Geochemistry, Geophysics, Geosystems

Key Points:
- We obtained three-dimensional magnetic models of intrusive bodies on La Gomera through inversion of aeromagnetic data
- The location of the plutonic core of La Gomera indicates that the volcanic submarine growth started to the north of the island
- The E-W strike of the main magnetic source suggests a regional tectonic control over the early emplacement of magmas

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Three-Dimensional Magnetic Models of La Gomera (Canary Islands): Insights Into the Early Evolution of an Ocean Island Volcano

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Abstract An aeromagnetic data set from the island of La Gomera was studied through two inverse modeling approaches that produced complementary views of the inner structure of this volcanic island: (1) a variable magnetization model that identified the main lateral magnetization contrasts and (2) a constant magnetization model that imaged the main magnetic source by assuming that it was a uniformly magnetized body. The modeling reveals intense magnetizations beneath the northern part of La Gomera, which occupy an important portion of the northern submarine edifice, correspond well with outcrops of the submarine volcano (Basal Complex), and confirm that most of the magnetic signal revealed by aeromagnetic mapping in the Canary Islands is due to the intense magnetizations of the intrusive complexes (plutonic bodies and dike complexes) emplaced during the initial stages of growth of the volcanic edifices. The consistency of our models with the results of a previous gravimetric study suggests that these intrusive complexes are denser and more magnetic than the surrounding rocks. The location of the main magnetic source reinforces the interpretation, first suggested by geological evidence, that the submarine and early subaerial growth of La Gomera started to the north of the present island. The elongated shape of these intrusive complexes with a nearly E-W strike agrees with the orientation of analogous structures on Tenerife and Gran Canaria, suggesting that the initial formation of the central islands of the Canary Archipelago was controlled by a set of regional fractures in a strike-slip tectonic framework.

Plain Language Summary Airborne magnetic mapping reveals differences in the rocks' magnetizations of buried geological structures. Through the application of inversion algorithms to magnetic anomaly data, three-dimensional models of the geological structures that are responsible for the measured anomalies can be obtained. In volcanic islands, most anomalies are created by the intrusive structures which formed as a result of the ascent and emplacement of molten magma that did not reach the surface, because when they cooled in the presence of the Earth's magnetic field, they acquired a strong remanent magnetization. The most important intrusive bodies are those emplaced during the early growth of the volcanic island, which occurred under the sea. Our magnetic models from La Gomera reveal that these intrusive bodies are located beneath the northern part of the island, suggesting that the center of the early volcano is under the sea to the north of the present coastline. This result is consistent with previous works based on geological evidence that hypothesized that volcanic activity in La Gomera started to the north and migrated southward in later stages. These intrusive bodies were also imaged by gravity anomaly data in a previous work that identified a dense structure corresponding with the highly magnetic body.

1. Introduction

The current morphology of a volcanic island is the result of the complex alternation of constructive (intrusion and effusion of volcanic rocks) and destructive (erosion and flank collapse) processes from the initial formation of the island until the present time. In the case of the Canary Islands (Figure 1(a)), the volcanic history of the islands spans periods of time that can reach several tens of million years in the oldest eastern islands of Fuerteventura and Lanzarote (Balogh et al., 1999; Coello et al., 1992) but only a few million years in the youngest western edifices of La Palma and El Hierro (Ancochea et al., 1993; Guillou et al., 1996).

Reconstructing the volcanic history of an ocean volcano requires understanding the formation and dynamics of rift zones, the mechanisms that trigger the occurrence of giant landslides and their interplay with
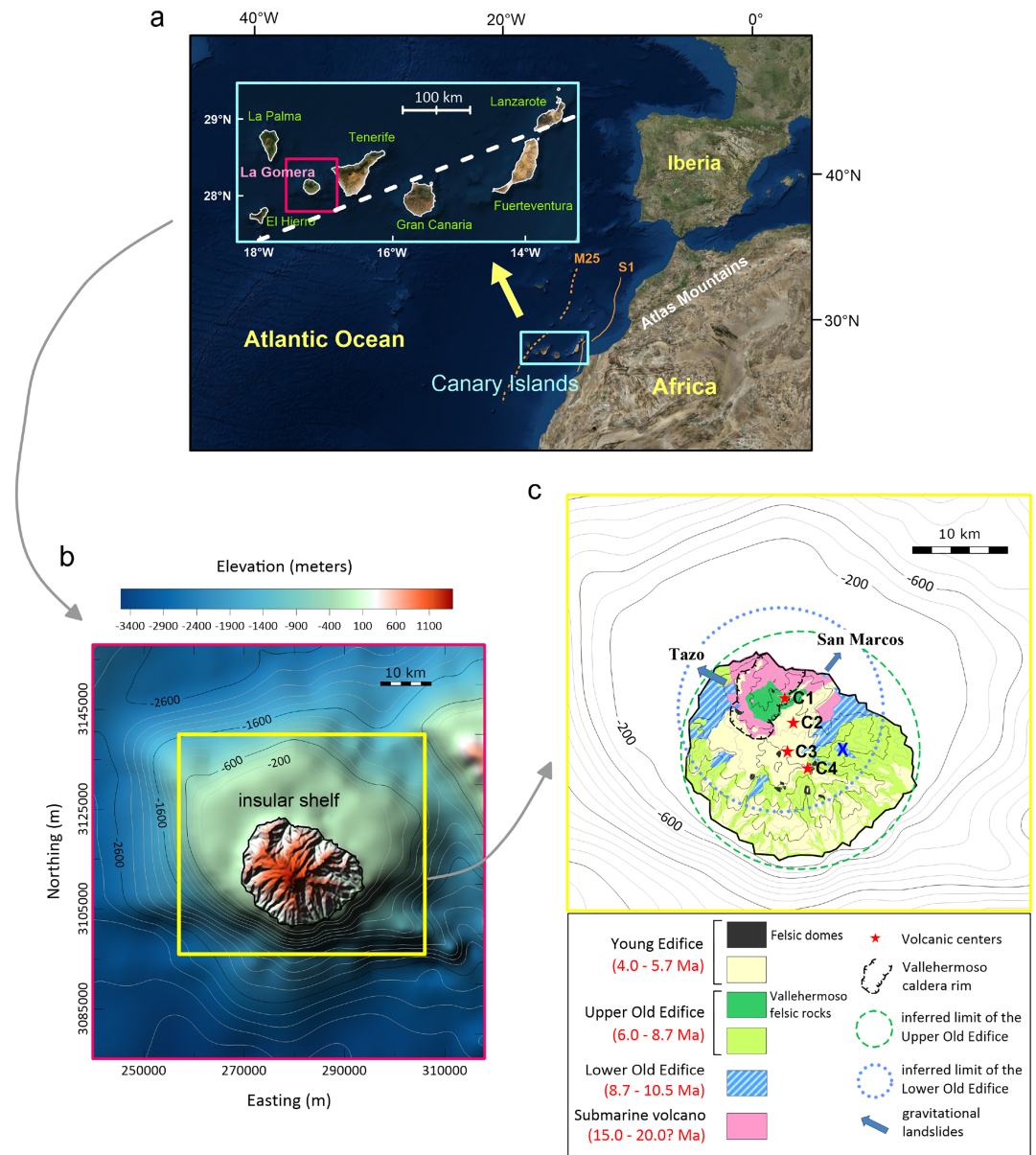
Figure 1. (a) Geographical location of the canary archipelago in the Atlantic Ocean, with identification of the seven major islands. Marine magnetic anomalies S1 and M25 are outlined (Verhoef et al., 1991). The dashed white line in the inset of the archipelago marks the position of the regional fracture deduced from geophysical data (Blanco-Montenegro et al., 2018; Bosshard & MacFarlane, 1970). (b) Digital elevation model of La Gomera volcanic edifice (bathymetry from ETOPO1 data with approximately 1,800 m resolution and topography from the Spanish *Instituto Geográfico Nacional* with 200 m resolution). (c) Geological sketch of the emerged portion of La Gomera based on the reconstruction of the volcanic evolution of this island proposed by Ancochea et al. (2006). See the figure legend for explanation of the different stages and elements represented. The red stars mark the positions of the four volcanic centers (from C1 to C4, in order of decreasing age) identified by Ancochea et al. (2008) through the geometric analysis of different dike swarms. The dark blue cross shows the location of the Hermigua lava sequence studied by Caccavari et al. (2015) for paleomagnetic purposes. See the text for details.

intrusive and eruptive events, or the formation of calderas. The initial stages of volcanic growth, in particular, are poorly understood because the products and structures emplaced at the early submarine stage are buried beneath more recent structures. Geological studies are mainly based on the analysis of the materials in outcrops, which represent a very small fraction of the total volume of a volcanic edifice; therefore, geophysical data, such as potential field data, play a key role in the imaging of the inner

structure of volcanic islands for understanding their evolution. On some occasions, the modeling of magnetic anomalies can provide us with information about the chronology of the different magmatic stages by comparing the observed magnetic polarities with the geomagnetic polarity time scale. In the Canary Islands, after the pioneering work of Bosshard and MacFarlane (1970), a number of gravity and/or magnetic studies have been carried out on some islands (e.g., Ablay & Kearey, 2000; Blanco-Montenegro et al., 2003; Blanco-Montenegro et al., 2008; Camacho et al., 2001; Gottsmann et al., 2008; Montesinos et al., 2005; Montesinos et al., 2006, among others). The marine area surrounding the islands has also been the object of a gravity and magnetic survey (Carbó et al., 2003; Catalán et al., 2003).

La Gomera is one of the less studied islands of the Canary Archipelago. Several characteristics make it different from the other Canaries: the outcrop of the submarine volcano (which is present in only two other islands of the archipelago: La Palma and Fuerteventura), the absence of Quaternary volcanic activity, and the apparently anomalous age of the island when it is interpreted within the framework of a hot spot model for the intraplate Canarian volcanism (Carracedo et al., 1998). In fact, geochronological knowledge of La Gomera contradicts the expected east-to-west age progression of a vertical mantle plume below a moving tectonic plate: The oldest materials that crop out in La Gomera, with ages estimated at 20 Ma (Abdel-Monem et al., 1971), formed prior to the oldest materials found in Tenerife, with ages of less than 12 Ma (Ancochea et al., 1990; Thirlwall et al., 2000). This "age anomaly" is one of the key points that requires a more complex explanation than a classic hot spot for Canary volcanism (Anguita & Hernán, 2000).

After the first modern studies on the geology of La Gomera (Bravo, 1964; Cantagrel et al., 1984; Cendrero, 1970), three reconstructions of the volcanic history of this island are recently proposed (Ancochea et al., 2006; Cueto et al., 2004; Paris et al., 2005). In the last 15 years, work has focused on the study of abundant dike swarms (Ancochea et al., 2003; Ancochea et al., 2008; Márquez et al., 2018; Rodríguez-Losada & Martínez-Frías, 2004), the study of marine geomorphological features (Llanes et al., 2009), the characterization of gravitational landslides by structural analysis (Casillas et al., 2010; Fernández et al., 2015), and paleomagnetic data for studying a Miocene geomagnetic polarity transition (Caccavari et al., 2015). This wealth of knowledge has provided us with a rather good picture of La Gomera subaerial volcanic history, although little is known about the construction of the submarine edifice.

