Gravity and magnetic anomalies in the allochthonous Órdenes Complex (Variscan belt, northwest Spain): Assessing its internal structure and thickness

José R. Martínez Catalán,[1] Fernando Álvarez Lobato,[1] Victor Pinto,[2] Juan Gómez Barreiro,[1] Puy Ayarza,[1] Juan José Villalaín,[3] and Albert Casas[2]

Received 31 December 2011; revised 24 August 2012; accepted 31 August 2012; published 16 October 2012.

[1] The Órdenes Complex is the largest Variscan allochthonous structure of NW Iberia, and preserves the suture of a long-standing Paleozoic ocean, probably the Rheic. Gravity and magnetic data, the latter specifically acquired on land for this study, show that the complex occupies the core of an open synform with a maximum depth of 9–10 km, which contrasts with the flat geometry of the lower crust and Moho discontinuity beneath. The maximum depth reached by the ophiolitic rocks marking the suture is around 7 km. The allochthonous units formed by basic and ultrabasic rocks are lens-shaped in section, and occur not only at the periphery of the complex, but form wide ribbons trending NE-SW to N-S. The Bouguer anomaly related with the longest of them, the Fornás Unit, previously used to support an autochthonous interpretation of the complexes, is modeled as a rootless, massive amphibolite body with a maximum thickness of 6 km located at the downthrown block of a large normal fault cutting across previous thrust faults and extensional detachments. The main magnetic anomalies are associated with ultrabasic rocks cropping out in the NW and SE, but a weak, wide anomaly in the central part of the complex is related with one or more thin layers of amphibolite partly mineralized with massive sulphides. The weakly arcuate geometry of this anomaly and of the Bouguer anomaly caused by the Fornás Unit may reflect the NE flank of the Central Iberian arc, an orocline whose core is occupied by the allochthonous complexes.

Citation: Martínez Catalán, J. R., F. Álvarez Lobato, V. Pinto, J. Gómez Barreiro, P. Ayarza, J. J. Villalaín, and A. Casas (2012), Gravity and magnetic anomalies in the allochthonous Órdenes Complex (Variscan belt, northwest Spain): Assessing its internal structure and thickness, *Tectonics*, *31*, TC5007, doi:10.1029/2011TC003093.

1. Introduction

[2] The allochthonous complexes of NW Iberia (Spain and Portugal) consist of dense basic and ultrabasic units alternating with units mostly consisting on lighter metasediments and orthogneisses. The complexes are surrounded by low-density metasediments, felsic metavolcanics, migmatites and granites. The contrasts in density make the complexes appropriated for gravity investigations, and thus, they were surveyed in the 1970's to elucidate their autochthonous or allochthonous character. In Spain, Bouguer gravity anomalies were interpreted in the Cabo Ortegal Complex (40 mGal) [*Van Overmeeren*, 1975] and the southern Órdenes Complex (25 mGal) [*Keasberry et al.*, 1976] as indicators of deeply rooted structures favoring an autochthonous interpretation. Both complexes were explained as resulting from a mantle plume or diapir emplaced during the early Paleozoic [*van Calsteren and Den Tex*, 1978; *van Calsteren et al.*, 1979].

[3] The alternative interpretation of the complexes representing remnants of a Variscan thrust plate [*Ries and Shackleton*, 1971] was supported by a re-evaluation of the Cabo Ortegal gravity anomaly by *Bayer and Matte* [1979], and by lithological and structural criteria, such as the presence of late Paleozoic ophiolites, high-pressure metamorphism, nappe staking, thrust imbricates, and tectonic mélanges.

[4] *Castaño et al.* [1981] modeled the Bouguer gravity anomaly of the Cabo Ortegal Complex with a folded klippe with geometry similar but more detailed than that used by *Bayer and Matte* [1979], and carried out a magnetic survey which also supported an allochthonous interpretation. But no attempts have been made to date to re-interpret the gravimetric anomalies of the southern Órdenes Complex since the pioneering work of *Keasberry et al.* [1976], and no magnetic survey has been carried out before to the scale of the whole complex.

[1]Departamento de Geología, Universidad de Salamanca, Salamanca, Spain.
[2]Departamento de Geoquímica, Petrología y Prospección Geofísica, Universidad de Barcelona, Barcelona, Spain.
[3]Laboratorio de Paleomagnetismo, Departamento de Física, Universidad de Burgos, Burgos, Spain.

Corresponding author: J. R. Martínez Catalán, Departamento de Geología, Universidad de Salamanca, ES-37008 Salamanca, Spain. (jrmc@usal.es)

0278-7407/12/2011TC003093

[5] While there are no longer doubts about the allochthonous character of the NW Iberian complexes, and the surface geology of the Órdenes Complex is presently known in detail [e.g., *Martínez Catalán et al.*, 2002], its geometry in depth was only based in an approximated down-plunge continuation of the folded structures whose axes are known to vary quickly along and across the complex. Many allochthonous units show a lens-shaped geometry in map view, for which no structural criteria permit a sound down-dip continuation, and the actual depth reached by the complex was unknown.

[6] On the other hand, the allochthonous complexes of NW Iberia occupy the core of the Central Iberian arc (Figure 1a), an orocline delineated by fold axes and magnetic anomalies in the surrounding autochthon [*Martínez Catalán*, 2011, 2012]. The arc was found by *Staub* [1926, 1928a] when he visited Spain with occasion of the XIV International Geological Congress, in 1926. He based his finding on the trends of Variscan folds, named the arc the Castilian bend, and included it on geological sketches of Europe in his book "Der Bewegungsmechanismus der Erde" [*Staub*, 1928b].

[7] However, *Lotze* [1929, 1945a] discussed the existence of the arc arguing that the folds maintained a NW-SE attitude in the SE of the Iberian Massif without being bent in the Toledo region. The influential contribution on the division of the Iberian Variscides by *Lotze* [1945b] did not consider the existence of an arc in Central Iberia and the same occurred with the successive subdivisions of the Iberian Massif [*Julivert et al.*, 1972; *Farias et al.*, 1987], all based on Lotze's work. The arc remained ignored until *Aerden* [2004] noticed its existence on the patterns delineated by the Variscan folds and the magnetic anomalies in the Central Iberian Zone. Figure 1b shows the map of magnetic anomalies of the Iberian Peninsula, based on aeromagnetic data by *Ardizone et al.* [1989] and *Miranda et al.* [1989]. Figure 1c depicts the axial trace of the main Variscan folds, according to *Martínez Catalán* [2012], and explains the discrepancy in *Staub*'s [1926, 1928a] and *Lotze*'s [1929, 1945a] observations: the first folds (D1) were bent by the arc in the SE of the Iberian Massif, while the long and continuous late folds (D3) have an axial planar attitude in relation to it, so that they were not bent by the Central Iberian arc, although they were by the Ibero-Armorican arc.

[8] It is unclear, however, whether or not the Central Iberian arc is also delineated by any structure in the allochthonous complexes, and if the arcuate shape of the central part of the Órdenes Complex, with its roughly circular string of basic and ultrabasic units (Figure 2), would be a possible candidate.

[9] This paper presents the interpretation of the gravity and magnetic anomalies of the Órdenes Complex based on forward modeling carried out to constrain its structure, estimate its maximum depth and evaluate whether or not its present configuration reflects the geometry of the Central Iberian orocline at its core.

2. Geological Setting

[10] The geology of NW Iberia is characterized by an autochthonous domain, a parauchthonous thrust sheet a few kilometres thick, and an allochthonous nappe stack cropping out in five allochthonous complexes.

[11] The autochthonous sequence consists of metasediments, metavolcanics and orthogneisses. It developed during the Late Proterozoic and Paleozoic in northern Gondwana, as indicated by sedimentary and faunal evidence and by detrital zircon age populations [*Martínez Catalán et al.*, 2004]. The parautochthon or Schistose Domain consists of Ordovician, Silurian and perhaps Early Devonian metasediments and volcanics, with stratigraphic and igneous affinities with the Iberian autochthon. It represents a distal part of the Gondwanan continental margin (references in *Martínez Catalán et al.* [2009]). Deformation and metamorphism are Variscan, and Early Carboniferous syn-orogenic, flysch-type deposits related to the emplacement of the allochthonous complexes occur in both the autochthon and parauthochthon domains [*Martínez Catalán et al.*, 2008].

[12] The complexes consist of allochthonous units characterized by a lithologic association and a particular tectonometamorphic evolution. These units are grouped according to their lithologic affinities and their relative position in the original nappe pile, and are separated from each other by faults, either thrusts or extensional detachments. The allochthonous units include pieces of the outermost basement of Gondwana, ophiolites derived from a Paleozoic ocean, and fragments of an ensialic Cambro-Ordovician island arc. Several of these units underwent subduction in early-Variscan times, and are considered to represent the suture of the Rheic Ocean, formed after its closure during the Variscan collision [*Arenas et al.*, 2007a; *Martínez Catalán et al.*, 2007; *Sánchez Martínez et al.*, 2007].

[13] Variscan granitoids are abundant in late-Variscan extensional domes, many of them gneiss domes, which alternate with synforms and structural basins whose core is occupied in NW Spain and northern Portugal by the allochthonous complexes.

3. Geology of the Órdenes Complex

[14] Órdenes is the largest of the Iberian complexes, with an outcropping area of 4,600 km^2, and shares with the other four the same types of allochthonous units and their stacking sequence. Following an overview of the main structural features of the complex, three sets of allochthonous units are described from top to bottom. The units occupying an intermediate position between upper and basal sets have oceanic affinities and are referred to as ophiolitic.

3.1. Structural Overview

[15] The geological map of the Órdenes Complex is shown in Figure 2, whereas Figure 3 depicts a schematic cross section based on the superposition of 9 partial sections across its central and southern parts. The complex is a klippe, the preserved remnant of large nappe stack formed by accretion of different peri-Gondwanan units [*Martínez Catalán et al.*, 2002; *Arenas et al.*, 2007a]. Thrust faults separate the different allocthonous units and also imbricate them internally. But also, many of the outer limits and internal boundaries are extensional detachments formed either during the accretionary process or during Late Variscan extensional collapse, and cutting across or reworking previous thrust faults [*Gómez Barreiro et al.*, 2007, 2010a].

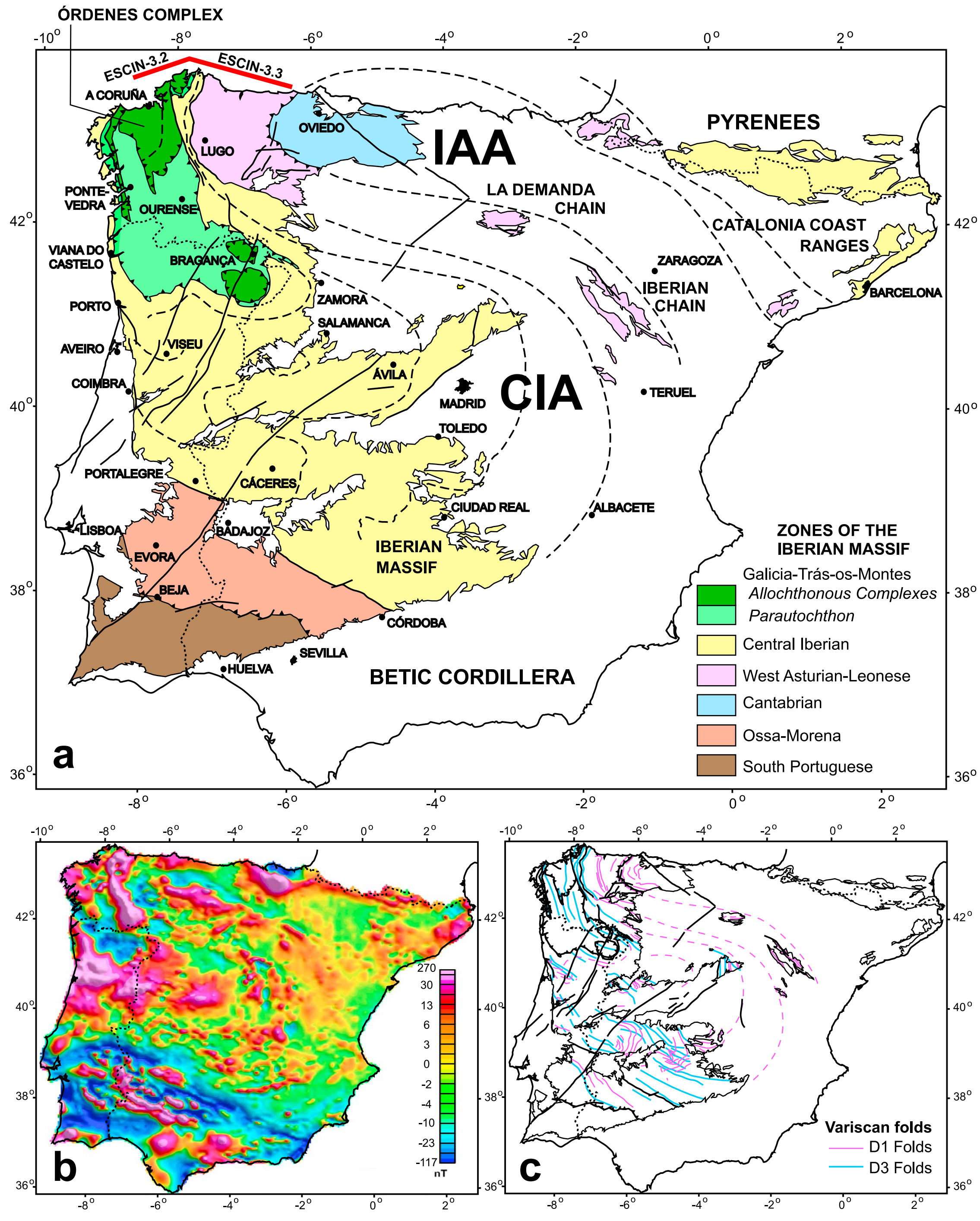

Figure 1. (a) Map showing the outcrops of the Variscan basement in the Iberian Peninsula and the subdivision in zones of the Iberian Massif. Dashed lines separate zones in covered areas and show the trend of early Variscan folds in the Central Iberian Zone. The two Variscan oroclines present in the peninsula, the Central Iberian (CIA) and Ibero-Armorican (IAA) arcs are outlined. Thick red lines offshore NW Iberia mark the location of marine seismic reflection profiles ESCIN-3.2 and ESCIN-3.3, shown in Figure 8. (b) Map of the magnetic anomalies in the Iberian Peninsula marking the two oroclines. Data from *Ardizone et al.* [1989] for Spain and *Miranda et al.* [1989] for Portugal. (c) Axial traces of the main Variscan folds. D1 folds are bent by both oroclines whereas D3 folds are commonly axial planar to the Central Iberian arc and bent only by the Ibero-Armorican arc. After *Aerden* [2004] and *Martínez Catalán* [2012].

