Imaging granitic plutons along the IBERSEIS profile

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Abstract

The parameters used for the acquisition of the IBERSEIS deep seismic reflection profile in the SW Iberian Peninsula provide seismic images of the deep crust as well as a high resolution section of the shallow subsurface. A very dense array of sources and receivers allowed high resolution tomographic studies in zones of special interest (granitic plutons). The three dimensional tomographic inversion produced velocity models along a 500 m wide and 1000 m deep strip along the IBERSEIS transect in the areas of La Bazana, La Dehesilla, Feria and Villafranca. In these high resolution velocity models (sampled by 50×50×50 m cells), high velocity anomalies indicate the geology and extension of the granitic plutons at depth. This directly correlates with the surface outcrops. Moreover, tomographic models provided valuable information for the geometry and characterization of fractured and fresh domains in a rock volume. Furthermore, a piggy back seismic acquisition experiment using additional seismic instrumentation from the University of Paris Sud (40-channel DMT) provided perpendicular, offline recordings of the Vibroseis sources. This additional recording system was deployed perpendicularly to the main IBERSEIS seismic reflection line and provided additional 3D control.

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1. Introduction

Granitic intrusions in the upper crust have been widely studied by means of several geophysical techniques. The most common among them have been gravimetric modeling (Bott and Smithson, 1967) and mapping of the anisotropy of magnetic susceptibility (Guillet et al., 1983; Román-Berdiel et al., 1995), combined with detailed surface information (Román-Berdiel et al., 1995; Yenes et al., 1999; Simancas et al., 2000; Galadí-Enríquez et al., 2003), to achieve large-scale 3D images which constrain the shape and extent of granitic bodies. Usually, this information, together with detailed surface geological observations, places valuable constraints on inferences about the ascent mechanism of granitic intrusions. Lately, seismic reflection techniques

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Fig. 1. Detailed geological map of the Ossa Morena Zone. Tramunt of the IBERSEIS profile (in blue). Studied areas (in orange) of La Bazana, La Dehesilla, Feria and Villafranca include some granitic plutons. Note the crooked line of acquisition geometry. In the tectonic map (on the lower right), the location and trace of the IBERSEIS deep seismic reflection profile are indicated by a discontinuous line and the green area shows the Albalá Granitic Pluton. Numbers along profile represent stations. Modified from Simancas et al. (2003).
also have been used successfully in delineating the internal structure of granitic bodies (Mair and Green, 1981) and to obtain information about the emplacement mechanism (Brown and Tryggvason, 2001).

During the last decade, granitic plutons also have been studied in detail as a topic of interest for environmental applications (Juhlin, 1995; Juhlin and Palm, 1999). Among the crystalline rocks, granites show appropriate properties to become the host sites for hazardous waste (Astudillo, 2001). Therefore, knowing the internal structure and properties of the rock is mandatory. Application of geophysical techniques to image the shallow subsurface has shown that it is a difficult target (Steeples et al., 1997). This is mostly due to the high degree of heterogeneity and variability of physical properties that characterize the near surface zone. The first few meters are strongly influenced by weathering, for example the flow of water through fractured zones modifies the physical properties and induces chemical reactions, thus altering the rock properties around the fractures and changing the velocity structure within the shallow layer. In order to obtain a reliable model of this shallow layer, high resolution studies must be undertaken. Previous work (Morey and Schuster, 1999; Marti et al., 2002a;b; Flecha et al., 2004) has shown that 3D source-controlled seismic tomography techniques can provide a detailed velocity model of a rock volume. In massifs composed by single rock types, seismic velocity is a valuable parameter because it can be correlated with other physical properties of the rock such as porosity and/or degree of fracturing (Escuder-Viruete et al., 2001, 2003).

The IBERSEIS seismic profile was designed to provide a detailed high-resolution crustal image of the Variscan Belt in the Southwestern Iberian Peninsula (Simancas et al., 2003; Carbonell et al., 2004). The dense source and receiver spacing (70 and 35 m respectively) and the crooked-line acquisition geometry, provide the opportunity to perform specialized processing to assess the shallow subsurface (Fig. 1). The trace of this profile intersects several granitic plutons in the Ossa Morena Zone (Fig. 1). Some of these plutons have already been studied at a crustal scale which is the case for the La Bazana pluton (Simancas et al., 2000), but no previous studies have been carried out to obtain a detailed model of the internal structure of the shallower parts of these bodies.

In order to provide three dimensional constraints in the neighbourhood of the granitic plutons, a complementary piggy-back acquisition experiment was carried out by the high resolution research team of the University of Paris Sud at Orsay. This research team provided a 40-channel DMT system which was deployed perpendicular to the trace of the main profile in four areas: La Bazana, La Dehesilla, Feria and Villafranca (Fig. 1).

