

Magnetic imaging of the feeding system of oceanic volcanic islands: El Hierro (Canary Islands)

Isabel Blanco-Montenegro,¹ Iacopo Nicolosi,² Alessandro Pignatelli²
and Massimo Chiappini²

¹Departamento de Física, Universidad de Burgos, Avda. de Cantabria s/n, 09006 Burgos, Spain. E-mail: iblanco@ubu.es

²Istituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Murata 605, 00143 Roma, Italy

Accepted 2008 January 7. Received 2008 January 7; in original form 2007 September 7

SUMMARY

El Hierro is the youngest of the Canary Islands, a volcanic archipelago in the central Atlantic, near the African coast. The subaerial part of the island shows the characteristic shape of three convergent ridges that has been interpreted as a triple-arm rift system. At least four giant landslides formed wide, horseshoe embayments that separate these ridges. Recent studies based on high-resolution bathymetry, however, showed that the submarine rift structure is much more complex. We analysed an aeromagnetic anomaly data set acquired in 1993 by the Spanish National Geographic Institute in order to obtain a structural model of the island from a magnetic point of view. A digital elevation model of the volcanic edifice was divided into a mesh of prismatic cells, each of them with a top corresponding to the topographic height (or bathymetric depth in the marine area) and a bottom at a constant depth of 4000 m below sea level. A three-dimensional (3-D) inversion algorithm and forward modelling along representative profiles provided us with a magnetization distribution containing valuable information about the inner structure of the island. The magnetic model cast new light on the rift structure of El Hierro. In particular, high magnetization values have been mainly interpreted as intrusive complexes on which rift zones are rooted. Their location confirms the hypothesis of a complex rift structure in the marine area. The inverse magnetization that characterizes the NE submarine rift area implies that this part of the volcanic edifice formed during the Matuyama and, therefore, predates the NW submarine rift zone, which is normally magnetized. The N–S rift zone extending southwards from the island seems to be shifted to the west with respect to the bathymetric high in this area. This result suggests that the original rift zone was located in the area where the highest magnetizations presently occur so that the present morphology may reflect the westward collapse of the original ridge. In addition, very low magnetizations characterize the areas affected by giant landslides, indicating that magnetic anomalies can provide important constraints on the distribution of these catastrophic events.

Key words: Inverse theory; Magnetic anomalies: modelling and interpretation; Oceanic hotspots and intraplate volcanism; Crustal structure; Atlantic Ocean.

1 INTRODUCTION

Ocean island volcanoes start their history as seamounts. During this early stage, they grow as a body of pillow lava, until eruptions become sufficiently shallow for gas expansion to lead to fragmentation of the lava (e.g. Jones 1966; Staudigel & Schmincke 1984). The proportion between pillow lavas and fragmental debris (hyaloclastites) in the bulk volume of oceanic islands is a matter of debate (e.g. Moore & Chadwick 1995; Garcia & Davis 2001).

After the formation of the seamount, the subaerial evolution of an ocean island continues through the shield stage, which consists of the outpouring of large amounts of basaltic magma, mainly through fissure eruptions. Generally, materials emplaced during this phase

represent about 90 per cent of the subaerial volume of the ocean island. The growth of the volcanic edifice in this stage usually develops along rift zones (MacDonald 1949; Fiske & Jackson 1972) and is accompanied by the intrusion of mafic dykes or sheets which make up coherent intrusion complexes (Walker 1986, 1987, 1992). The term ‘coherent’ was chosen by Walker (1992) to illustrate the high degree of parallelism and the high intrusion density (more than the 40 per cent and up to the 70 per cent of the bulk rock volume), which falls rapidly to near zero at the margins of the complexes. Knowledge about these intrusion complexes is crucial because they play a key role in volcano development. In fact, the structure of rift zones seems to control the stability of the volcanic edifice, and therefore, the occurrence of major collapses (Carracedo 1994; Carracedo

1999; Walker 1999; Walter *et al.* 2005). In the Canary Islands, the importance of giant landslides as major destructive processes in the evolution of the islands has been recently recognized after the identification of at least 14 such events (e.g. Watss & Masson 1995; Urgeles *et al.* 1997; Carracedo *et al.* 1999; Ablay & Hürlimann 2000; Gee *et al.* 2001a; Krastel *et al.* 2001; Masson *et al.* 2002).

Volcanic areas typically involve rocks with high magnetic mineral content that yield very intense magnetic anomalies. Thus, the internal structure of a volcanic edifice can be investigated from its magnetic anomaly pattern for new insights on its evolution (e.g. Hildenbrand *et al.* 1993; Lénat *et al.* 2001). Magnetic studies carried out on the Canary Islands of Tenerife (Blanco-Montenegro 1997; Araña *et al.* 2000), Gran Canaria (Blanco-Montenegro *et al.* 2003) and Lanzarote (Blanco-Montenegro *et al.* 2005) interpreted the sources of the most intense anomalies as intrusive bodies emplaced during the early stage of growth of the islands (mafic core) and the feeding system of the subaerial volcanism.

Airborne surveys are especially effective for mapping the spectrum of magnetic signals from both the emerged and submerged portions of the volcanic edifice. These signals include the higher resolution effects mapped at a few hundred metres above the topographic surface from structures buried at shallow depths beneath the volcanic edifice (e.g. Blanco-Montenegro *et al.* 2007) to the lower resolution effects acquired at more than a kilometre from the terrain from deep intrusive bodies (e.g. Blanco-Montenegro *et al.* 2005).

El Hierro is the youngest of the Canary Islands, and is located on the westernmost edge of the archipelago (Fig. 1). The subaerial part of the island includes three convergent ridges that have been interpreted for a triple-arm rift system (Fúster *et al.* 1993; Carracedo 1994; Münn *et al.* 2006). These ridges are separated by wide, horse-shoe embayments, related to the occurrence of at least four giant landslides (Holcomb & Searle 1991; Masson 1996; Urgeles *et al.* 1997; Carracedo *et al.* 1999; Gee *et al.* 2001a; Masson *et al.* 2002). The combined volume of these collapses is more than 400 km³ and considerably exceeds the island's present subaerial volume of about 140 km³ (Carracedo *et al.* 1999; Gee *et al.* 2001a).

An aeromagnetic survey carried out by the Spanish National Geographic Institute in 1993 in the Canary Islands (Socías & Mézcua 1996) revealed a dipolar magnetic anomaly over El Hierro. From this anomaly, Nicolosi *et al.* (2006) found the island's principal magnetization direction ($D = 13^\circ$, $I = 40^\circ$) using an equivalent source approach. In this paper, we focus on modelling and interpreting the magnetic anomalies of El Hierro with the goal of further characterizing the island's volcanic rift zones.

2 GEOLOGICAL SETTING

The Canary Islands are a group of volcanic ocean islands located in the eastern central Atlantic near the African coast (Fig. 1a).