Evolution models of La Gomera based on geological evidence propose that volcanic activity started in the north of the island and migrated southward in later stages (Ancochea et al., 2006; Ancochea et al., 2008). A few years after the publication of these works, a gravimetric study of La Gomera by Montesinos et al. (2011) confirmed this hypothesis, revealing a dense, large intrusive body just where Ancochea et al. (2006) had placed the hypothetical early volcanic edifice. To date, the gravimetric modeling by Montesinos et al. (2011) is the only geophysical study aimed at deciphering the inner structure of this island.

In this work, we present the results from magnetic modeling of aeromagnetic data acquired in La Gomera and its surrounding marine region in 1993 by the *Instituto Geográfico Nacional* of Spain (IGN) (Socías & Mézcua, 1996) and never before interpreted. This aeromagnetic study sheds new light on the early buried structures previously imaged by gravity data and provides us with a complementary view of the intrusive complexes emplaced during the submarine construction of La Gomera.

2. Geological Setting

The Canary Archipelago is a group of eight volcanic islands located near the western African passive continental margin in the Atlantic Ocean. The archipelago is bounded by marine magnetic anomalies M25 to the west and S1 to the east, between which the old Jurassic oceanic crust (150–180 Ma) seems to be magnetically "quiet" (Roest et al., 1992; Verhoef et al., 1991). The origin of the Canary Islands and, specifically, the interplay between magma upwelling from the mantle and regional crustal tectonics are still a matter of intense debate (see Blanco-Montenegro et al., 2018, and references therein for a recent review on this issue).

La Gomera is located to the west of Tenerife, which is the largest island of the whole archipelago (Figure 1 (a)). Its emerged part shows a nearly round shape with a diameter of approximately 24 km and a maximum height of 1,487 m in the center of the island. However, bathymetric data reveal that the volcanic edifice is much larger, with a diameter of approximately 50 km and a total height of approximately 4,500 m from

the sea bottom, and that the emerged portion is shifted to the south with respect to the center of the submarine edifice (Figure 1(b)).

The edifice's morphology evolved during the long volcanic history of the island, and the present geometry is far from what it was in its initial stages. Due to the long elapsed time from the end of volcanic activity in La Gomera approximately 4 Ma, the dismantling effect of erosion has been much greater than in the other islands of the archipelago. Marine erosion has acted along the island coastline, which has receded tens of kilometers since the island's formation, and intense wave erosion over the shallow part of the submarine edifice has produced an insular shelf at depths between 200 and 300 m (Figure 1(b)). In the subaerial edifice, many characteristic canyons or "barrancos" developed as a consequence of long-acting fluvial erosion (Llanes et al., 2009).

Like every volcanic island, La Gomera started its growth as a seamount. Materials belonging to this stage were named the Basal Complex in the first geological studies of the Canary Islands. On La Gomera, the Basal Complex is found in the northern part of the island (Figure 1(c)). The same complex crops out in Fuerteventura and La Palma but not in the rest of the Canary Islands. This geological unit is composed of plutonic rocks (gabbros, pyroxenites, wehrlites, hornblendites, and syenites), submarine volcanics (basaltic pillow lavas and some trachytic breccias), and marine sediments, and it is intruded by a very dense dike network (Bravo, 1964; Cendrero, 1970). These materials are strongly faulted and altered due to hydrothermal metamorphism. They represent the submarine stage of growth and the hypabyssal roots of the later subaerial stages (Ancochea et al., 2006).

Geochronological studies performed on plutonic rocks of the submarine volcano obtained ages between 20 and 15 Ma (Abdel-Monem et al., 1971; Cantagrel et al., 1984). These results mean that the oldest outcrops of plutonic rocks were probably emplaced approximately 20 Ma, but clearly, no information about the earlier buried intrusive complexes at the core of the submarine volcano is attainable, which means that the submarine growth might have started several million years earlier than 20 Ma.

As proposed by Ancochea et al. (2006), following the submarine stage of growth and probably after a volcanic hiatus of approximately 4 Myr, the subaerial edifice (Old Edifice) started to emerge at 10.5 Ma (Figure 1 (c)). This edifice represents the main structure of the island and is composed of a pile of gently outward-dipping basaltic lava flows several hundreds of meters thick and some breccia. This edifice is cut by numerous basaltic dikes, although trachytic to phonolitic dikes can also be found.

The growth of this edifice took place in two stages (Lower and Upper) separated by the occurrence of several flank collapses in its northern sector. The Lower Old Edifice was a large basaltic shield volcano with a diameter estimated as approximately 22 km built between 10.5 and 8.7 Ma. At approximately 9.4 Ma, the Tazo avalanche removed part of its northwestern flank, probably triggered by continuous magma injection through dikes in a rift zone oriented ENE-WSW (Casillas et al., 2010; Fernández et al., 2015). Later, the San Marcos avalanche affected the northeastern flank just before 8.6 Ma (Ancochea et al., 2006) (Figure 1c).

In the second stage (Upper Old Edifice), the activity migrated southward, and a composite volcano with a diameter of approximately 25 km was built. The Upper Old Edifice is mainly composed of a 500 m thick succession of basalt and trachybasalt lava flows and pyroclastic rocks. Two different felsic episodes have been identified during this stage, with ages from 8.6 to 7.8 Ma and from 7.5 to 6.4 Ma. The latter episode produced the Vallehermoso trachy-phonolitic complex in northern La Gomera, which consists of a 10 km wide cone sheet dike complex, a breccia deposit, and some felsic domes (Ancochea et al., 2003; Rodríguez-Losada & Martínez-Frías, 2004) emplaced inside an amphitheater-headed valley (Vallehermoso valley, Figure 1(c)). Ancochea et al. (2003) associated the cone sheet complex with an ancient single dome-shaped shallow magma chamber located approximately 1,650 m below the present sea level. Rodríguez-Losada and Martínez-Frías (2004) interpreted the Vallehermoso trachyphonolitic complex as the root of an old, intensely eroded felsic volcanic edifice and proposed that the migration of felsic magma through the dikes of the cone sheet complex caused the decompression of the magma chamber followed by the collapse of its roof, forming a 3 to 4 km wide caldera (Figure 1(c)). This interpretation was also suggested by Cueto et al. (1994). However, no agreement about the origin of this geomorphological feature has been reached. Ancochea et al. (2006) considered that the caldera-shaped morphology was formed by erosion in more recent times (younger than 4 Ma) because they found flows ascribed to the last eruptive stage in the caldera wall, whereas Paris et al.
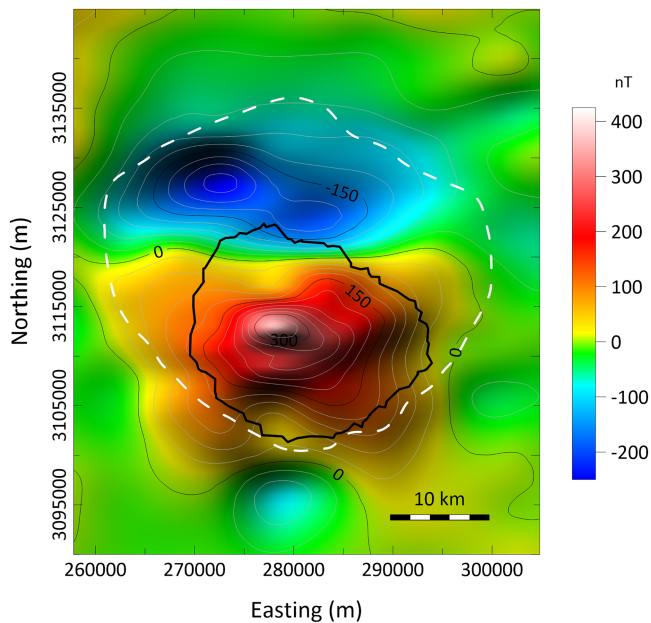
Figure 2. Magnetic anomaly map obtained from the aeromagnetic data acquired at a height of 2,000 m above sea level over La Gomera and the surrounding marine region by the *Instituto Geográfico Nacional* of Spain (Socías & Mézcua, 1996). The black line represents the coastline, whereas the dashed white line shows the base of the island shelf at a depth of approximately 250 m for reference. The grid cell size is 1 km. Coordinates are in the universal transverse Mercator projection (zone 28°N).

(2005) referred to this feature as the Garajonay embayment and related it to a gravitational landslide occurring at approximately 8 Ma.

From 5.7 to 4 Ma, the last stage of volcanic activity took place, resulting in the construction of the Young Edifice, which consists of a 1,000 m thick pile of basaltic, trachybasaltic, and trachyandesitic lava flows, sometimes interstratified with basaltic pyroclasts and some felsic lava domes. These materials covered the central and southern parts of the island and filled deep ravines in the north.

Through the geometric analysis of four radial basic dike swarms of different ages, Ancochea et al. (2008) obtained the locations of the volcanic centers responsible for these four intrusive events and concluded that the volcanic activity in La Gomera migrated southward during the construction of the island. The subaerial activity started to the north of the island (Magmatic Focus C1, corresponding to dikes with ages from 9.1 to 8.4 Ma ascribed to the Lower Old Edifice) and progressively migrated southward, first to Magmatic Focus C2 (with ages from 8.2 to 6.7 Ma, corresponding to the Upper Old Edifice), then to Magmatic Focus C3 (with ages from 5.5 to 4.4 Ma, during the Young Edifice stage), and finally to Magmatic Focus C4 (with ages from 5.3 to 4.0 Ma, also ascribed to the building of the Young Edifice) (Figure 1c).

From 4 to 2 Ma, very local and sporadic activity occurred, whereas from 2 Ma to the present time, volcanic activity in La Gomera has been completely absent (Ancochea et al., 2006). This fact makes this island unique among the Canary Archipelago.

3. Magnetic Data

In 1993, the IGN conducted an aeromagnetic survey of the Canary Islands. Over La Gomera and its surrounding marine area, flight lines were flown at an altitude of 2,000 m above sea level in the N-S direction with a distance between lines of 5 km, whereas tie lines were flown E-W with a separation of 20 km. In Socías and Mézcua (1996), a detailed explanation about the survey and the data processing can be found. For this study, we worked with a 1 km cell magnetic anomaly grid provided by the IGN and shown in Figure 2.

The aeromagnetic anomaly map of La Gomera displays a main magnetic dipole over the volcanic edifice with its low to the north and its high to the south and centered over the northern part of the emerged edifice. This pattern means that most of the magnetic signal is due to a main source that is characterized by a positive magnetization contrast with respect to the surrounding rocks.

It can be assumed that the location of this body is not centered over the island but is shifted toward the north and extends seaward. In order to center the anomaly over its source, we calculate the direction of magnetization and use that to reduce the magnetic data to the pole.

4. Estimation of the Total Magnetization Vector Direction

The physical magnitude responsible for the magnetic field of crustal origin (or magnetic anomaly field) is the magnetization of the rocks, which is a vector quantity resulting from the sum of two terms: a first component aligned in the direction of the Earth's magnetic field at the time of the magnetization acquisition (the remanent magnetization, $\mathbf{J_R}$) and a second component aligned with the Earth's present-day magnetic field (the induced magnetization, $\mathbf{J_I}$, proportional to the magnetic susceptibility of the rocks). The ratio J_R/J_I, known as the Koenigsberger ratio (Q), is usually larger than 1 in volcanic zones, where the remanent magnetization is mainly acquired when rocks cool below the Curie temperature of the magnetic minerals (thermoremanence). The direction of the total magnetization vector can differ significantly from the Earth's present-day magnetic field direction; therefore, to interpret a magnetic anomaly in a volcanic context, the total magnetization vector direction needs to be hypothesized or estimated.

