than 30 measured bulk densities of Tenerife rock types. Calculating the mean values for their reported rock types (except for Teno and Dorsal ridge basalts) and weighting the occurrence of effusive and flow deposits against fall deposits (0.8 vs. 0.2, respectively), to account for exposed CVC lithologies (Table 2), we derive 2200±271 kg/m^3. The mean value is consistent with our theoretical minimum correlation for r of about 3 km, providing a reasonable wavelength for topographic and gravity anomalies. We thus use a terrain density of 2200 kg/m^3 for our gravity reduction.

c) Gravity data reduction

Standard techniques for gravimetric data reduction for the effect of Earth and ocean tides, latitude and benchmark elevation were employed. Ocean loading effects were corrected using the Schwiderski global ocean tide model (Schwiderski, 1980). Continuous gravity observation, performed by an automated Burris gravity meter (B-28) in 2007 over a period of 8 days in the Las Cañadas caldera, revealed that residual ocean loading effects amount to less than 0.01 mGal and are thus negligible for our purpose.

The earlier gravity data were referenced to the absolute gravity reference IGSN71 (Morelli et al., 1974). In order to merge the data sets, we determined two sets of Bouguer anomalies, one using solely the new data and the second using only the earlier data. We then deduced an offset value, which produced a maximum autocorrelation between the two sets of anomaly data. This gravity offset was then used to combine the two data sets to form a single coherent set of gravity data. This technique involving global overlapping of individual data is superior to techniques based on matching few common benchmarks to calculate an offset value, as local inaccuracies could be propagated, resulting in an erroneous final data set.

Free-air and Bouguer corrections, respectively, were performed with respect to theoretical predictions based on GRS80 [Geodetic Reference System 1980] using a standard free-air gradient of -0.308 mGal/m and the above derived terrain density of 2200 kg/m^3 for the Bouguer correction

d) Terrain correction

To correct for the topographic effects (on-shore Tenerife, neighboring islands and off-shore areas) on gravity measurements, we employed an automated algorithm based on dense circular zones (34 zones from 1 m to 100 km radius, 894 compartments in total), similar to Hammer zones, around the individual benchmarks (Hammer, 1939). A 10 m digital elevation model (DEM), constructed from topographic maps provided by the Instituto Geografico Nacional (IGN), approximated the immediate on-shore topography up to 895 m distance from each gravity point. For on-shore distances greater than 895 m, we used a 100 m DEM. For the surrounding marine areas, satellite altimetry data (http://topex.ucsd.edu/cgi-bin/get_data.cgi and local charts were used to provide information about the local geoid and bathymetry (Smith and Sandwell, 1997). Similar to the Hammer reduction procedure, average elevations were calculated for each compartment and the terrain effect in each compartment was propagated to obtain the final terrain correction value for each benchmark.

The so derived terrain corrections for the gravity benchmarks vary between 8.8 mGal and 97.7 mGal, with an average of 19.3 mGal. The maximum correction applies to a benchmark at the base of Teide's summit cone. Possible errors in the choice of the terrain density ρ_t are accounted for in the modelling process. For this, an additional unknown $\delta\rho_t$**,** which represents a correction to the initially assumed terrain density, is included in the inversion routine as described below.

e) Regional gravity trend

A very long-wavelength component of gravity variations can be produced by crustal structures defining a regional trend in the resultant gravity data. This effect needs to be accounted for in creating a local Bouguer anomaly map of the CVC. We used Geosat and ERS 1 satellite altimetry and gravity data (http://topex.ucsd.edu/cgi-bin/get_data.cgi; (Sandwell and Smith, 1997)) to quantify the regional gravity trend considering an area up to a distance of 100 km around Tenerife and 3 km radial spacing between individual nodes.

Using the free-air satellite anomaly data combined with bathymetry and geoid heights, we determined the regional Bouguer anomaly taking 2900 kg/m^3 as the mean background density for oceanic crust (Carlson and Raskin, 1984). We determined a smoothed linear trend of 0.27±0.03 mGal/km with azimuth N113ºE, which represents the very long wavelength component superimposed on the local anomaly. It is in reasonable agreement with a general average value of 0.2 mGal/km obtained by Bosshard and MacFarlane (1970) extending from west of La Palma and El Hierro to Gran Canaria. This trend is believed to be due to crustal thickening towards the African continent.

Subtracting the regional trend from the data, we obtain the local Bouguer anomaly (Fig. 4), which highlights local sub-surface structures. These Bouguer anomaly data are then employed for the mathematical inversion.

5. Gravity inversion

a. Theory and sensitivity

The inverse gravimetric problem, namely the determination of a sub-surface density distribution consistent with an observed gravity anomaly, has an intrinsically non-unique solution (e.g. Al-Chalabi, 1971). Moreover, the available data are always insufficient and inaccurate to resolve ambiguities. One can, however, obtain realistic solutions by including additional constraints on model parameters (subsurface structure) and data parameters (statistical properties of inaccurate data, e.g. Gaussian distribution). The non-linear inversion methods that delineate the geometrical properties of anomalous bodies with prescribed density contrasts (e.g. Pedersen, 1979; Barbosa et al., 1997) are of course limited by the underlying hypothesis on source density. However, these techniques provide results worth exploring. For full non-linear treatments, methods based on the exploration of model possibilities often give the best results (Tarantola, 1988). This exploration process can for example be conducted randomly (Silva and Hohmann, 1983).

In this study we use the inversion routine presented in Camacho et al. (2000 and 2002), which has also been applied in other gravimetric studies (Camacho et al., 2001, 2007). The inversion process constructs a subsurface model defined by a 3-D aggregation of *M* parallelepiped cells, which are filled, in a "growth" process, by means of prescribed positive and/or negative density contrasts. The design equation to relate observables, i.e., the gravity anomaly Δg_i at *N* benchmarks (x_i, y_i, z_i), with modelling parameters, and residuals v_i is:

$$\Delta g_i = \sum_{j \in J^+} A_{ij} \Delta\rho_j^+ + \sum_{j \in J^-} A_{ij} \Delta\rho_j^- + \delta g_{reg} + \delta g_{top} + v_i \quad , \quad i = 1,...,N \quad , \tag{1}$$

where A_{ij} is the vertical attraction for unit density for the *j*-th parallelepiped cell upon the *i*-th observation point, $\Delta\rho_j^-$, $\Delta\rho_j^+$ are prescribed density contrasts (negative and positive) for the *j*-th cell, J^+, J^- are sets of indexes corresponding to the cells filled with positive or negative density values, and δg_{reg}, δg_{top} are optional terms for regional trend and additional topographical correction given by

$$\delta g_{reg} = p_0 + p_x(x_i - x_M) + p_y(y_i - y_M) \quad , \quad i = 1,...,N \quad , \tag{2}$$

$$\delta g_{top} = \delta\rho_T \; C_i \, . \tag{3}$$

Here p_0, p_x, p_y are parameters for the linear trend, x_M, y_M are averaged coordinates, C_i are coefficients for the terrain correction and $\delta\rho_T$ is an optional additional value with respect to the initially adopted terrain density. In Eqns. 1-3, J^+, J^- (cells filled with positive and negative density contrast), p_0, p_x, p_y, and $\delta\rho_T$ (regional parameters) are the main unknowns to be determined by the inversion.

The problem of non-uniqueness is usually approached by numerical techniques in the form of a generalised matrix inversion including some form of "perturbation" scheme such as the Levenberg-Marquardt method (e.g. Enmark, 1981; García-Abdeslem, 2000; Marinara and Hall, 2001). In short, the "perturbation" idea of the Levenberg-Marquardt method (and other similar methods) is a numerical approach that involves modification of the usual least square solution for the case of singularity or non-uniqueness, by an "ad-hoc" term or perturbation ($\lambda \boldsymbol{I}$; where $\boldsymbol{I}$ is an identity matrix), which may transform a singularity into non-singularity. Such solutions aim at minimising an objective function that is a combination of the l_2-norm of the residuals ("least squares fit") and the l_2-norm of the model parameters, using a positive value of λ for balance (the so-called damping factor or Lagrange multiplier). The methodology followed in our study can be considered as a generalisation of this numerical approach as outlined by Tarantola (1988). This author gives a general treatment of least-squares inversion methods by including them into a general theory, which represents the inversion problem as a problem of combination of inaccurate information. For instance, the least-squares inversion approach is presented as the combination of observable data with Gaussian uncertainties (given by a covariance matrix $\boldsymbol{Q_D}$) and information on the model, given by a previous model $\boldsymbol{m_{prev}}$ which is also subject to Gaussian uncertainties (given by a covariance matrix $\boldsymbol{Q_M}$). For the case where the previous model is exactly zero ($\boldsymbol{m_{prev}} \equiv \boldsymbol{0}$, no particular previous information on the model is available) the formulae of the general methodology of Tarantola are close to the numerical methods pointed out before. For the particular case of gravity inversions aiming at deriving a unique model of density distribution at depth, the general condition of l_2-minimisation of the model parameters becomes a minimisation condition for the total anomalous mass; i.e. a model involving anomalous bodies with simple and smoothed geometries *and* a minimum total mass is uniquely determined. Accordingly, in order to get unique results from our data inversion, we adopt a mixed minimisation condition, based on model “fitness” (least square fitness) and “smoothness” (total anomalous mass) (see also Camacho et al., 2002):

$$\mathbf{v}^T\, \mathbf{Q}_{\mathbf{D}}^{-1}\, \mathbf{v} + \lambda\ \ \mathbf{m}^T\, \mathbf{Q}_{\mathbf{M}}^{-1}\, \mathbf{m} = \min, \tag{4}$$

where $\boldsymbol{m} = \left(\Delta\rho_{1_1},\ldots,\Delta\rho_M\right)^T$ (superscript T denotes transpose of a matrix) are density contrast values for the M cells of the model, $\boldsymbol{v} = \left(v_1,\ldots,v_N\right)^T$ are residual values for the N data points, $\boldsymbol{Q_D}$ is an apriori covariance matrix for uncertainties of the gravity data, $\boldsymbol{Q_M}$ is an apriori covariance matrix for uncertainties of the model parameters, and λ is a factor for selected balance fitness/smoothness of the model. For practical applications λ is selected to produce uncorrelated inversion residuals. In traditional numerical inversion methods based on the Levenberg-Marquardt smoothing approach, an identity matrix $\boldsymbol{I}$ is used in place of $\boldsymbol{Q_M}$. However, taking into account that the cells of the model have different sensitivities (lower for deep or peripheral cells; see below), using a covariance matrix to quantify cell sensitivity based on its geometry and location, will produce more balanced and coherent minimization conditions for the model parameters, and will thus produce more consistent solutions.

In interpreting the inversion results a few important points need to be considered. Although the inversion routine counteracts the problem of non-uniqueness of results via the mixed minimum condition as explained above, there is still some degree of ambiguity in the results. Despite the complexity of the inversion, the resultant models should not be regarded as an exact replication of the sub-surface architecture, as both data collection and post-processing suffer from inaccuracies and assumptions. The modelled density contrasts should be seen as mean values for a particular spatial distribution of cells in the form of a smoothed model. The sensitivity to the data is dependent on the position of each cell within each the model. The sensitivity of very shallow, very deep and very peripheral cells is lower than those located beneath the survey area at depths of about 2 km below the surface. During inversion the size of the cells is variable to account for differences in sensitivity: very deep cells or very peripheral cells are larger then those cells located at shallow depth. Figure 5 shows results from a sensitivity test of the inversion for the particular case of the Tenerife study. We simulate an S-shaped anomalous body with a prescribed density contrast of 800 kg/m^3 located beneath the CVC. Using the same gravity benchmarks employed for the inversion as described in the next section, we calculate the resultant gravity value at each benchmark and then use these data for inversion. The inversion model gives an adequate representation of the simulated body in terms of its geometry. Distortions in the shape of the modelled body with respect to the simulated body are apparent for greater depths as well as in areas of insufficient gravity data. The density contrast is found to be ca. 400 kg/m^3 (i.e., 50% of the prescribed contrast), which represents the value consistent with the minimum total anomalous mass necessary to match the observed Bouguer anomaly (see previous section on inversion theory). In general, while the shape and distribution of the modelled anomalous bodies are indicative of their real features as shown by the above sensitivity analysis and also by the examples given by Camacho et al. (2002), due to the tendency of the methodology to produce models involving a minimum total anomalous mass, the density contrasts are likely to be stronger in reality. It is therefore impossible to attribute a finite “real” value to any density contrast.

b. Inversion of data

The operational method for solving the design system is a controlled 3-D growth of anomalous bodies by means of an exploratory approach, subject to the fit and smoothness conditions explained in the previous section.