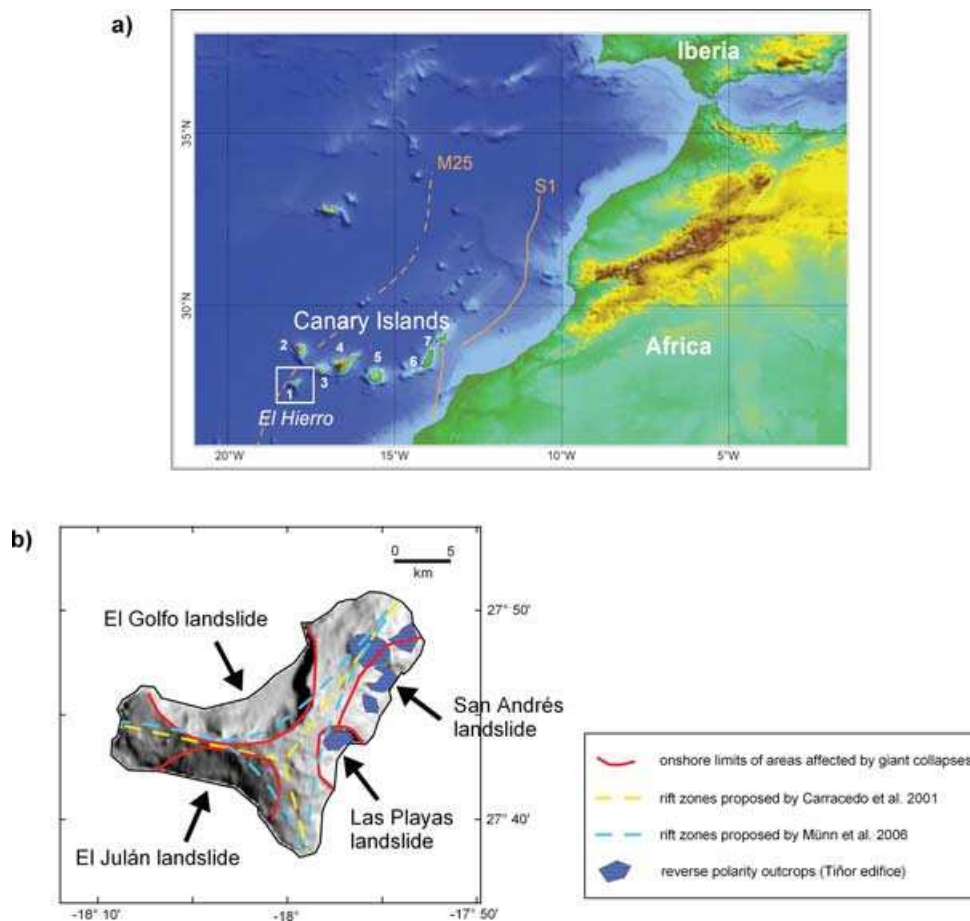


Figure 1. (a) Location of the Canary Islands, showing the position of El Hierro inside the archipelago (1 = El Hierro, 2 = La Palma, 3 = Gomera, 4 = Tenerife, 5 = Gran Canaria, 6 = Fuerteventura, 7 = Lanzarote). Marine magnetic anomalies S1 and M25 are also displayed (from Verhoef *et al.* 1991); (b) shaded relief model of El Hierro, showing: (1) the areas affected by the giant collapses mentioned in the text, (2) the subaerial triple-arm rift system proposed by different authors and (3) the reversely magnetized outcrops ascribed to the Tiñor volcanic phase (from Carracedo *et al.* 2001).

Volcanism in this area is related to a sheet-like mantle plume extending from the eastern Atlantic Ocean to central Europe, recently discovered by means of seismic tomography (Hoernle *et al.* 1995; Oyarzun *et al.* 1997; Montelli *et al.* 2004). The origin of these islands has been the subject of intense debate, since they present some characteristics that differ from classical examples of intraplate, hotspot volcanism (e.g. long-lived magmatism, absence of significant subsidence). An up-to-date review of the different proposed theories can be found in Anguita & Hernán (2000).

The islands were constructed on very old oceanic crust (150–180 Ma) ascribed to the so-called Jurassic Magnetic Quiet Zone, near the western African passive continental margin. The archipelago is bounded by anomalies S1 to the east and M25 to the west (Verhoef *et al.* 1991; Roest *et al.* 1992), with only the island of La Palma slightly shifted out of these limits (Fig. 1a). It is worth noting that the location of anomaly M25 is questionable because of its very small amplitude (Verhoef *et al.* 1991) which, in the vicinity of the Canaries, is indeed masked by the strong magnetic signal of the volcanic edifices. Volcanism seems to have started in the Upper Cretaceous in the easternmost islands (Le Bas *et al.* 1986; Blanco-Montenegro *et al.* 2005), which emerged above sea level in the Miocene. Radiometric dating reveals a rough east-to-west age progression for early subaerial activity, from about 20 Ma for Lanzarote and Fuerteventura (Coello *et al.* 1992) to 15 Ma for Gran Canaria (McDougall & Schmincke 1976), 12 Ma for Tenerife (Guillou *et al.* 2004), 11 for La Gomera (Ancochea *et al.* 2006), 2 Ma for La Palma (Ancochea *et al.* 1993) and 1.1 for El Hierro (Guillou *et al.* 1996).

The different stages of evolution of oceanic volcanic islands pointed out for Hawaii by Walker (1990) (submarine, followed by shield-building, declining, erosive and rejuvenation stages) can be also recognized in the Canaries: Fuerteventura, Lanzarote, Gran Canaria and Tenerife are at present in the post-erosional stage, while La Gomera is in the erosional phase and La Palma and El Hierro in the shield-building one (Carracedo *et al.* 2002).

El Hierro is the westernmost and youngest of the Canary Islands (Fig. 1b). The volcanic edifice rises 5500 m from the seafloor, located at about 4000 m depth. The emerged part of the island was built in the last 1.12 Ma during the upper Matuyama and the Brunhes chrons (Guillou *et al.* 1996). The present-day island of El Hierro is a fraction of the three successive volcanoes accreted onto earlier, partially destroyed edifices. The present subaerial volume is probably less than a third of the total volcanic products erupted (Carracedo *et al.* 2001). Its subaerial ‘stellate’ geometry has been interpreted as a classic case of a triple-armed rift system (Fig. 1b), where updoming magma produced least-effort fractures intersecting at angles of 120° (Fúster *et al.* 1993; Carracedo 1994). However, Münn *et al.* (2006) proposed that this rift configuration is due to gravitational spreading over deformable basal substrata. Thus, the characteristic ‘stellate’ morphology, typical of many oceanic seamounts and islands, resulted from concentrated volcanic activity along radiating rifts fed from central vents, where each rift is associated with the injection of dyke swarms and the building of a linear ridge (MacDonald 1949; Fiske & Jackson 1972). Nevertheless, an interpretation based only on the emerged part of the island is overly simplistic and may not account for the much larger submarine components. In fact, the high-resolution bathymetry data of El Hierro revealed wide areas of irregular morphology, mainly to the NE and NW, suggesting that the rifting may be more widespread beyond the narrow emerged zones of the island (Gee *et al.* 2001b). These authors also proposed that the anomalously long and steep-flanked Southern Ridge is part of an old and eroded volcanic edifice that evolved independently from the rest of El Hierro.

Radiometric dating and magnetic stratigraphy have allowed a precise reconstruction of the volcanic evolution of the emerged part of El Hierro (Guillou *et al.* 1996; Carracedo *et al.* 2001). Three main subaerial volcanic phases have been recognized: (i) the Tiñor volcano, (ii) the El Golfo edifice and (iii) rift volcanism. The Tiñor volcano, outcropping on the NE flank of the island, was the first stage of subaerial growth of El Hierro, between 1.12 and 0.88 Ma. Three subunits with distinct magnetozones reflect this volcano’s construction. The first is a basal unit of relatively thin, steeply dipping flows emplaced during the Matuyama pre-Jaramillo reverse polarity chron. The second is an intermediate unit of thicker lavas erupted during the Jaramillo normal polarity subchron that progressively trend to subhorizontal flows in the centre of the edifice and fill canyons on the flanks. The third is the Ventejís volcano group of emission vents emplaced the Matuyama post-Jaramillo reverse polarity chron. The Ventejís eruptions, with wide, well-preserved craters and lavas occupying valleys and canyons carved into older rocks, may have been the terminal explosive stage immediately preceding the collapse of the NW flank of Tiñor volcano. This collapse, which occurred at about 882 ka, was the first of the island’s giant landslides. It may have removed more than half of the volume of the subaerial part of the Tiñor edifice.

A new volcanic edifice, known as El Golfo, developed after the Tiñor landslide, between 545 and 176 ka, filled the NW-facing collapse embayment and spilled lava towards the E coast overlying the Tiñor volcano. El Golfo volcano developed entirely in the Brunhes period, and formed the bulk of El Hierro. It includes a lower basal unit composed mainly of strombolian and surtseyan pyroclastics with subordinate lava flows, and an upper unit composed predominantly of lava flows. The lower unit is cut by numerous dykes forming NE-, ESE- and WNW-trending swarms that match the present volcanic vent system and indicate that a triple rift system was an important feature of El Golfo edifice. The upper El Golfo unit is topped by several differentiated volcanics (trachybasalts and trachytes).

The rift volcanism is defined as the late stage of growth of the island, with simultaneous activity of all three rift arms. Materials from this phase were erupted from vents distributed all over the island and are represented by a thin layer of basic lavas, some of them filling the El Julán embayment and part of the El Golfo embayment. Activity continues through present times with moderate eruptive rates. The last eruption (Lomo Negro) may have taken place in 1793 within the northwestern rift zone (Hernández-Pacheco 1982).

Besides the Tiñor collapse, at least four other giant landslides have dismantled the island (Fig. 1b). The El Julán landslide took place at least 200 kyr ago, removing about 130 km³ of material of the SW flank of El Golfo edifice (Holcomb & Searle 1991; Gee *et al.* 2001a). In addition, the El Golfo collapse removed between 150 and 180 km³ of volcanic products from the NW flank of the volcanic edifice. This is the best known of the Canary Island landslides (Holcomb & Searle 1991; Masson 1996; Urgeles *et al.* 1997; Gee *et al.* 2001a; Masson *et al.* 2002), although its age is a matter of debate. Evidence from the offshore island flank indicates an age of about 15 ka (Masson 1996); however, onshore data suggest a much greater age, in the range 100–130 ka. This apparent contradiction has been overcome with the hypothesis of a two-phase collapse (Carracedo *et al.* 1999; Carracedo *et al.* 2001). The most recently discovered flank failures are two much smaller volume events on the eastern flank of the island. Day *et al.* (1997) initially interpreted the San Andrés normal fault system outcropping on the eastern flank of El Hierro as evidence for an aborted giant flank collapse. However, new offshore data proved the existence of debris deposits related to

two landslides in this area: the San Andres collapse (also named Las Playas II), with an estimated age between 176 and 250 ka, and the Las Playas collapse (also named Las Playas I), dated at 145–176 ka (Gee *et al.* 2001a; Masson *et al.* 2002).