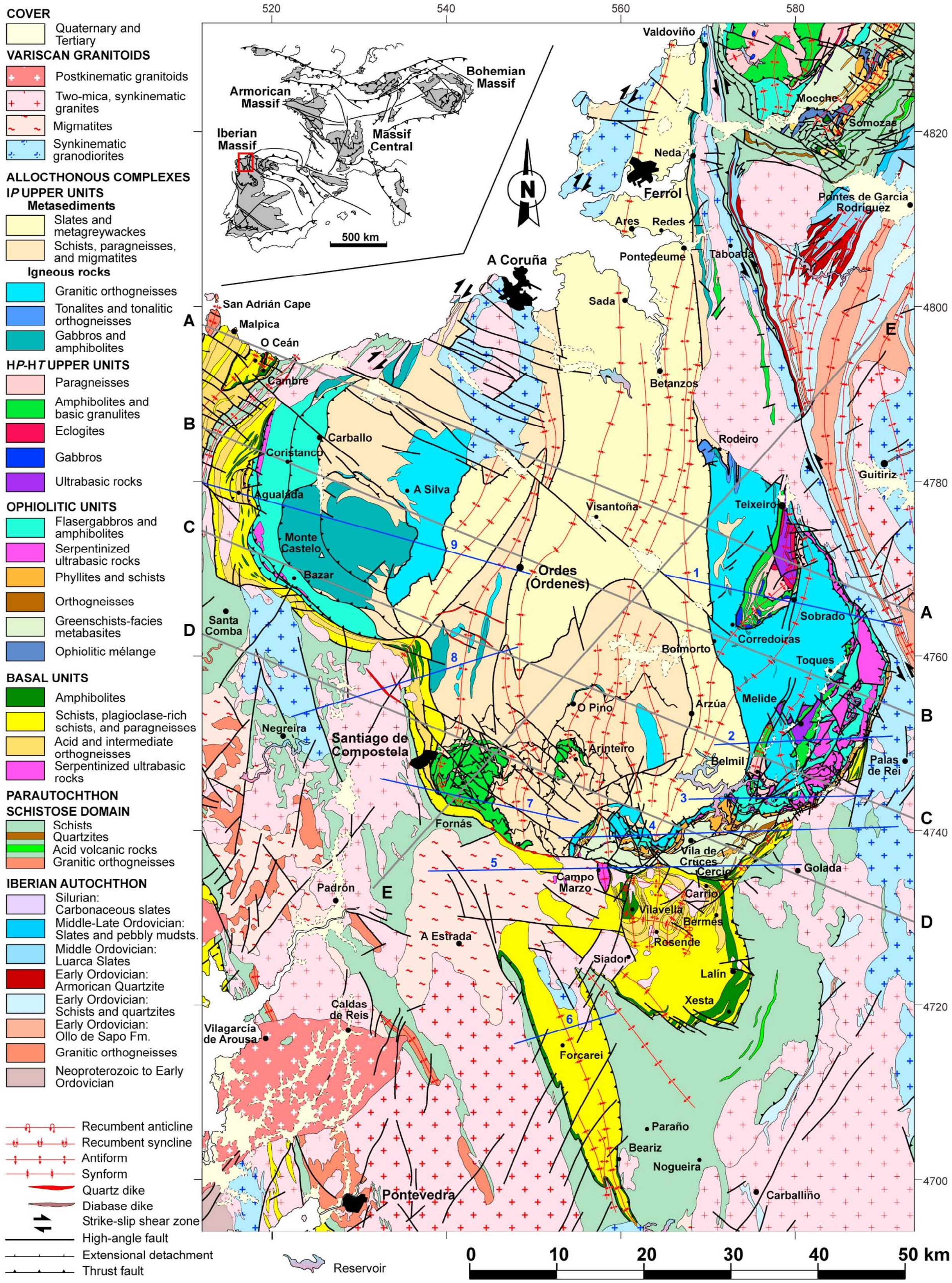

Figure 2. Geological map of the Órdenes Complex, based on *Martínez Catalán et al.* [2002]. Cabo Ortegal Complex (NE corner) after *Arenas et al.* [2009], and Malpica-Tui Complex (NW corner) after *Díez Fernández* [2011]. The location of the modeled sections A to E is indicated, as well as that of the geological sections 1 to 9 used to build the Figure 3. The inset shows the location of the studied area in the Variscan belt.

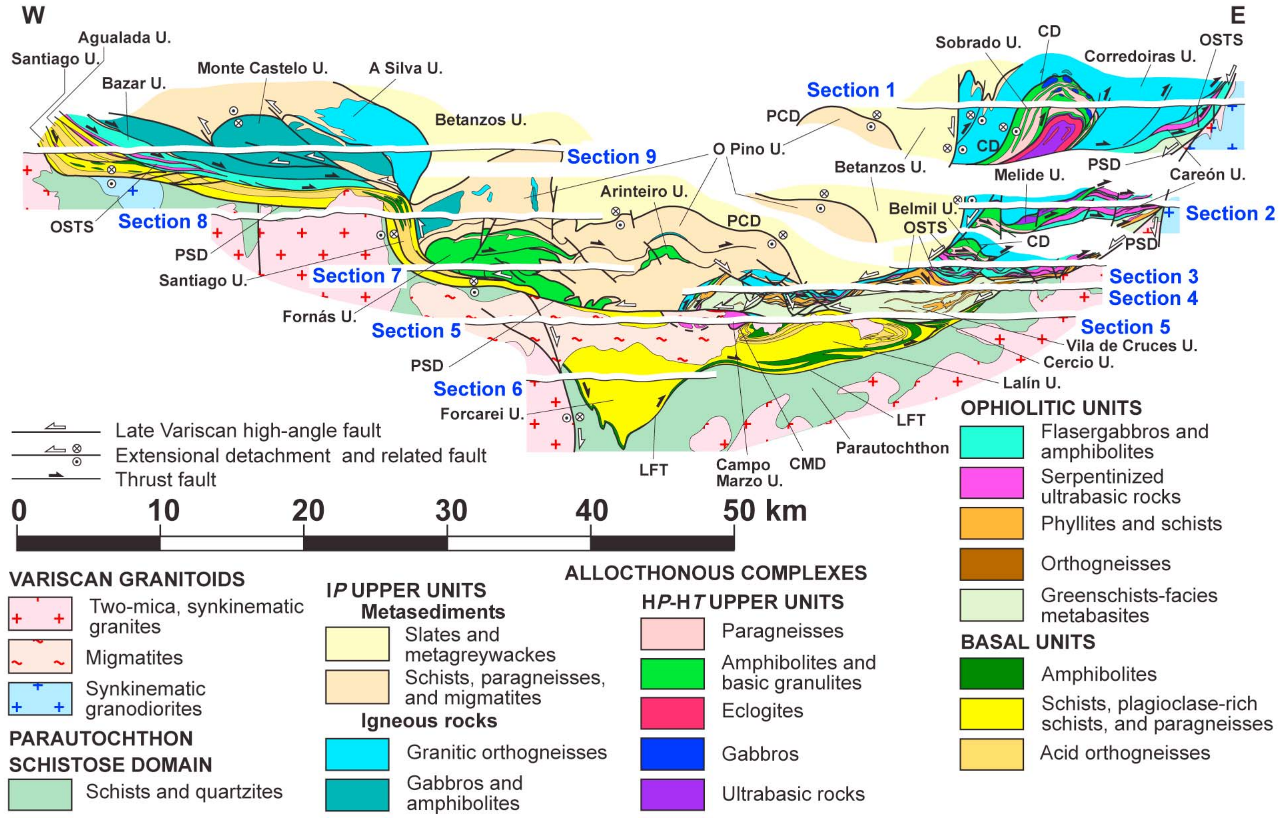

Figure 3. Schematic section across the Órdenes Complex based in the superposition of 9 partial sections across its central and southern parts, whose location is shown in Figure 2. The vertical scale of the full composite section is not constrained, and its aim is to show the allochthonous units, the main structures, and their mutual relationships. Modified after *Martínez Catalán et al.* [2002]. Abbreviations: CD, Corredoiras detachment; CMD, Campo Marzo detachment; LFT, Lalín-Forcarei thrust; OSTS, out-of-sequence thrust system; PCD, Ponte Carreira detachment; PSD, Pico Sacro detachment.

[16] The more important faults are the Lalín-Forcarei thrust (LFT), which limits the complex to the S, and the Pico Sacro detachment (PSD), which bounds its W part and separates the basal and ophiolitic units in the S. Most of the complex occupies the hanging wall to the PSD, with only the Lalín and Forcarei units occurring at its footwall. Kinematic criteria indicate a top-to-the-N or NNW movement for the PSD, whose spoon-like shape reflects a listric geometry. In fact, the PSD is the sole fault of a complex system of extensional detachments and faults that was partially reactivated in the S, where a quartz dike 9 km long and 150 m thick occupies a N-dipping fault cutting across the main PSD fault.

[17] Other important thrust faults and detachments occur inside the complex, and some are depicted in Figure 3 and referred to in the following sections. The superposition of several generations of thrusts and extensional detachments dismembered the original accretionary stack, and is the cause of the present lens-shaped geometry of the allochthonous units, together with the existence of two antiformal stacks in Sobrado and Belmil [*Martínez Catalán et al.*, 2002]. High angle faults exist, as in Sobrado and to the W of Melide and Belmil (Figure 2), but these are the steeply-dipping upper parts of an out-of-sequence thrust and a listric extensional detachment respectively (Figure 3). The faults and units were folded by open to tight, steep folds striking NNE-SSW, N-S and NNW-SSE. The complex was also deformed by late-Variscan strike-slip shear zones, responsible for its narrowing toward the N (Figure 2).

3.2. Upper Units

[18] These units overlie structurally the ophiolites and can be subdivided into two subgroups. The uppermost and more extensive subgroup includes units with intermediate pressure (I*P*) metamorphism. It occupies the central part of the Órdenes Complex and represents two thirds of its outcropping surface. Below, several discontinuous units with high pressure and high temperature metamorphism occur as small massifs and kilometer-scale lenses in the S and SE, and are known as H*P*-H*T* or catazonal upper units.

[19] The boundary between I*P* an H*P*-H*T* upper units in the E is a low-dipping, extensional fault known as the Corredoiras detachment (CD), that appears folded and limits the tectonic windows where the Sobrado and Belmil units crop out (Figures 2 and 3) [*Díaz García et al.*, 1999a]. In the SW, the same or an equivalent extensional detachment separates the amphibolitic Fornás Unit from the schists and paragneisses of O Pino Unit, but it is often overprinted by imbricated thrust faults.

3.2.1. IP Upper Units: Monte Castelo, Corredoiras, A Silva, O Pino, and Betanzos

[20] These units include a thick sequence of terrigenous metasediments and bodies of amphibolites, gabbros and orthogneisses. Metamorphic grade ranges from granulite facies in the lower parts to greenschist facies on top. Changes in metamorphic grade are abrupt and located at extensional detachments [*Martínez Catalán et al.*, 2002]. High-grade rocks including voluminous metaigneous bodies occupy the lowermost position: the Monte Castelo Unit (gabbro) and the Corredoiras and A Silva Units (orthogneisses). These are separated from the overlying schistose and mesozonal O Pino Unit by subtractive detachments, while a major low-dipping fault, the Ponte Carreira detachment (PCD), separates the mesozonal schists and paragneisses from the uppermost low-grade slates and greywackes of the Betanzos Unit (Figures 2 and 3).