From the full data set of 361 existing and 323 new gravity measurements we selected 392 data (Figs. 1 and 2) matching the following conditions: (i) a minimum distance between neighbouring benchmarks of equal or larger than 200 m for the new data (core of the data set) and (ii) equal or larger than 1000 m for the earlier data to account for gravimetric data obtained at the periphery of and outside the CVC. Outliers in the older gravity data were removed. The Bouguer anomaly value Δg_i at each benchmark (i= 1, 2, 3…, 392) and its coordinates were fed into the automated inversion. In a first step, the sub-surface volume was partitioned into 16850 parallelepiped cells. The cells had sides ranging from 330 m in the shallowest zone (3 km a.s.l.) to 2023 m at a depth of 24 km b.s.l., with an average side of 700 m. Matrix $\boldsymbol{Q_D}$ for the *a priori* covariance of gravity data was considered to be a diagonal matrix corresponding to an assumed standard deviation of ±0.4 mGal for the new data and ±1.2 mGal for the earlier gravity data. Matrix $\boldsymbol{Q_M}$ for *a priori* covariance of the cell distribution geometry was taken as a diagonal normalizing matrix of non-zero elements that matched the diagonal elements of $\boldsymbol{A}^T\boldsymbol{Q_D}^{-1}\boldsymbol{A}$, where $\boldsymbol{A}$ is the design matrix with elements A_{ij}. In a second step, we fitted a rough model based on prescribed (positive and negative) density values in the range between -250 kg/m^3 and 230 kg/m^3. Including the smoothing effect, the resultant anomalous density values for the model are -209 kg/m^3 and 184 kg/m^3. The value λ is automatically determined by assuming the condition of zero autocovariance for the final residuals.

The former model is obtained without any particular assumption towards the physical properties of the surrounding non-anomalous medium. The anomalous densities need to be added to some non-anomalous medium density to give the final finite subsurface density distribution. Assuming a homogeneous non-anomalous medium, the final model will be similar to the adjusted model. However, the bimodal evolution of Tenerife, with a basic oceanic shield-building phase succeeded by an evolved stratovolcano building phase warrants the assumption of a significant density contrast between shallower and deeper portions of the island and the crust. As a consequence, large positive density contrasts (>250 kg/m^3) at greater depth, may not be anomalous but rather reflect vertical and horizontal discontinuities with strong density contrasts with respect to shallower depths. A way to accommodate density stratification with increasing depth is to assume a stratified background medium during inversion. In doing so, we followed the hypothesis of a general background stratification, defined by a continuous exponential law for density increase with respect to depth z: $\Delta\rho = \rho_0 + a \exp(-b\ z)$, where ρ_0 is 2200 kg/m^3, a is 580 kg/m^3 and b is $54 \times 10^{-6}\ m^{-1}$. Values for a and b where calculated such as to avoid background density inversion; i.e., high density material overlying low density material in the model. We chose an exponential density increase rather than a linear increase to account for the fact that most of the interior of Tenerife is composed of mafic volcanics, while evolved (phonolitic) material was only erupted with the construction of both the Las Canadas edifice from 3.5 Ma onwards and the PV-PT complex (from 179 ka onwards). We estimate a minimum volume of Tenerife of 15000 km^3, with most of this volume associated with the mafic shield-building phase (ca. 90%). The remaining 10 % of volume includes the Las Cañadas edifice and the PV-PT complex. The maximum estimate for the volume of phonolitic material recognisable at the surface is 250-300 km^3, which mostly corresponds to the Las Cañadas phonolites. We thus assume a maximum proportion of 2% of evolved (phonolitic) as opposed to 98% of mafic material.

To produce quasi-homogeneous anomalous structures, we applied the same inversion process as explained above, but account for an anomalous positive density contrast decrease as a function of z: $\Delta\rho = \rho_0 - a\ exp(-b\ z)$. The adjusted inversion model has a "bell" shape with anomalous positive density decreasing, while the background medium shows an exponentially increasing density with depth, and the addition of both results in quasi-homogeneous structures embedded in a stratified medium.

While we discuss results from both homogenous and stratified background models, we choose to restrict our interpretations of the inversion results to those obtained from models based on a density-stratification of the background medium. We feel that, despite our simplified stratification, these models provide a more realistic account of the "real" density distribution beneath the CVC at greater depth compared to a homogeneous medium. The modelled shallow structures to depths of about 1000 m bsl differ insignificantly in either model, providing a sound basis for the interpretation of the immediate sub-surface, while accounting for stratification may more realistically image density variations at greater depth. A general value of 41 kg/m^3 can be assumed as the mean sensitivity of the cells in either model.

6. Results

a. Bouguer and local anomaly

Fig. 2 shows the Bouguer gravity anomaly map. The anomaly is centred around an average value of 256 mGal with a standard deviation of 25 mGal. The central volcanic complex is dominated by higher than average values, which produce a local positive anomaly (Fig. 4) of more than 45 mGal centred at the western edge of the Las Cañadas caldera, an area known as Boca Tauce (see Fig. 1C and Table 1). A 5 km-wide curvilinear gravity high follows the margin of the LCC wall and connects Boca Tauce with La Fortaleza at the eastern boundary of the LCC. The Boca Tauce gravity high correlates well with a pronounced magnetic high in the same area (et al., 2007). In general, the gravity highs of the CVC correlate well with observed magnetic highs extending from Boca Tauce along the LCC towards La Fortaleza (García et al., 2007), as well as with a high-velocity zone (5-6 km/s) located south of the PV-PT complex (Araña et al., 2000; Watts et al., 1997). The relative gravity low over PT (and extending northwards) correlates with a low velocity zone (3-5 km/s) and a magnetic low (García et al., 2007). Somewhat disconnected from the central high, the Teno massif shows an isolated gravity high with values similar to those observed at the intersection between the Dorsal ridge and the LCC. The overall impression is that the CVC, and Tenerife in general, are formed by a high density core with a pronounced gravity low centred in the LCC beneath Pico Teide. This area is dominated by the strongest horizontal gravity gradient of about 8 mGal/km and a N45ºE azimuth. The northern boundary of the Boca Tauce high coincides with a break in topographic slope between the Ucanca plain and the start of the Icod valley. If one were to project the north-westernmost part of the LCC wall towards the PV-PT complex, the imaginary line would follow the Boca Tauce gravity high's northernmost border (50 mGal isogal). Gravity values around 30 mGal dominate the northern part of the PV-PT complex, an almost 50% decrease compared to the gravity maximum.

b. Gravity inversion

i. Homogenous background

Inversion results shown in Figures 6 and 7 are obtained using the new gravity data only. The root mean square error in the inversion is 0.42 mGal (Fig. 8). Horizontal sections through the 3-D model between 2000 m elevation and 2000 m below sea level (bsl) show a central low density body located beneath the PV-PT complex (Fig. 6). The low density feature with a decrease in density of almost 300 kg/m^3 from background values, appears to be irregularly shaped and inclined from Pico Viejo towards the NE, following the strike of the Dorsal Ridge. The body reaches its maximum width of ca. 6 km at around sea level and also extends beneath Montaña Blanca and the entire northern slope of Pico Teide (Fig. 6). Short-wavelength positive densities down to ca. 1500 m elevation appear to follow the LCC wall from its northwesternmost part anticlockwise towards La Fortaleza. This high-density structure becomes more or less coherent at 1000 to 500 m elevation, from where the structure extends to at least 1000 m below sea level. From there onwards the high-density body seems to be restricted beneath and beyond (westwards of) the Ucanca sector of the LCC. Minimal density contrasts dominate the centre of the LCC and the adjacent Santiago rift as well as along a zone opening towards the SW from the southwestern part of the LCC (particularly prominent between +500 m and -1000 m elevation). This lower density zone in the Boca Tauce high-density body (Figs. 6, 9) may have important bearings on gravity and GPS time series collected over the past years (see section 7e). Low density bodies invoked at the western and northern periphery of the surveyed area suffer from inaccuracies in the computational domain (wall effects) and are thus ignored for the moment. We shall see that employing the complete data set leads to a better resolution of these anomalous bodies Northwest and North of the PV-PT complex.

Inversion of the complete data (Figs. 9 and 10) confirms the results for the LCC and the PV-PT complex obtained from inversion of the new data only. The main change compared with the previous inversion relates to a deterioration in inversion residuals to 0.67 mGal (an almost 80% increase; Fig. 11). Again the horseshoe shaped high-density body, which opens towards the NW, dominates the CVC. This body follows the topographic expression of the LCC wall to a depth of ca. 1000 m bsl surrounding a low-density body located beneath the PV-PT complex. Below 1000 m bsl neutral densities dominate the centre of the CVC, before the high-density body forms a distorted heart-shape in plan view at a depth of ca 6000 m bsl, underlying the major part of the CVC. A set of high density bodies are inferred at the northern slopes of the PV-PT complex, which align to form a second horseshoe shape extending from 1000 m elevation to at least sea level. These bodies form a more or less coherent western, southern and eastern boundary of neutral density material extending northward to the shoreline. The root of this body appears to extend to at least 3000 m below sea level N of PT and NW of La Fortaleza forming the northern boundary of the prominent central low-density body located to the south (Fig. 10). This northern horseshoe-shaped body is separated (at least above sea level) from the Boca Tauce body by a neutral density feature aligned along the Santiago rift. Three other individual shallow low-density features with densities similar to those of the central CVC are worth highlighting. One is located in the Santiago rift close to the location of the most recent eruption on Tenerife (Chinyero in 1909) and directly adjacent to another similar-sized low-density body to the north, whose location coincides roughly with the inferred western edge of the Icod valley. The second is located beneath the western wall of the La Orotava valley and the third south-east of Guajara peak, along the strike of the Rocas de García spur of the LCC (see Fig. 1C). A particular common feature, despite their very low densities, is that these zones are either only shallow rooted or they narrow at depth to below the spatial resolution of the inversion. Below 8000 m bsl the up to 35 km wide high-density core dominates central Tenerife mimicking today's shape of the island at depth, while the Teno gravity high is at its largest between depths of 2000 and 6000 m bsl. Both high-density bodies stand in stark contrast to the surrounding medium with neutral densities at depths in excess of 6000 m bsl. However, this contrast is highly biased and exaggerated by assuming a background of homogeneous density.

ii. Density-stratified background

Effects of a density stratified background on inversion results become significant below sea level (Figs. 12 and 13). We obtain density contrasts in excess of 600 kg/m3 between low and high densities, being significantly skewed towards a higher density contrast for the central core of the island. As expected, at greater depth the density contrast between the background medium and the dense core decreases significantly compared to the homogeneous medium inversion results (50 vs. 220 kg/m^3, respectively) and is assumed to be closer to reality. Particular anomalous features, highlighted in the previous section up to about sea level, are also found in the new inversion and are hence not repeated here. The most obvious difference relates to the low density "depression" modelled beneath the LCC and PV-PT complex below sea level. While the homogeneous inversion gives a contrast of more than 200 kg/m^3, creating the impression of a bowl-shaped density decrease within the high-density core of the island up to 5000 m bsl. (profiles f-i in Fig. 10), the stratified inversion significantly decreases the maximum depth of this depression. Still maintaining both a bowl-shape and a similar density contrast against the high-density core, the structure now only extends to about 2000 m bsl (profiles f-i in Fig. 13).

7. Gravity model interpretation and discussion

a. General considerations

We limit our interpretation of the data to the immediate CVC and from depths of 4000 m bsl upwards. The model results do not significantly alter inferences on the deep structures of the CVC (> 4 km bsl), the Teno massif or the Dorsal Ridge as put forth by previous studies (Ablay and Kearey, 2000; Camacho et al., 1991), since all of these were based on the same gravity data set collected outside the CVC. A fundamental controversy on the deep structure relates to whether the core of Tenerife is formed by an uplifted basement block as suggested by Araña et al. (2000) or as a result of intrusion of mafic magma forming dense gabbroic plutons (Ablay and Kearey, 2000). The different theories brought forward are potentially heavily biased towards the employed data modelling (full inversion in the former case as opposed to forward modelling and parameter estimation in the latter), as both studies rely on the same onshore gravimetric data set. It would appear necessary to include marine gravity data in modelling the deep structure beneath Tenerife to obtain more conclusive results.