In the present work, three-dimensional high-resolution first arrival travel time tomographic inversions were performed using the first arrivals of the Vibroseis shots along the IBERSEIS profile that were recorded by both the main acquisition SERCEL and the DMT piggy-back recording systems. Crooked-line geometry along the IBERSEIS profile justifies the use of a 3D tomographic scheme by means of which a velocity model along 500 m wide and 500 to 1500 m deep strip is produced.

2. Geological and geophysical background

Exposed within the Iberian Massif are abundant plutonic rocks of Late Proterozoic and Paleozoic age. In this work four areas have been studied: La Bazana, La Dehesilla, Feria and Villafranca, all of which lie in the Ossa Morena Zone (SW Iberian Peninsula) (Fig. 1). Among the granites cropping out in those areas, geochronological data are available only for the Salvatierra de Barros granite, in La Dehesilla area (516 Ma, U–Pb monazites, Oschner, 1993). Deformation fabrics suggest a Carboniferous emplacement for the La Bazana and Feria granites (Simancas et al., 2003).

In the La Bazana area, the granitic pluton lies to the south of the town of Jerez de los Caballeros (Fig. 1) and consists of a 20 km² circular outcrop with a 250 m thick thermal aureole. Contacts with host rocks are shallowly dipping especially in the northern part of the area where contacts dip 15–20° to the north. The timing of the intrusion is not well defined but is certainly later than the first Hercynian deformation phase and probably is also later than the second deformation phase (Coullant et al., 1981).

In the La Dehesilla zone, the profile intersects the Salvatierra de Barros granite, a pre-Hercynian elongated

<table>
<thead>
<tr>
<th>Lithology</th>
<th>Velocity (km/s)</th>
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<tbody>
<tr>
<td>Amphibolite</td>
<td>6.06</td>
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<tr>
<td>Basalt</td>
<td>5.60</td>
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<tr>
<td>Eclogite</td>
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<tr>
<td>Gneiss</td>
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<td>Greywacke</td>
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<td>Schists</td>
<td>5.49</td>
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<tr>
<td>Slates</td>
<td>5.80</td>
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Fig. 2. a) P wave velocity log (left) and fracturation index (right) for the Albalá Pluton and statistical analysis for two regions: b) from 0 to 170 m, and c) from 250 to 500 m. The shallower region features a high variability with a mean value of 5.17 km/s for velocity and 5.83 for fracturation index while the deeper region shows a more regular distribution of the velocities and a higher mean value 5.52 km/s for velocity and 1.51 for fracturation index.
plutonic outcrop of 60 km², intruded in Upper Proterozoic rocks. The magmatic intrusion gave rise to a 1 km thick thermal aureole.

Little information is known about the Feria granitic body, which is located to the west of Feria. The identified granitic outcrop is not crossed by the profile but, as discussed in more detail below, a velocity anomaly can be identified at depth. Furthermore the surface geology suggests that the granite body extends towards the east, beneath the surface cover.

Villafranca area includes the Badajoz-Córdoba Shear Zone which represents the limit between two main tectonic units, the Ossa Morena Zone to the SW and the Central Iberian Zone to the NE. This area is highly heterogeneous; it includes some high-pressure metamorphic rocks, including retroeclogites and amphibolites with oceanic chemical signatures (Simancas et al., 2003), which contrast with slates and schists.

Compressional wave velocities for representative of those found along the profile have been obtained from laboratory measurements of rocks in several areas around the world (Table 1). Naturally, such measurements represent typical velocity values, which can change depending on water saturation, chemical composition and degree of metamorphism (Carmichael, 1982). In the area, greywackes, schists and slates are slightly metamorphized therefore the velocity expected for these rocks should be lower than values presented in Table 1. Furthermore, the rocks in the area were affected by Hercynian deformation that
may have resulted in an alteration of mechanical properties and a reduction in velocity. Log velocity data and fracturation index for granite (Fig. 2) were available to a depth of 500 m from a borehole in the Albalá Pluton (Escuder-Viruete et al., 2001; Martí et al., 2002a,b; Escuder-Viruete et al., 2003), which is located in a nearby area. Following this data, high velocity zones imaged in tomographic models can be correlated with granitic plutons in some cases. From the log measurements, two major domains can be differentiated as shown in the statistical analyses in Fig. 2: a shallower one from 0 to 170 m depth that features highly variable velocities due to fracturing and weathering, as shown in fracturation index graph, and a deeper one from 250 to 500 m depth with a more regular velocity distribution. Note that in the Villafranca zone some other high velocity materials outcrop along the trace of the profile as amphibolites, gneisses and eclogites (Fig. 1) that will be also mapped in the velocity models.