3.2.2. HP-HT Upper Units: Sobrado, Melide, Belmil, and Fornás

[21] The three first units crop out in the E of the complex, and consist of paragneisses and basic and ultrabasic metaigneous rocks. The metabasites include metagabbros, garnet-clinopyroxene granulites and eclogites, variably retrograded to the amphibolite facies [*Vogel*, 1967; *Hubregtse*, 1973]. The tectonothermal evolution includes an Early to Middle Devonian, high-*P* granulite to eclogite facies metamorphic event followed by decompression and partial melting and then, successively, by a penetrative mylonitization in the amphibolite facies, recumbent folding, and thrusting under greenschist facies conditions [*Marcos et al.*, 1984; *Gil Ibarguchi et al.*, 1990; *Fernández-Suárez et al.*, 2007; *Gómez Barreiro et al.*, 2006, 2007].

[22] The Fornás Unit crops out in the SW, and consists of heterogeneous and well-foliated amphibolites, whereas ultrabasic rocks are very scarce. *Van Zuuren* [1969] described granulite-facies relics, but the dominant amphibolite-facies foliation developed during the exhumation, in a shear zone which puts the unit into contact with the overlying mesozonal schists and paragneisses [*Gómez Barreiro*, 2007]. This shear zone is a subtractive detachment, and was subsequently affected by recumbent folds with E vergence, and imbricated by thrust faults (Figure 3). Massive sulphide deposits [*Badham and Williams*, 1981; *Williams*, 1983] characterize the Fornás Unit, and have been mined NW of Fornás and in the Arinteiro area (Figure 2). The mineralization is associated to fluid circulation in the extensional shear zone, according to *Castiñeiras et al.* [2002] and *Gómez Barreiro et al.* [2002].

3.3. Ophiolitic Units: Careón, Bazar, and Vila de Cruces

[23] Rocks of oceanic affinity occur in three different and tectonically imbricated slices known as the units of Vila de Cruces, in the S, Careón, in the SE, and Bazar, in the W (Figures 2 and 3).

[24] The Vila de Cruces Unit consists of greenschist-facies basic rocks (greenstones) and metapelites with rare acid orthogneisses, serpentinites and cherts. It represents a Late Cambrian, supra-subduction zone ophiolite formed at the opening of the Rheic Ocean [*Arenas et al.*, 2007b]. Mesozonal relics in the basic rocks indicate an early, amphibolite facies regional metamorphism, whereas a low to intermediate temperature and high pressure metamorphic gradient has been identified in the metapelites. The unit was affected by two phases of recumbent folding followed by ESE-directed thrusts with abundant internal imbricates or duplexes.

[25] The Careón Unit represents the basal parts of an ophiolitic sequence, characterized by the abundance of pegmatitic gabbros, either preserved or transformed into flasergabbros and amphibolites. These are underlain by ultrabasic rocks, and this sequence was repeated by E-directed thrust faults, in three main thrust sheets with pervasive internal imbrication. The unit, of Early-Middle Devonian age, has been interpreted as a supra-subduction zone ophiolite formed during the closure of the Rheic Ocean [*Díaz García et al.*, 1999b; *Pin et al.*, 2002; *Sánchez Martínez et al.*, 2007; *Gómez Barreiro et al.*, 2010b].

[26] The Bazar Unit consists of serpentinized dunites and isotropic gabbros with minor intrusions of pegmatoid gabbros. The deformation is heterogeneous, with ductile shear zones repeating the basic and ultrabasic association. The unit represents a typical N-MORB oceanic lithosphere formed in the Late Cambrian and subsequently affected by low pressure granulitic metamorphism and retrograded under amphibolite and greenschist facies conditions [*Sánchez Martínez*, 2009].

3.4. Basal Units: Agualada, Santiago, Lalín, Forcarei, and Cercio

[27] The basal units crop out in the SE, S and W of the Órdenes Complex, and can be continued to the W in the Malpica-Tui Unit (Figure 2). They consist of pelitic schists, metagreywackes, and paragneisses alternating with acid and intermediate orthogneisses, amphibolites, and eclogites. These rocks record a high pressure regional metamorphism caused by their subduction following the closure of the Rheic Ocean [*Arenas et al.*, 1995; *Martínez Catalán et al.*, 1996].

[28] The basal units are folded by a large recumbent anticline, whose lower, reverse limb is sheared and cut by the LFT. In the S, the Lalín and Forcarei units occupy the core of two synforms and are bounded by the PSD on top and the LFT at the bottom. The Cercio Unit occurs in a narrow strip to the NE of the Lalín Unit (Figures 2 and 3). The Santiago Unit prolongs the Lalín and Forcarei units toward the W and N, and is bounded by the PSD, now at the bottom, and by the basal thrust of the ophiolitic Bazar Unit on top. The Santiago Unit was overlain by another thrust sheet of which only a small tectonic slice, the Agualada Unit, is preserved. The Lalín Unit is locally topped by an ultrabasic sheet, the Campo Marzo Unit, a fragment of one of the overlying ophiolitic units.

4. Data Acquisition and Processing

4.1. Gravimetry

[29] In the framework of a project leaded by the Spanish Agency of Nuclear Wastes (ENRESA), 973 new gravity measurements were made in 1988 in Galicia (NW Spain) and merged with the pre-existing data of the Instituto Geográfico Nacional (IGN) [*Mezcua et al.*, 1996]. Data were acquired with a LaCoste-Romberg model G gravimeter, and an International Gravity Standardization Net 1971 system reference (IGSN71) [*Morelli et al.*, 1974] was established with stations separated less than 50 km from each other. The

stations were selected to be at easily locatable points in the topographical map such as kilometre stones, road junctions, etc. The position at each station was measured with a GPS Garmin eTrex with ±5 m accuracy in the horizontal coordinates, and altitude was obtained from benchmarks and barometric levelling with an Air altimeter with an accuracy of ±0.1 m. In order to correct the gravimeter and barometric drifts, the measurement cycles were done in a time period less than 3 hours.

[30] The accuracy of individual readings was maintained through regular reoccupation of each station and the reference stations. Also, pre-existing data were re-evaluated acquiring again 5% of the previous measurements. Duplicate gravity measurements for the two data sets revealed a root mean square error of ±0.23 mGal, which is acceptable for a regional study and indicates that the different data sets can be used together. Some erroneous data were removed. The result were 2,233 gravity stations in Galicia, of which 846 are in the area covered by the map of Figures 2 and 4.

[31] A complete Bouguer anomaly was recalculated for the entire new dataset using the Geodetic Reference System formula of 1967 (GRS-67) and a mean density of 2,670 kg/m^3. Terrain corrections were made around each station to a distance of 22 km using two sets of digital terrain models.

[32] The Bouguer anomaly is shown in Figure 4, where the main contacts have been included to allow comparison with the geological map of Figure 2. Two maps showing the result of applying a gradient operator are also shown, reduced to one third of the scale of the main map, in the insets at the upper and lower left corners. The vertical gradient is simply the result of calculating the first derivative of the anomaly in the vertical direction. For the horizontal gradient, the operator consists on the square root of the summed squares of horizontal gradients, calculated as the first derivatives of the anomaly along the E-W and N-S axes.

4.2. Magnetometry

[33] The aeromagnetic map of Spain [*Ardizone et al.*, 1989] was acquired over the peninsular part of the country at an altitude of 3,000 m above the sea level (inset in Figure 5). This low resolution dataset was acquired along N-S lines separated 10 km and control E-W lines 40 km apart. It shows only the large wavelength anomalies allowing regional interpretations, but it is too rough to interpret the structure of the Órdenes Complex in detail. To obtain a higher resolution magnetic map, data have been acquired on land covering the whole complex. Two Geometrics G-856 and one Scintrex ENVI-MAG proton magnetometers were used, one of them registering every 5 minutes in a base station to correct for the diurnal variation.

[34] Eight field campaigns were made between October, 2003 and September, 2008, a period of low and progressively decreasing solar activity The reference base station was established close to O Pino (UTM: E552760, N4752499; height: 404 m), in the central area of the Órdenes Complex (Figure 2), and other six second order bases were used for different campaigns and tied with the main base station at O Pino to correct for the secular variation. Measurements were taken as far as possible from power lines, buildings, cars and other metallic objects, and looking for the best signal intensity and coherence of measured magnetic field intensity in places with strong magnetic gradients.

[35] The survey covers an area of 5,800 km^2, with 2,266 measured stations. Diurnal and secular variations, altitude and magnetic latitude were corrected with respect to the base station at O Pino, and relative anomalies were calculated in relation to the first measurement taken at the main base station the first day of acquisition, October, 19th, 2003. The higher and lower values of the magnetic field were always measured in outcrops of serpentinized ultrabasic rocks, with the largest anomalies being +4,509 and −1,461 nT. The calculated anomalies show a continuum of values ranging between −500 and around +1,500 nT. Only 8 positive and 6 negative values fall out of these limits, which were taken as reference for despiking.

[36] The International Geomagnetic Reference Field [*Maus et al.*, 2005] for the coordinates, height and date of first day of acquisition at the reference base of O Pino is 45,370 nT, whereas the measured intensity was 45,331.9 nT. This yields an absolute anomaly of −38.1 nT, which was added to the relative anomalies at all the stations to correct them to a mean absolute value. The resulting anomaly map is shown in Figure 5, where the main contacts have been included to allow comparison with the geological map of Figure 2. The inset in the lower left corner shows the aeromagnetic map published by the IGN [*Ardizone et al.*, 1989] reduced to one third of the scale of the main map.

5. Overview of Gravity and Magnetic Anomalies

[37] The Bouguer anomaly in the Órdenes Complex (Figure 4) shows negative values in the SE corner and positive in the rest of the map, with the zero contour roughly parallel to the coastline but 80–90 km inland. This pattern reflects the progressive thinning of the continental crust toward the coast, and is confirmed by the smooth gradient characterizing the southern third of the map. To the N, several maxima exceeding 35 mGal in the Belmil and Melide units, 50 mGal over the Monte Castelo gabro, 55 mGal over the Fornás amphibolitic unit, and 75 mGal in the Cabo Ortegal Complex (NE corner), are clearly related to the allochthonous units bearing basic and ultrabasic rocks. The 55 mGal anomaly over the Fornás Unit continues toward the NE, indicating the continuation of the unit in depth, beneath the schists and paragneisses of the I*P* upper units. A minimum of less than 10 mGal is associated to the granodiorite of A Coruña.

[38] The main magnetic anomalies (Figure 5) coincide with the ophiolitic and H*P*-H*T* upper units cropping out in the periphery of the central part of the Órdenes Complex. They are mostly related to outcrops of ultrabasic rocks and, with lesser amplitudes, to the amphibolites of Fornás and Arinteiro, characterized by concentrations of massive sulphides, and the greenstones of the Vila de Cruces Unit. The inner part of the complex is characterized by negative anomalies, except for an N-S striking, 20 km wide band where they tend to approach zero and locally reach positive values. Toward the S, this band coincides with the elongated Bouguer anomaly related with the Fornás Unit. In the S of the complex, the Lalín and Forcarei units show local, very weak (±50 nT) anomalies.

[39] The large amplitudes of the Bouguer anomaly are related to basic and, to a lesser extent, ultrabasic rocks, while those of the magnetic anomaly are linked to ultrabasic rocks.