In this work, we applied a linear inversion method to the magnetic data for La Gomera for estimating the inclination (I) and declination (D) of the total magnetization vector of the main magnetic source (Nicolosi et al., 2006). We assumed that this body can be characterized by a bulk magnetization with a constant direction. The method uses a simple equivalent source geometry (a flat layer) to reproduce the observed magnetic anomaly. This layer is divided into a collection of N rectangular prisms that are magnetized along a constant direction (i.e., the length of the magnetization vector J varies from prism to prism, though its direction remains constant). After choosing the suitable inclination (I) and declination (D) ranges within which the source magnetization is expected to be, the magnetization distribution is found by linear inversion of the magnetic anomaly data for each magnetization direction defined by a pair (I, D) (i.e., model *mod(I,D)*, made up of J_i, for $i = 1, N$). By calculating the misfit (χ^2) between the observed magnetic anomaly and the anomaly created by each model, it is possible to quantify which model is the best to resemble the observed anomaly. Therefore, the actual magnetization direction is estimated as the pair (I, D) of the best inverse model.

We applied this method to the magnetic anomaly for La Gomera (Figure 2). We worked with a flat source layer composed of cubic prismatic cells with sides of 2 km and the top of the layer located at sea level. It should be emphasized that the shape of the inversion layer is irrelevant, since the method is based on an "equivalent" source approach in order to find just the magnetization direction, not the source geometry. The magnetic field direction was modeled with the eleventh generation of the International Geomagnetic Reference Field (IGRF) (Finlay et al., 2010) for La Gomera at the epoch of the survey (1993.8), defined by an inclination $I = 38.6°$ and a declination $D = −8.4°$. Through the inversion of the magnetic anomaly of La Gomera, we obtained a magnetization distribution on the source layer for 255 pairs of values (I, D), where I and D were within the ranges from 10° to 80° and − 45° to 45°, respectively, at intervals of 5°.

Once the general trend of the misfit was characterized, we refined the estimate of the magnetization direction by repeating the procedure in more detail for a small (I, D) range around the minimum χ^2 identified previously. That is, we used values from 30° to 50° in inclination and from −15° to 5° in declination at intervals of 2.5°. The results are shown in Figure 3.

From this analysis, we concluded that the magnetization direction of the main magnetic source in La Gomera is probably defined by an inclination $I = 42.5°$ and a declination $D = −2.5°$. When compared with the direction of the geocentric axial dipole field for this latitude ($I = 47°$, $D = 0°$), which is the average expected direction when the remanence acquisition spans more than 10^5 years, we can note that both directions are close but that they do not exactly coincide. Our results are consistent with the mean paleomagnetic direction obtained by Caccavari et al. (2015) in a sequence of 25 normal polarity lava flows belonging to the Old Edifice (see location in Figure 1(c)), which was defined by an inclination $I = 42.4°$ and a declination $D = 359.6°$ ($\alpha_{95} = 5.1°$). This consistency indicates the reliability of our method for the estimation of the mean magnetization direction in La Gomera. Moreover, the agreement between our result and the paleomagnetic direction indicates that the remanent component is by far the most important contribution to the bulk magnetization of the magnetic sources in this island or, in other words, that the rocks in La Gomera are characterized by a Koenigsberger ratio $Q \gg 1$.

In Figure 4(a), we show the reduced-to-the-pole magnetic anomaly map of La Gomera, which was calculated under the assumption that the direction of the total magnetization vector of the magnetic sources is defined by an inclination $I = 42.5°$ and a declination $D = −2.5°$, whereas for the Earth's magnetic field, the direction is given by the IGRF (Finlay et al., 2010) ($I = 38.6°$, $D = −8.4°$). This transformation converts a dipolar anomaly with normal polarity (with its low to the north and its high to the south) into a magnetic high centered over its source, so that identifying correlations with geological/topographic features is easier. In the case of La Gomera, the main magnetic dipolar anomaly (Figure 2) is transformed into a magnetic high centered over the northern coast of the island, in good correspondence with the geometry of the Basal Complex outcrops (Figure 4(a)).

When comparing the reduced-to-the-pole magnetic anomaly map of La Gomera with the Bouguer gravity anomaly map shown in Figure 4(b) (Montesinos et al., 2011), strong correlations are evident. Both maps reveal a main source beneath the northern part of La Gomera and extending seaward, which is characterized both by positive magnetization and density contrasts with respect to the surrounding rocks. The implications of this extraordinary correlation are discussed later in the manuscript, based on the models that are described in the following section.
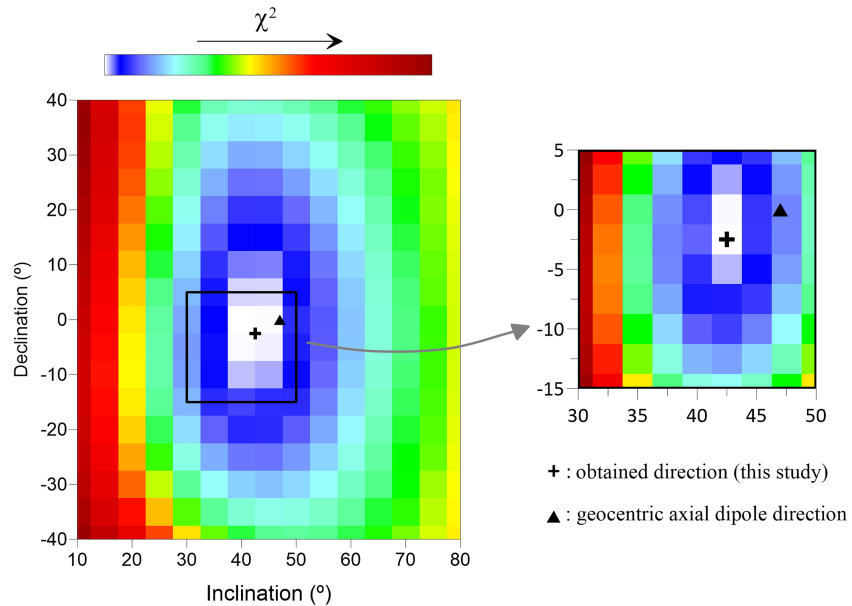
Figure 3. Results from estimating the direction of the main source magnetization vector through the method proposed by Nicolosi et al. (2006). The minimum misfit (χ^2) between the observed anomaly and the model anomaly corresponds to the inclination (I) and declination (D) of the source magnetization. (left) calculation made from 10° to 80° for I and from −40° to 40° for D at intervals of 5°. (right) calculation made from 30° to 50° for I and from −15° to 5° for D at intervals of 2.5°. The obtained direction is given by $I = 42.5°$ and $D = −2.5°$. The geocentric axial dipole direction is defined by $I = 47°$ and $D = 0°$.

5. Magnetic Models

We designed a modeling strategy based on two different assumptions with the aim of obtaining two extreme models that provided us with complementary images of the inner structure of La Gomera. A similar approach was successfully applied to magnetic data from Tenerife (Blanco-Montenegro et al., 2011).
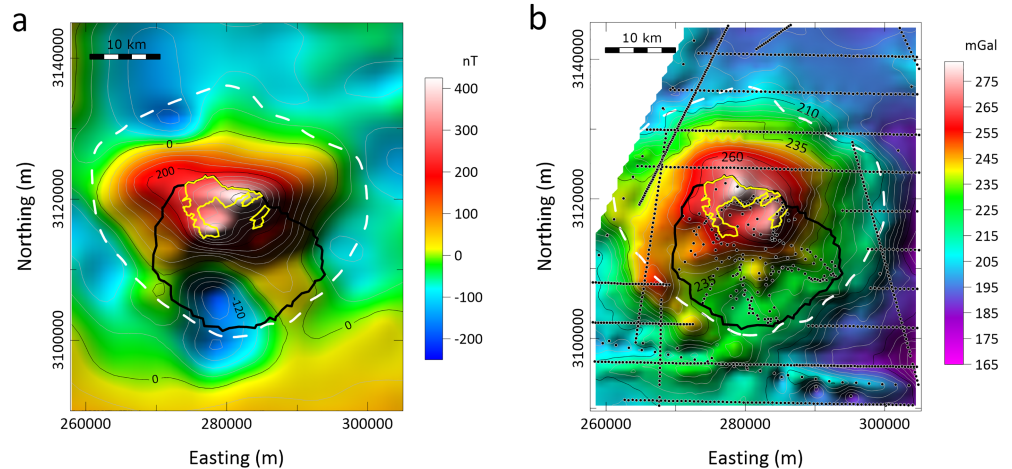

Figure 4. (a) Reduced-to-the-pole magnetic anomaly map of La Gomera, obtained assuming that the magnetization direction is defined by an inclination I = 42.5° and a declination D = −2.5°. (b) Bouguer gravity anomaly of La Gomera published by Montesinos et al. (2011), which was based on land and marine gravity data (dots indicate the measurement points). The Bouguer anomaly was obtained assuming a density of 2,560 kg/m³ for the terrain and 1,027 kg/m³ for the sea water. In both figures, the black line represents the coastline, the dashed white line shows the base of the island shelf at a depth of approximately 250 m, and the yellow line delineates the outcrops of the submarine volcanic units (Basal Complex) in the northern part of the island (see Figure 1(c)). Coordinates are in the universal transverse Mercator projection (zone 28°N).

The goal of the first approach was to find the location of the main lateral magnetization contrasts throughout the island, with no interest in their possible variations with depth, to be correlated with geological features and structures with near-vertical geometries (Figure 5a). The second approach was aimed at modeling the main magnetic source by assuming that it could be represented by a uniformly magnetized body (Figure 5b). Each of the modeling approaches enhances certain geometric properties of the sources to be interpreted within the volcanological context of an ocean island volcano.

5.1. First Approach: Location of Lateral Magnetization Contrasts Through Linear Inversion

In this approach, the source was assumed to be confined to a layer of variable thickness, with its top defined by the island's topography/bathymetry and a constant bottom located at a depth approximately coinciding with the base of the volcanic edifice (Figure 5a). This layer was discretized into a set of prismatic cells of constant base ($1,000 \times 1,000$ m^2) and variable height (from the flat bottom at 3,000 m below sea level (bsl) to the terrain height at each prism's location). Through a linear inversion approach (see Blanco-Montenegro et al., 2011, section 5.1, for details of the mathematical formulation), we obtained a magnetization distribution within this source layer. That is, for each prism at a location defined by coordinates (x, y), a magnetization J_{xy} was obtained, which represented an average value of the actual magnetization at this location from the surface to the prism bottom. This approach helped to locate the main magnetization contrasts, considering that they are near-vertical contacts.

We assumed that all prisms were magnetized along a common direction given by an inclination $I = 42.5°$ and a declination $D = -2.5°$ (which was the direction obtained through the analysis described in section 4), whereas for the ambient magnetic field, we used the direction given by the IGRF (Finlay et al., 2010), with an inclination $I = 38.6°$ and a declination $D = -8.4°$.