The new gravity data in combination with a cleaned set of the existing data, however, enables the assessment of the shallow and intermediate sub-surface architecture of the CVC and its evolution in unprecedented detail and this shall be the focus for the remaining part of the paper.

Fig. 14 identifies particular geometric features in the sub-surface density distribution beneath the CVC.

First and foremost, the complex appears to be built on two intersecting structural features:

i) a NE-SW striking high density ridge forming the southern part of the Las Cañadas edifice with a direct link to the Dorsal Ridge and

ii) a NW-SE striking structure linking the Teno massif to the CVC via the Santiago rift.

At their intersection at the SW part of the Ucanca caldera, a graben-like structure is modelled by the inversion (Figs. 9, 14). This structure may have played an important role during the reactivation of the complex in 2004, as explained in section 7e. This graben is following the NE-SW trend described above and may be linked to a graben structure exposed in deposits of the Ucanca formation in the caldera wall close to the intersection of the Roques de García and the caldera wall (Galindo et al., 2005). It is obvious that the intersection of these two lineaments controlled the evolution of the CVC. It is interesting to note that the Dorsal Ridge appears to be linked directly with the older Las Cañadas edifice and it is therefore not extending beneath the PV-PT complex to intersect the Santiago rift beneath Pico Viejo as proposed earlier (Ablay et al., 1998; Carracedo, 1994). The intersection is likely to be situated further south within the Ucanca sector of the LCC.

b. The core of the CVC

The general picture emerging from the inversion results is that a high density body extending from depth (in excess of 4 km bsl) to shallow levels forms the core of CVC. This core appears to be partly associated with a fundamental mafic shield building phase of Tenerife similar to other volcanic ocean islands. Remnants of the shield are exposed at the Roques del Conde sequence, and the Teno and Anaga massifs up to elevations of nearly 1000 m. Shallowing of the structure to near surface levels to the west of the LCC may be attributed to the formation of the more or less conical Boca Tauce volcano (Fig 12, for z = 1000m). Eruptive products of the Boca Tauce volcano include lavas and pyroclastic rocks rich in mafic minerals and plagioclase cumulates. Rock densities for this sequence can exceed 2900 kg/m^3 and represent the densest rocks exposed nowadays at the CVC. It is thus likely that the modelled density contrasts, in excess of 370 kg/m^3, are indicative of these dense rocks and even denser deeper-seated plutonitic rocks including cumulates (see Ablay and Kearey, 2000, for estimates on cumulate densities). The long-wavelength positive magnetic anomaly detected in this area is consistent with the interpretation of an old mafic volcanic edifice (Araña et al., 2000; García et al., 2007). The Boca Tauce lithologies with Lower Group ages of up to 3.5 Ma are exposed in the South western part of the LCC's Ucanca sector and adjacent valleys. These rocks occur also as accidental fragments at the PV summit, erupted during a phreatic phase in the central crater as part of the 1792 Narices del Teide fissure eruption. This highlights that a pre-Las Cañadas edifice also extended beneath what is now the CVC early in the evolution of Tenerife and contradicts inferences of three isolated proto-Tenerife islands (Teno, Anaga and Roques del Conde; see Ancochea et al., 1990; Walter, 2003). As a consequence, the high-density body, modelled to extend to shallow depth beneath PV, may indeed be part of the Boca Tauce edifice (Fig. 13, profile f).

Including both Lower and Upper Group lithologies, and thus also the Boca Tauce as its westernmost entity, the Las Cañadas edifice was constructed up to 179ka. We interpret the horseshoe-shaped gravity ridge, with positive density contrasts of up to 310 kg/m^3 following the LCC wall, as remnants of this dominant edifice. A rather dramatic petrological and volcanological change occurred with the formation of Upper Group lithologies which resulted from an increased in the eruption of evolved phonolitic magmas and thus increasingly highly explosive volcanism. The slight reduction in modelled densities along the ridge may reflect an overall reduction in the bulk density of Upper Group lithologies due to the occurrence of lower density magmas and lavas and a higher proportion of pyroclastic deposits during the construction of the LCC.

c. The shallow structure of the CVC

One of the most important inferences from the models is that the shallow subsurface beneath the CVC is not entirely composed of high-density material.

Four zones of low density appear to characterise the shallow structure beneath the CVC up to surface levels:

i) the bowl-shaped density low beneath the PV-PT complex (discussed in detail in section 7d),

ii) a NNE-SSW trending low density region made up by two gravity lows located in the Icod valley and crossing the Santiago rift at an angle of ca. 80º (Fig. 12 for z =1000 to -1000m, and Fig. 14 for z = 500m),

iii) a linear alignment of low density bodies connecting the Icod low density body with a low beneath the Tigaiga massif at the western border of the Orotava Valley (Figs. 12, 14), and

iv) two density lows southeast of Guajara Peak, at the southern slopes of the Las Cañadas edifice.

All four zones show similar negative density contrasts, mainly due to the general assumptions behind the inversion approach. Except for the Icod anomaly, all low density bodies appear to be shallow rooted, with maximum extension to around sea level (Figs. 12 and 14). The Icod low density body appears to be deep-rooted, extending from the ground surface to around 2000m below sea level. The area underlain by this body is dominated by mafic dykes and normal faults exposed in road cuts, which document the extensional stress field mirrored also by the abundance of young mafic cones along the Santiago rift, including the 1909 Chinyero cone. It is therefore likely that this body has a deep structural control such as a fault or damage zone potentially associated with dykes. Low densities may result from hydrothermal fluid migration creating secondary void space and alteration, corrosion and/or active fracturing and faulting along these structural elements. It also appears that this zone played an dominant role during the recent reactivation of the CVC, as discussed in more detail in section 7e.

The North-South profile A in Fig. 13, reveals the pronounced asymmetry in the distribution of high-density material between surface levels and 3000 bsl. Whereas the high density body reaches the near-surface beneath the southern portion of the LCC, the area below and north to the PV-PT complex is dominated by lower density material except for the shallow rooted horseshoe alignment of high-density material forming the northern border of the low-density interior of the PV-PT complex (Fig.

13). The strong N-S asymmetry has also been highlighted in seismic velocity (Watts et al., 1997) and aeromagnetic data (Araña et al., 2000; García et al. 2007). It has been suggested by both Araña et al. (2000) and Ablay and Kearey (2000), that these anomalies are due to low density, partly chaotic and unconsolidated volcanic rocks (mainly mafic and phonolitic lavas), erupted from the PV-PT complex over its lifetime from 179 ka onwards. These deposits represent the major infill of the Icod valley. Our model clearly supports these earlier inferences, yet we can put further constraints on the destruction of the Las Cañadas edifice and the formation of the Las Cañadas caldera.

The absence of a surface expression of a northern caldera wall has led various authors to suggest that the LCC may indeed have formed as a result of a large lateral mass wasting (Cantagrel et al., 1999; Ancochea et al., 1999; Watts and Masson, 2001). In their conceptual model, the LCC wall is the headwall of the Icod landslide due to its "striking resemblance to the head scars of large landslides" (Watts and Masson, 2001). While landslides undoubtedly played an important role in the geological evolution of Tenerife (Ablay and Hürlimann, 2000), our investigation does not find any evidence for a lateral collapse origin of the LCC. Quite the opposite, we find clear evidence supporting its formation by vertical collapse.

First, neutral density material is not only infilling the Las Cañadas depression but also extending to considerable (>2000 m bsl) depth, significantly displacing the underlying high density body. This displacement requires a deep structural perturbation unlikely to be induced by a surficial landslide with a maximum penetration depth of 1000 m as inferred for the Icod case (Hürlimann et al., 2000). The perturbation is consistent with a down faulting of a sizeable part of the high density interior of the Las Cañadas edifice and possible alteration in the form of lateral landslides directed to the north during Lower Group times.

Second, short wavelength high-density bodies in the Diego Hernández sector, shown in Fig. 6 (for z=1500m), delineate an elliptic pattern surrounding a central neutral density body and may be interpreted as shallow intrusions. The inferred semi-major axis of this feature strikes NNW-SEE and matches electromagnetic observations in this area (Coppo et al. 2008), which identified a NNW-SSE elongated funnel-shaped conductive layer at depth. This area is also characterised by a well defined magnetic low as revealed by recent aeromagnetic data (García et al., 2007). The semi-minor axis of the elliptic alignment of the high-density bodies matches the semi-minor axis of the electromagnetic resistivity print as well as the magnetic low and we propose that these features are related, i.e., have a common source. The distribution of the high-density bodies resembles intrusions along a ring fault, which is consistent with the interpretation of the conductive layer representing the remnant of an older edifice affected by vertical collapse. The resistivity prints and the morphology of the conductive layer led Coppo et al. (2008) to propose the initiation of the collapse in the SE part of the Diego Hernández sector. The abundance of high-density bodies in that part of the caldera depression is in perfect agreement with ring fault formation and initiation of the vertical collapse there. The combination of results from these potential field investigations (gravity, magnetotellury and magnetics) provides irrefutable evidence for a vertical collapse origin of the LCC, which is also supported by the abundance of voluminous products of phonolitic explosive (caldera-forming) volcanism on the island (Martí et al., 1994; Edgar et al., 2007; Pittari et al, 2008)

It has been suggested by various authors that the head of the Icod valley is buried beneath eruptive products of the PV-PT complex (Martí et al., 1997; Martí et al., 1998; Ablay and Hürlimann, 2000). The horseshoe-shaped alignment of shallow rooted high density bodies to the north of the complex gives the impression of a structural barrier between the complex and the topographic expression of the Icod valley, coinciding with a significant break in slope (Fig. 12, for z = 1000m; Fig. 13, profile A). One could suspect that parts of this structure represent the northern (buried) caldera wall. It is furthermore interesting to note that the maximum opening of the structure matches the maximum width of the Icod valley and we thus interpret that structure to be associated with the formation of the landslide valley. Shallow AMT resistivity prints at the northern slope of the PV-PT complex identify a dramatic shallowing of a conductive body below a resistive layer in the areas highlighted by these high density bodies (Coppo, 2007). This author interprets the conductive layer as the décollement of the Icod landslide, most probably coinciding with the El Mortalon layer, which is thought to be the gliding plane of the slide (Bravo, 1962; Cantagrel et al., 1999). We propose that some of the high density bodies represent intrusives along the (sub)vertical lateral failure planes of the slide, marking its side walls. Similar features are observed elsewhere in the form of basic magmatic intrusions along structures resulting from lateral mass wasting on ocean islands, such as Hawaii or Reunion (Oehler et al., 2004). The headwall may also be either marked by an intrusion or coincide with the remnant of the northern caldera wall. We cannot provide a conclusive answer as to the fate of the northern caldera wall and its role during the formation of the Icod valley, but all evidence points towards a remnant structure below the PV-PT complex whether it be the Icod head scar or the northern caldera wall or (probably most likely) a combination of both. The key finding here is that the headwall of the Icod valley is located well outside (to the N of) the current caldera depression and cannot thus have had any role in the formation of the LCC wall.

d. The interior of the PV-PT complex

The interior of the PV-PT complex appears to be made up of low density material extending from close to the surface to about sea level. The horizontal extent of the density low is from Pico Viejo in the west to Montaña Blanca in the east of the complex. This marked density low has an overall irregular shape with a finger-like protrusion below PV. There are several possibilities to explain the low densities below the complex.

First, the complex is dominated by phonolitic eruptive products; mostly lava flows and pumice fall deposits with the lowest bulk densities (as low as about 1100 m^3/kg as measured in the field; see Table 2 and Ablay and Kearey (2000), as well as more primitive highly-vesiculated lavas, also with bulk densities lower than the background density.

Second, the complex may, to some extent, be hydrothermally altered and internally eroded causing secondary void space leading to lower bulk densities. Surface expressions of hydrothermal alteration zones are restricted to the area of the Roques de García, the lower part of the caldera wall and within the youngest Pico Teide summit crater. Remnants of two older Teide craters, exposed at ca. 3500 m close to the upper cable car stop, exhibit fumarolic activity at the time of this writing. The bulk density of the highly altered summit crater deposits is well below the background density. Assuming that at least parts of the interior of the complex have undergone a similar degree of alteration, one would expect lower densities for the interior of the complex, as perhaps best exemplified by the conduit-shaped low density feature beneath PV extending upwards and to the west from the centre of the density low (Figs. 6, 7 and 13). In fact, recent electromagnetic data show a highly conductive body beneath Montaña Blanca with electrical resistivities of less than 20 ohm m (Coppo et al., 2008), a clear indication for either the presence of shallow hydrothermal alteration or a geothermal system. With the water table being located well below 400 m below the caldera floor (Gottsmann et al., 2006 and references therein), i.e. < 1800 m asl, it is conceivable that large parts of the immediate subsurface beneath Montaña Blanca (summit at 2800 m asl) is hydrothermally altered rather than hosting saline ground water. The total extent of hydrothermal alteration of the complex is not well defined but both our gravimetric as well as the AMT data indicate that a rather substantial volume of the total volume of the complex of ca. 9 km^3 may be substantially altered and structurally weakened. Of course these findings have important bearings on the stability of the complex, with northern slopes showing angles of inclination of 38º or more. With a history of several landslides, the northern flank of the complex is a likely locus for future mass wasting facilitated by internal corrosion of the complex.