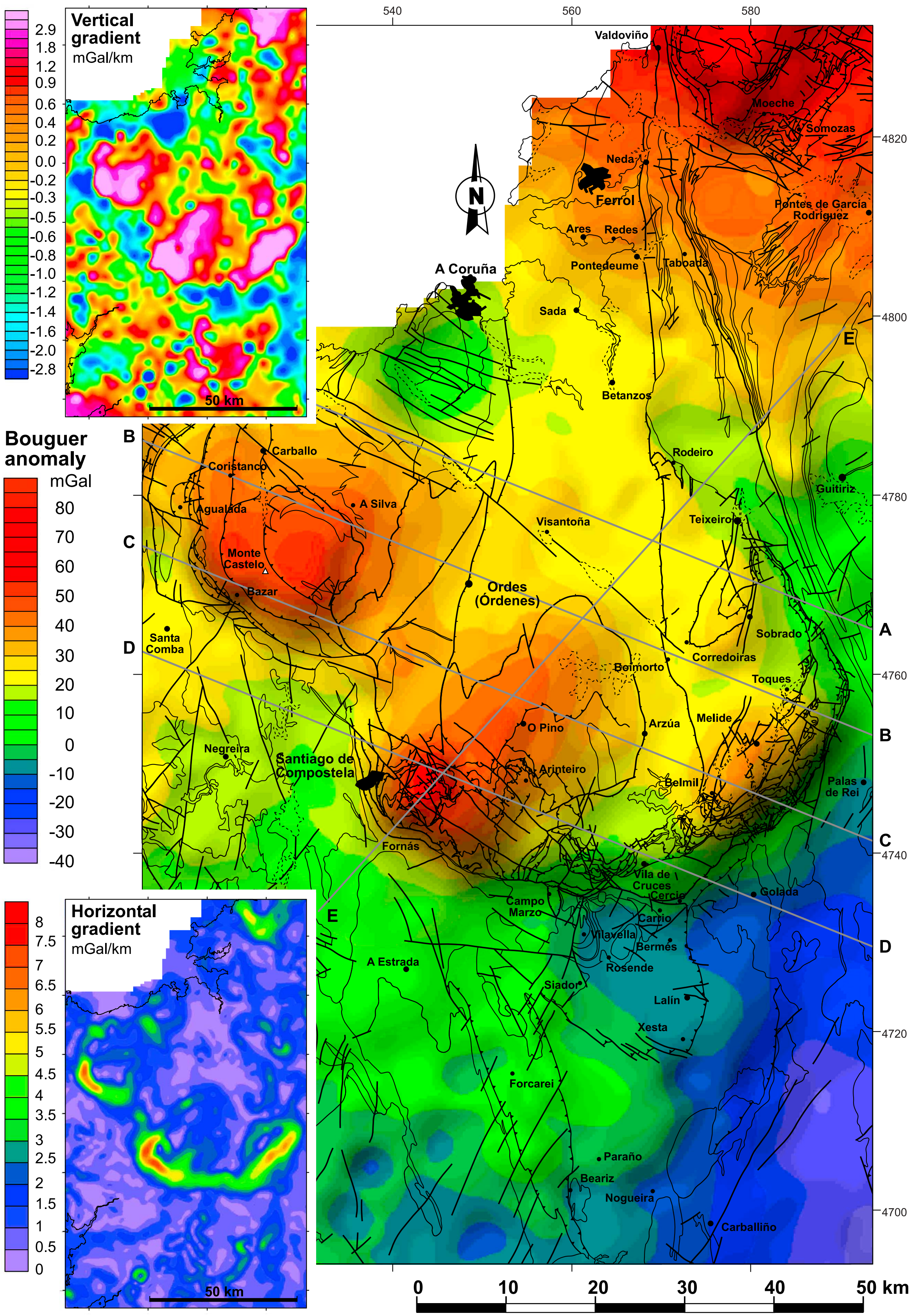
Vertical gradient
mGal/km
2.9
1.8
1.2
0.9
0.6
0.4
0.2
0.0
-0.2
-0.3
-0.5
-0.6
-0.8
-1.0
-1.2
-1.4
-1.6
-2.0
-2.8
50 km
Bouguer anomaly
mGal
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
Horizontal gradient
mGal/km
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
50 km
540
560
580
4820
4800
4780
4760
4740
4720
4700
N
Valdoviño
Moeche
Somozas
Neda
Ferrol
Pontes de Garcia Rodriguez
Ares
Redes
Pontedeume
Taboada
A Coruña
Sada
Betanzos
Rodeiro
Guitiriz
Teixeiro
Carballo
Coristanco
A Silva
Agualada
Visantoña
Monte Castelo
Bazar
Ordes (Órdenes)
Santa Comba
Sobrado
Corredoiras
Boimorto
Toques
Melide
Arzúa
O Pino
Negreira
Santiago de Compostela
Arinteiro
Belmil
Palas de Rei
Fornás
Vila de Cruces
Golada
Campo Marzo
Cercio
Carrio
Vilavella
Bermes
A Estrada
Rosende
Siador
Lalín
Xesta
Forcarei
Paraño
Beariz
Nogueira
Carballiño
A
B
C
D
E
0
10
20
30
40
50 km

Figure 4

Because both basic and ultrabasic rocks occur together in the ophiolitic and H*P*-H*T* upper units, the largest amplitudes of both anomalies coincide. The horizontal gradient of gravity field, shown in the lower left corner of Figure 4, has been found extremely useful in delineating edges between blocks of differing density [*Blakely and Simpson*, 1986]. The steepest horizontal gradients of the gravity anomaly, that are located directly over the edge of the bodies, are in reasonably good agreement with the main magnetic anomalies (Figure 5).

6. Forward 2-D Modeling

6.1. Density and Magnetic Properties

[40] Table 1 summarizes the measured density and magnetic susceptibility of representative rocks of the Órdenes Complex and its relative autochthon. The arithmetic means and standard deviation (σ) of the different groups and some individual units are shown. Density was measured on 280 non-weathered samples from the allochthonous complex and 47 from its relative autochthon with a hydrostatic scale, weighing them first in air and then in water, and applying Archimedes' principle.

[41] High densities of around 3,000 kg/m^3 characterize the basic rocks of the complex, with the highest values yielded by the eclogites and basic granulites of the H*P*-H*T* Sobrado and Melide units. Scarcely serpentinized ultrabasic rocks from these units yielded values close to 3,000 kg/m^3 too, but this kind of rocks are variably and often heavily serpentinized. A mean of 2,820 kg/m^3 was obtained for ultrabasic rocks of the ophiolitic units.

[42] Schists and paragneisses of the complex show values around 2,700 kg/m^3, although higher values are found in the high-pressure schists and paragneisses of the basal units (2,770 kg/m^3). The slates and low-grade Ordovician schists of the autochthon to the E of the Órdenes Complex show also relatively high values, with a mean of 2,710 kg/m^3, but with values up to 2,800 kg/m^3 common in very fresh samples free of quartz veins. Early Ordovician orthogneisses and Variscan granitoids are the lighter rocks, with densities around 2,640 and 2,610 kg/m^3 respectively. The mean of densities measured in the autochthon, 2,673 kg/m^3, is close to the density used to apply the Bouguer plate correction (2,670 kg/m^3).

[43] 399 measurements of the magnetic susceptibility were taken with a Kappameter KT-6 in the allochthonous units, mostly on outcrops but also on samples, and 100 measurements were taken on the relative autochthon. Ultrabasic rocks yield the highest values, which are extremely variable even to the scale of the same outcrop. A mean of 0.04 SI was obtained in both the H*P*-H*T* upper units and in the ophiolitic units, with a maximum of 0.12 SI.

[44] Basic rocks have in general very low magnetic susceptibilities, around 0.001 SI, with a few exceptions. The amphibolites of the Cercio Unit have a mean of 0.04 SI, and the greenschist-facies metabasites of the Vila de Cruces Unit a mean of 0.011 SI, although individual samples from both units may reach values around 0.1 SI. High susceptibility values were found in massive sulphides associated with amphibolites of the Arinteiro and Fornás Units. Mined, open quarries are presently closed and were not accessible, and very few outcrops with fresh sulphides were found, but a few samples from the collection of the Universidad de Salamanca were available. Values ranging from 0.001 to 0.08 SI were measured in them, with 0.005 to 0.03 SI being the most common.

[45] The metasediments, orthogneisses and granites show practically no ferromagnetic behaviour at all, and only the felsic orthogneisses of the basal units reach 0.001 SI.

[46] Natural Remanent Magnetization (NRM) was investigated in a few samples of basic and ultrabasic rocks showing high intensity of remanence values (Table 2). The analyses were performed in the Laboratory of Paleomagnetism of the Universidad de Burgos using a cryogenic magnetometer 2 G-Enterprises. Two samples of ultrabasic rocks from the ophiolitic units with magnetic remanence exceeding the measuring rank of the cryogenic magnetometer were measured with an AGICO JR5A spinner magnetometer.

[47] The relationships between Natural Remanent Magnetization (NRM) and magnetic susceptibility of the samples investigated is shown in Figure 6, with indication of isolines of the Königsberger ratio (Qn) between remanent and induced magnetization. The remanence is relatively high in one of the two samples of the Vila de Cruces greenstones (Qn = 0.69) and in one amphibolite from the Cercio Unit (Qn = 0.34). Remanence is high to extremely high in the ultrabasic rocks of the ophiolitic units, but also quite variable, with Königsberger ratios ranging between 0.5 and 114. In these cases the remanent magnetization can be considered as significant comparing with the induced magnetization. The orientation of the magnetic remanence is also quite variable from one sample to the other, even for adjacent drill cores and for different parts of the same drill core.

6.2. Modeling Procedure

[48] Modeling has been limited to the central part of the Órdenes Complex, as it is the wider and the one with more units involved. It forms a band striking W-E, up to 82 km wide, on which all the allochthonous units described are represented or can be projected down-plunge from the southern part of the complex. Four parallel sections (A-D) and one cutting across them at an angle of 70° (E) have been selected for modeling. The parallel sections have a N112°E strike, roughly normal to the structural grain, mostly defined by large, NNE-SSW folds (Figures 2 and 3), and are separated 11 km from each other. The transverse section has a N42°E strike and runs along the axis of the Bouguer anomaly linked to the Fornás Unit.

[49] The sections have been designed to cut across the significant units with basic and ultrabasic rocks, which are the sources of the main gravity and magnetic anomalies. Section A crosses the Bazar and Careón ophiolites and the Sobrado H*P*-H*T* upper unit, sections B and C cross the same ophiolites, the Monte Castelo gabbro and the Melide and

Figure 4. Bouguer anomaly map of the Órdenes Complex. Contour interval is 5 mGal, and UTM coordinates are in km. The location of modeled sections A to E is shown and the main geological contacts are depicted to allow comparison with Figure 2. The inset in the upper and lower left corners shows respectively the vertical and horizontal gravity gradients to one third of the scale of the main map and contour intervals in mGal/km.

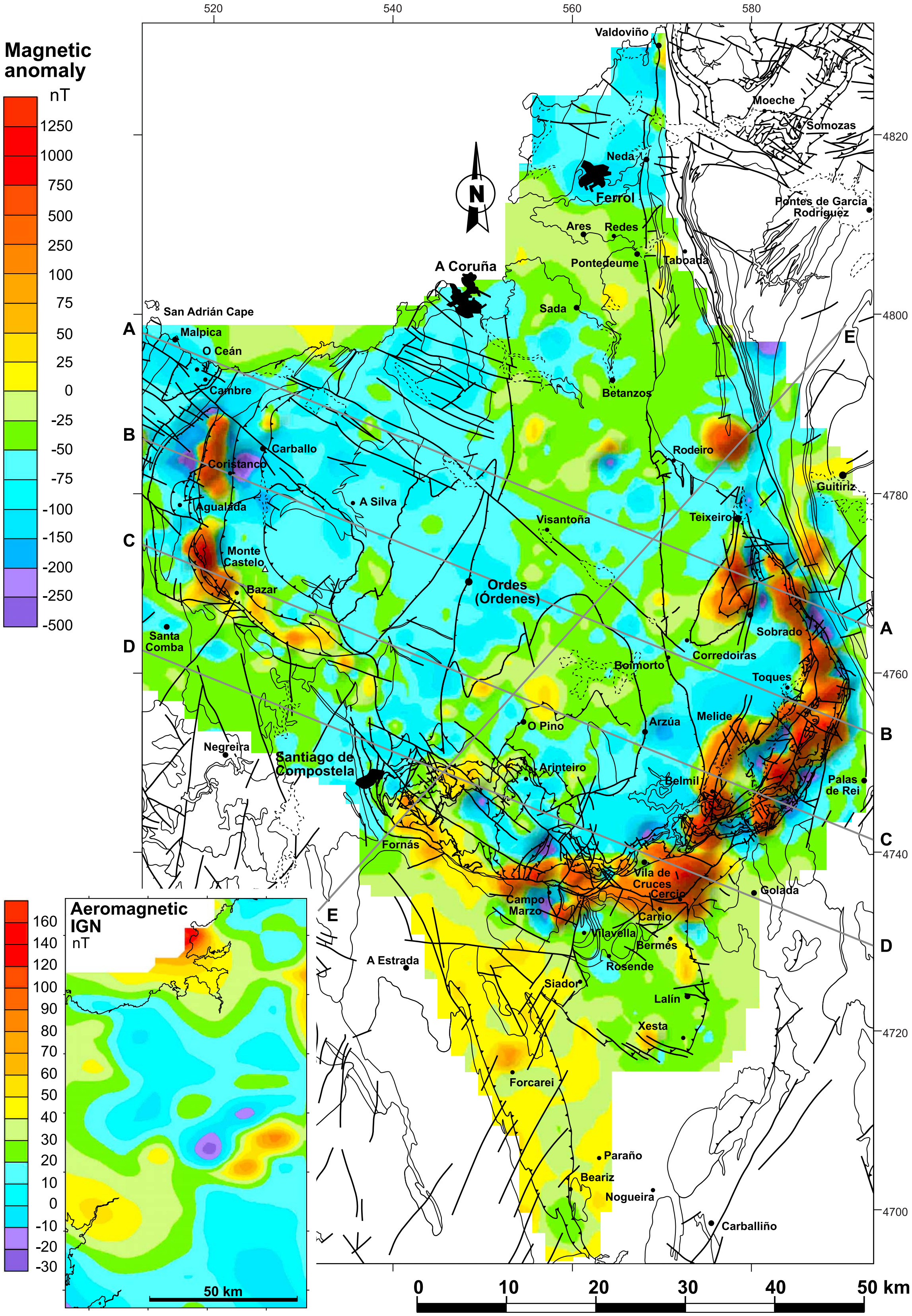

Figure 5. Magnetic anomaly map of the Órdenes Complex including the main geological contacts and the location of modeled sections A to E. The inset in the lower left corner shows the aeromagnetic residual anomaly after *Ardizone et al.* [1989] to one third of the scale of the main map.