The resulting model is shown in Figure 6.

It is worth mentioning here that if the magnetic signal of La Gomera were due to the magnetization contrast between a uniformly magnetized volcanic edifice and the surrounding air/water, the result of this inversion would be a homogeneous magnetization distribution. It is evident that our results are far from this scenario, revealing intense magnetization gradients, especially in the northern part of La Gomera.

5.2. Second Approach: Constant Magnetization Source Modeling by Nonlinear Inversion Based on a Genetic Algorithm

In our second modeling approach, we modeled the main magnetic source by assuming that most of the magnetic signal can be reproduced by a uniformly magnetized body (Figure 5(b)). This approach implies that the effects of other minor sources or heterogeneities are neglected on a first approximation. This hypothesis is reasonable when the magnetic field is sampled at a height of a few kilometers from the source (the magnetic anomaly data set of La Gomera was measured at 2,000 m above sea level), filtering out small-scale variations such that the magnetic anomaly map displays the effects of bulk magnetization.

The modeling of the source of this magnetic anomaly was accomplished by means of the inverse approach developed by Montesinos et al. (2016). The method builds a three-dimensional model of a uniformly magnetized source through a nonlinear inversion based on a genetic algorithm, for which the subsurface volume is discretized into a mesh of rectangular prims. The input information includes the direction of the magnetic field of the Earth at the time of the survey (modeled by the IGRF), the direction of the source magnetization (estimated through the analysis of the magnetic anomaly described in the previous section), and the intensity of the source magnetization (hypothesized, as we explain later).

The algorithm starts with an initial population of source models where every prism is assigned a magnetization $J = 0$, and it searches the optimum solution through an evolutionary process by applying selection, mutation, and crossover operators to the population. At each stage of the process, for each magnetization distribution, an error function is used to quantify the quality of the model as a solution of the inverse problem. The error function is formulated as the sum of (a) the differences between the observed magnetic data and the model magnetic anomaly and (b) a quadratic expression of the model parameters (Schwarz, 1979). The iterative evolution procedure is repeated until the error reaches a minimum value, which is chosen according to the precision of the data. Then, a smoothing operator is applied to the models with the aim of producing compact sources with a smooth geometry by minimizing the source volume. The solution is
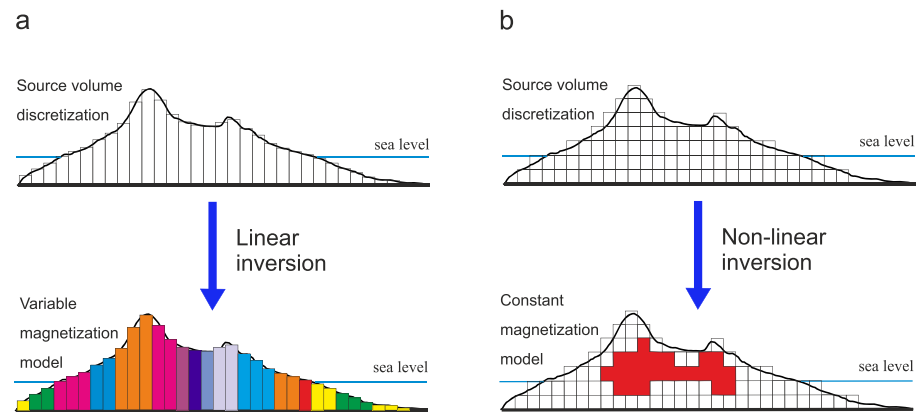
Figure 5. Qualitative illustration of the two inverse modeling approaches described in the text for a generic geological situation (for simplicity, we show two-dimensional pictures although the inversions are carried out in three dimensions). (a) Variable magnetization model: The subsurface is discretized into a set of rectangular vertical prisms, with their tops defined by the topography and their bottoms at a constant depth, and the magnetization distributions (represented with different colors) are found by linear inversion. (b) Constant magnetization model: The subsurface is discretized into a set of rectangular prisms distributed in a number of layers from the topography to a certain depth; then, assuming that the source is a uniformly magnetized body with magnetization J, the prism distributions with nonnull magnetization (red prisms) are found through nonlinear (genetic) inversion.

found when the best model fits the observed data successfully according to the fixed limit or if, after several stages, it does not improve upon the previous model. In Montesinos et al. (2016), a detailed explanation of this inverse approach can be found.

To carry out the inversion procedure, we assumed that the direction of the ambient magnetic field of the Earth was given by an inclination $I = 38.6°$ and a declination $D = -8.4°$ and that the direction of the source magnetization was defined by an inclination $I = 42.5°$ and a declination $D = -2.5°$. Regarding the intensity of the source magnetization, J, we started working with a range of possible values that were chosen considering the typical magnetizations of volcanic rocks, which are on the order of several ampere per meter (Hunt et al., 1995), and assumed that the source body was surrounded by nonmagnetic rocks.

Strictly speaking, what we call magnetization (J) in our model is really a magnetization contrast (ΔJ) between the source and the surrounding rocks. Considering that the Canary Islands were built over weakly magnetized (Bleil & Pedersen, 1983), very old (Jurassic) oceanic crust (Roest et al., 1992; Verhoef et al., 1991), it is reasonable to assume that $\Delta J \cong J$. Therefore, for simplicity, we considered that the crustal rocks within which the intrusive complex of La Gomera was emplaced have null magnetization. It is worth emphasizing that the imaging of the magnetic source does not strictly depend on the absolute magnetization values chosen for the source (J) and the surrounding oceanic crust (J_{crust}) but just on the contrast between them $\Delta J = J - J_{crust}$.

By analyzing the results of the inversion, we concluded that the actual source magnetization J ranges from 1 to 3 A/m since outside this range, the obtained models had unreasonable geometric properties (source bottom located at depths incompatible with the geological context for the lowest values of J and discontinuous bodies for the highest values of J). In addition, outside the range from 1 to 3 A/m, the fit of the inverse models was very poor, indicating the unsuitability of J values lower than 1 A/m and higher than 3 A/m, which were not able to reproduce the observed magnetic anomaly with reasonable accuracy.

To obtain the final models presented here, we built a mesh consisting of 17,566 rectangular prisms that covered the same area as the magnetic anomaly grid and were organized in 11 layers from the topographic/bathymetric surface (defined using ETOPO1 data) to a depth of 12,500 m. Each prism had a size of 1,000 m × 1,000 m in the N-S and E-W directions. The prism height (vertical dimension) was 1,000 m for the layers with depths between 500 m above sea level and 8,500 m bsl and 2,000 m for the deepest layers, located at depths from 8,500 to 12,500 m bsl. The choice of a maximum depth of 12,500 m for the inversion volume was based on the results of several tests, which showed that for magnetizations equal or larger than
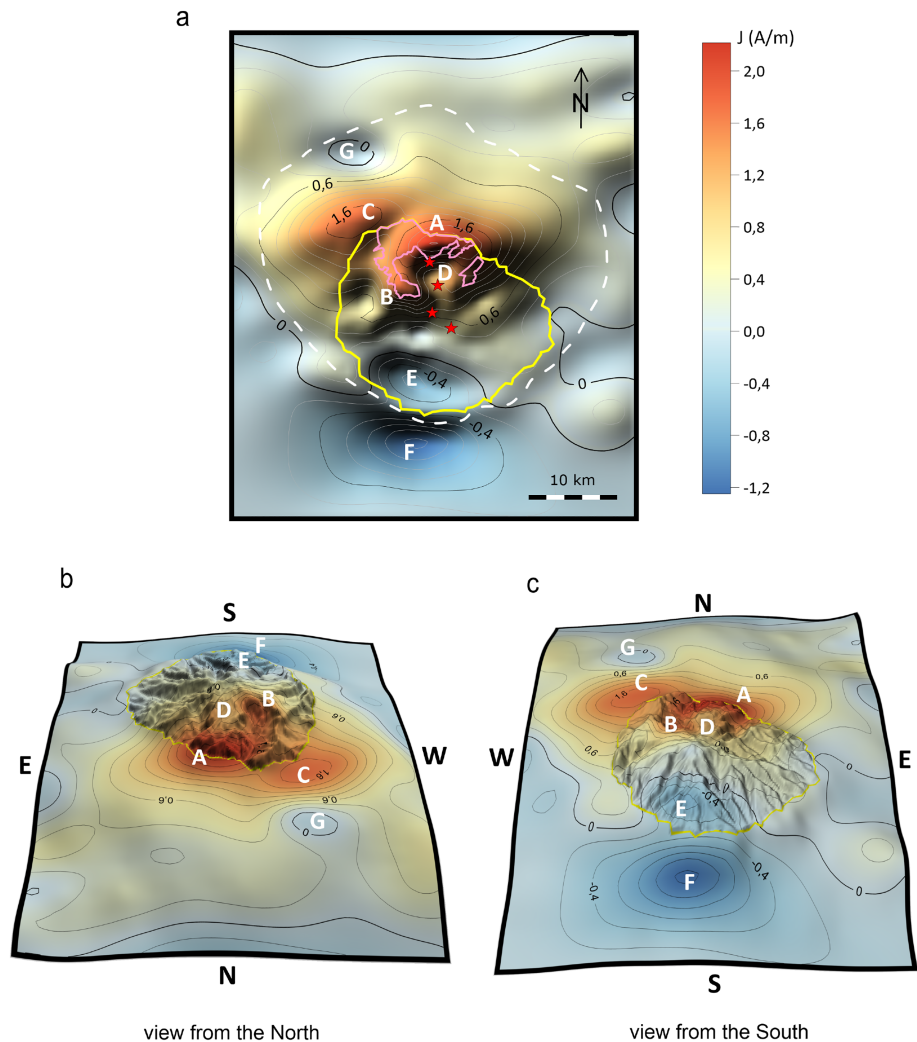
Figure 6. Three views of the magnetization distribution obtained through the linear inversion of the magnetic anomaly data from La Gomera (variable magnetization model). The source volume is defined by the topography/bathymetry (top) and a flat surface at the base of the volcanic edifice (bottom). At each point, the value of J represents the average magnetization of the prismatic volume beneath the point, from the topographic height to the bottom depth. The most interesting features are identified with letters and discussed in the text (magnetization highs: A–C; magnetization lows: D–G). (a) Color-shaded and contour representation of the magnetization distribution. Several features are superimposed to help in the interpretation of the model: The areas where the submarine volcano (Basal Complex) crops out (pink line) (Figure 1c), the volcanic centers identified by Ancochea et al. (2008) (red stars), the island's coastline (yellow line) and the boundary of the island shelf (white dashed line). (b and c) two perspective views (from the north and from the south) of the same magnetization model, superimposed on the shaded digital terrain model of La Gomera (Figure 1b).

1.5 A/m, the source bottom obtained through the magnetic anomaly inversion was always shallower than 10,000 m.

To perform the inversion for the lowest magnetization (J = 1 A/m), we inserted three additional 2,000 m thick layers to the mesh described above, reaching a bottom depth of 18,500 m. Therefore, the number of prisms increased from 17,566 to 23,101 in this case.