3 MAGNETIC DATA AND MODELLING

3.1 Magnetic data

In 1993 October the Spanish National Geographic Institute carried out an aeromagnetic survey of the Canary Islands. The region was divided in seven blocks which were flown at different altitudes and with different spatial resolution. The details of the survey as well as of the data processing can be found mainly in Socías & Mézcua (1996) as well as in Blanco-Montenegro *et al.* (2003). Over El Hierro Island and offshore, the survey altitude was 2000 m, with main survey lines flown N–S with a separation of 5000 m between lines. In addition, tie-lines were flown E–W with a separation of 20000 m between lines. External field variations were corrected using two base stations deployed at Tenerife and Lanzarote. The main field was removed from the data using the 1995 version of the IGRF (IAGA 1995). The data were levelled and interpolated into a regular grid using the method of Akima (1970).

For this study, we used the 2 km-cell magnetic anomaly grid of the whole Canary region upward continued to 3800 m, which is just above the Teide peak in Tenerife that is the highest point of the archipelago. From this grid, we have extracted the magnetic anomaly map of El Hierro shown in Fig. 2 for analysis. We obtained a

magnetic model of the internal structure of El Hierro using anomaly interpretative techniques described in the three sections that follow below.

3.2 Reduction to the pole

Reduction to the pole is a useful transformation that converts a magnetic anomaly map into its equivalent at the geomagnetic pole, where the inducing field is vertical (Baranov & Naudy 1964). Therefore, in the transformed map the spatial correlation between an anomaly and its source body becomes more straightforward than in the general case of an inclined magnetic field and magnetization. For this reason, reduction to the pole is a common strategy in magnetic interpretation.

Most reduction-to-the-pole algorithms assume that both the ambient magnetic field and the magnetization have constant directions along the studied area, which must be known in advance. In the case of El Hierro, we used the main magnetic field direction given by the IGRF at the time of the survey ($D = -10^\circ$, $I = 40^\circ$) whereas for the magnetization we used the value obtained by Nicolosi *et al.* (2006) through the analysis of the main magnetic anomaly ($D = 13^\circ$, $I = 40^\circ$). The reduced-to-the-pole magnetic anomaly map of El Hierro is shown in Fig. 3.

3.3 3-D inversion

The magnetic anomaly pattern of El Hierro (Fig. 2) is characterized by an intense normal dipolar anomaly that overlies the island.

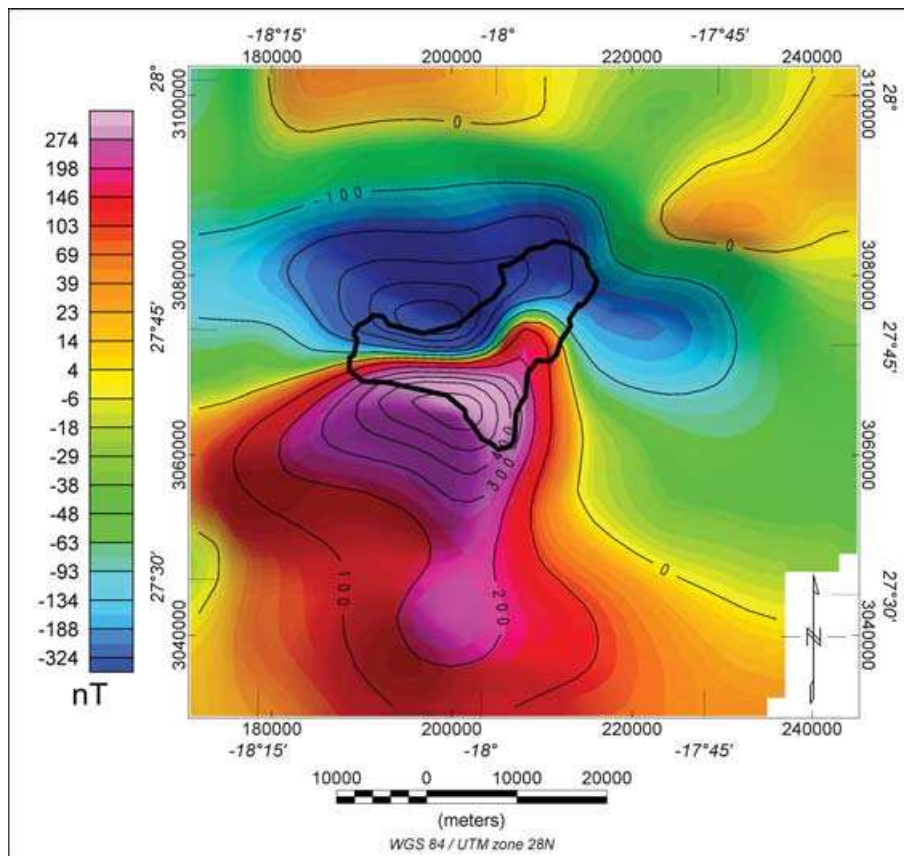


Figure 2. Aeromagnetic anomaly map of El Hierro. Two main anomalies can be easily identified: an intense normal dipole over the island and a much weaker reverse dipole in the marine area to the northeast of the island. Coordinates correspond to the Universal Transverse Mercator projection (zone 28N).

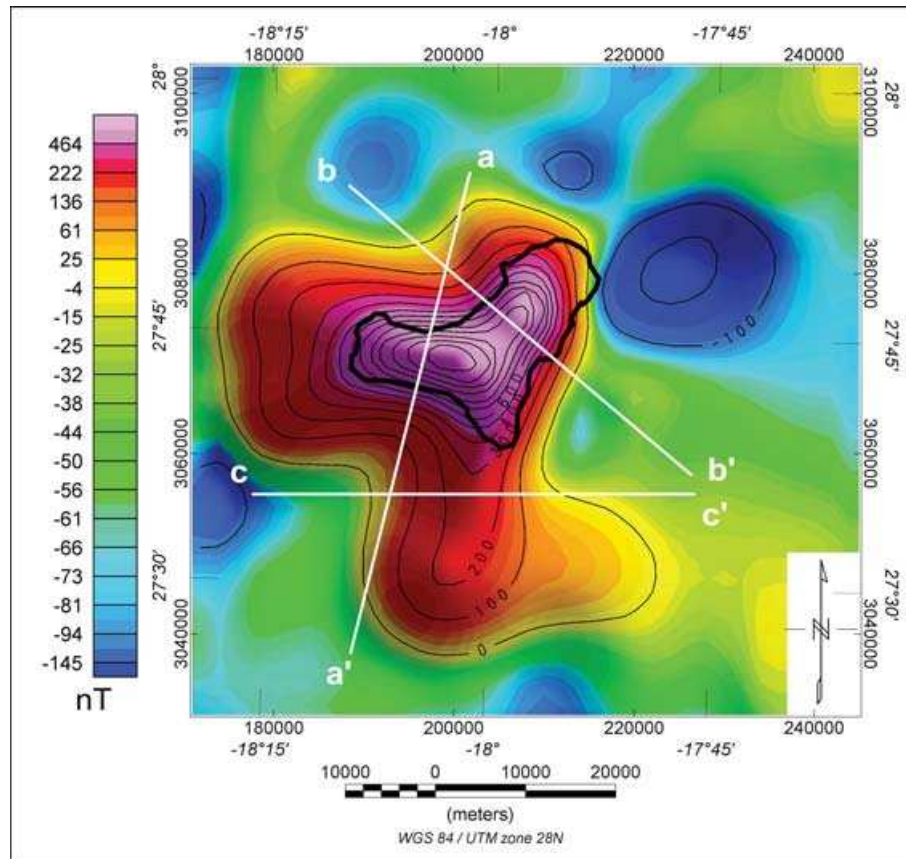


Figure 3. Reduced-to-the-pole aeromagnetic anomaly map of El Hierro, calculated using the magnetization direction obtained through the analysis of the main dipolar anomaly ($D = 13^\circ$, $I = 40^\circ$) (Nicolosi *et al.* 2006). The three profiles used for the forward modelling are also shown. Coordinates correspond to the Universal Transverse Mercator projection (zone 28N).

Offshore to the east a much weaker inverse dipolar anomaly is also evident. In the reduced-to-the-pole map (Fig. 3), these anomalies appear as a magnetic high over the island and a magnetic low over the northeastern submarine edifice. We designed a modelling strategy aimed at investigating whether the observed anomaly could be explained by uniformly magnetized topography or whether, on the contrary, lateral magnetization contrasts are present inside the volume of the volcano. We chose to approach this modelling through inversion.

Magnetic inversion is limited by the non-uniqueness inherent to potential fields, where an infinite number of magnetization distributions can reproduce an observed magnetic anomaly field (see, for instance, Blakely 1995). In particular, it is especially difficult to obtain the depth to the sources and, therefore, to identify horizontal magnetic contacts. Considerable efforts have been made in recent years to overcome this difficulty (e.g. Li & Oldenburg 1996; Fedi & Rapolla 1999; Pignatelli *et al.* 2006; Caratori Tontini *et al.* 2006). However, the location of lateral magnetization contrasts can be achieved quite easily through inversion.