Table 1. Measurements of Density and Magnetic Susceptibility in the Órdenes Complex and Its Relative Autochthon

		Density ρ (kg/m3)			Susceptibility κ (SI)		
Group	Lithology	N°	Mean	σ	N°	Mean	σ
I*P* Upper units	Slates, schists, and paragneisses	9	2686	67	58	0.0003	0.0001
	Granitic orthogneisses	27	2641	108	35	0.0002	0.0002
	Gabbros and amphibolites	15	2953	60	29	0.0009	0.0012
H*P*-H*T* Upper units	Paragneisses	5	2702	37	5	0.0003	0.0001
	Mafic rocks	47	3046	156	56	0.0008	0.0012
	Amphibolites (Fornás Unit)	21	2999	101	39	0.0006	0.0002
	Ultramafic rocks	2	2970	91	12	0.0376	0.0246
Ophiolitic units	Flasergabbros and amphibolites	66	2966	93	34	0.0010	0.0011
	Serpentinized ultramafic rocks	7	2823	272	47	0.0426	0.0288
	Phyllites and schists	22	2703	175	1	0.0004	–
	Greenschist-facies metabasites	19	2773	180	18	0.0105	0.0178
Basal units	Schists and paragneisses	20	2767	89	13	0.0003	0.0002
	Felsic orthogneisses	6	2642	111	9	0.0013	0.0037
	Amphibolites (Santiago-Lalín Units)	14	2929	68	7	0.0006	0.0003
	Amphibolites (Ceán Unit)	–	–	–	26	0.0092	0.0189
	Amphibolites (Cercio Unit)	–	–	–	10	0.0403	0.0262
Relative autochthon	Slates and low-grade schists	22	2711	81	18	0.0002	0.0001
	High-grade schists and paragneisses	12	2674	77	13	0.0002	0.0001
	Metavolcanics	2	2596	33	6	0.0002	0.0001
	All metasediments and volcanics	36	2692	82	37	0.0002	0.0001
	Variscan granitoids	11	2608	71	63	0.0001	0.0001
	All rocks of the relative autochthon	47	2673	87	100	0.0001	0.0001

Belmil H*P*-H*T* upper units, section D crosses the Fornás and Vila de Cruces units, and section E crosses the four previous sections cutting the Fornás Unit following the large axis of the associated Bouguer anomaly.

[50] Forward 2¾-D modeling (Figures 7 and 9) was carried out using commercial software GM-SYS 4.7 and 7.3 of Northwest Geophysical Association on both the Bouguer gravity anomaly and the magnetic anomaly, with the length of all allochthonous units in the direction normal to the section being limited according to the geological map and the anomalies themselves.

[51] The standard model densities (ρ) of the different lithologies were taken from the mean values of Table 1, and rounded to the closest multiple of 10. They are listed in kg/m^3 in the legend inserted in section C of Figure 9 together with the corresponding standard values of the magnetic susceptibility (κ) in SI units. When a different value of density and/or susceptibility was used, it is included in the corresponding section in red color, indicating the unit or part of the unit with values differing from the standards.

[52] The remanent magnetization has been considered in some bodies of ultrabasic rocks and amphibolites. Some correspond to the values listed in Table 2, but in many cases, their inclusion in the models produced results at odds with the measured anomalies, so that alternative values were chosen to fit them. In the bodies modeled with remanent magnetization, it is indicated in red characters as NRM followed by the magnetization in A/m and the declination and inclination angles. But its meaning is not clear due to the extreme variability of the NRM vector. It is interpreted as resulting from a sum of components whose importance varies for the different units, outcrops, samples and cores.

Table 2. Magnetic Remanence and Königsberger Ratio of Samples With High NRM Values[a]

			Remanent Magnetization				
Group	Unit	Lithology	NRM (A/m)	Decl. (deg)	Incl. (deg)	Susceptibility κ (SI)	Königsberger Ratio Qn
H*P*-H*T* Upper units							
	Sobrado	Serpentinized ultramafic rock	0.41	27	47	0.0249	0.47
Ophiolitic units							
	Bazar	Serpentinized ultramafic rock	1.17	158	37	0.0542	0.55
	Bazar	Serpentinized ultramafic rock	291.63	96	26	0.0703	113.56
	Careón	Serpentinized ultramafic rock	249.83	317	−43	0.1097	59.36
	Careón	Serpentinized ultramafic rock	2.61	169	72	0.0616	1.17
	Vila de Cruces	Greenschist-facies metabasite	0.13	37	70	0.0428	0.08
	Vila de Cruces	Greenschist-facies metabasite	2.59	350	27	0.1045	0.69
Basal units							
	Cercio	Amphibolite	0.86	352	48	0.0701	0.34

[a]All values are means of 8–10 analyses of cores from the same sampling site.

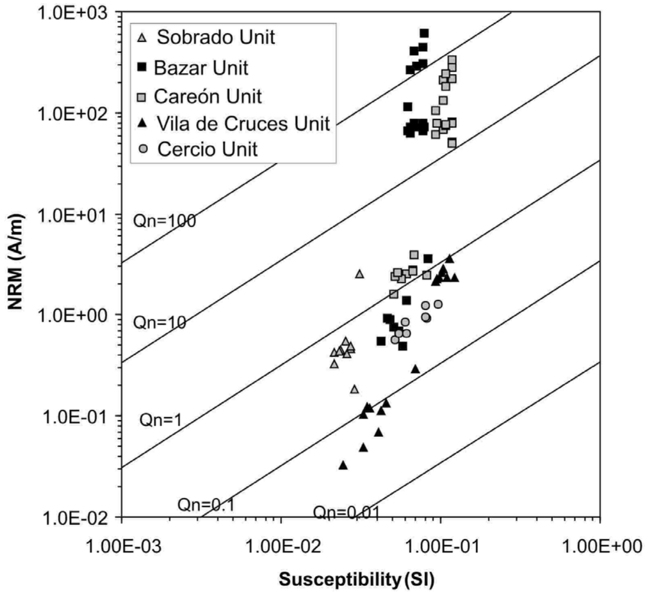

Figure 6. Natural Remanent Magnetization (NRM) versus susceptibility of rocks from magnetically significant units of the Órdenes Complex, with isolines of the Königsberger ratio (Qn) indicated. Logarithmic scale.

Specifically, the different contribution of viscous components to the NRM, carried by a variable amount of unstable magnetic grains explains the directional variability. The purpose of assigning values to them is to show that some bodies are better modeled adding remanence to their induced magnetization, considering that remanence is much higher than induced magnetization.

[53] No separation of regional and residual gravity anomalies was made, implying that the models must take into account large possible anomaly sources such as the geometry of the Moho discontinuity or heterogeneities deep in the crust. A deeper Moho to the E of the Órdenes Complex, or an anomalously low-density crust there is necessary to fit the regional anomaly in the models. But while the low-density anomaly is unjustified, as granites are much more abundant around and to the W of the Órdenes Complex than to the E, a deeper Moho is supported by published seismic data.

[54] Onland refraction/wide-angle seismic data acquired in the area show the Moho weakly ascending toward the NW [*Córdoba et al.*, 1987].In addition, two vertical incidence seismic reflection profiles shot offshore, ESCIN-3.2 and ESCIN-3.3 [*Alvarez-Marrón et al.*, 1996; *Ayarza et al.*, 1998, 2004], , show the lower crust thicker to the E, under the West Asturian-Leonese Zone, than to the W, under the allochthonous complexes (see Figure 8 and location of the profiles in Figure 1). The Moho discontinuity is assumed to occur at the base of a narrow, highly reflective band at 8–10 s (two way travel time) in profile ESCIN-3.2 and the westernmost edge of profile ESCIN-3.3, and below a broad reflective band starting at 7 s and going down to more than 12 s in the rest of the latter.

[55] It has been proposed that the Moho drop, from 8–9 to 12–13 seconds, roughly equivalent to a jump from 28–30 to 36–40 km, is due to the imbrication of the Cantabrian Zone basement beneath the West Asturian-Leonese Zone. The Cantabrian Zone (Figure 1) is a thin-skinned thrust belt, 180 km wide and shortened more than 50%. Around 100 km of its original basement moved to the W, apparently underthrusting that of the West Asturian-Leonese Zone, late in Variscan times, and escaping late-Variscan crustal re-equilibration which affected more internal domains [*Ayarza et al.*, 1998, *Martínez Catalán et al.*, 2003].

[56] According to the previous considerations, the geometry of the Moho and that of the boundary between upper and lower crust were included in the gravity models together with that of the allochthonous units (Figures 7 and 9), using the seismic data as a reference. The upper and middle crust includes the relative autochthon of the Órdenes Complex, and has been modeled with a mean density of 2,670 kg/m^3 and zero magnetic susceptibility. For the lower crust, a density of 2,900 kg/m^3 has been assumed, and for the mantle, 3,260 kg/m^3, following *Ayarza and Martínez Catalán* [2007].

[57] In the case of the magnetic anomaly, no residual was separated because the only significant sources of anomalies are assumed to occur in the Órdenes Complex. Other possible sources are equivalent units in the Cabo Ortegal Complex, to the NE, but they are too far (more than 45 km from section A) to significantly affect the modeling of the Órdenes allochthonous units. The magnetic source occurring to the E, in the Lugo Dome [*Aller et al.*, 1994; *Ayarza and Martínez Catalán*, 2007], might cause a general increase of the anomalies to the ESE, as it is at only 10 km apart from sections A and B. However, this anomaly shows a strong gradient and quickly disappears to the W. As no smooth increase of the anomaly occurs in any of the sections of the Órdenes Complex to the E, the influence of the Lugo Dome is assumed to be negligible.

6.3. Interpretation of Model Sections

[58] Figure 7 shows the resulting geometry of the main crustal units modeled: the allochthonous complexes, the upper and middle crust of the relative autochthon, the lower continental crust and the mantle. The Órdenes Complex appears as an open synform with second order open folds, which has not any reflect in the underlying lower crust or the Moho discontinuity.

[59] Figure 9 shows the modeling of the allochthonous units with their more common lithologies, and the observed and calculated Bouguer and magnetic anomalies. These are numbered from 1 to 12 (plus the relative autochthon) in the legend inserted in section D and described in the figure caption.

[60] The western part of sections A and B cut the Malpica-Tui Complex, which causes a positive gravity anomaly related to the relatively high density of its metasediments and that of a granodioritic orthogneiss. This complex is bounded by steeply dipping faults and according to the models reaches a depth of 6–7 km, in agreement with the geological interpretation of *Díez Fernández et al.* [2011]. The two sections continue through the metasediments and granitoids of the parautochthon, characterized by a gravity low, and together with section C cross the whole Órdenes Complex at its central, broadest part.

[61] Gravity highs appear associated to basic and ultrabasic rocks of the ophiolitic units of Bazar, to the W, and

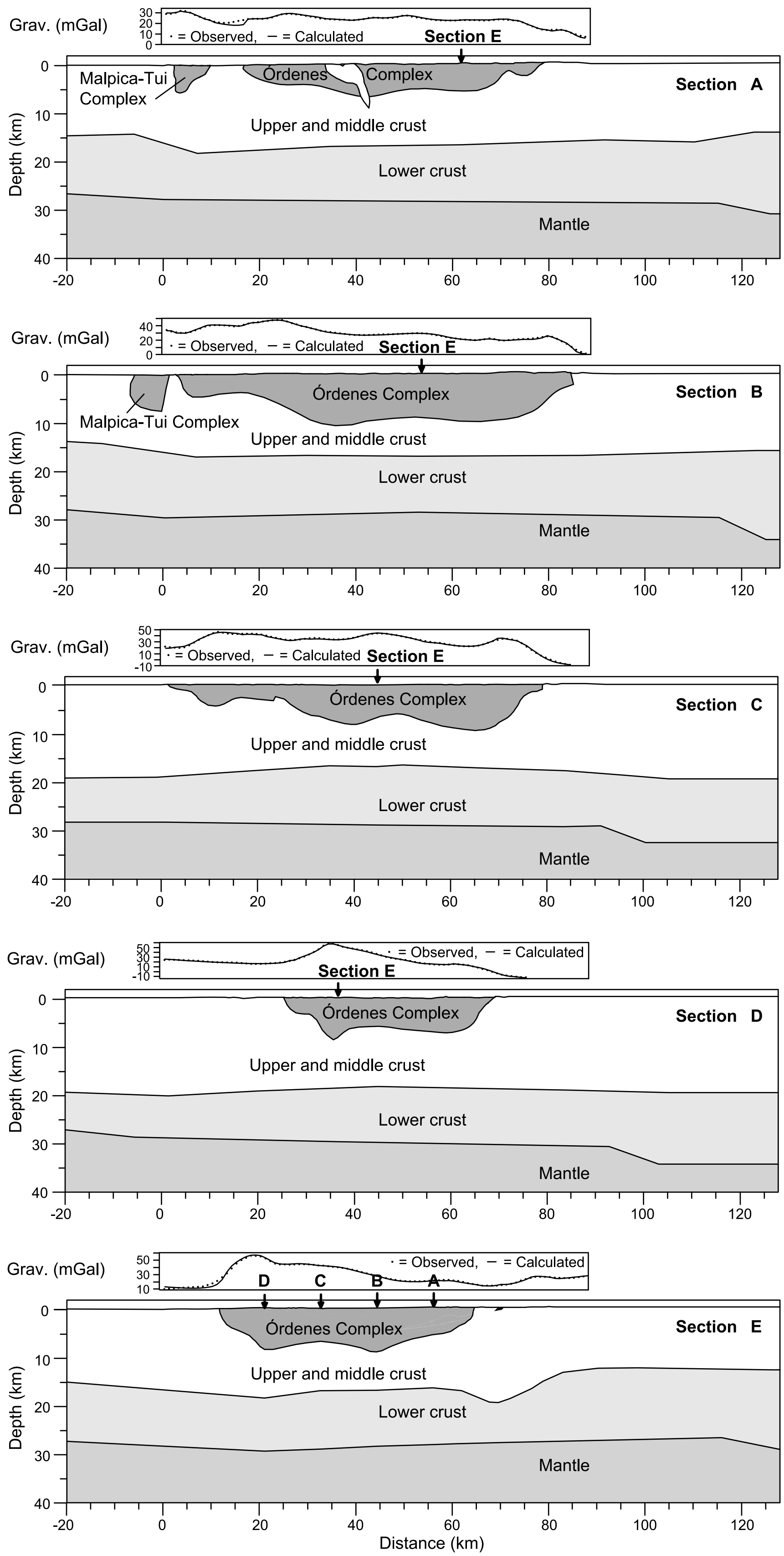
Grav. (mGal)
· = Observed, — = Calculated
Section E
Malpica-Tui Complex
Órdenes Complex
Section A
Section B
Section C
Section D
Section E
D
C
B
A
Upper and middle crust
Lower crust
Mantle
Depth (km)
Distance (km)