In Figure 7, we show the source models obtained for magnetization values of 1, 1.5, 2, 2.5, and 3 A/m for comparison. For each model, the model magnetic anomaly and the residual anomaly (calculated as the difference between the observed anomaly and the model anomaly) are displayed in Figure 8. In Table 1, we summarize the main properties of the models, that is, volume, bottom depth, and root-mean-square error of the residual anomaly. It can be noted that changing the magnetization affects the volume and the
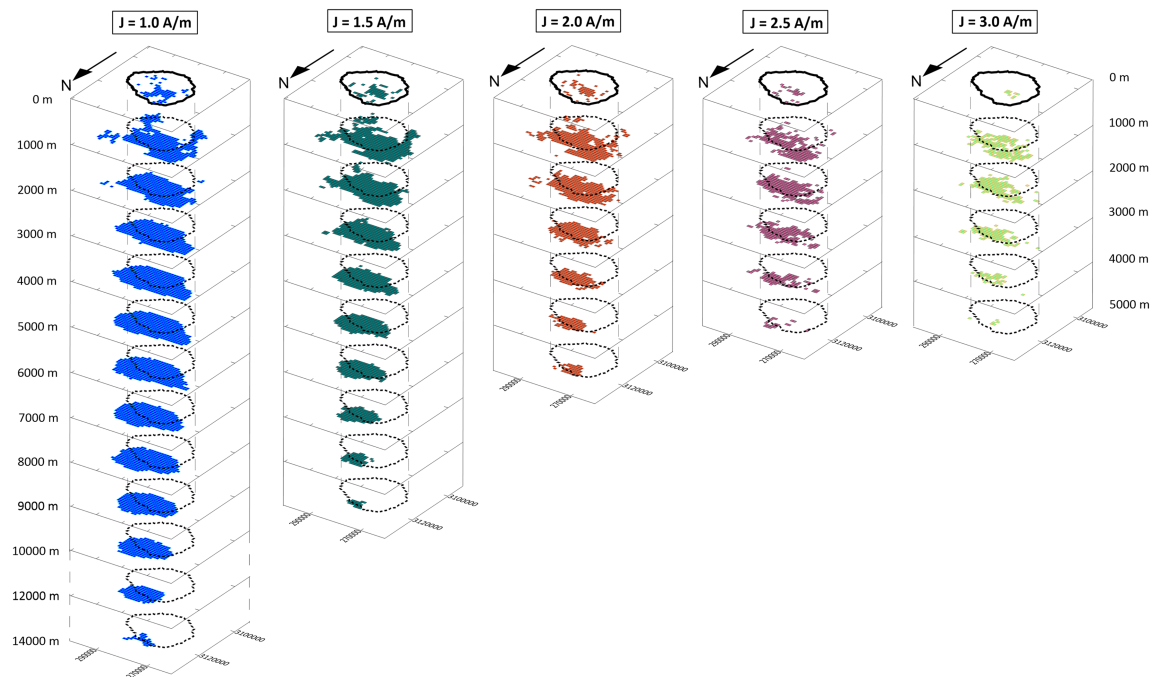
Figure 7. Constant magnetization models: Horizontal sections of the source models obtained through the inversion of the magnetic anomalies from La Gomera (shown in Figure 2) for different magnetization values (J), assuming that the main source is a homogeneously magnetized body.

depth to the bottom of the source. Moreover, the models obtained for magnetizations J = 2.5 A/m and J = 3.0 A/m show discontinuous bodies, and the fits of their anomalies (quantified through the root-mean-square error of the residual anomalies) are worse than those for magnetizations less than 2.5 A/m.

Some of the Canary Islands have been the subject of detailed seismic modeling in recent years, but this is not the case of La Gomera. In the nearby islands, seismic studies placed the Moho discontinuity at depths between 15 and 18 km bsl in Tenerife (e.g., Dañobeitia & Canales, 2000; Lodge et al., 2012; Watts et al., 1997), at 14 km in La Palma (Lodge et al., 2012), and at 12 km in El Hierro (García-Yeguas et al., 2014). High velocity bodies at the core of the islands were imaged by seismic tomography, revealing that intrusive structures reach depths up to 8–10 km bsl in Tenerife (Lodge et al., 2012) and 10–12 km in El Hierro (Gorbatikov et al., 2013). In Tenerife, low velocity zones at 8–10 km bsl were identified and interpreted as partial melt regions (Lodge et al., 2012), whereas a high seismic attenuation zone was found at 6–10 km (Prudencio et al., 2015) beneath the whole island. Both seismic features have been considered evidence of magmatic underplating beneath Tenerife, probably related with a magnetization decrease at those depths.

This crustal framework implies that the magnetic model obtained for a magnetization J = 1 A/m in La Gomera, with the source bottom located at approximately 15 km bsl (therefore, close to the expected depth of the crust–mantle boundary), is probably too thick to be considered a realistic image of the source body, but it cannot be discarded since the source seem to be contained within the crust.

Based on these results, we consider that the model obtained assuming a source magnetization J = 1.5 A/m could be a good representation of the actual source, with geometric properties that are intermediate among the rest of the models and are geologically reasonable. This model is shown in detail in Figure 9 to be discussed in the following section. This does not mean that the other models displayed in Figure 7 were discarded. In fact, all of them contribute to sketch a picture of the mafic core of La Gomera.

6. Discussion

The sources of the magnetic anomalies measured above the Earth's surface are the magnetization contrasts among the different buried geological bodies. Due to the high concentration of magnetic minerals in volcanic rocks, magnetic anomalies in volcanic areas are intense. In particular, intrusive rocks (plutonic bodies
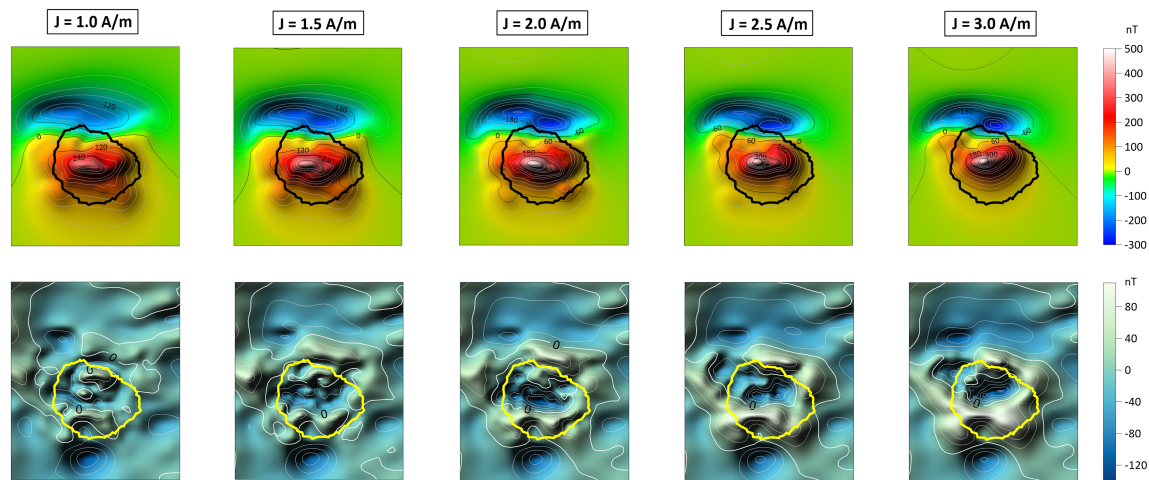
Figure 8. Magnetic anomaly (upper panels) and residual anomaly (lower panels) of the inversion models shown in Figure 7. The residual magnetic anomaly was obtained as the difference between the observed magnetic anomaly (Figure 2) and the magnetic anomaly of each inversion model. The island's coastline is marked with black (upper panel) and yellow (lower panel) lines.

and dike complexes) of mafic composition are responsible for most of the magnetic signal measured in volcanic environments through aeromagnetic mapping, as we explain in the following paragraphs.

To reduce the intrinsic ambiguity involved in potential field modeling, we have obtained two models that are able to reproduce the observed magnetic anomaly data from La Gomera. Depending on the hypotheses on which they are based, each model enhances certain properties of the sources. Therefore, the models must be understood as complementary views of the inner structure of this volcanic island, while the actual magnetization distribution within the volcanic edifice is surely a combination of both.

The variable magnetization model (Figure 6) demonstrates that vertical magnetization contrasts are present within the volcanic edifice of La Gomera. The model reveals high magnetization values in the northern part of the island, both over the subaerial (Zones A and B) and submarine portions of the edifice (Zone C). Magnetization High A is the most intense and is centered just over the northern coastline of La Gomera (see also Figure 9).

The locations of Areas A and B coincide with outcrops of the submarine volcano (Basal Complex) in the northern part of the island (see Figure 6a), following their shape (Area B is exactly over the southernmost units of the Basal Complex). This correlation suggests that intrusive rocks of the early submarine volcanic growth are the main source of the magnetic anomalies observed for La Gomera. An important portion of the Basal Complex corresponds to plutonic rocks, among which the following compositions can be found: peridotites, pyroxenites, olivine gabbros, gabbros, alkaline gabbros, and syenites (Cendrero, 1970). Except for syenites, all the other plutonic rocks are strongly magnetic and are characterized by high densities (Hunt et al., 1995). In addition, the Basal Complex materials are intruded by numerous dikes, most of them basaltic in composition, that acted as feeders of the Lower Old Edifice and represent between 70% and 80% of

Table 1
Compilation of the Geometric Properties of the Constant Magnetization Models Displayed in Figure 7 (Volume and Bottom Depth)

J (A/m)	Bottom depth (m)	Source volume (km^3)	RMSE of the residual anomaly (nT)
1.0	15,500	3,704	19
1.5	9,500	1,859	21
2.0	7,500	1,117	28
2.5	6,500	703	34
3.0	5,500	473	40