Let us consider a continuous distribution of magnetization $\mathbf{J}(\mathbf{r})$ inside a source volume V , with a constant direction given by the unit vector \mathbf{t} . The magnetic anomaly ΔT measured at the position \mathbf{r}' outside the volume V is given by:

$$\Delta T(\mathbf{r}') = \frac{\partial^2}{\partial f \partial t} \int_V \frac{J(\mathbf{r})}{|\mathbf{r} - \mathbf{r}'|} dv, \quad (1)$$

where \mathbf{f} is the unit vector along the ambient magnetic field direction. If the source volume is divided into a set of N homogeneous

prismatic subvolumes, and the magnetic anomaly is measured at a discrete set of M points, then eq. (1) can be rewritten as:

$$\Delta T_m = \sum_{i=1}^N G_{i,m} J(\mathbf{r}_i) \quad m = 1, M, \quad (2)$$

where

$$G_{i,m} = \frac{\partial^2}{\partial f \partial t} \int_V \frac{1}{|\mathbf{r}_i - \mathbf{r}_m|} dv,$$

$J(\mathbf{r}_i)$ is the magnetization of the subvolume V_i , and ΔT_m is the magnetic anomaly measured at station m . The kernel $G_{i,m}$ represents the magnetic anomaly at station m due to the subvolume V_i with unit magnetization along direction \mathbf{t} .

In matrix form, eq. (2) becomes

$$\mathbf{T} = \hat{G}\mathbf{J}, \quad (3)$$

where \mathbf{T} is the M -vector of magnetic data, \mathbf{J} is the N -vector of magnetizations and \hat{G} is the $M \times N$ kernel with elements that were determined using the magnetic effect for the rectangular prism from Sharma (1986).

The estimation of the source magnetization, \mathbf{J} , can be achieved by solving the linear system reported in eq. (3). In general, systems of this kind are underdetermined and overconstrained, and their solution must be found by means of numerical techniques (Jackson 1972; Press *et al.* 1992).

In the case of El Hierro, we have considered a source volume made up of a single layer of $3 \text{ km} \times 3 \text{ km}$ prismatic cells, each

of them with a top corresponding to the topographic height (or bathymetric depth, in the marine area) and a bottom at the constant depth of 4000 m, which is approximately the depth of the seafloor in the area surrounding the island. For the digital terrain model, we used the SRTM data (<ftp://e0srp01u.ecc.nasa.gov>) for topography and the global 2-min bathymetry grid (http://topex.ucsd.edu/WWW_html/mar_topo.html) from Smith & Sandwell (1997), as well as the results from Gee *et al.* (2001b).

We assumed that all cells were magnetized with $D = -13^\circ$ and $I = 40^\circ$, which is the direction that characterizes the total magnetization vector of the main magnetic source and, therefore, can be considered representative of the volcanic edifice as a whole (Nicolosi *et al.* 2006).

The magnetization distribution obtained through the described inversion process is shown in Fig. 4. These results clearly suggest strong lateral contrasts in magnetization intensity within the volcanic edifice of El Hierro. However, this approach cannot constrain the vertical extension of the magnetic sources because the inversion assumed each cell to be homogeneously magnetized from the topographic top to the bottom at 4 km b.s.l. Further modelling is necessary, as described in the next section, to investigate possible depth extents of these magnetization contrasts.

3.4 Forward modelling

To resolve possible depth attributes for the magnetization variations in Fig. 4, we modelled the magnetic crust along the three profiles crossing the main rift zones (see Fig. 3). Fig. 5 gives the results from 2.75-D forward modelling of the reduced-to-the-pole magnetic anomalies. For the modelling, we used the algorithm proposed by Won & Bevis (1987) based on the analytical expressions from Talwani & Heirtzler (1964) and Rasmussen & Pedersen (1979).

We considered all the crust to be magnetic, which is to say that magnetic sources are present down to about 15 km b.s.l., the estimated Moho depth in this area (Bosshard & MacFarlane 1970; Watts 1994). It is obvious, however, that most of the magnetic signal is due to structures located within the upper few kilometres of the crust.

We assumed that the volcanic edifice extends from the surface down to a depth of 4 km b.s.l. which is roughly the depth of the seafloor around El Hierro. The total magnetization assigned to the volcanic edifice (3 A m^{-1}) is an average value based on the available paleomagnetic results (Watkins 1973; Abdel-Monem *et al.* 1972; Guillou *et al.* 1996). Beneath the volcanic products of El Hierro, we included an 11-km-thick oceanic crust with the bulk normal magnetization of 2 A m^{-1} that agrees with magnetization models of the Jurassic crust (e.g. Hayling & Harrison 1986).

In areas where debris deposits have been identified and related to giant flank collapses, we considered the presence of weakly magnetized materials overlying the lava piles of the volcanic edifice. These layers are several hundred metres thick, in accordance with the results of Gee *et al.* (2001a). The low magnetization value assigned to these structures (0.5 A m^{-1}) is related to the fact that only the induced component of the magnetization vector is expected to contribute to the magnetic anomaly pattern, since the volcanoclastic nature of these deposits leads to a chaotic distribution of remanence within them.

The lateral geometries of the intrusive complexes, which are the main sources of the anomalies, are based on the magnetization distribution of Fig. 4. We extended these bodies to the crust–mantle boundary, since volcanic activity in El Hierro has been fed by a deep magmatic source during its entire history and evidence of shal-

low magma chambers is lacking (Carracedo *et al.* 2001). The total magnetization intensity contrasts for the intrusive complexes of the different rift zones were obtained by fitting the observed anomalies. However, magnetization intensities must not be interpreted in absolute terms, since it is clear that assuming a smaller vertical extension for the anomalous structures would lead to higher magnetization values.

4 INTERPRETATION AND DISCUSSION

In Fig. 4 we show the magnetization distribution obtained through the described inversion procedure that neglects the horizontal magnetization contrasts that could be present inside the volume of the volcanic edifice. We can interpret the magnetization at each node of the grid as a value representative of the volume of the cell beneath, and as an average of the actual magnetization along the vertical direction.

If the homogeneous topography were the source of the observed anomaly pattern, then the inversion would produce an almost constant magnetization distribution. However, the results shown in Fig. 4 demonstrate that intense lateral magnetization contrasts are present within the volcanic edifice. It is worth mentioning that, using a forward approach, we also verified that a uniformly magnetized terrain cannot account for the observed magnetic anomalies of El Hierro.

As was mentioned in Section 1, oceanic volcanic islands in their early growth stages evolve along rift zones rooted in intrusive complexes of dyke clusters. Given the intense magnetizations that usually characterize volcanic dykes and their vertical extensions, we expect these intrusion complexes to be sources of intense magnetic anomalies. In particular, the geometry of these structures causes the magnetization contrasts between them and the surrounding bedrock (i.e. piles of lava flows and hyaloclastites) to occur across nearly vertical boundaries that our inversion can readily image. Thus, the results of our magnetic inversion suggest that deep intrusive complexes are present within El Hierro and that they are more intensely magnetized than the surrounding lavas. In Fig. 4(a), we identified with capital letters the most noteworthy magnetic sources in order to discuss their origin from a volcanological point of view. In addition, we plotted in bold dashed lines the rift zones through El Hierro from Carracedo *et al.* (2001), Gee *et al.* (2001b) and Münn *et al.* (2006) to investigate their possible correlations with the magnetic sources.

It is interesting to mention the striking correlation among the lowest magnetization values and the areas affected by landsliding (see Figs 1b and 4). In these areas, an important volume of volcanoclastic material is present resulting from the different flank collapses of the volcanic edifice. The chaotic distribution of volcanic debris from the flank collapses of the volcanic edifice broke up remanent magnetization. Thus, only the relatively weak induced component survives to produce the low magnetic signals of the landslides. This fact, as well as a low density in comparison with the surrounding massive volcanic structures (dykes, lava flows), would explain the low magnetic signal associated with landslides. In the forward models shown in Fig. 5 we have included several hundred metres of thick debris deposits overlying the volcanic edifice that reproduce the observed magnetic anomalies.