Petrological evidence points towards the existence of shallow magma chambers (at depths of around sea level) feeding past phonolitic eruptions at the complex (Ablay et al., 1998; Triebold et al., 2006; Andujar, 2007). It is possible that the rather clearly defined lower boundary of the low-density body, resolved by the stratified background model (Figs. 12 and 13), marks the transition from hydrothermally altered material to remnant magma reservoirs. At a depth of about 1000 m bsl a neutral density contrast is modelled which increases with depth to a contrast of ca 100 kg/m^3, forming a sizable (several km^3 in volume) bowl-shaped body beneath the complex, clearly separated from the high density material forming the core of the Las Cañadas edifice. One would expect that partially crystallised phonolitic magma would have a density similar to background densities and one could propose this region to at least host remnants of highly evolved magmatic bodies. Whether or not these bodies contain eruptable material, if defined by a critical abundance of melt, may not be resolved by the available gravimetric data.

e. Relation to recent unrest

The sub-surface density distribution allows us to put these new findings in relation to geodetic and seismic observations performed during the recent reactivation of the CVC in spring 2004 and onwards. Details on investigation strategies and results can be found in the recent papers by Gottsmann et al. (2006), Almendros et al. (2007), Fernández et al. (2007), and Martí et al. (2008a). Two features are worth highlighting.

First, the low-density body identified inside and crossing the Icod valley southwestwards (Fig. 14) underlies the zone in which the most drastic residual gravity changes were documented in the first few months of the reactivation. It is fair to assume a relationship between this deeply rooted negative density anomaly and the documented sub-surface mass changes. This area has also been recognised to undergo periodic ground deformation, as shown by recent DGPS and InSAR observations (Fernández et al., 2004). The spatio-temporal gravity changes as well as the seismic data have been interpreted to reflect aqueous fluid migration at depth during the period of reactivation. We therefore propose that the perturbation of the CVC, as documented by the various geophysical techniques, may be rooted in the low-density body. Upward movement of pressurised aqueous liquids may have been controlled by pre-existing structural weaknesses. Mass addition was also documented in the Ucanca sector of the LCC along the Santiago Rift (Gottsmann et al., 2006). Accounting for the dominant NW-SE structural control of the CVC, linking the LCC to the Teno massif, it appears reasonable that this structure controlled most of the changes at depth. In fact, results from the inversion of integrated stacked DInSAR and GPS data collected between 2003 and 2006 are in very good agreement with this hypothesis (Fernández et al., 2008).

Second, a joint GPS and gravity benchmark located just outside the topographical expression of the Ucanca wall underwent significant ground deformation and gravity changes during the period of reactivation, which were difficult to interpret (Gottsmann et al., 2006). The new gravity inversion results put this benchmark inside an inferred graben structure at the intersection of the two dominant structural lineaments as documented above (Figs. 6 and 9). Indeed from a topographical perspective a sizeable part (> 200m length) of the Ucanca caldera wall is missing in this particular area . Its dissected nature as well as the abundance of slickensides on (sub)vertical surface outcrops provides geomorphological and geological evidence for a tectonic control on the evolution of this part of the LCC. These features are indicative for relative extension, possible graben formation and structural weakening. The ground deformation and density changes observed between 2004 and 2005 in this area are consistent with localised pressurisation/depressurisation cycles and associated mass and density changes over periods of a few months or less. Fernández et al. (2008) found deformation sources whose position, depth, radius, pressure and mass evolve over time. Displacements occur particularly along low-density zones (including the southwestern part of the Ucanca depression) and areas surrounding high-density bodies (see Fig. 14). It appears that again shallow and localised sub-surface dynamics were controlled by the dominant structural entities of the CVC at the time of its reactivation.

8. Summary and Conclusion

We present a new set of gravimetric data from the central volcanic complex on Tenerife, which, coupled with a full 3-D data inversion, enabled unprecedented insights into the shallow sub-surface structure beneath the complex.

1. The centre of the island is dominated by a high-density core expressed by a local gravity high, which is formed by the intersection of two principal structural lineaments oriented at about right angles: the Teno-Santiago rift and the Dorsal ridge. These structures have controlled the morphological and volcanic evolution of both the island and the central complex over the past few million years and appears to continue controlling sub-surface dynamics as shown during the recent reactivation of the complex in 2004.
2. Based on a combination of gravimetric and geological data we propose the existence of a central volcanic complex early in the evolution of Tenerife. The phonolitic complex, beneath the centre of the island, most likely formed within an early shield structure. Construction of isolated volcanic edifices forming the three corners of the island is not supported by our data. The asymmetric density distribution below sea level is consistent with the removal of

significant proportions of the early central edifice in the form of lateral landslides directed to the north during Lower Group times.

3. We find strong evidence for a vertical collapse origin of the Las Cañadas caldera both from gravimetric data alone as well as from its excellent correlation with results from recent electromagnetic and aeromagnetic investigations. The distribution of small and shallow high-density bodies in the Diego Hernández sector is consistent with intrusions along a ring fault marking the periphery of a funnel-shaped conductive layer interpreted to represent the base of the Diego Hernández caldera.

4. A horseshoe-shaped alignment of high-density bodies at shallow depth to the north of the Pico Viejo - Pico Teide complex is interpreted to represent shallow intrusions into a scar left behind by the Icod landslide, marking the horizontal extent of the slide as well as its head wall. The head wall is nowadays buried beneath eruptive products of the youngest volcanic complex on the island, and thus does not relate in any way to the currently exposed LCC wall. The Icod valley head wall may represent parts of the northern caldera wall, formed by the superposition of three vertical collapses over the past 1 Ma.

5. The interior of the PV-PT complex is characterised by a cylindrically shaped body extending from depths of ca. 3000 m bsl to about sea level. This body of neutral density is interpreted to represent the current plumbing system of the complex. Above sea level, low density material dominates the shallow interior of the complex and is

thought to result from a combination of evolved eruption products (dominantly phonolitic air-fall and intermediate to evolved vesiculated lavas) with a significant degree of hydrothermal alteration leading to internal corrosion.

Future geophysical investigations at the CVC aiming at resolving the temporal evolution of the sub-surface in light of the recent reactivation should take into account the results presented here. Two points are worth mentioning. First, the degree of internal alteration of the PV-PT complex needs to be better assessed and implications for slope stability need to be considered. Edifice collapse may have severe impacts in its own right but may also impact on magmatic systems at depth (Reid, 2004). Such scenarios need to be accounted for in quantitative risk assessment and monitoring programs need to provide critical baseline data.

Second, the control of the two dominant structural lineaments on the evolution of the central volcanic complex is evident throughout its history. These structures appear to define preferential pathways for both aqueous fluid and magma migration. Monitoring networks should hence include coverage of these structures in addition to the immediate PV-PT complex.

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Table and figure captions

Table 1: Simplified stratigraphic scheme for the island of Tenerife, showing the major constructive and destructive episodes. * indicates major vertical collapse, † indicates major lateral collapse (landslide). Modified and simplified after Edgar (2003).

Table 2: Measured bulk densities of lithologies exposed at the Central Volcanic Complex. Values taken from Ablay and Kearey (2000).

Figure 1. A) Location of Canary Islands off African West coast. B) Topographic models of Tenerife (28.32˚N, 16.57˚ W) showing main structural units (B and C) and locations of new gravity benchmarks (squares in C). Coordinates in B) and C) are given in UTM (m). Key to (B): Dorsal R. = Dorsal Ridge, Icod V. = Icod Valley, LCC = Las Cañadas caldera, OV =La Orotava Valley, Santiago R. = Santiago Rift, R. del Conde =Roque del Conde, PV-PT = Pico Viejo – Pico Teide complex, Tg = Tigaiga massif.

Key to (C): BT = Boca Tauce, GP = Guajara Peak, LF = La Fortaleza, MB = Montaña Blanca, PT = Pico Teide, PV = Pico Viejo, RdG = Roques de García, SR = Santiago, Rift, sectors of the Las Cañadas caldera (with decreasing age): UC = Ucanca, GJ = Guajara, DH = Diego Hernández.

Figure 2. Bouguer anomaly (mGal) map of Central Tenerife. Points indicate location of benchmarks selected for inversion of gravity data. Coordinates given in UTM (m).

Figure 3. The optimal theoretical terrain density corresponds to the density giving the minimum correlation between short-wave components of topography and gravity for distances up to a radius r around any given benchmark. The graph shows the relationship between terrain density and average radius r (bold line). A terrain density value of 2200 (kg/m^3), indicated by the thick line, is finally chosen, accounting for both the low correlation between short wave components and measured rock densities reported in Table 2.

Figure 4. Local gravity anomaly for the central volcanic complex, obtained by subtracting a general linear SE-NW trend of 0.27 mGal/km with azimuth N113ºE from the local Bouguer anomaly. This local anomaly data is employed for data inversion.

Figure 5. Sensitivity test of the inversion methodology based on a simulation of an anomalous density body located beneath the CVC. a) shows Bouguer gravity anomaly caused by the anomalous body at the benchmarks shown by black and grey circles. b) Plan view and vertical cross section of the simulated body with vertical S-shape geometry. c) Resulting 3D model from the inversion. Tick mark separation in a) –c) on all axes is 2000 m. Distortions of the inverted structure compared to the simulated body arise from data distribution and from the tendency of the inversion method to produce rounded, smoothed structures, particularly for deep (> 6 km) and peripheral zones, for which cell sensitivity is lower.

Figure 6. Horizontal sections at selected depths through the 3-D model of density contrasts (kg/m^3) beneath the CVC employing local gravity anomaly data from 323 new gravity measurements. A homogeneous background density is assumed for data inversion. Circle marks graben-like structure within the Boca Tauce high density body (see section 7 for discussion).

Figure 7: Vertical W-E profiles (a to g) and one S-N profile (A) through the 3D model of density contrasts (kg/m^3) beneath the CVC from inversion of 323 new gravity measurements. Horizontal section indicates trail lines of profiles. Model is based on assuming a homogeneous density background.

Figure 8: Inversion statistics for inversion of data from 323 new gravity measurements presented in Figs. 6 and 7. Root mean square inversion residual is 420 μGal = 0.42 mGal.

Figure 9: Horizontal sections at selected depths through the 3-D model of density contrasts (kg/m^3) beneath the CVC. A homogeneous background density is assumed for data inversion. Circle marks graben-like structure within the Boca Tauce high density body (see section 7 for discussion).

Figure 10. Vertical W-E profiles (a to k) and one S-N profile (A) through the 3D model of density contrasts (kg/m^3) beneath the CVC. Horizontal section indicates trail lines of profiles.

Figure 11. Inversion statistics for inversion results presented in Fig. 9. Root mean square inversion residual is 0.67 mGal.

Figure 12. Horizontal sections at selected depths through the 3-D model of density contrasts (kg/m^3) derived by assuming a density-stratified background beneath the CVC.

Figure 13. Vertical W-E profiles (a to k) and one S-N profile (A) through the 3D model of density contrasts (kg/m^3) beneath the CVC. Horizontal section indicates trail lines of profiles. Model is based on assuming a density-stratified background.

Figure 14: Dominant density anomalies characterising the shallow parts beneath the CVC include i) a NE-SW striking high density ridge forming the southern part of the Las Cañadas edifice with a direct link to the Dorsal Ridge (DR) and a NW-SE striking structure linking the Teno massif to the CVC via the Santiago rift (both marked by lines); ii) two low density bodies (encircled) including (i) the bowl-shaped density low beneath the PV-PT complex, (ii) a NNE-SSW trending low density region located in the Icod valley and crossing the Santiago rift, (iii) a line density lows connecting the Icod low to the Tigaiga massif (Tg), and (iv) two density lows to the south of the caldera wall. At depths > 3000 m bsl the high-density core of the CVC resembles the outline of the current island.