Note. The fit quality was quantified through the root-mean-square error (RMSE) of the residual anomaly (Figure 8, lower panel), which was calculated as the difference between the observed anomaly (Figure 2) and the model anomaly (Figure 8, upper panel) for each magnetization.
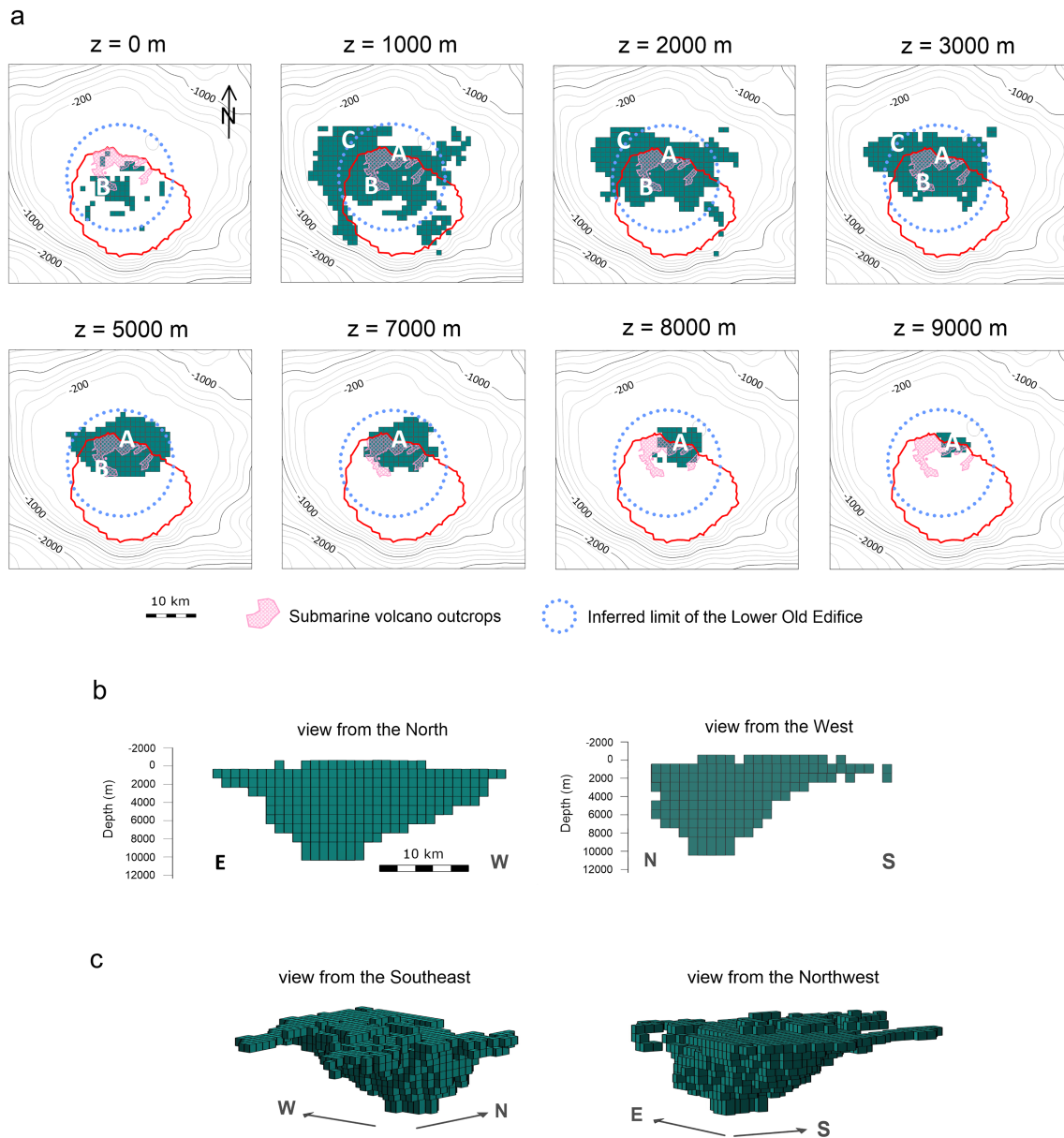
Figure 9. Magnetic model obtained by nonlinear inversion for a magnetization J = 1.5 A/m, which can be considered a good representation of the main magnetic source beneath La Gomera, assuming that this source is a uniformly magnetized body. (a) Horizontal sections at different depths below sea level (z) of the described magnetic model. The contours show the bathymetry around the island, based on ETOPO1 data. The island's coastline is shown in red. The locations of the submarine volcano outcrops (Figure 1(c)) are superimposed to analyze possible correlations. The rough limits inferred by Ancochea et al. (2006) for the old shield basaltic volcano (Lower Old Edifice) are also indicated. Labels A–C identify the high magnetization areas in Figure 6. (b) Vertical views of the model from the north and from the west. (c) Three-dimensional perspective views of the model from the southeast and from the northwest.

the total rock volume of this complex (Ancochea et al., 2006; Cendrero, 1970). These basaltic dike swarms are strongly magnetic, near-vertical structures; therefore, they represent an important contribution to the measured magnetic anomalies, together with the mostly gabbroic plutonic bodies already mentioned.

This result is especially relevant because previous studies based on aeromagnetic data from other islands of the archipelago where the submarine volcanoes do not crop out (e.g., Blanco-Montenegro et al., 2003, 2005, 2011) related the sources of the magnetic anomalies to the intrusive complexes emplaced at the early stages of growth of the islands. Now, our study on La Gomera confirms this interpretation.

The variable magnetization model reveals a third magnetization high (C) in the marine area to the northwest of the island (Figure 6). This zone suggests that intrusive rocks similar to those beneath Area A are

also present beneath C. This magnetization pattern implies that two intrusive events occurred during a normal polarity chron of the Earth's magnetic field and were responsible for the emplacement of the plutonic core of the early submarine volcanic edifice of La Gomera. Therefore, it is likely that Basal Complex materials are also present under the sea in the vicinity of the northwestern coast of the island.

Magnetization High B is located just over the southern rim of the Vallehermoso caldera. In Tenerife, strongly magnetized areas with rounded shapes were correlated with the intrusion of dikes favored by the decompression caused by gravitational collapses (Blanco-Montenegro et al., 2011). It is possible that in La Gomera, the high magnetizations revealed in Area B could have a similar origin. The magnetization high in this area may indicate that a high concentration of mafic dikes exists below the southern headwall of the Vallehermoso valley.

The High Magnetization Areas A and B are interrupted by the Magnetization Low D, which is located near the trachyphonolitic rocks of the Vallehermoso complex. Felsic rocks are usually less magnetic than mafic rocks (Hunt et al., 1995), and the presence of rocks with this composition in this area could be a possible explanation for the decrease in the magnetization revealed by our model, in contrast with the mafic rocks of the Basal Complex. This description applies to both the extrusive and intrusive materials of the Vallehermoso stratovolcano. In fact, a hypothetical syenitic ancient magma chamber at shallow depth beneath this area could contribute to the relatively low magnetization revealed by the model since syenites are characterized by very low magnetizations. This interpretation was also proposed to explain a magnetic low associated with the syenitic crystallized magma chamber beneath the Tejeda caldera in Gran Canaria (Blanco-Montenegro et al., 2003). It is worth noting that the density model obtained from gravity data in La Gomera by Montesinos et al. (2011) also found a low-density body (named H, see their Figure 7) in coincidence with our Low Magnetization Zone D. This correlation seems to support the interpretation that shallow felsic materials (both intrusive and extrusive) of the Vallehermoso stratovolcano, with both low magnetization and low density, are the source of this anomaly.

The magnetic model also reveals some negative magnetization contrasts that are evidenced by the presence of three magnetization lows (labeled E–G in Figure 6). Low E is displayed over the southernmost portion of the La Gomera subaerial edifice, just where Montesinos et al. (2011) (see their Figure 6) found a low-density body. To the south of the island, over the marine edifice, another magnetization low is detected (F). The third low, G, is less intense and occupies a small area in the marine area to the northwest of the island near the boundary of the island shelf. The presence of these lows could be explained by (a) structures surrounded by materials with higher magnetization or (b) structures that acquired their remanent magnetization during a reverse polarity chron. With no additional constraints, it is not possible to elucidate which of these two options is the most realistic.

In particular, Magnetic Low E is displayed over an area covered by materials of the Young Edifice. Montesinos et al. (2011) related the source of the gravity low identified in the same area with the feeding system of this volcanic stage. From the magnetic point of view, it is not clear whether the negative magnetization contrast between this body and the surrounding rocks is due to a reverse polarity or to a magnetization decrease related to a different lithology or alteration, since no information about these parameters is available. Despite the uncertainty about the origin of the Magnetic Low E, the fact that the same body was imaged both by gravity and magnetic data suggests that a structural difference is present in the southern part of La Gomera, where the Young Edifice materials are found, with respect to the northern part.

The source model obtained by assuming that the magnetic signal is created by a uniformly magnetized body with normal polarity (the constant magnetization model shown in Figures 7 and 9) reveals a body located beneath the northern part of the island, with a significant portion of it in the submarine part of the edifice, especially to the northwest of the island. In the variable magnetization model, the high magnetization areas in the northern part of La Gomera appear as two different structures (A/B and C). The modeling of the main source with constant magnetization produces a continuous structure in which these two areas overlap. The highest magnetization values of Area A with respect to C in the variable magnetization model (Figure 6) are replaced by a greater depth extension for the intrusive body beneath A in the northern coast in the constant magnetization model (Figures 7 and 9). With the information deduced from the two modeling approaches, it becomes evident that the most important intrusive complexes of La Gomera are located beneath Area A. Solely with magnetic data, it is not possible to discern whether these intrusive structures are more

magnetic (for instance, due to the higher concentration of mafic dikes beneath this zone) or have a greater vertical extent beneath A than beneath C (because the roots of the intrusive structure are located beneath A, as the deepest sections of the models in Figures 7 and 9 reveal).

The intensity of the main magnetic anomaly over La Gomera (amplitude of approximately 600 nT from the maximum to the minimum) is lower than those of magnetic dipolar anomalies measured over other Canary Islands at similar distances from the sources, such as the nearby Tenerife (amplitude of approximately 1,500 nT) or Gran Canaria (amplitude of approximately 1,000 nT) (Socías & Mézcua, 1996). This contrast implies that the source of this anomaly is a body defined by a magnetization that is lower than those characterizing the magnetic sources in the other islands or, alternatively, that it is thinner. In Tenerife, the main magnetic source was modeled with a magnetization of 3 A/m (Blanco-Montenegro et al., 2011), whereas in Gran Canaria, intrusive structures were modeled with a value of approximately 4 A/m (Blanco-Montenegro et al., 2003; Blanco-Montenegro et al., 2018). In La Gomera, from the modeling of the main magnetic source as a uniformly magnetized body, we conclude that the source magnetization is probably less than 3 A/m. The lower bulk magnetization of the La Gomera intrusive core, in comparison with those of the equivalent bodies in Tenerife and Gran Canaria, could be explained by the high degree of hydrothermal alteration observed in the Basal Complex materials on La Gomera (Casillas et al., 2010; Rodríguez-Losada & Martínez-Frías, 1998). Alternatively, it could be related with the geochronology of the intrusive core, about which no data are available. Considering the age of La Gomera volcanism, it is expected that the construction of the island encompassed both normal and reverse geomagnetic polarity chrons (Paris et al., 2005). Depending on the duration and age of the magmatic event responsible for the intrusion, two different scenarios could be outlined to account for the normal polarity magnetization: (1) the emplacement and cooling of the intrusive body occurred in a (relatively) short time corresponding to a normal polarity chron or (2) the emplacement and cooling of the intrusive body lasted a period of time long enough to encompass several geomagnetic chrons with opposite polarity but with dominance of normally magnetized rocks over reversely magnetized ones. In the latter case, the bulk magnetization of the source would be less intense than in the former, perhaps explaining the apparent low magnetization values deduced from the magnetic modeling.

The high correlation between the magnetic and gravity signals of La Gomera (see Figure 4) indicates that the plutonic core of the submarine volcano is not only more magnetic but also denser than the surrounding rocks, despite the chemical alteration and fracturing observed in the outcrops of intrusive materials in the submarine volcano. In other volcanic contexts, different situations have been observed. For instance, in the Etnean region, a dense but demagnetized intrusive body representing the hydrothermally altered feeding system of an old volcano was identified by geophysical data (Nicolosi et al., 2016). On La Gomera, our results suggest that hydrothermal alteration may have decreased but not canceled the remanent magnetization of the intrusive bodies, which still have higher magnetizations than the surrounding rocks.