Figure 7

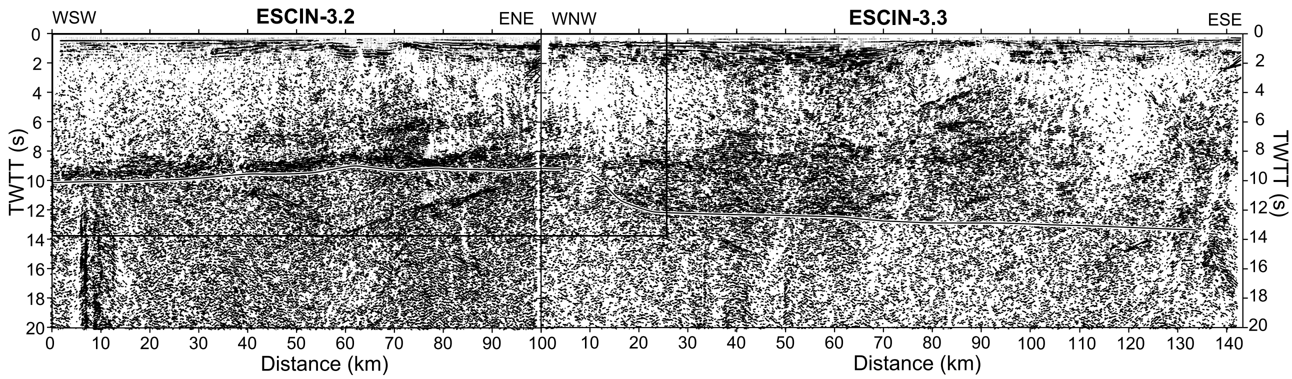

Figure 8. Marine seismic reflection profiles ESCIN-3.2 and ESCIN-3.3 [*Alvarez-Marrón et al.*, 1996; *Ayarza et al.*, 1998]. The Moho discontinuity (black line) is assumed to occur at the base of highly reflective lower crust. The rectangle in the left half indicates approximately the equivalent part of the crust and mantle modeled in sections A and B.

Careón, to the E, to the gabbroic massif of Monte Castelo, and to the H*P*-H*T* units of Sobrado, Melide and Belmil, in the eastern part of the complex (Figure 9). The anomaly related to the gabbro massif can be identified up to section A, where it does not longer outcrop (Figure 2), indicating the buried continuation of the Monte Castelo Unit to the NNE.

[62] The same occurs with the Fornás Unit, a massive amphibolitic body cropping out to the S of section D, but whose gravimetric imprint continues up to section A. This body causes the largest Bouguer anomaly of the Órdenes Complex (55 mGal), that *Keasberry et al.* [1976] interpreted as a deep-rooted structure supporting an autochthonous interpretation for the complexes. In sections D and E, it is modeled as a lens progressively thicker to the W and SW, where its depth reaches up to 6 km. Our models reinforce the allochthonous interpretation and show that the Fornás Unit is the largest mafic body of the Órdenes Complex, a conclusion not evident from the map. Its upper boundary is affected by recumbent folds and thrusts, and its bottom is cut by an important thrust fault reactivated as an extensional detachment [*Gómez Barreiro et al.*, 2006, 2007, 2010a]. Its abrupt western termination (Figure 9, sections D and E) is interpreted as a normal fault, associated to the Pico Sacro detachment (PSD) and partially occupied by a quartz dike (Figure 2). To the N, the continuation of the Fornás Unit is suggested by open gravity highs in the central part of sections A, B, C and E, which have been modeled with an irregular amphibolite body reaching a thickness of 2–3 km.

[63] Additional features are weak gravity lows occurring above the granodiorite of A Coruña (section A) and where the metasediments of the I*P* upper units are thick. A relatively dense body (2,760 kg/m^3) has been included to the E in sections A, B, and E to fit the Bouguer anomaly. They represent relatively dense, Early Ordovician schists of the Iberian autochthon.

[64] According to the models, the maximum depth reached by the Órdenes Complex is around 9 km, locally 10 km in section B, where the complex has its maximum width. However, this depth should be considered with caution, as the density contrast between the basal units and the relative autochthon is weak. The maximum depth of the massive basic and ultrabasic rocks, that is, of the rocks marking the suture and those above it, does not exceed 6–7 km.

[65] The main magnetic anomalies are associated with the ultrabasic rocks of the ophiolitic and H*P*-H*T* upper units. The highly serpentinized bodies of the ophiolitic units of Bazar (in the W), Careón, and Vila de Cruces (in the E), and the H*P*-H*T* upper units of Sobrado, Melide and Belmil (in the E), are responsible for local anomalies exceeding 1000 nT. But despiking and gridding have smoothed the values, that in the chosen sections do not exceed 700 nT (Figures 5 and 9). A remanent magnetization has been included to fit the observed values in some of the ultrabasic bodies of the Bazar, Careón, Vila de Cruces, Sobrado, and Melide units, and in one supposedly occurring as an enclave in granitoids in what could be the continuation to the N of the Sobrado Unit (Figures 2, 5, and 9, section E).

[66] Minor magnetic anomalies in the central part of the Órdenes Complex, occupied by metasediments of the I*P* upper units, may be related with the Arinteiro Unit, a thin layer of amphibolite partly mineralized with massive sulphides, which crops out between sections C and D in an open, N-plunging antiform. The weak magnetic highs in sections A to C and E, probably correspond to the buried continuation of this layer, for which a magnetic susceptibility of 0.080 SI has been used in the models. Other mineralized amphibolite bodies occur at the core and toward the top of the Fornás Unit, and explain similar magnetic highs in sections D and E. This magnetic anomaly continues further

Figure 7. Geometry of the main crustal units deduced from gravity modeling of sections A to E. The Bouguer anomaly is shown on top of model sections. The Órdenes Complex appears as an open synform with no reflect on the underlying lower crust and the Moho discontinuity. The upper and middle crust have been modeled with a mean density of 2,670 kg/m^3, the lower crust with 2,900 kg/m^3, and the mantle with 3,260 kg/m^3. All of them are supposed to have negligible magnetic susceptibility. For densities and magnetic susceptibilities used in the Órdenes and Malpica-Tui complexes, see Figure 9. The intersection of each section with the others is indicated with arrows.

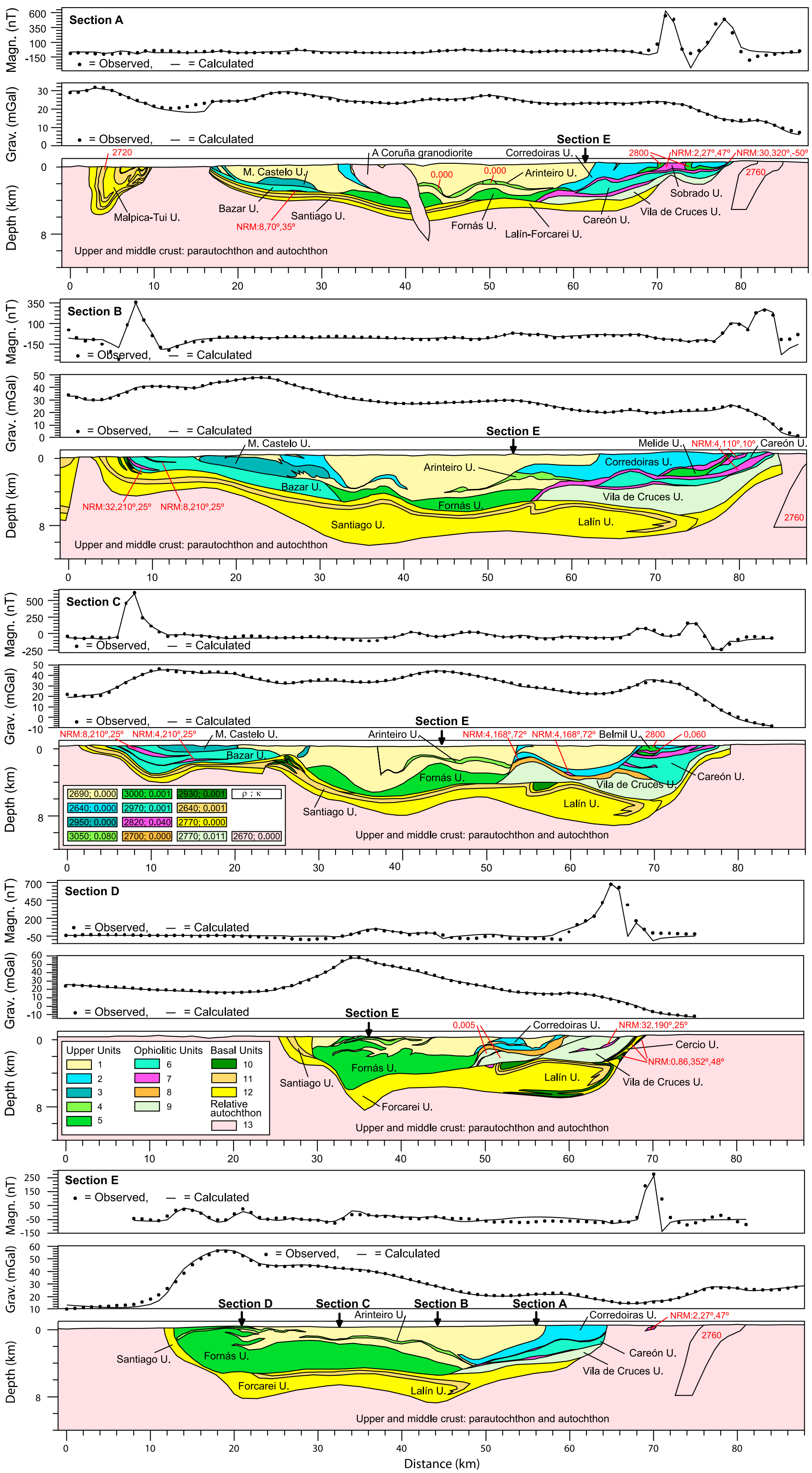
Section A
Section B
Section C
Section D
Section E
Magn. (nT)
Grav. (mGal)
Depth (km)
• = Observed, — = Calculated
A Coruña granodiorite
Corredoiras U.
Arinteiro U.
M. Castelo U.
Bazar U.
Santiago U.
Malpica-Tui U.
Fornás U.
Lalín-Forcarei U.
Lalín U.
Forcarei U.
Sobrado U.
Vila de Cruces U.
Careón U.
Melide U.
Belmil U.
Cercio U.
Upper and middle crust: parautochthon and autochthon
Upper Units
Ophiolitic Units
Basal Units
Relative autochthon
Distance (km)

Figure 9

N through O Pino up to Ferrol, showing a change in orientation from SW-NE to S-N.

7. Implications for Orogenic Processes

[67] In contrast with the common preservation of sutures as steeply dipping shear zones, the nappe mode of occurrence of that of NW Iberia, cropping out in five complexes over an area 300 km long and 100 km wide, helps to individualize allochthonous units of different provenance and meaning, characterize their lithological associations, identify different metamorphic signatures and metamorphic gradients, find crosscutting relationships, and establish their tectonic evolution. Insights on the geometry of the allochthonous units can be obtained from the geological maps and down-plunge continuation of folds in cross sections, but as they contain large massifs with contrasting physical properties, potential field data have been used to further constrain the geometry of those in the largest of the allochthonous complexes in Iberia.

[68] The gravity and magnetic models of the Órdenes Complex confirm previous ideas concerning the tectonic meaning of the allochthonous complexes of NW Iberia and support some of the orogenic processes invoked for their emplacement and evolution. The main of them is the fact that they represent an allochthonous, rootless suture, whose emplacement and subsequent deformation resulted in dismembering of the units involved.

[69] All allochthonous units had been much thicker than their presently preserved parts, according to the peak pressures yielded by thermobarometric calculations [*Gil Ibarguchi et al.*, 1990; *Arenas et al.*, 1995; *Gómez Barreiro et al.*, 2007]. The lens-shaped geometry of most units and the pinch and swell aspect of the rest, which is confirmed by the models, has been explained in part by repeated thrusting (accretionary plus out-of-sequence thrusts related to emplacement), and in part by extensional tectonics [*Martínez Catalán et al.*, 2002]. Large extensional detachments developed both during emplacement by thrusting [*Martínez Catalán et al.*, 1996; *Díaz García et al.*, 1999a; *Díez Fernández et al.*, 2011], and during the later extensional collapse of the orogen [*Gómez Barreiro et al.*, 2010a; *Díez Fernández et al.*, 2012].