Squares in image Z=-1000 m indicate surface projections of positions of ground deformation sources between 2003 and 2006 (Fernández, et al., 2008). It is interesting to note that most source locations are found in areas defined by shallow subsurface negative density anomalies and/or along major structural building blocks of the CVC. See Fig. 12 for scale of density contrasts.

Figure and Tables
Click here to download Figure(s): StrucGrav_Tenerife_draft180608_Figures.doc

TABLE 1

Stage	Unit	Subunit	Event / Formation	Landslide
Post- shield Volcanism			Historic eruptions (e.g. Chinyero 1909)	
Post- shield Volcanism	Flank Eruptions	Dorsal Series (1.8 Ma-); Santiago Series (0.3 Ma-)		
Post- shield Volcanism	Central Volcanic Complex	PV-PT Formation	Pico Viejo series 2	
Post- shield Volcanism	Central Volcanic Complex	PV-PT Formation	Pico Teide series 2	
Post- shield Volcanism	Central Volcanic Complex	PV-PT Formation	Pico Viejo series 1	
Post- shield Volcanism	Central Volcanic Complex	PV-PT Formation	Pico Teide series 1	
Post- shield Volcanism	Central Volcanic Complex	PV-PT Formation	Early episode	
Post- shield Volcanism	Las Cañadas Edifice	Upper Group	* Climatic caldera collapse (0.18 Ma)	† Icod landslide (0.2-0.13 Ma)
Post- shield Volcanism	Las Cañadas Edifice	Upper Group	Diego Hernández Formation (0.57 - 0.18 Ma)	
Post- shield Volcanism	Las Cañadas Edifice	Upper Group	* Climatic caldera collapse (0.57 Ma)	† La Orotava landslide (0.57 -0.54 Ma)
Post- shield Volcanism	Las Cañadas Edifice	Upper Group	Guajara Formation (0.85 - 0.57 Ma)	† Güimar landslide (0.83 -0.57 Ma)
Post- shield Volcanism	Las Cañadas Edifice	Upper Group	* Climatic caldera collapse (1.07 Ma?)	
Post- shield Volcanism	Las Cañadas Edifice	Upper Group	Ucanca Formation (1.57 - 1.07 Ma)	
Post- shield Volcanism	Las Cañadas Edifice	Lower Group	**Lower Group sequence (3.8 - 1.57 Ma)**: Roques de Gracia; Montón de Trigo; Las Pilas; El Cedro; El Cabezón; Boca Tauce volcano (3.8 - 3.5 Ma)	
Shield construction	Old Basaltic Series		Roque Del Conde Massif (11.6 - 3.5 Ma)	
Shield construction	Old Basaltic Series		Teno Massif (6.7 - 5 Ma)	† Teno landslide (5.6 Ma?)
Shield construction	Old Basaltic Series		Anaga massif (6.5 - 3.3 Ma)	† Anaga landslide (~ 6 Ma)

TABLE 2

Rock type	Bulk density (m^3/kg)
phonolitic pumice fall	1080
phonolitic pumice	1390
phonolitic ignimbrite	2540
phonolitic lava	2350
phonolitic obsidian	2200
intermediate lava	2230
historic basalt	2890
mean	2201
stdev	271

FIGURES

Figure 1a

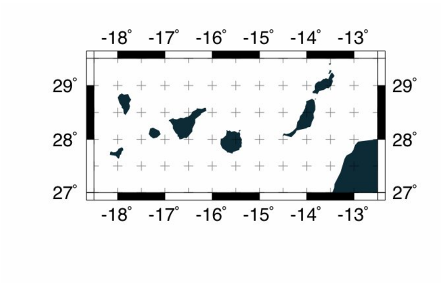
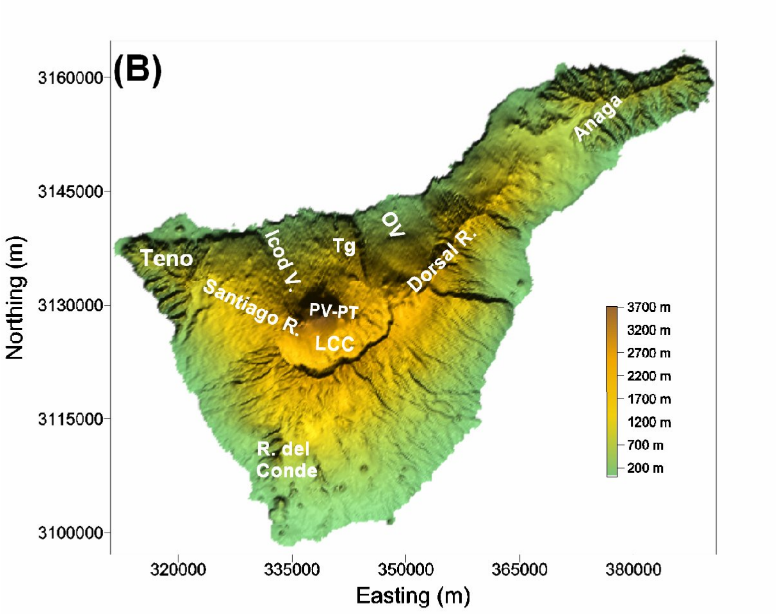


Figure 1b



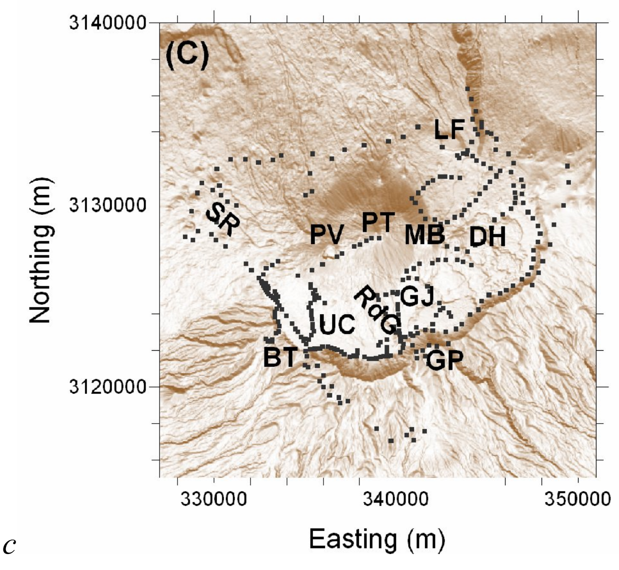
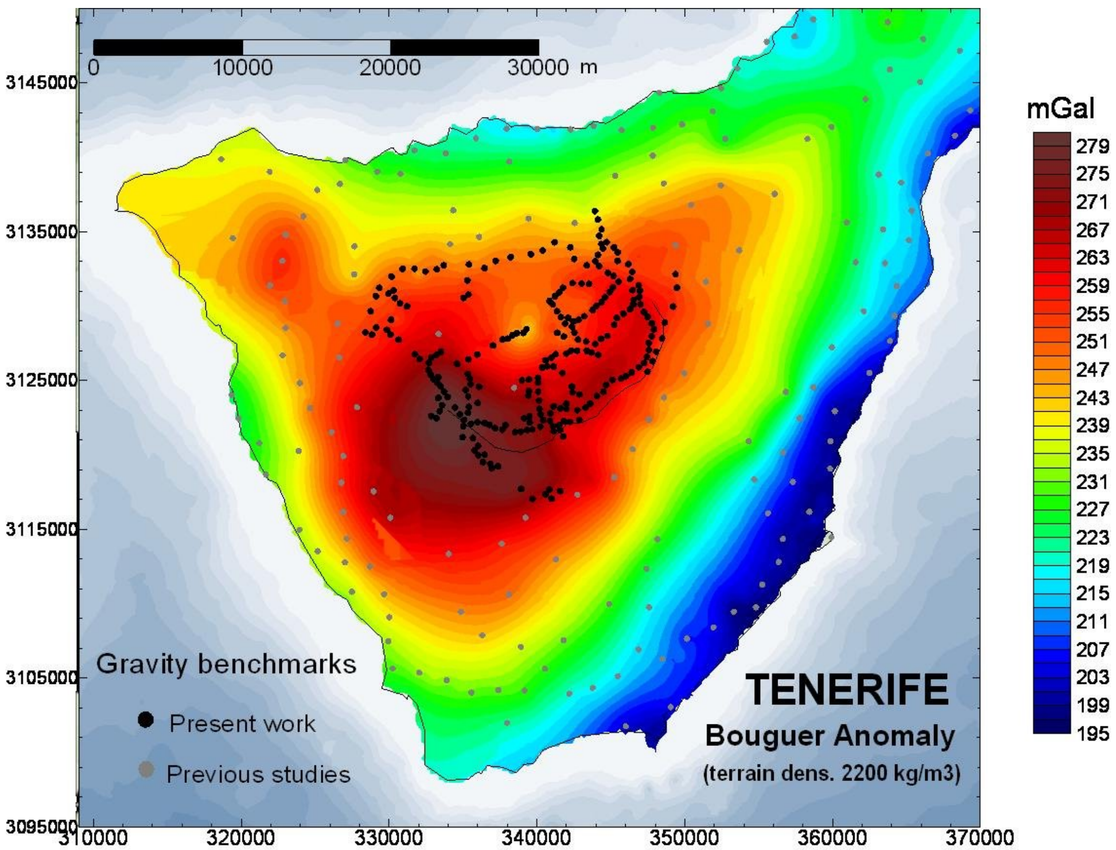


Figure 1c



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227
223
219
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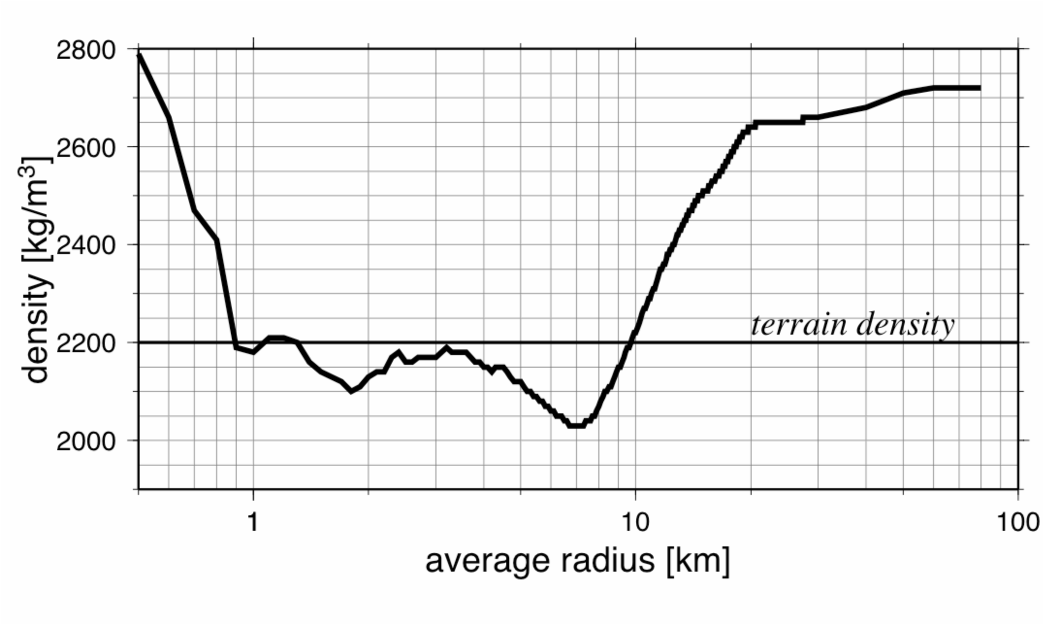
203
199
195
Gravity benchmarks
Present work
Previous studies
TENERIFE
Bouguer Anomaly
(terrain dens. 2200 kg/m3)