The location of the main intrusive structures in the northern part of La Gomera, mainly beneath the portion of the edifice that is presently under the sea, supports the hypothesis of Ancochea et al. (2006, 2008) that the volcanic activity started to the north of the subaerial edifice and migrated southward in later stages. Moreover, the consistency between the magnetic models presented in this work and the gravimetric models of Montesinos et al. (2011) reinforces this interpretation, revealing that the intrusive complexes emplaced at the beginning of La Gomera formation are both denser and more magnetic than the surrounding rocks.

Elongate intrusive structures with a nearly E-W strike (Zone C, Figures 6 and 9) reflect the results obtained on the nearby island of Tenerife, where the plutonic core revealed by the modeling of aeromagnetic data was also elongated in the E-W direction (Blanco-Montenegro et al., 2011). The agreement between the strikes of both intrusive bodies supports the idea that the initial growth of the central Canary Islands was controlled by the presence of crustal fractures at the regional scale that favored the ascent of magma along preferential directions. A recent paper based on the modeling of an elongated reverse polarity magnetic anomaly over the submarine edifice of Gran Canaria (Blanco-Montenegro et al., 2018) demonstrated tectonic control on the emplacement of magmas at the initial stages of submarine growth of this island. On Gran Canaria, the strike of the intrusive body detected in the northwestern portion of the submarine edifice is ENE-WSW, coinciding with the tectonic feature first suggested by Bosshard and MacFarlane (1970) between Tenerife and Gran Canaria and later recognized in other works (Mantovani et al., 2007; Mézcua et al., 1992) (Figure 1a).

On La Gomera, our results are supported by geological evidence. Cendrero (1970) analyzed the strikes of 250 basalt dikes in the Basal Complex and obtained a dominant direction of N70–80°. Fernández et al. (2015) identified four tectonic episodes in the evolution of the Basal Complex during the building of the subaerial shield volcano (Lower Old Edifice) characterized by extension along the following directions: (1) ENE-WSW to NE–SW, (2) NNE–SSW, (3) NNW–SSE, and (4) NE–SW. These authors suggested that the episodes were the results of relative displacements along crustal-scale fractures with orientations of ENE-WSW and NW-SE, pointing to the relevance of the ENE-WSW regional fractures during the first stages of building the Old Edifice. Finally, Márquez et al. (2018) identified an unnoticed E-W volcanic rift in the Lower Old Edifice eastern flank, which is consistent with our results.

Therefore, based on the results obtained on Gran Canaria, Tenerife, and La Gomera from the modeling of aeromagnetic anomalies, where the intrusive cores of the three islands display elongated shapes with ENE-WSW (Gran Canaria) and E-W (Tenerife and La Gomera) strikes, we suggest that the initial formation of these islands was controlled by a set of regional fractures in a strike-slip tectonic regime, an idea that was suggested by Anguita and Hernán (2000).

7. Conclusions

The analysis and modeling of magnetic anomalies are powerful tools for imaging the subsurface structure in volcanic environments because volcanic rocks contain significant amounts of magnetic minerals and the resulting anomalies are intense, revealing the magnetization contrasts among the different buried geological bodies. Aeromagnetic surveying is especially useful because it enables the rapid mapping of large areas with homogeneous data distributions. In the case of volcanic islands, airborne magnetic surveys provide regularly distributed data over both the emerged parts and the submarine edifices, therefore completing our view of the volcanic system based on gravity data acquired by land surveying.

In this work, we studied an aeromagnetic data set for the island of La Gomera through two different inverse modeling approaches that provided us with complementary views of the inner structure of the island. The first approach was useful for finding the location of the main lateral magnetization contrasts (variable magnetization model) with no information about their depth attributes. The second approach (constant magnetization model) modeled the geometry of the main magnetic source by assuming that it could be represented by a uniformly magnetized body. The horizontal location (in the *XY* plane) of the main magnetization contrasts is a common property of both modeling results that can be noted by comparing the variable magnetization model in Figure 6 with the constant magnetization model in Figure 9. The main uncertainties affect the depth properties of the sources: Due to the hypothesis on which it is based, the variable magnetization modeling does not reveal horizontal magnetic contacts, whereas for the constant magnetization modeling, the source depth attributes depend on the assumed magnetization value, J (see Figure 7). The geologic interpretation of our results must consider these limitations.

Both modeling approaches reveal that intense magnetizations are present beneath the northern part of La Gomera. The main magnetic source is a body magnetized with normal polarity centered over the northern coast of the island and occupying an important portion of the northern submarine edifice. The outcrops of volcanic materials ascribed to the submarine volcano (Basal Complex) in the areas characterized by high magnetizations allow us to confirm that most of the magnetic signal revealed by aeromagnetic mapping in the Canary Islands is due to the intense magnetizations of the intrusive complexes (plutonic bodies and dike complexes) emplaced during the initial stages of growth of the volcanic edifices. This interpretation was suggested in our previous magnetic studies of other islands in the Canary Archipelago (Gran Canaria, Lanzarote, El Hierro, and Tenerife), where the early submarine volcanoes do not crop out, but for the first time, our work on La Gomera has confirmed this idea.

Our models of the main magnetic source are extraordinarily consistent with the gravimetric model obtained by Montesinos et al. (2011) from gravity anomaly data. This similarity implies that the intrusive complexes emplaced at the beginning of La Gomera formation are denser and more magnetic than the surrounding rocks, although the magnetic properties seem to be weakened due to hydrothermal alteration when compared with those on other islands of the Canary archipelago. These complementary views of the inner structure of the island reinforce the interpretation, first suggested by geological evidence, that the submarine and early subaerial growth of La Gomera started to the north of the present island (Ancochea et al., 2003, 2006).

In addition, the elongated shape of these intrusive complexes with a nearly E-W strike agrees with the orientation of a similar structure in Tenerife (Blanco-Montenegro et al., 2011) and is consistent with the ENE-WSW strike of an intrusive body in Gran Canaria also modeled with magnetic anomaly data (Blanco-Montenegro et al., 2018). These results suggest that the initial formation of the central islands of the Canary Archipelago was controlled by a set of regional fractures in the strike-slip tectonic regime first suggested by Bosshard and MacFarlane (1970), along which the ascent and emplacement of magmas took place.

References

Abdel-Monem, A., Watkins, N. D., & Gast, P. W. (1971). Potassium-argon ages, volcanic stratigraphy, and geomagnetic polarity history of the Canary Islands: Lanzarote, Fuerteventura, gran Canaria, and La Gomera. *American Journal of Science*, *271*, 490–521.

Ablay, G. J., & Kearey, P. (2000). Gravity constraints on the structure and volcanic evolution of Tenerife. *Journal of Geophysical Research*, *105*, 5783–5796.

Ancochea, E., Brändle, J. L., Huertas, M. J., Cubas, C. R., & Hernán, F. (2003). The felsic dikes of La Gomera (Canary Islands): Identification of cone sheet and radial dike swarms. *Journal of Volcanology and Geothermal Research*, *120*, 197–206.

Ancochea, E., Brändle, J. L., Huertas, M. J., Hernán, F., & Herrera, R. (2008). Dike-swarms, key to the reconstruction of major volcanic edifices: The basic dikes of La Gomera (Canary Islands). *Journal of Volcanology and Geothermal Research*, *173*, 207–216. https://doi.org/10.1016/j.jvolgeores.2008.01.020

Ancochea, E., Fúster, J. M., Ibarrola, E., Cendrero, A., Coello, J., Hernán, F., et al. (1990). Volcanic evolution of the island of Tenerife (Canary Islands) in light of new K-Ar data. *Journal of Volcanology and Geothermal Research*, *44*, 231–249. https://doi.org/10.1016/0377-0273(90)90019-C

Ancochea, E., Hernán, F., Cendrero, A., Cantagrel, J. M., Fúster, J. M., Ibarrola, E., & Coello, J. (1993). Constructive and destructive episodes in the building of a young oceanic island, La Palma, Canary Islands and genesis of the Caldera de Taburiente. *Journal of Volcanology and Geothermal Research*, *60*, 243–262.

Ancochea, E., Hernán, F., Huertas, M. J., Brändle, J. L., & Herrera, R. (2006). A new chronostratigraphical and evolutionary model of La Gomera: Implications for the overall evolution of the Canarian archipelago. *Journal of Volcanology and Geothermal Research*, *157*, 271–273. https://doi.org/10.1016/j.jvolgeores.2006.04.001

Anguita, F., & Hernán, F. (2000). The Canary Islands origin: A unifying model. *Journal of Volcanology and Geothermal Research*, *103*, 1–26.

Balogh, K., Ahijado, A., Casillas, R., & Fernández, C. (1999). Contributions to the chronology of the basal complex of Fuerteventura, Canary Islands. *Journal of Volcanology and Geothermal Research*, *90*, 81–101.

Blanco-Montenegro, I., Montesinos, F. G., & Arnoso, J. (2018). Aeromagnetic anomalies reveal the link between magmatism and tectonics during the early formation of the Canary Islands. *Scientific Reports*, *8*(1), 42. https://doi.org/10.1038/s41598-017-18813-w

Blanco-Montenegro, I., Montesinos, F. G., García, A., Vieira, R., & Villalaín, J. J. (2005). Paleomagnetic determinations on Lanzarote from magnetic and gravity anomalies: Implications for the early history of the Canary Islands. *Journal Geophysical Research*, *110*, B12102. https://doi.org/10.1029/2005JB003668

Blanco-Montenegro, I., Nicolosi, I., Pignatelli, A., & Chiappini, M. (2008). Magnetic imaging of the feeding system of oceanic volcanic islands: El Hierro (Canary Islands). *Geophysical Journal International*, *173*, 339–350.

Blanco-Montenegro, I., Nicolosi, I., Pignatelli, A., García, A., & Chiappini, M. (2011). New evidence about the structure and growth of ocean island volcanoes from aeromagnetic data: The case of Tenerife, Canary Islands. *Journal of Geophysical Research*, *116*, B03102. https://doi.org/10.1029/2010JB007646

Blanco-Montenegro, I., Torta, J. M., García, A., & Araña, V. (2003). Analysis and modelling of the aeromagnetic anomalies of gran Canaria (Canary Islands). *Earth Planet. Science Letters*, *206*, 601–616. https://doi.org/10.1016/S0012-821X(02)01129-9

Bleil, U., & Pedersen, N. (1983). Variations in magnetization intensity and low-temperature titanomagnetite oxidation of ocean floor basalts. *Nature*, *301*, 384–388.

Bosshard, E., & MacFarlane, D. J. (1970). Crustal structure of the western Canary Islands from seismic refraction and gravity data. *Journal of Geophysical Research*, *75*, 4901–4918.

Bravo, T. (1964). Estudio geológico y petrográfico de la isla de La Gomera. *Estudios Geológicos*, *20*, 1–56.

Caccavari, A., Calvo-Rathert, M., Goguitchaichvili, A., Soler, V., Huaiyu, H., & Vegas, N. (2015). An integrated palaeomagnetic, palaeointensity and $^{40}Ar/^{30}Ar$ investigation on a Miocene polarity transition recorded in a lava sequence in La Gomera, Canary Islands. *Geophysical Journal International*, *200*, 1297–1316. https://doi.org/10.1093/gji/ggu481

Camacho, A. G., Montesinos, F. G., Vieira, R., & Arnoso, J. (2001). Modeling of crustal anomalies of Lanzarote (Canary Islands) in light of gravity data. *Geophysical Journal International*, *147*, 403–414.