In the subaerial part of the island, the highest magnetization values correspond to the E–W rift zone (structure A in Fig. 4, see also profile aa' in Fig. 5). This strongly magnetized structure exhibits a linear geometry with the same strike as the rift. We can therefore, relate this source to the dyke system that fed the activity of El Golfo

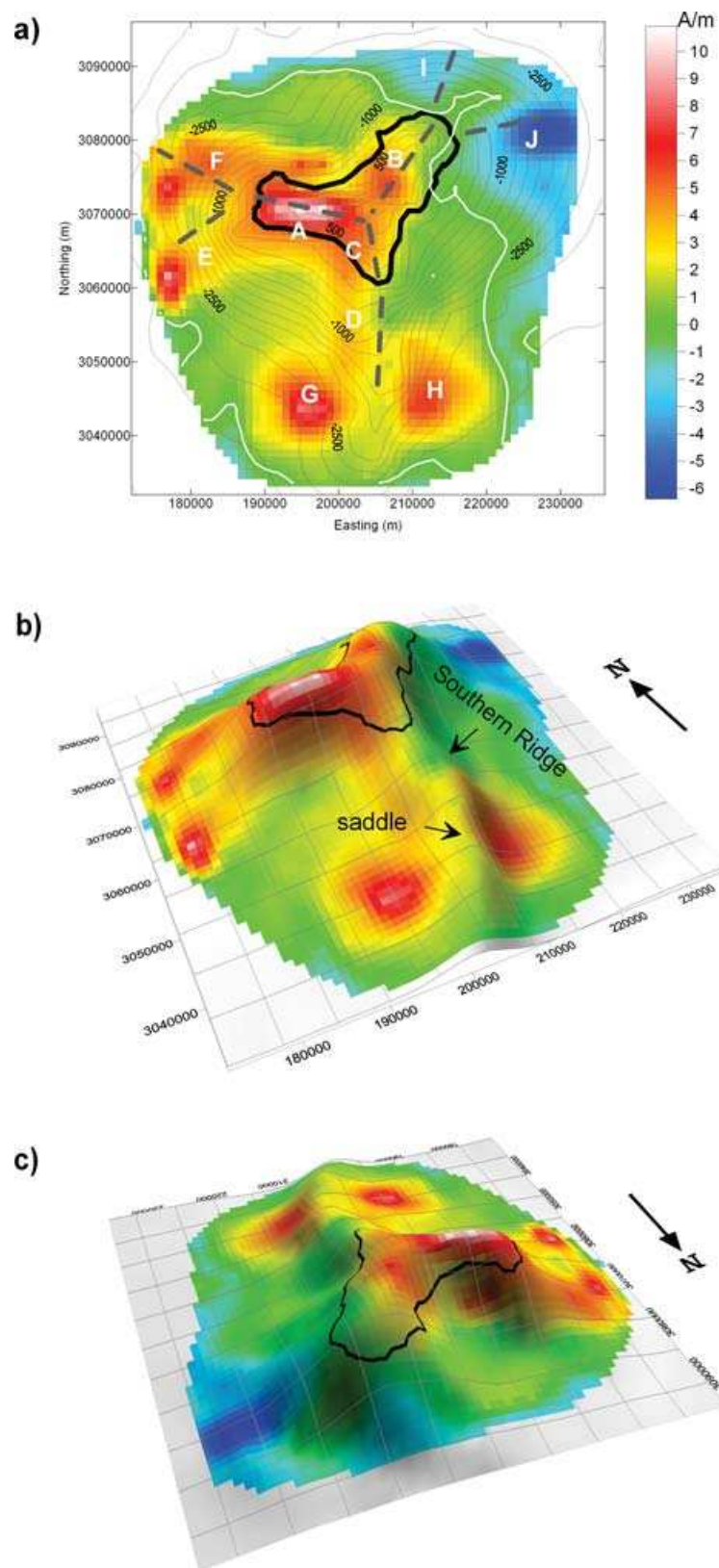


Figure 4. Magnetization distribution obtained through 3-D inversion of the magnetic anomalies of El Hierro on the topographic slab. For the sake of clarity, we have interpolated the results of the inversion onto a 1-km cell grid: (a) the areas of interest discussed in the text are identified with capital letters. The dashed grey lines show the rift zones in both the subaerial (Carracedo 1994) and submarine parts of the island (Gee *et al.* 2001b). Black contours correspond to bathymetric depths and topographic heights, with labels in metres. The white line shows the zero-magnetization contour; (b) and (c) 3-D plots of the magnetization distribution, where the magnetization grid has been superimposed onto the 3-D model of the terrain used for the inversion. Coordinates correspond to the Universal Transverse Mercator projection (zone 28N).

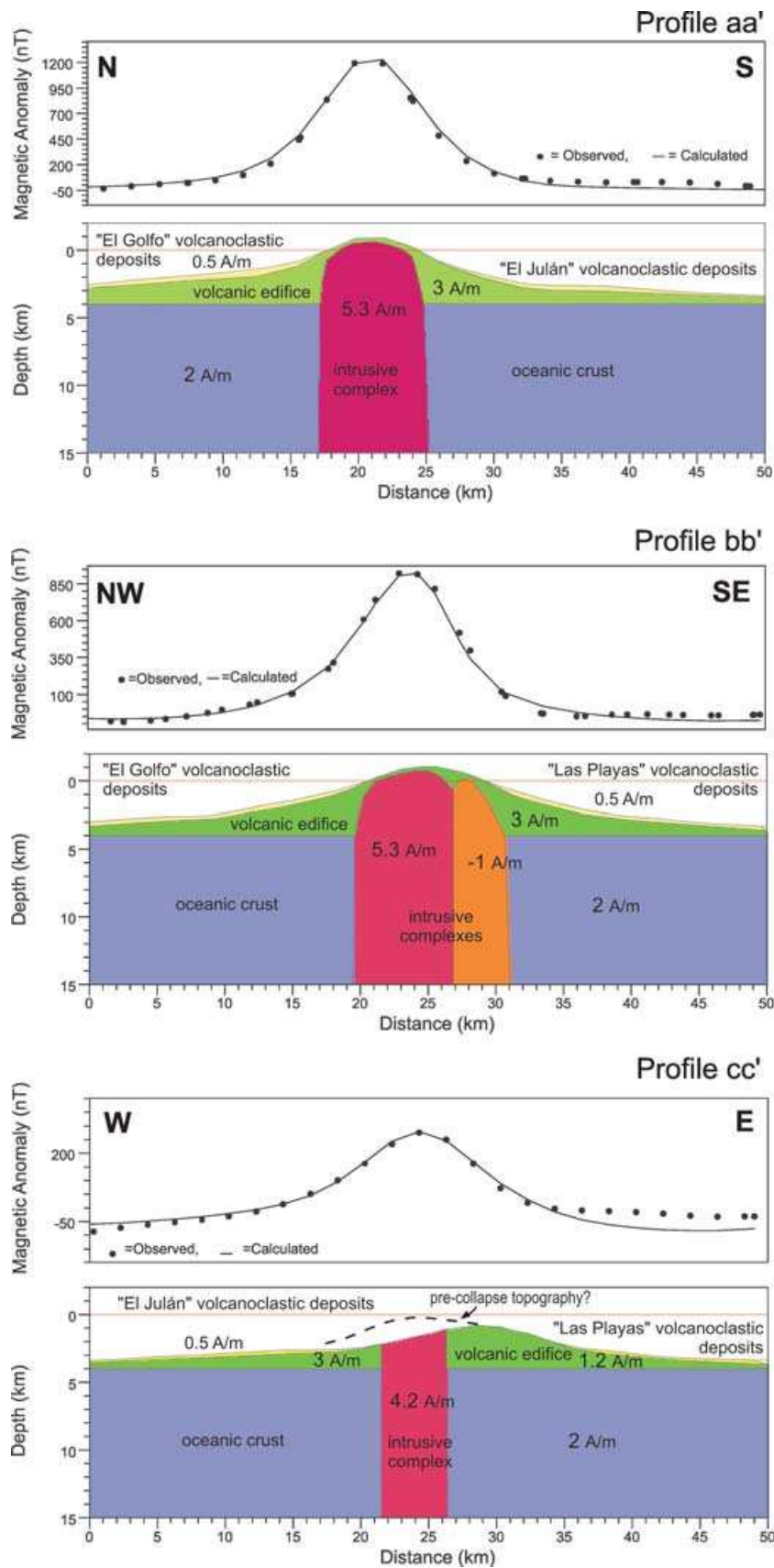


Figure 5. Forward models along the three profiles (aa', bb' and cc') shown in Fig. 3 that cross the main rift zones of El Hierro. The total magnetization values that characterize each body are shown (a negative sign indicates reverse polarity).

volcano. This edifice represents, from the volumetrical point of view, the most important stage of activity of El Hierro, so it is reasonable that the intrusive complex beneath this rift zone contain the largest dyke concentration in the island, a situation that would explain the high magnetization values obtained in the model.

Contrary to the E–W rift zone, the NE subaerial rift is not related to an elongate magnetized structure. Instead, a magnetization high in the area (structure B in Fig. 4) is truncated by an almost N–S discontinuity, to the east of which the magnetization intensity decreases considerably. Indeed, the zero-magnetization contour suggests the presence of reversely magnetized structures in the eastern part of this area. This result is strongly consistent with the magnetostratigraphic models that place the initial formation of the Tiñor edifice in the reverse polarity upper Matuyama as shown in Fig. 1(b) (Guillou *et al.* 1996; Carracedo *et al.* 2001). The superposition of reversely and normally magnetized structures in the eastern part of El Hierro may then mask the linear magnetic effects of the intrusive complex underlying the rift. Structure B of Fig. 4 probably represents the feeding system of the latest stage in the formation of the eastern rift, magnetized during the Brunhes chron.