[70] The fact that the Órdenes Complex appears as a large, open synform with no apparent reflect in the underlying lower crust and the Moho discontinuity provides insights on the late Variscan extensional collapse to a crustal scale. Gneiss domes and abundant syn- to late kinematic granitoids surround the complex, which seems to occupy the place left by lateral, centrifugal flow of the underlying crust. The gravity models support the hypothesis of *Block and Royden* [1990] that isostatic compensation in orogens occurs primarily by regional-scale flow of material within the relatively low-viscosity part of the crust instead of the mantle. In NW Iberia, the middle and lower crust was hot enough towards the end of the Variscan cycle as to underwent partial melting, and behaved as a low viscosity layer permitting domes to rise [*Martínez Catalán et al.*, 2007, 2009; *Alcock et al.*, 2009], accompanied by voluminous granitic intrusions, while allowing the Moho to remain flat. Only underthrusting of the basement of the Cantabrian Zone beneath the West Asturian-Leonese Zone in late Variscan times escaped re-equilibration creating a Moho steep to the E of the modeled sections.

[71] The lower boundary of the middle crust is also rather smooth, but is somewhat elevated beneath the Órdenes Complex in sections C, D, and E (Figure 7), a possible additional indication of centrifugal crustal flow.

[72] Evidence of bending about a vertical axis of the Fornás and Arinteiro units is provided by a wide, 75 km long magnetic anomaly running from Fornás through Arinteiro and O Pino with a SW-NE attitude, and then rotating anticlockwise to a S-N strike up to Ferrol. Also the gravity high above the Fornás Unit can be followed to the N by weak maxima that correlate with the magnetic anomaly, easier to follow in the map of vertical gradient included in the upper left corner of Figure 4. The bend is probably related with the formation of the Central Iberian arc, whose core is occupied by the allochthonous complexes, and represents part of its NE limb.

8. Conclusions

[73] Potential field data have been used to constrain the geometry of the Órdenes Complex and its units. Gravity and magnetic models confirm previous ideas about the tectonic meaning of the allochthonous complexes of NW Iberia and support some of the orogenic processes invoked for their emplacement and evolution. Gravity is the main tool for constraining the overall geometry of the complex and the shape and depth of significant units. An open synform with maximum depths of 9–10 km contrasts with the smooth geometry of the middle-lower crust interface and the flat Moho discontinuity. This suggests that low-viscosity crust underlying the complex underwent lateral flow during late Variscan extension and collapse, moving apart from it to form gneiss domes to the E and W. This was the main cause of preservation of the allochthonous stack there, a conclusion that can be extended to the rest of allochthonous complexes of NW Iberia. The maximum depth reached by the

Figure 9. Gravity and magnetic models for sections A to E showing only the continental crust including the complexes of Órdenes and part of Malpìca-Tui. The standard model densities (in kg/m^3) and magnetic susceptibilities (SI units) are depicted in the inset in section C. When a different value of density and/or magnetic susceptibility was used, or a magnetic remanence (NRM in A/m, declination, inclination) was included in the model, the values differing from the standards are indicated by labels with red characters. Colors of the allochthonous units correspond approximately to those used on Figures 2 and 3, and are listed in the inset in section D: I*P* upper units: 1- metasediments; 2- granitic orthogneisses; 3- gabbros and amphibolites; 4- amphibolites bearing massive sulphides. H*P*-H*T* upper units: 5- basic granulites, amphibolites and scarce paragneisses. Ophiolitic units: 6- flasergabbros and amphibolites; 7- serpentinized ultrabasic rocks (also in the H*P*-H*T* upper units); 8- phyllites and schists; 9- greenschists-facies metabasites. Basal units: 10- amphibolites; 11- felsic and granodioritic orthogneisses; 12- schists and paragneisses. Parautochthon and autochthon: 13- metasediments, orthogneisses and Variscan granitoids. The intersection of each section with the others is indicated with arrows.

rootless suture of the Rheic Ocean, represented by the ophiolitic units, is around 6–7 km.

[74] The Bouguer gravity anomalies and, to a lesser extent, the magnetic anomalies, corroborate that the allochthonous units formed by basic and ultrabasic rocks are lens-shaped, as suggested by the geologic map and confirmed by structural interpretations. However, dense and in many cases magnetically strong rocks do not only occur at the periphery of the Órdenes Complex, as the geological map might suggest, but form bands trending N-S to NE-SW, as demonstrated by the down-plunge continuation of the Monte Castelo gabbro and the Fornás amphibolites to the NE and N.

[75] The Fornás Unit, which had been interpreted as a deep-rooted structure favoring an autochthonous interpretation of the complexes, can be modeled as a massive but rootless amphibolite body reaching a maximum thickness of 6 km in the downthrown NE block of the Pico Sacro normal fault, and showing a progressively decreasing thickness to the N, NE and E.

[76] The main magnetic anomalies are associated with the ultrabasic rocks of the ophiolitic and H*P*-H*T* upper units cropping out in the NW and SE of the Órdenes Complex. Minor magnetic anomalies in its central part are related with one or more thin layers of amphibolite partly mineralized with massive sulphides, mostly occurring on top or above the Fornás Unit.

[77] The U-shaped string delineated by basic and ultrabasic units in the periphery of the central part of the Órdenes Complex does not represent the core of the Central Iberian arc. However, the weakly arcuate form of a 75 km long magnetic anomaly, which rotates from a SW-NE attitude in the S to an S-N trend northward, reflects the NE flank of the arc.

[78] **Acknowledgments.** This contribution has been funded by the research projects BTE2001-0963-C02-01, CGL2004-04306-C02-01/BTE, CGL2007-65338-C02-02/BTE, and CGL2011-22728 of the Dirección General de Investigación (Spanish Ministry of Science and Innovation), co-financed by European Funds of Regional Development (FEDER). We thank I. Socías, of the Instituto Geográfico Nacional, and J. M. Miranda, of the Centro de Geofisica da Universidade de Lisboa, for providing the data used in plotting the map of magnetic anomalies of the Iberian Peninsula. We are also grateful to C. Moro and M. L. Cembranos, of the Departamento de Geología, Universidad de Salamanca, for facilitating samples of massive sulphides from Fornás and Arinteiro to carry out measurements of the magnetic susceptibility. J. G. B. thanks financial support by the Spanish Ministry of Science and Innovation through the Ramón y Cajal program. J. B. Edel and J. M. Lardeaux are kindly acknowledged for their comments and recommendations, which contributed to improve the manuscript.

References

Aerden, D. G. A. M. (2004), Correlating deformation in Variscan NW-Iberia using porphyroblasts; implications for the Ibero-Armorican Arc, *J. Struct. Geol.*, *26*, 177–196, doi:10.1016/S0191-8141(03)00070-1.

Alcock, J. E., J. R. Martínez Catalán, R. Arenas, and A. Díez Montes (2009), Use of thermal modelling to assess the tectono-metamorphic history of the Lugo and Sanabria gneiss domes, Northwest Iberia, *Bull. Soc. Geol. Fr.*, *180*, 179–197, doi:10.2113/gssgfbull.180.3.179.

Aller, J., H. J. Zeyen, A. Pérez-Estaún, J. A. Pulgar, and J. M. Parés (1994), A 2.5D interpretation of the eastern Galicia magnetic anomaly (northwestern Spain): Geodynamical implications, *Tectonophysics*, *237*, 201–213, doi:10.1016/0040-1951(94)90255-0.

Alvarez-Marrón, J., et al. (1996), Seismic structure of the northern continental margin of Spain from ESCIN deep seismics profiles, *Tectonophysics*, *264*, 153–174, doi:10.1016/S0040-1951(96)00124-2.

Ardizone, J., J. Mezcua, and I. Socías (1989), Mapa aeromagnético de España peninsular, Escala 1:1.000.000, Inst. Geogr. Nac., Madrid.

Arenas, R., F. J. Rubio Pascual, F. Díaz García, and J. R. Martínez Catalán (1995), High-pressure micro-inclusions and development of an inverted metamorphic gradient in the Santiago Schists (Ordenes Complex, NW Iberian Massif, Spain): Evidence of subduction and syn-collisional decompression, *J. Metamorph. Geol.*, *13*, 141–164, doi:10.1111/j.1525-1314.1995.tb00211.x.

Arenas, R., J. R. Martínez Catalán, S. Sánchez Martínez, F. Díaz García, J. Abati, J. Fernández-Suárez, P. Andonaegui, and J. Gómez Barreiro (2007a), Paleozoic ophiolites in the Variscan suture of Galicia (northwest Spain): Distribution, characteristics and meaning, in *4-D Evolution of Continental Crust*, edited by R. D. Hatcher Jr. et al., *Mem. Geol. Soc. Am.*, *200*, 425–444, doi:10.1130/2007.1200(22).

Arenas, R., J. R. Martínez Catalán, S. Sánchez Martínez, J. Fernández-Suárez, P. Andonaegui, J. A. Pearce, and F. Corfu (2007b), The Vila de Cruces Ophiolite: A remnant of the early Rheic Ocean in the Variscan suture of Galicia (NW Iberian Massif), *J. Geol.*, *115*, 129–148, doi:10.1086/510645.

Arenas, R., S. Sánchez Martínez, P. Castiñeiras, T. E. Jeffries, R. Díez Fernández, and P. Andonaegui (2009), The basal tectonic mélange of the Cabo Ortegal Complex (NW Iberian Massif): A key unit in the suture of Pangea, *J. Iberian Geol.*, *35*, 85–125.

Ayarza, P., and J. R. Martínez Catalán (2007), Potential field constraints on the deep structure of the Lugo gneiss dome (NW Spain), *Tectonophysics*, *439*, 67–87, doi:10.1016/j.tecto.2007.03.007.

Ayarza, P., J. R. Martínez Catalán, J. Gallart, J. J. Dañobeitia, and J. A. Pulgar (1998), Estudio Sísmico de la Corteza Ibérica Norte 3.3: A seismic image of the Variscan crust in the hinterland of the NW Iberian Massif, *Tectonics*, *17*, 171–186, doi:10.1029/97TC03411.

Ayarza, P., J. R. Martínez Catalán, J. Alvarez-Marrón, H. Zeyen, and C. Juhlin (2004), Geophysical constraints on the deep structure of a limited ocean-continent subduction zone at the north Iberian margin, *Tectonics*, *23*, TC1010, doi:10.1029/2002TC001487.

Badham, J. P. N., and P. J. Williams (1981), Genetic and exploration models for sulphide ores in metaophiolites, NW Spain, *Geology*, *76*, 2118–2127.

Bayer, R., and P. Matte (1979), Is the mafic/ultramafic massif of the Cabo Ortegal (NW Spain) a nappe emplaced during a Variscan obduction?—A new gravity interpretation, *Tectonophysics*, *57*, T9–T18, doi:10.1016/0040-1951(79)90138-0.

Blakely, R. J., and R. W. Simpson (1986), Approximating edges of source bodies from magnetic or gravity anomalies, *Geophysics*, *51*, 1494–1498.

Block, L., and L. H. Royden (1990), Core complex geometries and regional scale flow in the lower crust, *Tectonics*, *9*, 557–567, doi:10.1029/TC009i004p00557.

Castaño, S., A. Carbó, and J. R. Martínez Catalán (1981), Investigación de la posición estructural del Complejo de Cabo Ortegal en base a datos gravimétricos y magnetométricos, *Cuad. Geol. Ibérica*, *7*, 471–487.

Castiñeiras, P., J. Gómez Barreiro, J. R. Martínez Catalán, and R. Arenas (2002), Nueva interpretación petrológica y tectónica de las anfibolitas pobres en calcio del antiforme de Arinteiro (NO del Macizo Ibérico). I: Descripción de las anfibolitas pobres en calcio y rocas asociadas, *Geogaceta*, *32*, 83–85.

Córdoba, D., E. Banda, and J. Ansorge (1987), The Hercynian crust in northwestern Spain: A seismic survey, *Tectonophysics*, *132*, 321–333, doi:10.1016/0040-1951(87)90351-9.

Díaz García, F., J. R. Martínez Catalán, R. Arenas, and P. González Cuadra (1999a), Structural and kinematic analysis of the Corredoiras Detachment: Evidence for early variscan orogenic extension in the Ordenes Complex, NW Spain, *Int. J. Earth Sci.*, *88*, 337–351, doi:10.1007/s005310050269.

Díaz García, F., R. Arenas, J. R. Martínez Catalán, J. González del Tánago, and G. Dunning (1999b), Tectonic evolution of the Careón ophiolite (northwest Spain): A remnant of oceanic lithosphere in the Variscan belt, *J. Geol.*, *107*, 587–605, doi:10.1086/314368.

Díez Fernández, R. (2011), *Evolución estructural y cinemática de una corteza continental subducida: La Unidad de Malpica-Tui (NO del Macizo Ibérico)*, *Ser. Nova Terra*, vol. 40, 228 pp., Inst. Univ. Geol. Isidro Parga Pondal, Coruña, Spain.