Cantagrel, J. M., Cendrero, A., Fúster, J. M., Ibarrola, E., & Jamond, C. (1984). K-Ar chronology of the volcanic eruptions in the Canarian archipelago: Island of La Gomera. *Bulletin of Volcanology*, *47*(3), 597–609.

Carbó, A., Muñoz-Martín, A., Llanes, P., Álvarez, J., & EZZ Working Group (2003). Gravity analysis offshore the Canary Islands from a systematic survey. *Marine Geophysical Researches*, *24*(1-2), 113–127. https://doi.org/10.1007/s11001-004-1336-2

Carracedo, J. C., Day, S., Guillou, H., Rodríguez Badiola, E., Canas, J. A., & Pérez Torrado, F. J. (1998). Hotspot volcanism close to a passive continental margin: The Canary Islands. *Geological Magazine*, *135*, 591–604.

Casillas, R., Fernández, C., Colmenero, J. R., de la Nuez, J., García-Navarro, E., & Martín, M. C. (2010). Deformation structures associated with the Tazo landslide (La Gomera, Canary Islands). *Bulletin of Volcanology*, *72*(8), 945–960. https://doi.org/10.1007/s00445-010-0373-8

Catalán, M., Martín Dávila, J., & Working Group, Z. E. E (2003). A magnetic anomaly study offshore the canary archipelago. *Marine Geophysical Researches*, *24*(1-2), 129–148. https://doi.org/10.1007/s11001-004-5442-y

Cendrero, A. (1970). The volcano-plutonic complex of La Gomera (Canary Islands). *Bulletin of Volcanology*, *34*, 537–561.

Coello, J., Cantagrel, J. M., Hernán, F., Fúster, J. M., Ibarrola, E., Ancochea, E., et al. (1992). Evolution of the eastern volcanic ridge of the Canary Islands based on new K-Ar data. *Journal of Volcanology and Geothermal Research*, *53*, 251–274.

Cueto, L. A., Barrera, J. L., & Gómez, J. A. (1994). La caldera de hundimiento de Vallehermoso, Isla de La Gomera (Canarias). *Boletín Geológico y Minero*, *105-4*, 7–12.

Cueto, L. A., Gómez, J. A., Balcells, R., Barrera, J. L., Pineda, A., Cerrato, M., et al. (2004). *Mapa Geológico de España, 1:25.000, hojas n° 1.097 I–II, III y IV y 1105 I y IV*. Madrid, Spain: IGME.

Dañobeitia, J. J., & Canales, J. P. (2000). Magmatic underplating in the canary archipelago. *Journal of Volcanology and Geothermal Research*, *103*, 27–41.

Fernández, C., Casillas, R., de la Nuez, J., García-Navarro, E., & Camacho, M. A. (2015). Deformation of the substratum of a large shield volcano: Triggering factor for past flank collapses in the old volcanic edifice of La Gomera, Canary Islands. *Geological Society of America Bulletin*, *127*, 443–463. https://doi.org/10.1130/B30971.1

Finlay, C. C., Maus, S., Beggan, C. D., Bondar, T. N., Chambodut, A., Chernova, T. A., et al. (2010). International geomagnetic reference field: The eleventh generation. *Geophysical Journal International*, *183*, 1216–1230. https://doi.org/10.1111/j.1365-246X.2010.04804.x

García-Yeguas, A., Ibáñez, J. M., Koulakov, I., Jakovlev, A., Romero-Ruiz, M. C., & Prudencio, J. (2014). Seismic tomography model reveals mantle magma sources of recent volcanic activity at El Hierro Island (Canary Islands, Spain). *Geophysical Journal International*, *199*, 1739–1750. https://doi.org/10.1093/gji/ggu339

Gorbatikov, A. V., Montesinos, F. G., Arnoso, J., Yu Stepanova, M., Benavent, M., & Tsukanow, A. A. (2013). New features in the subsurface structure model of El Hierro Island (canaries) from low-frequency microseismic sounding: An insight into the 2011seismo-volcanic crisis. *Surveys in Geophysics*, *34*, 463–489. https://doi.org/10.1007/s10712-013-9240-4

Gottsmann, J., Camacho, A. G., Martí, J., Wooller, L., Fernández, J., García, A., & Rymer, H. (2008). Shallow structure beneath the central volcanic complex of Tenerife from new gravity data: Implications for its evolution and recent reactivation. *Physics of the Earth and Planetary Interiors*, *168*, 212–230. https://doi.org/10.1016/j.pepi.2008.06.020

Guillou, H., Carracedo, J. C., Pérez-Torrado, F., & Rodríguez Badiola, E. (1996). K-Ar ages and magnetic stratigraphy of a hotspot-induced, fast grown oceanic island: El Hierro, Canary Islands. *Journal of Volcanology and Geothermal Research*, *73*, 141–155.

Hunt, C. P., Moskowitz, B. M., & Banerjee, S. K. (1995). Magnetic properties of rocks and minerals. In T. J. Ahrens (Ed.), *A handbook of physical constants: Rock physics and phase relations*, Boca Raton, Florida, USA: CRC Press, Inc., (pp. 189–204). AGU reference shelf

Llanes, P., Herrera, R., Gómez, M., Muñoz, A., Acosta, J., Uchupi, E., & Smith, D. (2009). Geological evolution of the volcanic island La Gomera, Canary Islands, from analysis of its geomorphology. *Marine Geology*, *264*, 123–139. https://doi.org/10.1016/j.margeo.2009.05.001

Lodge, A., Nippress, S. E. J., Rietbrock, A., García-Yeguas, A., & Ibáñez, J. M. (2012). Evidence for magmatic underplating and partial melt beneath the Canary Islands derived using teleseismic receiver functions. *Physics of the Earth and Planetary Interiors*, *212–213*, 44–54. https://doi.org/10.1016/j.pepi.2012.09.004

Mantovani, E., Viti, M., Babucci, D., & Albarello, D. (2007). Nubia-Eurasia kinematics: An alternative interpretation from Mediterranean and North Atlantic evidence. *Annals of Geophysics*, *50*, 341–366.

Márquez, A., Herrera, R., Izquierdo, T., Martín-González, F., López, I., & Martín-Velázquez, S. (2018). The dyke swarms of the old volcanic edifice of La Gomera (Canary Islands): Implications for the origin and evolution of volcanic rifts in oceanic island volcanoes. *Global and Planetary Change*, *171*, 255–272. https://doi.org/10.1016/j.gloplacha.2017.12.004

Mézcua, J., Buforn, E., Udías, A., & Rueda, J. (1992). Seismotectonics of the Canary Islands. *Tectonophysics*, *208*, 447–452.

Montesinos, F. G., Arnoso, J., Benavent, M., & Vieira, R. (2006). The crustal structure of El Hierro (Canary Islands) from 3-D gravity inversion. *Journal of Volcanology and Geothermal Research*, *150*, 283–299. https://doi.org/10.1016/j.jvolgeores.2005.07.018

Montesinos, F. G., Arnoso, J., & Vieira, R. (2005). Using a genetic algorithm for 3-D inversion of gravity data in Fuerteventura (Canary Islands). *International Journal of Earth Sciences (Geologische Rundschau)*, *94*(2), 301–316. https://doi.org/10.1007/s00531-005-0471-6

Montesinos, F. G., Arnoso, J., Vieira, R., & Benavent, M. (2011). Subsurface geometry and structural evolution of La Gomera Island based on gravity data. *Journal of Volcanology and Geothermal Research*, *199*, 105–117. https://doi.org/10.1016/j.jvolgeores.2010.10.007

Montesinos, F. G., Blanco-Montenegro, I., & Arnoso, J. (2016). Three-dimensional inverse modelling of magnetic anomaly sources based on a genetic algorithm. *Physics of the Earth and Planetary Interiors*, *253*, 74–87. https://doi.org/10.1016/j.pepi.2016.02.004

Nicolosi, I., Blanco-Montenegro, I., Pignatelli, A., & Chiappini, M. (2006). Estimating the magnetization direction of crustal structures by means of an equivalent source algorithm. *Physics of the Earth and Planetary Interiors*, *155*, 163–169. https://doi.org/10.1016/j.pepi.2005.12.003

Nicolosi, I., D'Ajello Caracciolo, F., Branca, S., Ferlito, C., & Chiappini, M. (2016). The earliest open conduit eruptive center of the Etnean region: Evidence from aeromagnetic, geophysical, and geological data. *Bulletin of Volcanology*, *78*(7), 1–11. https://doi.org/10.1007/s00445-016-1042-3

Paris, R., Guillou, H., Carracedo, J. C., & Pérez Torrado, F. J. (2005). Volcanic and morphological evolution of La Gomera (Canary Islands) based on new K-Ar ages and magnetic stratigraphy: Implications for oceanic island evolution. *Journal of the Geological Society of London*, *162*, 501–512.

Prudencio, J., Ibáñez, J. M., Del Pezzo, E., Martí, J., García-Yeguas, A., & De Siena, L. (2015). 3D attenuation tomography of the volcanic island of Tenerife (Canary Islands). *Surveys in Geophysics*, *36*(5), 693–716. https://doi.org/10.1007/s10712-015-9333-3

Rodríguez-Losada, J. A., & Martínez-Frías, J. (1998). Ancient oxide- and sulphide-mineralization in the islands of Tenerife and La Gomera (canary archipelago, Spain). *Mineralium Deposita*, *33*, 639–643.

Rodríguez-Losada, J. A., & Martínez-Frías, J. (2004). The felsic complex of the Vallehermoso caldera: Interior of an ancient volcanic system (La Gomera, Canary Islands). *Journal of Volcanology and Geothermal Research*, *137*, 261–284. https://doi.org/10.1016/j.jvolgeores.2004.05.021

Roest, W. R., Dañobeitia, J. J., Verhoef, J., & Collette, B. J. (1992). Magnetic anomalies in the Canary Basin and the Mesozoic evolution of the Central North Atlantic. *Marine Geophysical Researches*, *14*, 1–24.

Schwarz, K. P. (1979). Geodetic improperly posed problems and their regularization. *Bolletino di Geodesia e Scienze Affini*, *3*, 389–416.

Socías, I., & Mézcua, J. (1996). *Levantamiento aeromagnético del archipiélago canario. (Publicación Técnica 35)*. Madrid, Spain: Instituto Geográfico Nacional.

Thirlwall, M. F., Singer, B. S., & Marriner, G. F. (2000). ^{39}Ar-^{40}Ar ages and geochemistry of the basaltic shield stage of Tenerife, Canary Islands, Spain. *Journal of Volcanology and Geothermal Research*, *103*, 247–297. https://doi.org/10.1016/S0377-0273(00)00227-4

Verhoef, J., Collette, B. J., Dañobeitia, J. J., Roeser, H. A., & Roest, W. R. (1991). Magnetic anomalies off West Africa (20–38°N). *Marine Geophysical Researches*, *13*, 81–103.

Watts, A. B., Pierce, C., Collier, J., Dalwood, R., Canales, J. P., & Hens-Tock, T. J. (1997). A seismic study of lithosphere flexure in the vicinity of Tenerife, Canary Islands. *Earth and Planetary Science Letters*, *146*, 431–447.