Figure 2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2400
2200
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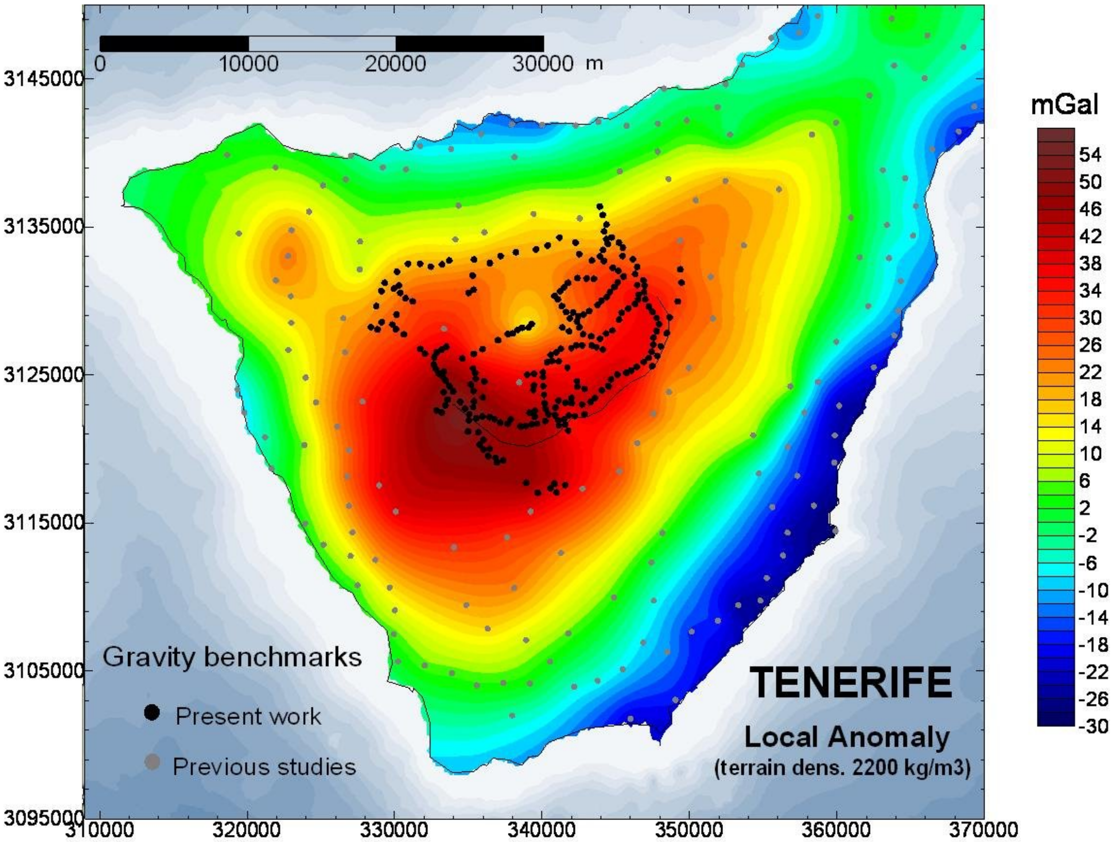
density [kg/m^3]
terrain density
1
10
100
average radius [km]

Figure 3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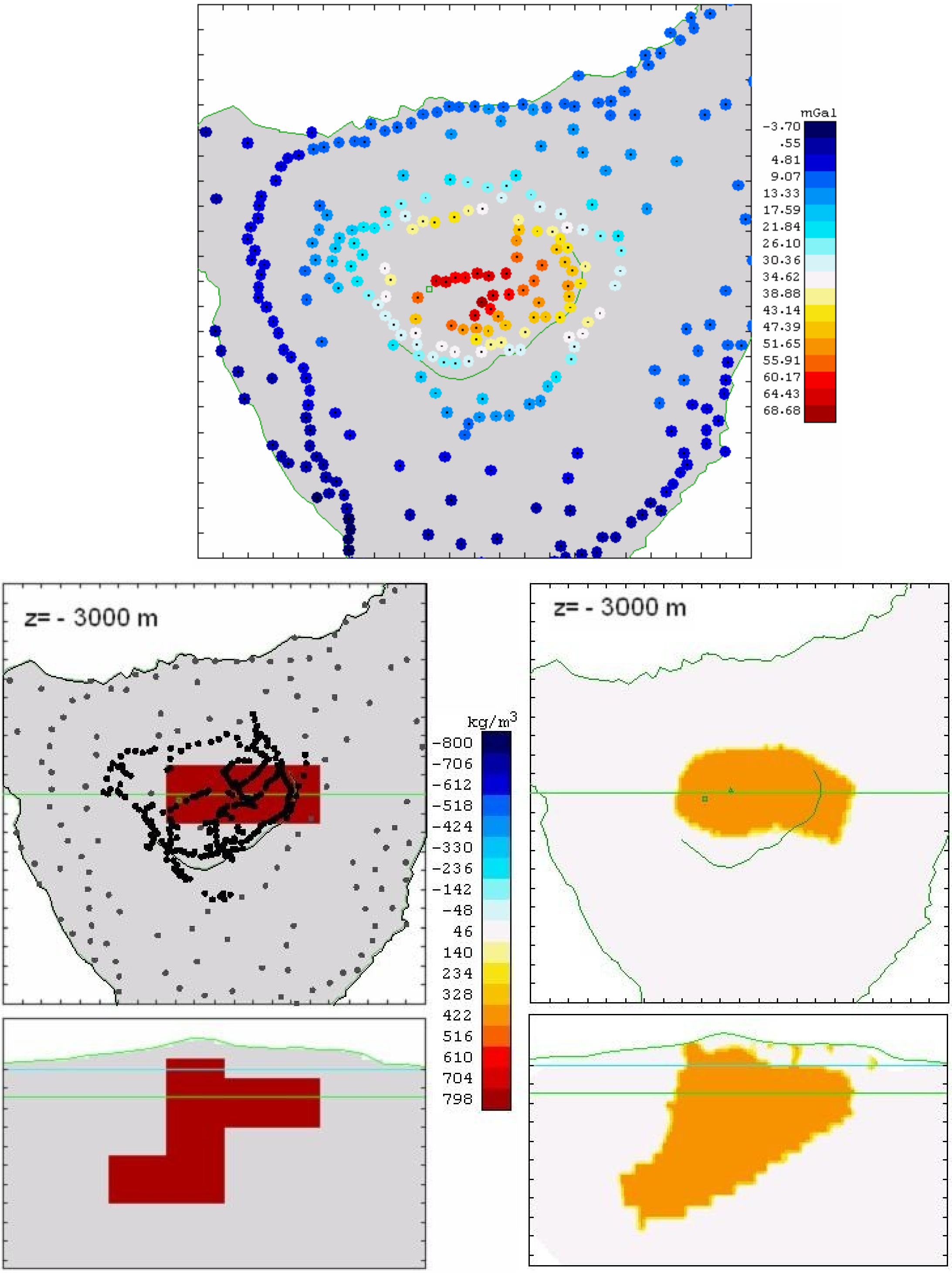
Gravity benchmarks
Present work
Previous studies
TENERIFE
Local Anomaly
(terrain dens. 2200 kg/m3)

Figure 4

Figure 5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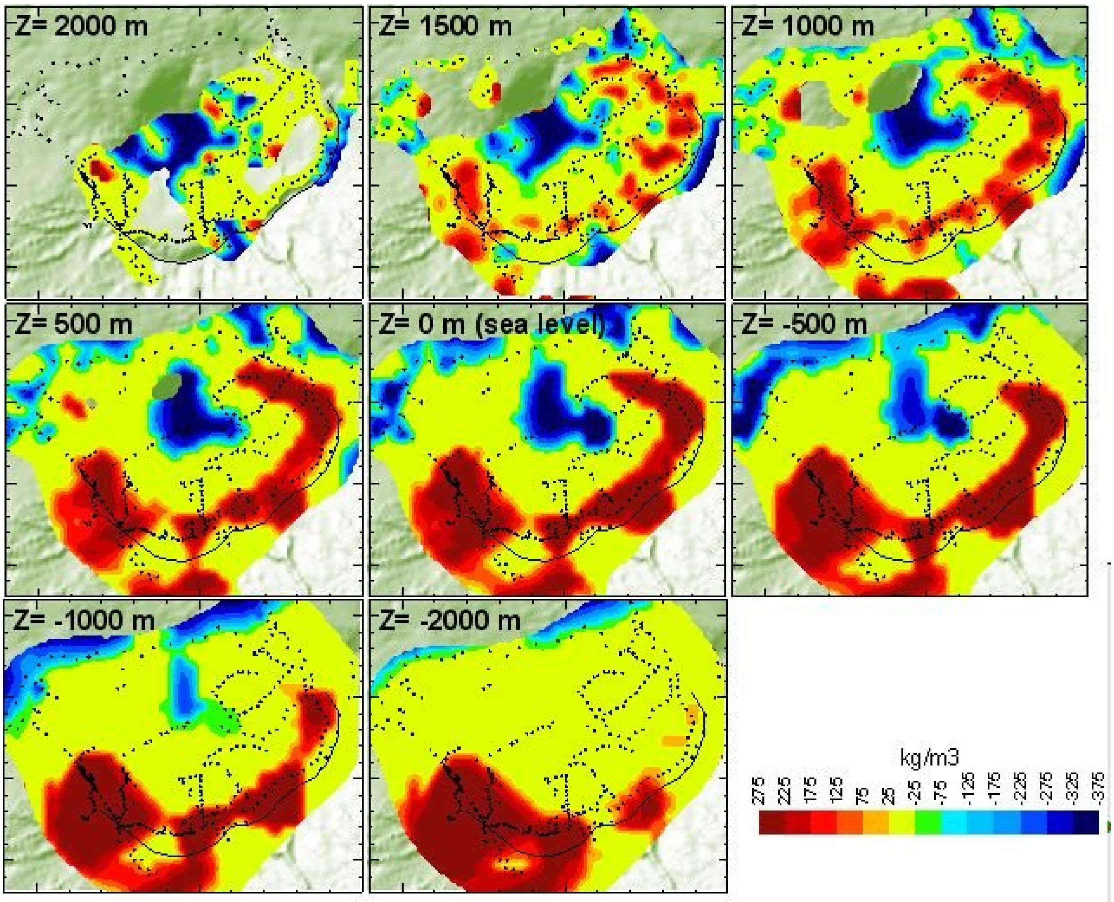
.55
4.81
9.07
13.33
17.59
21.84
26.10
30.36
34.62
38.88
43.14
47.39
51.65
55.91
60.17
64.43
68.68
z= - 3000 m
z= - 3000 m
kg/m3
-800
-706
-612
-518
-424
-330
-236
-142
-48
46
140
234
328
422
516
610
704
798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Z= 1500 m
Z= 1000 m
Z= 500 m
Z= 0 m (sea level)
Z= -500 m
Z= -1000 m
Z= -2000 m
kg/m3
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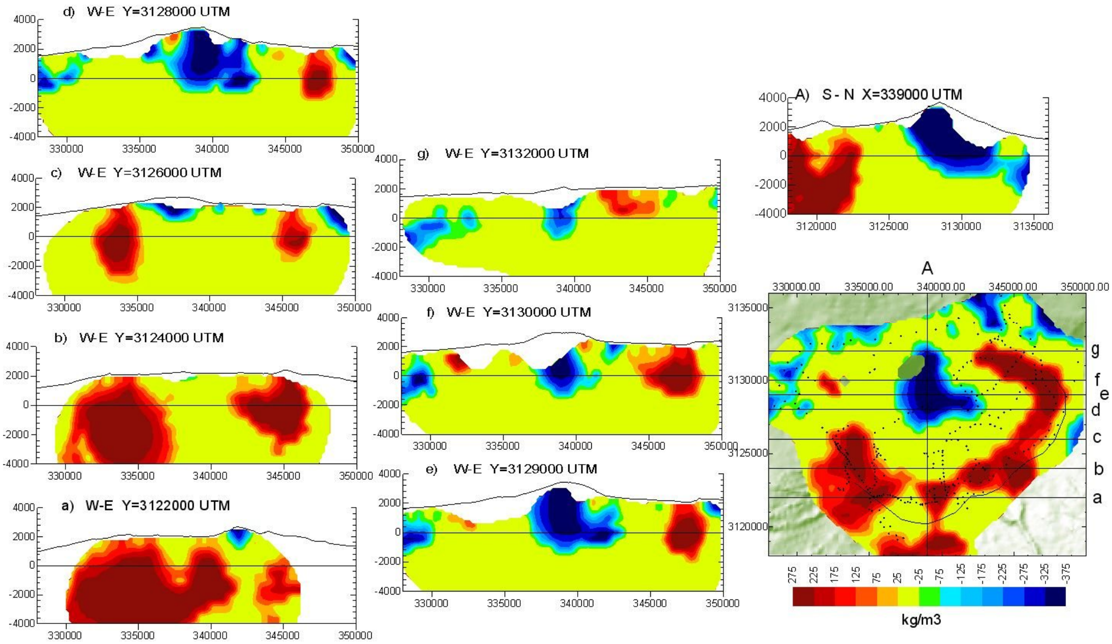
225
175
125
75
25
-25
-75
-125
-175
-225
-275
-325
-375