Díez Fernández, R., J. R. Martínez Catalán, R. Arenas Martín, and J. Abati Gómez (2011), Tectonic evolution of a continental subduction-exhumation channel: Variscan structure of the basal allochthonous units in NW Spain, *Tectonics*, *30*, TC3009, doi:10.1029/2010TC002850.

Díez Fernández, R., J. R. Martínez Catalán, J. Gómez Barreiro, and R. Arenas (2012), Extensional flow during gravitational collapse: A tool for setting plate convergence (Padrón migmatitic dome, Variscan belt, NW Iberia), *J. Geol.*, *120*, 83–103, doi:10.1086/662735.

Farias, P., G. Gallastegui, F. González-Lodeiro, J. Marquínez, L. M. Martín Parra, J. R. Martínez Catalán, J. G. de Pablo Maciá, and L. R. Rodríguez

Fernández (1987), Aportaciones al conocimiento de la litoestratigrafía y estructura de Galicia Central, *Mem. Fac. Ciênc. Univ. Porto*, *1*, 411–431.
Fernández-Suárez, J., R. Arenas, J. Abati, J. R. Martínez Catalán, M. J. Whitehouse, and T. E. Jeffries (2007), U-Pb chronometry of polymetamorphic high-pressure granulites: An example from the allochthonous terranes of the NW Iberian Variscan belt, in *4-D Evolution of Continental Crust*, edited by R. D. Hatcher Jr. et al., *Mem. Geol. Soc. Am.*, *200*, 469–488, doi:10.1130/2007.1200(24).
Gil Ibarguchi, J. I., M. Mendia, J. Girardeau, and J. J. Peucat (1990), Petrology of eclogites and clinopyroxene-garnet metabasites from the Cabo Ortegal Complex (northwestern Spain), *Lithos*, *25*, 133–162, doi:10.1016/0024-4937(90)90011-O.
Gómez Barreiro, J. (2007), *La Unidad de Fornás: Evolución tectonometamórfica del SO del Complejo de Órdenes*, *Ser. Nova Terra*, vol. 32, 291 pp., Inst. Univ. Geol. Isidro Parga Pondal, Coruña, Spain.
Gómez Barreiro, J., P. Castiñeiras, J. R. Martínez Catalán, and R. Arenas (2002), Nueva interpretación petrológica y tectónica de las anfibolitas pobres en calcio del antiforme de Arinteiro (NO del Macizo Ibérico). II: Estructura e implicaciones para la génesis de las anfibolitas pobres en calcio, *Geogaceta*, *32*, 87–90.
Gómez Barreiro, J., J. R. Wijbrans, P. Castiñeiras, J. R. Martínez Catalán, R. Arenas, F. Díaz García, and J. Abati (2006), ^{40}Ar/^{39}Ar laserprobe dating of mylonitic fabrics in a polyorogenic terrane of NW Iberia, *J. Geol. Soc.*, *163*, 61–73, doi:10.1144/0016-764905-012.
Gómez Barreiro, J., J. R. Martínez Catalán, R. Arenas, P. Castiñeiras, J. Abati, F. Díaz García, and J. R. Wijbrans (2007), Tectonic evolution of the upper allochthon of the Órdenes Complex (northwestern Iberian Massif): Structural constraints to a polyorogenic peri-Gondwanan terrane, in *The Evolution of the Rheic Ocean: From Avalonian-Cadomian Active Margin to Alleghenian-Variscan collision*, edited by U. Linnemann et al., *Spec. Pap. Geol. Soc. Am.*, *423*, 315–332, doi:10.1130/2007.2423(15).
Gómez Barreiro, J., J. R. Martínez Catalán, R. Díez Fernández, R. Arenas, and F. Díaz García (2010a), Upper crust reworking during gravitational collapse: The Bembibre-Pico Sacro detachment system (NW Iberia), *J. Geol. Soc.*, *167*, 769–784, doi:10.1144/0016-76492009-160.
Gómez Barreiro, J., J. R. Martínez Catalán, D. Prior, H. R. Wenk, S. Vogel, F. Díaz García, R. Arenas, S. Sánchez Martínez, and I. Lonardelli (2010b), Fabric development in a Middle Devonian intraoceanic subduction regime: The Careón ophiolite (northwest Spain), *J. Geol.*, *118*, 163–186, doi:10.1086/649816.
Hubregtse, J. J. M. W. (1973), Petrology of the Mellid area, a Precambrian polymetamorphic rock complex, Galicia, N.W. Spain, *Leidse Geol. Med.*, *49*, 9–31.
Julivert, M., J. M. Fontboté, A. Ribeiro, and L. Conde (1972), Mapa Tectónico de la Península Ibérica y Baleares, Escala 1:1.000.000, Inst. Geol. y Min. de España, Madrid.
Keasberry, E. J., P. W. C. van Calsteren, and R. P. Kuijper (1976), Early Palaeozoic mantle diapirism in Galicia, *Tectonophysics*, *31*, T61–T65, doi:10.1016/0040-1951(76)90114-1.
Lotze, F. (1929), *Stratigraphie und Tektonik des Keltiberischen Grundgebirges (Spanien)*, *Beitr. Geol. Westlich. Mediterrangeb.*, vol. 3, Weidmann, Berlin.
Lotze, F. (1945a), Einige Probleme des Iberischen Meseta, *Geotekt. Forsch.*, *6*, 1–12.
Lotze, F. (1945b), Zur Gliederung der Varisziden der Iberischen Meseta, *Geotekt. Forsch.*, *6*, 78–92.
Marcos, A., J. Marquínez, A. Pérez-Estaún, J. A. Pulgar, and F. Bastida (1984), Nuevas aportaciones al conocimiento de la evolución tectonometamórfica del Complejo de Cabo Ortegal (NW de España), *Cuad. Lab. Xeol. Laxe*, *7*, 125–137.
Martínez Catalán, J. R. (2011), Are the oroclines of the Variscan belt related to late Variscan strike-slip tectonics?, *Terra Nova*, *23*, 241–247, doi:10.1111/j.1365-3121.2011.01005.x.
Martínez Catalán, J. R. (2012), The Central Iberian arc, an orocline centred in the Iberian Massif and some implications for the Variscan belt, *Int. J. Earth Sci.*, *101*, 1299–1314, doi:10.1007/s00531-011-0715-6.
Martínez Catalán, J. R., R. Arenas, F. Díaz García, F. J. Rubio Pascual, J. Abati, and J. Marquínez (1996), Variscan exhumation of a subducted Paleozoic continental margin: The basal units of the Ordenes Complex, Galicia, NW Spain, *Tectonics*, *15*, 106–121, doi:10.1029/95TC02617.
Martínez Catalán, J. R., F. Díaz Garc, R. Arenas, J. Abati, P. Castiñeiras, P. González Cuadra, J. Gómez Barreiro, and F. Rubio Pascual (2002), Thrust and detachment systems in the Ordenes Complex (northwestern Spain): Implications for the Variscan-Appalachian geodynamics, in *Variscan-Appalachian Dynamics: The Building of the Late Paleozoic Basement*, edited by J. R. Martínez Catalán et al., *Spec. Pap. Geol. Soc. Am.*, *364*, 163–182.
Martínez Catalán, J. R., R. Arenas, and M. A. Díez Balda (2003), Large extensional structures developed during emplacement of a crystalline thrust sheet: The Mondoñedo nappe (NW Spain), *J. Struct. Geol.*, *25*, 1815–1839, doi:10.1016/S0191-8141(03)00038-5.
Martínez Catalán, J. R., J. Fernández-Suárez, G. A. Jenner, E. Belousova, and A. Díez Montes (2004), Provenance constraints from detrital zircon U-Pb ages in the NW Iberian Massif: Implications for Paleozoic plate configuration and Variscan evolution, *J. Geol. Soc.*, *161*, 461–473.
Martínez Catalán, J. R., et al. (2007), Space and time in the tectonic evolution of the northwestern Iberian Massif. Implications for the comprehension of the Variscan belt, in *4-D Evolution of Continental Crust*, edited by R. D. Hatcher Jr. et al., *Mem. Geol. Soc. Am.*, *200*, 403–423, doi:10.1130/2007.1200(21).
Martínez Catalán, J. R., J. Fernández-Suárez, C. Meireles, E. González Clavijo, E. Belousova, and A. Saeed (2008), U–Pb detrital zircon ages in synorogenic deposits of the NW Iberian Massif (Variscan belt): Interplay of Devonian-Carboniferous sedimentation and thrust tectonics, *J. Geol. Soc.*, *165*, 687–698, doi:10.1144/0016-76492007-066.
Martínez Catalán, J. R., et al. (2009), A rootless suture and the loss of the roots of a mountain chain: The Variscan belt of NW Iberia, *C. R. Geosci.*, *341*, 114–126, doi:10.1016/j.crte.2008.11.004.
Maus, S., et al. (2005), The 10th generation international geomagnetic reference field, *Phys. Earth Planet. Inter.*, *151*, 320–322, doi:10.1016/j.pepi.2005.03.006.
Mezcua, J., A. Gil, and R. Benarroch (1996), *Estudio gravimétrico de la Península Ibérica y Baleares*, 7 pp., Inst. Geogr. Nac., Madrid.
Miranda, J. M., A. Galdeano, J. C. Rossignol, and L. A. Mendes Victor (1989), Aeromagnetic anomalies in mainland Portugal and their tectonic implications, *Earth Planet. Sci. Lett.*, *95*, 161–172, doi:10.1016/0012-821X(89)90174-X.
Morelli, C., C. Gantar, T. Honkasalo, R. K. McConnel, J. G. Tanner, B. Szabo, U. Uotila, and C. T. Whalen (1974), The International Gravity Standardization Net 1971 (IGSN71), *Spec. Publ., 4*, Int. Assoc. of Geod., Paris.
Pin, C., J. L. Paquette, J. F. Santos Zalduegui, and J. I. Gil Ibarguchi (2002), Early Devonian supra-subduction zone ophiolite related to incipient collisional processes in the Western Variscan Belt: The Sierra de Careón unit, Ordenes Complex, Galicia, in *Variscan-Appalachian Dynamics: The Building of the Late Paleozoic Basement*, edited by J. R. Martínez Catalán et al., *Spec. Pap. Geol. Soc. Am.*, *364*, 57–71.
Ries, A. C., and R. M. Shackleton (1971), Catazonal complexes of northwest Spain and north Portugal remnants of a Hercynian thrust plate, *Nature Phys. Sci.*, *234*, 65–69.
Sánchez Martínez, S. (2009), *Geoquímica y geocronología de las ofiolitas de Galicia*, *Ser. Nova Terra*, vol. 37, 351 pp., Inst. Univ. Geol. Isidro Parga Pondal, Coruña, Spain.
Sánchez Martínez, S., R. Arenas, F. Díaz García, J. R. Martínez Catalán, J. Gómez Barreiro, and J. A. Pearce (2007), The Careón Ophiolite, NW Spain: Supra-subduction zone setting for the youngest Rheic Ocean floor, *Geology*, *35*, 53–56, doi:10.1130/G23024A.1.
Staub, R. (1926), Gedanken zum Strukturbild Spaniens, *Vierteljs. Naturf. Ges. Zürich*, *71*, 196–260.
Staub, R. (1928a), Gedanken zum Strukturbild Spaniens, *Extrait des Comptes-Rendus, XIV Congrès Géologique International, 1926*, 50 pp., Gráficas Reunidas, Madrid.
Staub, R. (1928b), *Der Bewegungsmechanismus der Erde dargelegt am Bau der irdischen Gebirgssysteme*, 270 pp., Gebrüder Borntraeger, Berlin.
van Calsteren, P. W. C., and E. Den Tex (1978), An early paleozoic continental rift system in Galicia (Spain), in *Tectonics and Geophysics of Continental Rifts*, edited by I. B. Ramberg and E. R. Neumann, pp. 125–132, Reidel, Dordrecht, doi:10.1007/978-94-009-9806-3_12.
van Calsteren, P. W. C., N. A. I. M. Boelrijk, E. H. Hebeda, H. N. A. Priem, E. Den Tex, E. A. T. H. Verdurmen, and R. H. Verschure (1979), Isotopic dating of older elements (including the Cabo Ortegal mafic-ultramafic complex) in the Hercynian Orogen of NW Spain: Manifestations of a presumed Early Paleozoic Mantle-plume, *Chem. Geol.*, *24*, 35–56, doi:10.1016/0009-2541(79)90011-1.
Van Overmeeren, R. A. (1975), A gravity investigation of the catazonal rock complex at Cabo Ortegal (NW Spain), *Tectonophysics*, *26*, 293–307, doi:10.1016/0040-1951(75)90096-7.
Van Zuuren, A. (1969), Structural petrology of an area near Santiago de Compostela (NW Spain), *Leidse Geol. Med.*, *45*, 1–71.
Vogel, D. E. (1967), Petrology of an eclogite -and pyrigarnite- bearing polymetamorphic rock Complex at Cabo Ortegal, NW Spain, *Leidse Geol. Med.*, *40*, 121–213.
Williams, P. J. (1983), The genesis and metamorphism of the Arinteiro-Bama Cu deposits, Santiago de Compostela, northwestern Spain, *Econ. Geol.*, *78*, 1689–1700, doi:10.2113/gsecongeo.78.8.1689.