One possible model that accounts for the observed anomalies along profile bb' is that proposed in Fig. 5, in which two adjacent vertical bodies, normally and reversely magnetized respectively, are present beneath the eastern part of the island. These structures may reflect normally and reversely magnetized intrusive complexes emplaced during the formation of El Golfo and Tiñor edifices, respectively. The low negative magnetization intensity contrast required to fit Tiñor anomalies may account for the likely presence of both reversely and normally magnetized dykes within this intrusive complex, since the Tiñor chronology include the reverse polarity Matuyama chron and the normal polarity Jaramillo subchron (Guillou *et al.* 1996; Carracedo *et al.* 2001). This intrusive complex would extend towards the northeast where most of the Matuyama components of the Tiñor edifice developed.

The third arm of the subaerial rift is essentially oriented N–S and includes the magnetization contrast labelled C in the southern part of the island that probably also represents an intrusion complex that extends to the south seaward. However, this high intensity magnetization is offset west of the rift zone axis proposed by Carracedo *et al.* (2001) and Münn *et al.* (2006). This disagreement suggests the limitations of deducing the subsurface properties of a rift zone only from outcropping dykes, cone alignments, topographic ridges and other shallow crustal evidence.

In the offshore areas west of El Hierro, two divergent, approximately linear magnetized structures labelled E and F are evident in Fig. 4. These results are strikingly consistent with high-resolution bathymetric data that suggest the seaward bifurcation of the onshore rift zones along NE and SW trends (Gee *et al.* 2001b). However, the magnetic inversion results put the rift axis E slightly south of the bathymetrically constrained axis proposed by Gee *et al.* (2001b). To the end of the two rifts the magnetic model of Fig. 4 reveals the presence of highly magnetized areas that could represent lava flows associated with the rift activity. Gee *et al.* 2001b identified two bathymetric features in this area that they interpreted as lobes of ponded lava (see also fig. 1b of Mitchell *et al.* 2003).

The magnetic structure on the NE flank also agrees with the idea of two separate rift zones (labelled I and J in Fig. 4). In this case, however, the submarine rifts appear to be characterized by a negative magnetization value, providing us with very valuable information about their age. Gee *et al.* (2001b) claimed that the similar morphological features of the NW and NE ridges might indicate a similar age and origin, although they recognized that no other data supported

this conclusion. Our magnetic data prove that the NE rifts were formed in a period of reverse polarity of the Earth's magnetic field, while the NW rifts formed during a normal polarity chron. Taking into account the magnetic stratigraphy of El Hierro of Guillou *et al.* (1996), it seems likely that the NE submarine rifts formed during the Matuyama chron, thus predating the emplacement of the NW rifts, which probably took place in the Brunhes chron. Indeed, the oldest reversely magnetized materials of El Hierro (Tiñor edifice), which acquired their remanence during the upper part of the Matuyama, outcrop near this area (see Fig. 1b). The fact that anomaly J has a non-linear morphology might indicate that, in addition to the dyke system underlying the rift, its source could be also related to a pile of submarine lava flows pertaining to the Tiñor edifice. In fact, Mitchell *et al.* (2002) identified some terraces of lava in this area.

The low positive magnetizations displayed in the central zone of the northeastern submarine edifice, between areas I and J, is similar to the magnetizations obtained over the areas affected by the giant collapses of El Golfo, El Julán y Las Playas (Fig. 1). This could suggest that the area between rift zones I and J may also have experienced a landslide, a result that is in accordance with its smooth bathymetry (Mitchell 2007, personal communication).

In the area of the southern ridge, and as an extension of zone C in Fig. 4, we see a linear zone of high magnetization values (zone D) that is shifted to the west with respect to the ridge itself and to the rift zone axis proposed by Gee *et al.* (2001b). This is also evident in the reduced-to-the-pole magnetic anomaly map (Fig. 3), and cannot be explained in terms of the IGRF-induced magnetization or the magnetic remanence that we assumed for the inversion.

Furthermore, we have downloaded some marine magnetic profiles of the US National Geophysical Data Center (NGDC) GEODAS database (<http://www.ngdc.noaa.gov/mgg/geodas/geodas.html>) to verify the location of the magnetic high in the area of the southern ridge. Three surveys (TAG711DO, V2908 and DSDP46GC) carried out in the 1970s acquired magnetic data along tracks that included profiles to the south of El Hierro traversing the southern ridge. In all of them there appears a clear magnetic high shifted to the west with respect to the ridge axis that confirms the location of the aeromagnetic high.

This result suggests that the bathymetric ridge is offset to the east of the main intrusion complex underlying the rift zone as inferred by the modelling in Fig. 5. Thus, the feeding system of the southern ridge is probably located west of the bathymetric high that may be largely the consequence of the massive landslides in this area. Gee *et al.* (2001b) also noted that 'some parts of the Southern Ridge north of 27°30'N may have been affected by landsliding, although the exact boundaries are unclear.' Therefore, magnetic data interpretation might provide with fresh evidence on this point.

To the south of the rift, and at both sides of it, the model shows two strongly magnetized structures (G and H in Fig. 4), which could be interpreted as lava piles that flowed from the ridge.

Gee *et al.* (2001b) identified a saddle in the southern ridge, at a distance of about 15 km from the coastline, that divides it into two parts with different morphological characteristics (see Fig. 4b). They also proposed that the southern ridge south of the saddle is a structure older than the other submarine rift zones. The magnetic model shown in Fig. 4 clearly reveals the different natures of the northern and the southern parts, showing that to the south of the saddle the ridge is almost demagnetized, although unfortunately our magnetic data do not cover its complete extension.

This low normal magnetization could be explained in several ways. For instance, it could be a consequence of the formation of the rift during a time span comprising both normal and reverse polarities

of the Earth's magnetic field. The superposition of reversely and normally magnetized materials, the latter being the most important in terms of volume and/or the shallowest, would produce a low normal bulk magnetization. This would be in accordance with a chronology for the southern ridge spanning from the Upper Matuyama (including the Jaramillo or even the Olduvai normal polarity subchrons) to the Lower Brunhes. In this case, the southern ridge would be roughly coeval with the NE submarine rifts, but previous to the NW submarine rifts, as previously discussed. If the formation of the southernmost part of the southern ridge were restricted to a normal polarity chron, however, then any straightforward conclusion about its age could be drawn (Olduvai?, Jaramillo?, Brunhes?), and indeed the origin of such anomalous low magnetization should be further investigated.

Finally, it is interesting to mention a recent gravimetric survey that has led to a 3-D density model of El Hierro (Montesinos *et al.* 2006). The gravity study is based mainly on a land survey, therefore, allowing an appropriate description of the gravity anomalies in the subaerial part of the island, but less reliable in the marine area. For this reason, it is possible to compare the magnetic and gravimetric models only in the emerged part of the edifice. The magnetic and gravity crustal models are quite similar. In fact, the gravity anomaly also points to a N–S rift shifted to the west of the location proposed by previous authors, coincident with magnetic structure C from Fig. 4. The main difference between magnetic and gravity results is the location of the high density body in the area of the NW rift, which appears to be shifted to the north compared to the magnetic structure that appears to represent the feeding system of this rift (structure A in Fig. 4). However, this different location could be linked to a poor definition of the gravity anomaly field in the area of El Golfo embayment, due to the lack of gravity data in the near offshore.

5 CONCLUSIONS

Magnetic anomalies constitute a powerful tool in the characterization of volcanic rift zones, since the intrusive complexes underneath them are strongly magnetized structures that create an intense magnetic signal. In comparison with other methods, which are generally based only on surface data, magnetic anomalies provide a more complete image of the internal structure of a volcanic island, since they contain information about the whole of the volcanic edifice. Furthermore, the interpretation of magnetic models in light of the geomagnetic chronology of a volcanic island can provide fresh constraints on the timing of rift zone formation.

The method proposed in this paper to model magnetic anomalies, which consists of 3-D inversion on a topographic slab (i.e. the source volume is limited by the topographic surface and a flat bottom at the base of the volcanic edifice), constitutes an 'ad hoc' approach to the identification and location of volcanic rift zones, since it effectively detects nearly vertical magnetization contrasts. In addition, the algorithm has the advantages of being stable and fast. Taking into account that most of the magnetic signal in volcanic areas is due to remanent magnetization, it is best to estimate the average direction of the total magnetization vector before applying the inverse procedure.