Figure 6


d) W-E Y=3128000 UTM
c) W-E Y=3126000 UTM
b) W-E Y=3124000 UTM
a) W-E Y=3122000 UTM
g) W-E Y=3132000 UTM
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e) W-E Y=3129000 UTM
A) S - N X=339000 UTM
A
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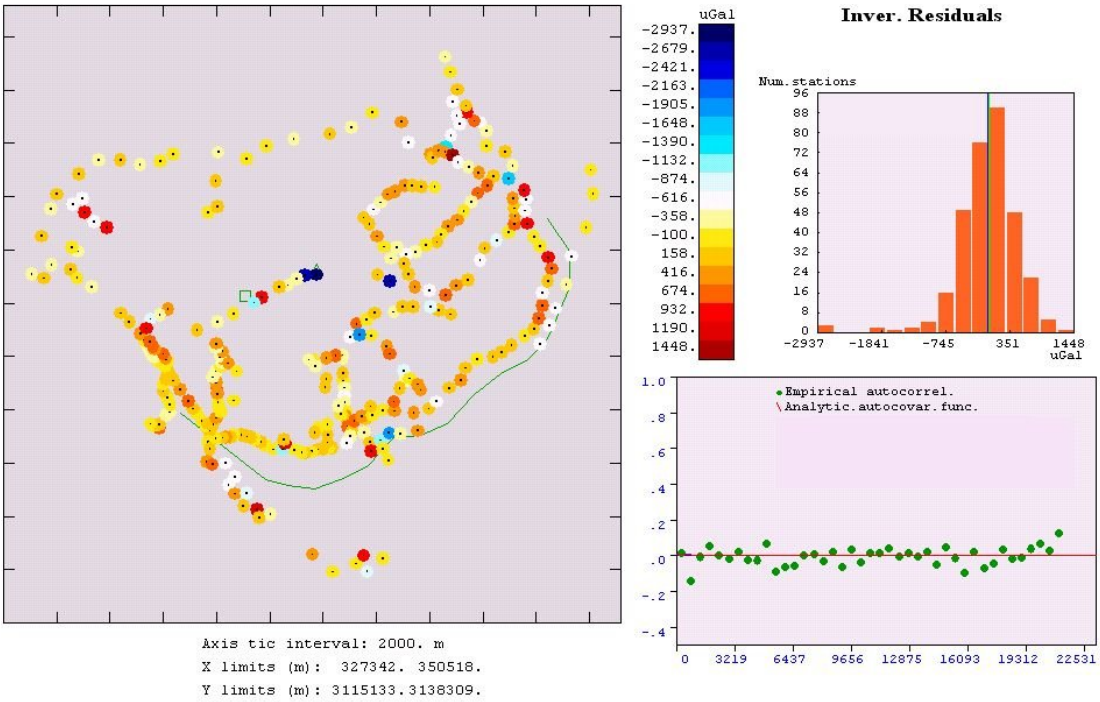
Figure 7


uGal
Inver. Residuals
Num. stations
uGal
Empirical autocorrel.
Analytic. autocovar. func.
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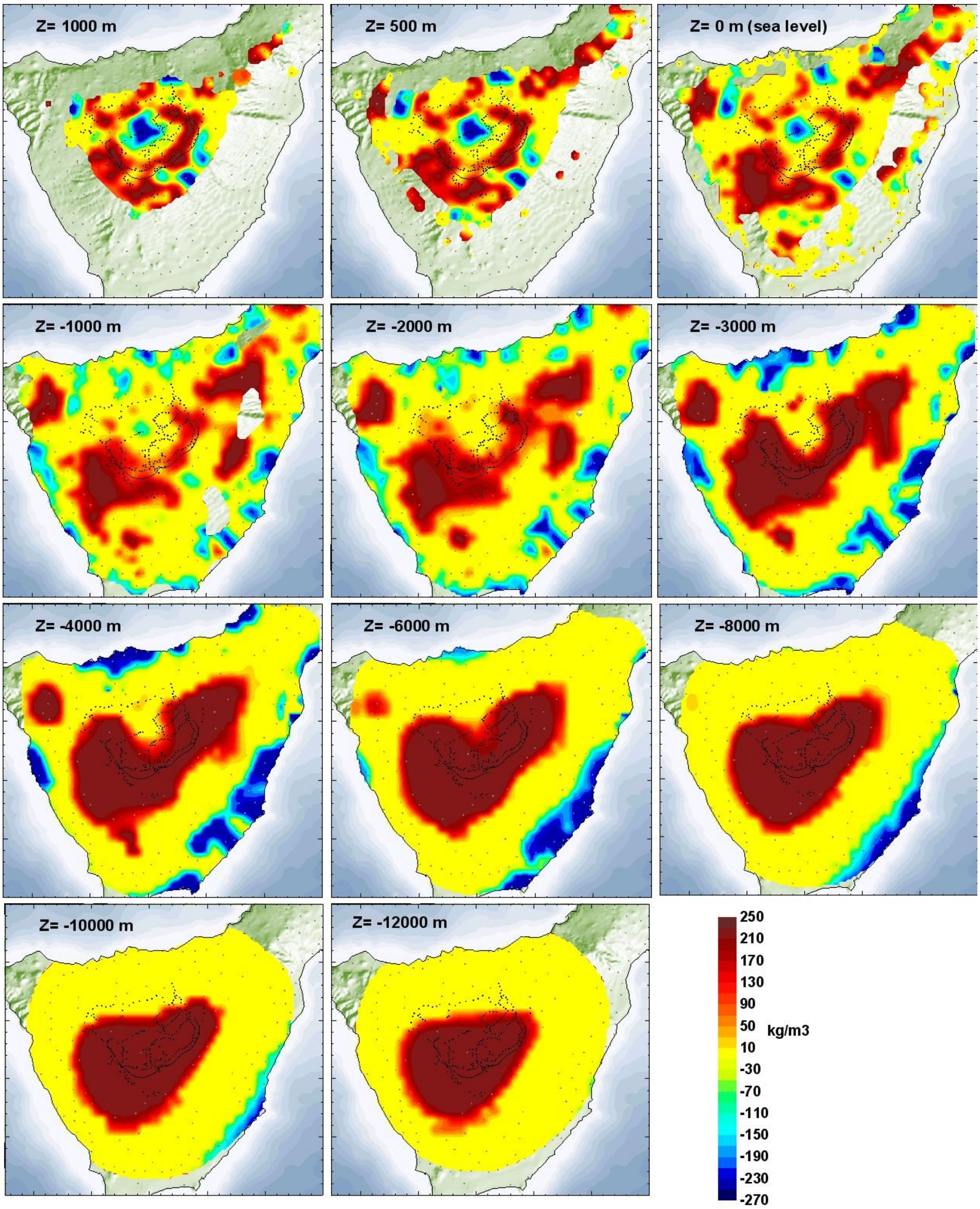
Y limits (m): 3115133. 3138309.

Figure 8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Z= 500 m
Z= 0 m (sea level)
Z= -1000 m
Z= -2000 m
Z= -3000 m
Z= -4000 m
Z= -6000 m
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Z= -10000 m
Z= -12000 m
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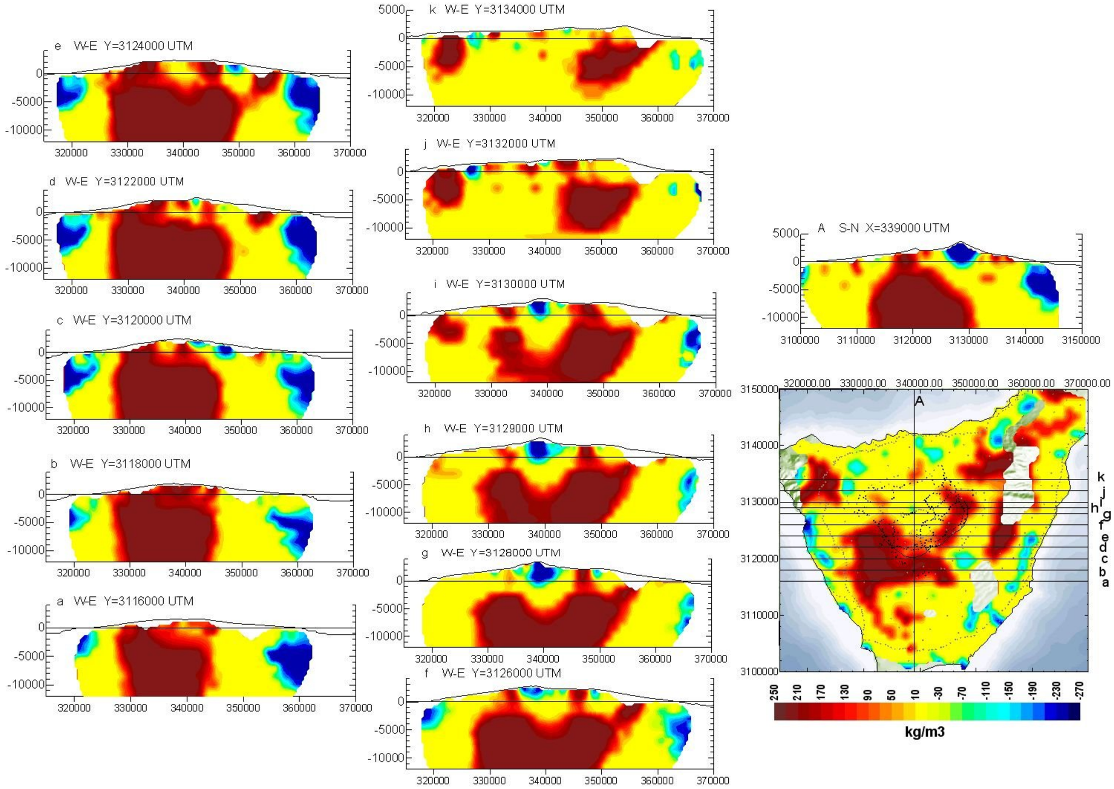
-270
kg/m3

Figure 9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d W-E Y=3122000 UTM
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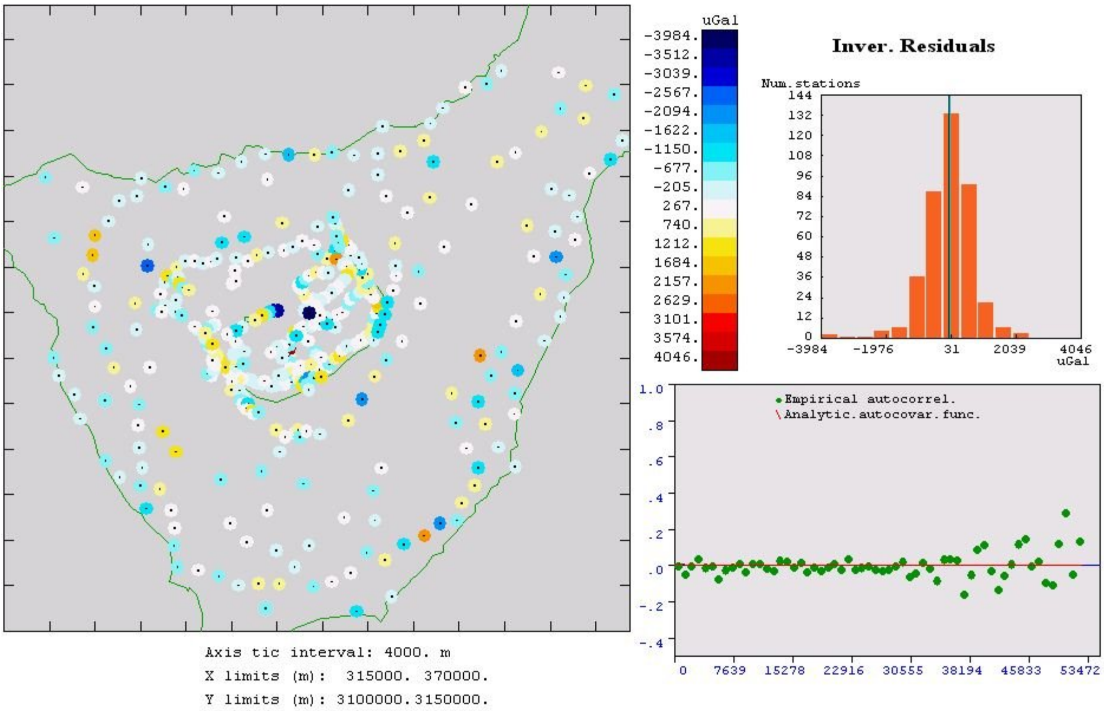
b W-E Y=3118000 UTM
a W-E Y=3116000 UTM
k W-E Y=3134000 UTM
j W-E Y=3132000 UTM
i W-E Y=3130000 UTM
h W-E Y=3129000 UTM
g W-E Y=3128000 UTM
f W-E Y=3126000 UTM
A S-N X=339000 UTM
kg/m3

Figure 10



uGal
-3984.
-3512.
-3039.
-2567.
-2094.
-1622.
-1150.
-677.
-205.
267.
740.
1212.
1684.
2157.
2629.
3101.
3574.
4046.
Inver. Residuals
Num.stations
144
132
120
108
96
84
72
60
48
36
24
12
0
-3984
-1976
31
2039
4046
uGal
Empirical autocorrel.
Analytic.autocovar.func.
1.0
.8
.6
.4
.2
.0
-.2
-.4
0
7639
15278
22916
30555
38194
45833
53472
Axis tic interval: 4000. m
X limits (m): 315000. 370000.
Y limits (m): 3100000.3150000.