The interpretation of the magnetic anomalies of El Hierro has provided us with very interesting results regarding the island's internal structure. The location of highly magnetized vertical structures, interpreted as intrusive complexes, confirms previous hypotheses about a complex rift structure in the marine area, although these new results suggest that some rift axes may be shifted with respect

to previous interpretations. The inverse magnetization that characterizes the NE submarine rift area implies that this part of the volcanic edifice formed during the Matuyama, and therefore, predates the normally magnetized NW submarine rift zone. The N–S rift zone, which extends from the southern part of the island to the south in the submarine edifice, seems to be shifted to the west with respect to the bathymetric high in this area. One possible interpretation for this shift is that the rift zone was originally located where the highest magnetizations are now detected, and that the present morphology is a consequence of the giant landslides that occurred in this area in the past. The magnetic model also provides new evidence about the different nature of the southern submarine ridge south of the bathymetric saddle located at 27°30'N, where the rift appears to be almost demagnetized. In addition, very low magnetizations characterize the areas affected by giant landslides (El Golfo embayment to the north, El Julán embayment to the south and Las Playas embayment to the east), indicating that magnetic anomalies can provide important constraints on the distribution of these catastrophic events.

Further refinement of this study with new high-resolution aeromagnetic data over El Hierro would allow a more precise definition of the rift zones of this oceanic volcanic island. In addition, palaeomagnetic sampling of the southern ridge would provide new information about the magnetic properties of this structure that, interpreted in the framework of the geomagnetic chronology of the island, could contribute to understanding the timing of its formation.

ACKNOWLEDGMENTS

We are grateful to I. Socías from the *Instituto Geográfico Nacional* of Spain for providing us with the aeromagnetic data of the Canary Islands. Neil Mitchell and an anonymous referee provided thorough reviews that helped us improve the paper. This work was carried out during two research stays of I. Blanco Montenegro at the *Istituto Nazionale di Geofisica e Vulcanologia* (INGV) of Rome (Italy) funded by the Spanish Ministry of Education and Science (Secretaría de Estado de Universidades e Investigación, Ayudas de Movilidad PR-2006-0308 y PR-2007-0049). This research has been partially funded by project BU003B06 of the 'Junta de Castilla y León' (Spain).

REFERENCES

- Abdel-Monem, A., Watkins, N.D. & Gast, P.W., 1972. Potassium-Argon ages, volcanic stratigraphy, and geomagnetic polarity history of the Canary Islands: Tenerife, La Palma and Hierro, *Am. J. Sci.*, **272**, 805–825.
- Ablay, G.J. & Hürlimann, M., 2000. Evolution of the north flank of Tenerife by recurrent giant landslides, *J. Volcanol. Geotherm. Res.*, **103**, 135–159.
- 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, *J. Volcanol. Geotherm. Res.*, **60**, 243–262.
- Ancochea, E., Hernán, F., Huertas, M.J., Brändle, J.L. & Herrera, R., 2006. A new chronostratigraphical and evolutionary model for La Gomera: implications for the overall evolution of the Canarian Archipelago, *J. Volcanol. Geotherm. Res.*, **157**, 271–293.
- Anguita, F. & Hernán, F., 2000. The Canary Islands origin: a unifying model, *J. Volcanol. Geotherm. Res.*, **103**, 1–26.
- Akima, H., 1970. A new method of interpolation and smooth curve fitting based on local procedures, *J. A.C.M.*, **17**, 589–602.
- Araña, V., Camacho, A.G., García, A., Montesinos, F.G., Blanco, I., Vieira, R. & Felpeto, A., 2000. Internal structure of Tenerife (Canary Islands) based

- on gravity, aeromagnetic and volcanological data, *J. Volcanol. Geotherm. Res.*, **103**, 43–64.
- Baranov, V. & Naudy, H., 1964. Numerical calculation of the formula of reduction to the magnetic pole, *Geophysics*, **29**, 67–79.
- Blakely, R.J., 1995. *Potential Theory in Gravity and Magnetic Applications*, 441 pp., Cambridge Univ. Press, New York.
- Blanco-Montenegro, I., 1997. Análisis e interpretación de las anomalías magnéticas de tres calderas volcánicas: Decepción (Shetland del Sur, Antártida), Furnas (S. Miguel, Azores) y Las Cañadas del Teide (Tenerife, Islas Canarias), *PhD thesis*, Universidad Complutense de Madrid (Spain).
- 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. Sci. Lett.*, **206**, 601–616.
- Blanco-Montenegro, I., Montesinos, F.G., García, A., Vieira, R. & Villalain, J.J., 2005. Paleomagnetic determinations on Lanzarote from magnetic and gravity anomalies: implications for the early history of the Canary Islands, *J. geophys. Res.*, **110**, B12102, doi:10.1029/2005JB003668.
- Blanco-Montenegro, I., De Ritis, R. & Chiappini, M., 2007. Imaging and modelling the subsurface structure of volcanic calderas with high-resolution aeromagnetic data at Vulcano (Aeolian Islands, Italy), *Bull. Volcanol.*, **69**, 643–659, doi: 10.1007/s00445-006-0100-7.
- Bosshard, E. & MacFarlane, D.J., 1970. Crustal structure of the Western Canary Islands from seismic refraction and gravity data, *J. geophys. Res.*, **75**, 4901–4918.
- Caratori Tontini, F., Cocchi, L. & Carmisciano, C., 2006. Depth-to-the-bottom optimization for magnetic data inversion: magnetic structure of the Latium volcanic region, Italy, *J. geophys. Res.*, **111**, B11104, doi:10.1029/2005JB004109.
- Carracedo, J.C., 1994. The Canary Islands: an example of structural control on the growth of large oceanic-island volcanoes, *J. Volcanol. Geotherm. Res.*, **60**, 225–241.
- Carracedo, J.C., 1999. Growth, structure, instability and collapse of Canarian volcanoes and comparisons with Hawaiian volcanoes, *J. Volcanol. Geotherm. Res.*, **94**, 1–19.
- Carracedo, J.C., Day, S.J., Guillou, H. & Pérez-Torrado, F.J., 1999. Giant Quaternary landslides in the evolution of La Palma and El Hierro, Canary Islands, *J. Volcanol. Geotherm. Res.*, **94**, 169–190.
- Carracedo, J.C., Badiola, E.R., Guillou, H., de la Nuez, J. & Pérez-Torrado, F.J., 2001. Geology and volcanology of La Palma and El Hierro, Western Canary Islands, *Estud. Geol.*, **57**, 175–273.
- Carracedo, J.C. *et al.*, 2002. Cenozoic volcanism II: the Canary Islands, in *The Geology of Spain*, pp. 439–472, eds Gibbons, W. and Moreno, T., The Geological Society of London, London.
- Coello, J. *et al.*, 1992. Evolution of the eastern volcanic ridge of the Canary Islands based on new K-Ar data, *J. Volcanol. Geotherm. Res.*, **53**, 251–274.
- Day, S.J., Carracedo, J.C. & Guillou, H., 1997. Age and geometry of an aborted rift collapse: the San Andres fault system, El Hierro, Canary Islands, *Geol. Mag.*, **134**, 523–537.
- Fedi, M. & Rapolla, A., 1999. 3-D inversion of gravity and magnetic data with depth resolution, *Geophysics*, **64**, 452–460.
- Fiske, R.S. & Jackson, E.D., 1972. Orientation and growth of Hawaiian volcanic rifts: the effect of regional structure and gravitational stresses, *Proc. R. Soc. Lond.*, **A329**, 299–326.
- Fúster, J.M., Hernán, F., Cendrero, A., Coello, J., Cantagrel, J.M., Ancochea, E. & Ibarrola, E., 1993. Geocronología de la isla de El Hierro (Islas Canarias), *Bol. R. Soc. Esp. Hist. Nat. (Sec. Geol.)*, **88**, 85–97.
- García, M.O. & Davis, M.G., 2001. Submarine growth and internal structure of ocean island volcanoes based on submarine observations of Mauna Loa volcano, Hawaii, *Geology*, **29**, 163–166.
- Gee, M.J.R., Watts, A.B., Masson, D.G. & Mitchell, N.C., 2001a. Landslides and the evolution of El Hierro in the Canary Islands, *Mar. Geol.*, **177**, 271–293.
- Gee, M.J.R., Masson, D.G., Watts, A.B. & Mitchell, N.C., 2001b. Offshore continuation of volcanic rift zones, El Hierro, Canary Islands, *J. Volcanol. Geotherm. Res.*, **105**, 107–119.
- 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, *J. Volcanol. Geotherm. Res.*, **73**, 141–155.
- Guillou, H., Carracedo, J.C., Paris, R. & Pérez-Torrado, F.J., 2004. Implications for the early shield-stage evolution of Tenerife from K/Ar ages and magnetic stratigraphy, *Earth Planet. Sci. Lett.*, **222**, 599–614.
- Hayling, K.L. & Harrison, C.G.A., 1986. Magnetization modeling in the north and equatorial Atlantic ocean using MAGSAT data, *J. geophys. Res.*, **91**, 12 423–12 443.
- Hernández-Pacheco, A., 1982. Sobre una posible erupción en 1793 en la isla de El Hierro (Canarias), *Estud. Geol.*, **38**, 15–25.
- Hildenbrand, T.G., Rosenbaum, J.G. & Kauahikaua, J.P., 1993. Aeromagnetic study of the island of Hawaii, *J. geophys. Res.*, **98**, 4099–4119.
- Hoernle, K., Yang, Y.S. & Graham, D., 1995. Seismic and geochemical evidence for large-scale mantle upwelling beneath the eastern Atlantic and western and central Europe, *Nature*, **374**, 34–39.
- Holcomb, R.T. & Searle, R.C., 1991. Large landslides from oceanic volcanoes, *Mar. Geotechnol.*, **10**, 19–32.
- IAGA Div. V, Working Group 8, 1996. International geomagnetic reference field, 1995 revision, *Geophys. J. Int.*, **125**, 318–321.
- Jackson, D.D., 1972. Interpretation of inaccurate, insufficient and inconsistent data, *Geophys. J. Roy. Astron. Soc.*, **28**, 97–109.
- Jones, J.G., 1966. Intraglacial volcanoes of South-West Iceland and their significance in the interpretation of the form of the marine basaltic volcanoes, *Nature*, **212**, 586–588.
- Krastel, S., Schmincke, H.-U., Jacobs, C.L., Rihm, R., Le Bas, T.P. & Alibés, B., 2001. Submarine landslides around the Canary Islands, *J. geophys. Res.*, **106**, 3977–3997.
- Le Bas, M.J., Rex, D.C. & Stillman, C.J., 1986. The early magmatic chronology of Fuerteventura, Canary Islands, *Geol. Mag.*, **123**, 287–298.
- Lénat, J.-F., Gibert-Malengreau, B. & Galdeano, A., 2001. A new structural model for the evolution of the volcanic island of Réunion (Indian Ocean), *J. geophys. Res.*, **106**(B5), 8645–8663.
- Li, Y. & Oldenburg, D.W., 1996. 3-D inversion of magnetic data, *Geophysics*, **61**, 394–408.
- MacDonald, G.A., 1949. Petrography of the island of Hawaii, *U.S. Geol. Surv. Prof. Pap.* 214-D.
- McDougall, I. & Schmincke, H.-U., 1976. Geochronology of Gran Canaria, Canary Islands: age of shield building volcanism and other magmatic phases, *Bull. Volcanol.*, **40**, 57–77.
- Masson, D.G., 1996. Catastrophic collapse of the volcanic island of El Hierro 15 ka ago and the history of landslides in the Canary Islands, *Geology*, **24**, 231–234.
- Masson, D.G., Watts, A.B., Gee, M.J.R., Urgeles, R., Mitchell, N.C., Le Bas, T.P. & Canals, M., 2002. Slope failures on the flanks of the western Canary Islands, *Earth-Sci. Rev.*, **57**, 1–35.
- Mitchell, N.C., Masson, D.G., Watts, A.B., Gee, M.J.R., Urgeles, R., 2002. The morphology of the submarine flanks of volcanic ocean islands. A comparative study of the Canary and Hawaiian hotspot islands, *J. Volcanol. Geotherm. Res.*, **115**, 83–107.
- Mitchell, N.C., Dade, W.B. & Masson, D.G., 2003. Erosion of the submarine flanks of the Canary Islands, *J. geophys. Res.*, **108**(F1), 6002, doi:10.1029/2002JF000003.
- Montelli, R., Nolet, G., Dahlen, F., Masters, G., Engdahl, E.R. & Hung, S.H., 2004. Finite-frequency tomography reveals a variety of plumes in the mantle, *Science*, **303**, 338–343.
- Montesinos, F.G., Arno, J., Benavent, M. & Vieira, R., 2006. The crustal structure of El Hierro (Canary Islands) from 3-D gravity inversion, *J. Volcanol. Geotherm. Res.*, **150**, 283–299.
- Moore, J.G. & Chadwick, W.W., 1995. Offshore geology of Mauna Loa and adjacent areas, Hawaii, in *Mauna Loa Revealed: Structure, Composition, History and Hazards*, pp. 21–44, eds Rhodes, J.M. & Lockwood, J.P., American Geophysical Union.
- Münn, S., Walter, T.R. & Klügel, A., 2006. Gravitational spreading controls rift zones and flank instability on El Hierro, Canary Islands, *Geol. Mag.*, **143**, 257–268.
- Nicolosi, I., Blanco-Montenegro, I., Pignatelli, A. & Chiappini, M., 2006. Estimating the magnetization direction of crustal structures by means

- of an equivalent source algorithm, *Phys. Earth Planet. Int.*, **155**, 163–169.
- Oyarzun, R., Doblas, M., López-Ruiz, J. & Cebriá, J.M., 1997. Opening of the central Atlantic and asymmetric mantle upwelling phenomena: implications for long-lived magmatism in western North Africa and Europe, *Geology*, **25**, 727–730.
- Pignatelli, A., Nicolosi, I. & Chiappini, M., 2006. An alternative 3D inversion method for magnetic anomalies with depth resolution, *Ann. Geophys.*, **49**, 1047–1053.
- Press, W.H., Teukolsky, S.A., Vetterling, W.T. & Flannery, B.P., 1992. *Numerical Recipes in C: The Art of Scientific Computing*, 2nd edn, 994 pp., Cambridge Univ. Press, New York.
- Rasmussen, R. & Pedersen, L.B., 1979. End corrections in potential field modelling, *Geophys. Prosp.*, **27**, 749–760.
- 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, *Mar. Geophys. Res.*, **14**, 1–24.
- Sharma, P.V., 1986. *Geophysical Methods in Geology*, 432 pp., Elsevier, Amsterdam.
- Smith, W.H.F. & Sandwell, D.T., 1997. Global seafloor topography from satellite altimetry and ship depth soundings, *Science*, **277**, 1957–1962.
- Socias, I. & Mézcua, J., 1996. *Levantamiento aeromagnético del archipiélago canario*, Publicación Técnica no. 35, 28 pp., Instituto Geográfico Nacional, Madrid.
- Staudigel, H. & Schmincke, H.-U., 1984. The Pliocene seamount series of La Palma, Canary Islands, *J. geophys. Res.*, **89**, 11195–11215.
- Talwani, M. & Heirtzler, J.R., 1964. Computation of magnetic anomalies caused by two-dimensional bodies of arbitrary shape, in *Computers in the Mineral Industries, Part 1. Geological Sciences no. 9*, pp. 464–480, ed. Parks G.A., Stanford Univ. Publ., Leedland, USA.
- Urgeles, R., Canals, M., Baraza, J., Alonso, B. & Masson, D., 1997. The most recent megalandslides of the Canary Islands: El Golfo debris avalanche and Canary debris flow, west El Hierro Island, *J. geophys. Res.*, **102**, 20 305–20323.
- Verhoef, J., Collette, B.J., Dañobeitia, J.J., Roeser, H.A. & Roest, W.R., 1991. Magnetic anomalies off West Africa (20–38° N), *Mar. Geophys. Res.*, **13**, 81–103.
- Walker, G.P.L., 1986. Koolau dike complex, Oahu: intensity and origin of a sheeted-dike complex high in a Hawaiian volcanic edifice, *Geology*, **14**, 310–313.
- Walker, G.P.L., 1987. The dike complex of Koolau Volcano, Oahu: the internal structure of a Hawaiian rift zone, in *Volcanism in Hawaii*, pp. 961–993, eds Decker, R.W., Wright, T.L. and Stauffer, P.W., U.S. Geol. Surv. Prof. Paper 1350.
- Walker, G.P.L., 1990. Geology and volcanology of the Hawaiian Islands, *Pacific Sci.*, **44**, 315–347.
- Walker, G.P.L., 1992. “Coherent intrusion complexes” in large basaltic volcanoes – a new structural model, *J. Volcanol. Geotherm. Res.*, **50**, 41–54.
- Walker, G.P.L., 1999. Volcanic rift zones and their intrusion swarms, *J. Volcanol. Geotherm. Res.*, **94**, 21–34.
- Walter, T.R., Troll, V.R., Cailleau, B., Belousov, A., Schmincke, H.-U., Amelung, F. & v.d. Bogaard, P., 2005. Rift zone reorganization through flank instability in ocean island volcanoes: an example from Tenerife, Canary Islands, *Bull. Volcanol.*, **67**, 281–291.
- Watkins, N.D., 1973. Palaeomagnetism of the Canary Islands and Madeira, *Geophys. J. R. Astr. Soc.*, **32**, 249–267.
- Watts, A.B., 1994. Crustal structure, gravity anomalies and flexure of the lithosphere in the vicinity of the Canary Islands, *Geophys. J. Int.*, **119**, 648–666.
- Watts, A.B. & Masson, D.G., 1995. A giant landslide on the north flank of Tenerife, Canary Islands, *J. geophys. Res.*, **100**, 24487–24498.
- Won, I.J. & Bevis, M., 1987. Computing the gravitational and magnetic anomalies due to a polygon: algorithms and Fortran subroutines, *Geophysics*, **52**, 232–238.