Figure 11

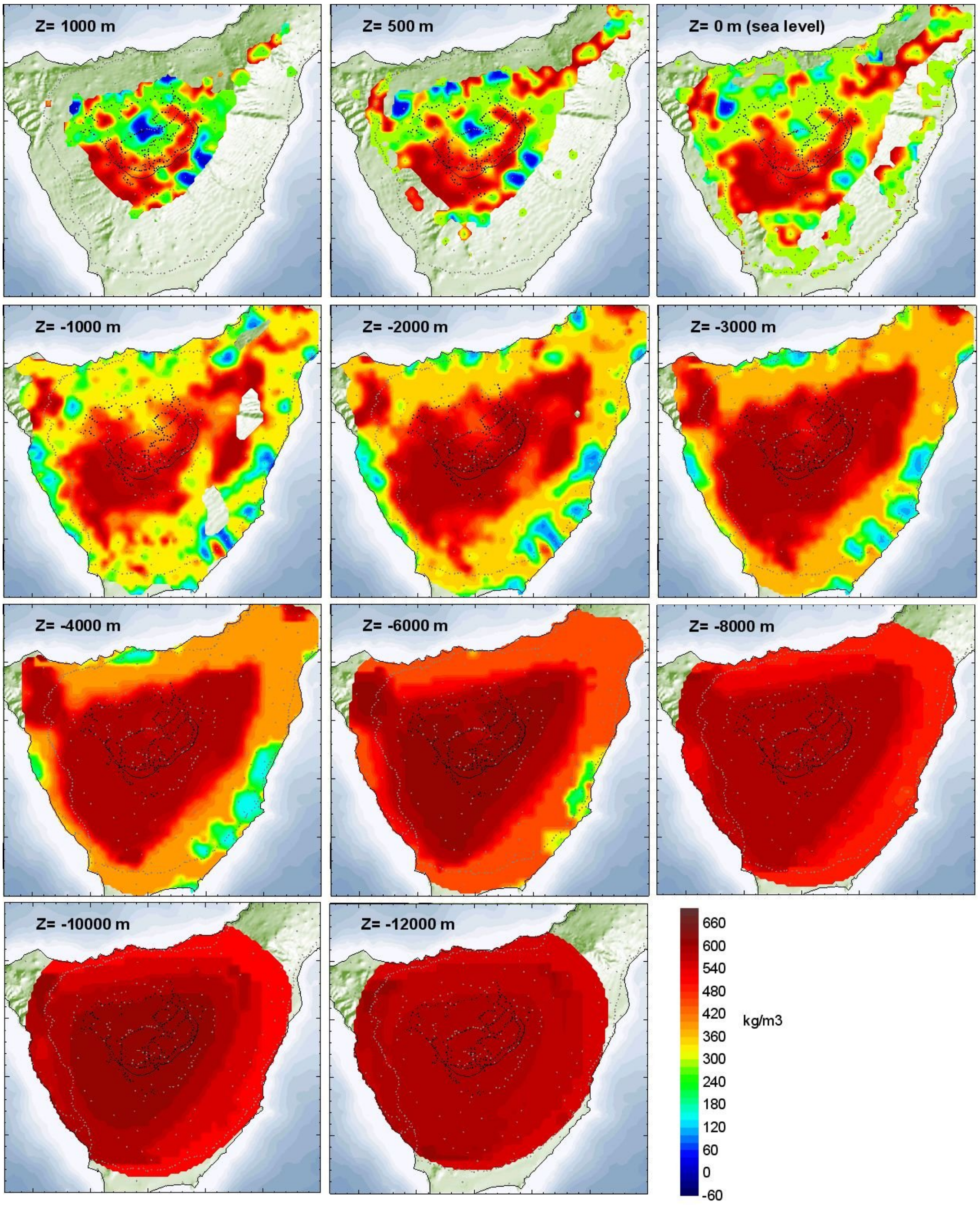

Z= 1000 m
Z= 500 m
Z= 0 m (sea level)
Z= -1000 m
Z= -2000 m
Z= -3000 m
Z= -4000 m
Z= -6000 m
Z= -8000 m
Z= -10000 m
Z= -12000 m
660
600
540
480
420
360
300
240
180
120
60
0
-60
kg/m3

Figure 12

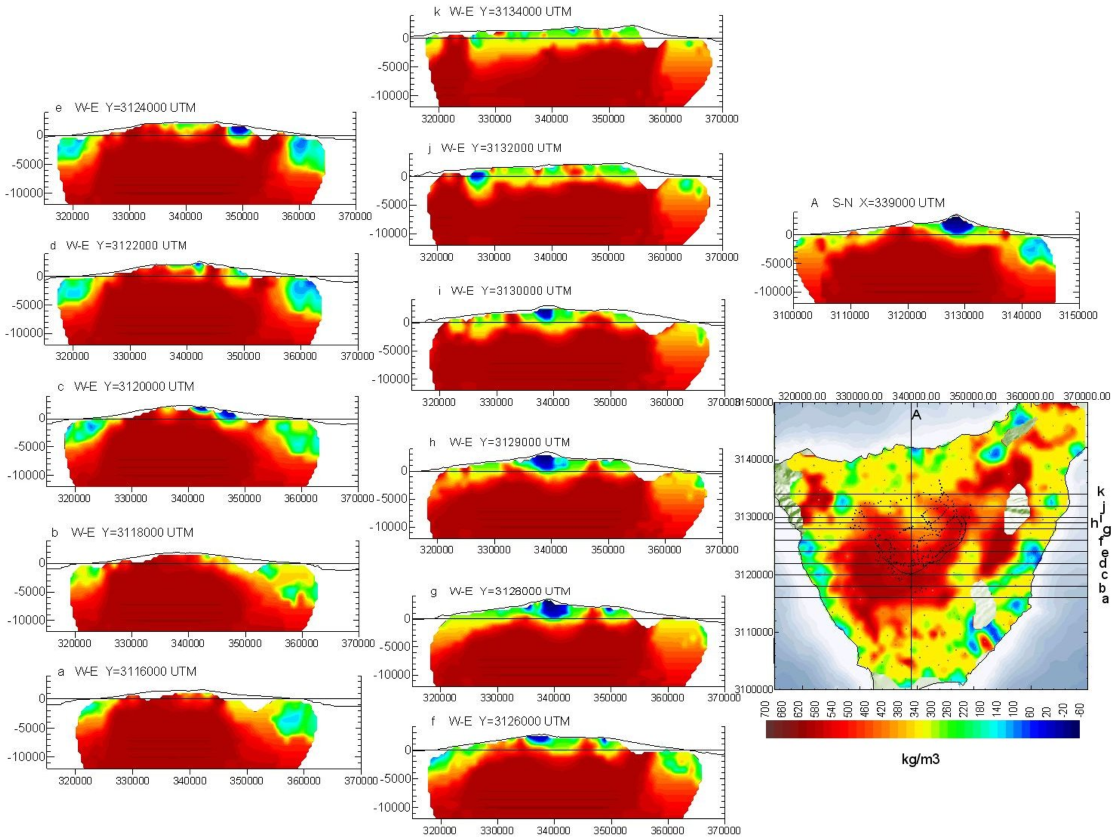

k W-E Y=3134000 UTM
e W-E Y=3124000 UTM
j W-E Y=3132000 UTM
A S-N X=339000 UTM
d W-E Y=3122000 UTM
i W-E Y=3130000 UTM
c W-E Y=3120000 UTM
h W-E Y=3129000 UTM
b W-E Y=3118000 UTM
g W-E Y=3128000 UTM
a W-E Y=3116000 UTM
f W-E Y=3126000 UTM
kg/m3

Figure 13

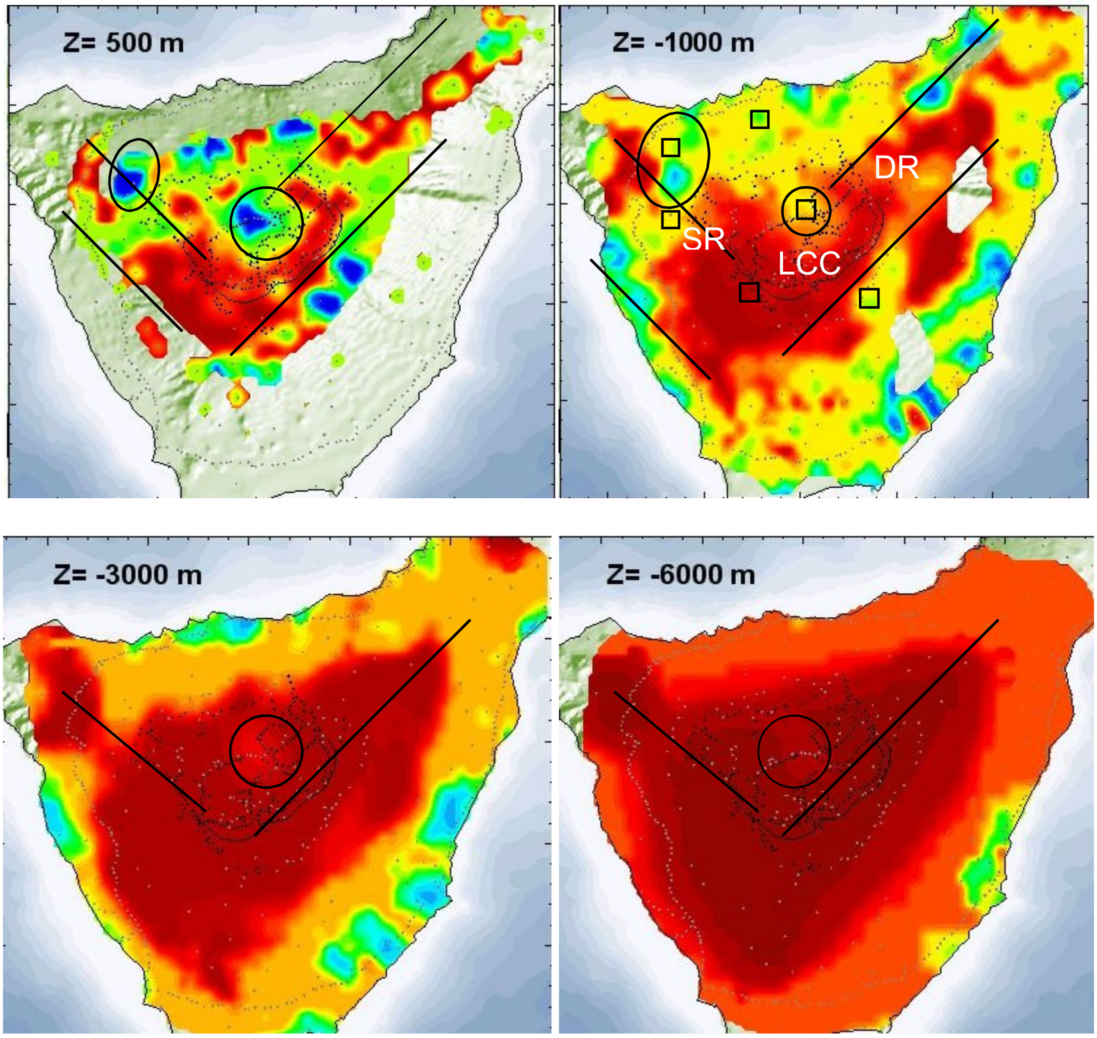


Figure 14