Fig. 4. Tomographic results of the La Bazana area. a) Ray coverage diagram, (white color below topography stands for coverage exceeding 900 rays), b) velocity model where ray coverage is not null and geology mapped at surface, and c) residual travel times for La Bazana area. Horizontal white band in the upper part of the images shows the topography. Vertical white bands are due to the lack of receivers because of the presence of towns. Red dashed lines delineate interpreted pluton boundaries.
3. Data processing

3.1. Data acquisition

The IBERSEIS deep seismic reflection profile was acquired in the southwestern part of the Iberian Massif during spring–summer 2001. Four 22-metric-ton Vibroseis trucks functioned as sources and a 20 s Vibroseis sweep with a frequency band from 8 to 80 Hz was used as input. The trace of the profile followed roads which resulted in a crooked-line geometry. Stations were deployed every 35 m, and sources were located with a spacing of 70 m between array centers. During the acquisition a minimum of 240 channels were active (Table 2). Details of the acquisition, processing, interpretation and application on the large scale profile can be found in Simancas et al. (2003) and Carbonell et al. (2004).

Additional instrumentation consisted of a 40-channel DMT system that provided perpendicular offline recordings of the Vibroseis shots. This instrumentation was deployed on the granitic bodies in the area of study, with a receiver-station spacing of 25 m.

3.2. Seismic tomography

First arrival seismic tomography, which was employed in this study, uses as inputs the travel times between sources and receivers and their locations. To achieve accurate first break picking, pre-processing is mandatory. In this case some first arrivals were not very clear and a bandpass Butterworth filter was applied (5–10–50–60 Hz) to improve the data quality and increase the signal-to-noise ratio (Fig. 3). Data from the IBERSEIS profile were amplitude corrected for spherical divergence to enhance signal at long offsets.

The tomographic inversion has been carried out using the “PSstomo” software developed by Benz et al. (1996) and Tryggvason (1998). In this software package, a 3D finite-difference scheme is applied to

![Image](image_url)
The iterative process. Final model results for each of the four studied are presented below.

4. Results

4.1. La Bazana

This area features a high velocity zone in the subsurface between stations 4400 and 4500 (Fig. 4a) which correlates with the exposed La Bazana granitic pluton (Fig. 1). Velocities up to 5800 m/s are observed in the inner part of the anomaly, inferred to correlate with the granitic body at depth, while near the interpreted margins of the granitic body, velocities decrease down to 5200 m/s. On the basis of its correlation with outcropping granite at the surface and the sharp velocity gradients toward the margins of the body, the contacts between granite and country rock can be inferred. Furthermore, the observed difference in velocities inside the granite probably correlates with rock properties. High velocities (inner core of the pluton) are likely related with fresh and unaltered rock and lower velocities could be indicative of alteration of...
the rock due to the interaction between granite and host rock in the emplacement process as suggested by granitic log velocities in Fig. 2. The ray coverage diagram (Fig. 4b) shows that the velocity model is well constrained in the high velocity zone from the surface to a depth of 700 m.

4.2. La Dehesilla

In the La Dehesilla area, the velocity model from the tomographic inversion displays an extensive high-velocity region (5200–5300 m/s) between stations 5000 and 5300 (Fig. 5). The upper limit of this anomaly is at a depth of 700 m at station 5000 and becomes shallower towards the NE until it reaches the topographic surface at station 5150. From station 5150 to about station 5300, the anomaly can be followed along the surface and correlates with the location of the Salvatierra de Barros granitic unit (Fig. 1). The ray coverage diagram shows good coverage down to a depth of 900 m and, therefore the velocity model can be considered reliable to this depth. The horizontal irregularity of the high velocity anomaly between stations 5000 and 5300 can be caused by: (1) the crooked-line geometry of the acquisition and (2) the high deformation of the granitic body indicated in the geological mapping which results in narrow gradients which could be caused by narrow fractured areas within the granitic body. Probably, the image is a result of both contributions.

In order to separate both effects, a dense 3D experiment would be required. The inferred transition from the granitic body to the host rock is characterized by a smooth velocity gradient, which may be a consequence of the 1 km thick thermal aureole caused by the intrusion. These results also support an interpretation that the Salvatierra de Barros complex extends at depth to the SW.

Fig. 7. Tomographic results of the Villafranca area. a) Velocity model for the Villafranca area and geology mapped at surface. Velocity model is only shown where cells are sampled by rays. b) Residual travel times. Horizontal white band in the upper part of the images shows the topography. Vertical white bands are due to the lack of receivers because of the presence of towns.
4.3. Feria

A prominent high-velocity anomaly is mapped in this area between stations 5650 and 5700 (Fig. 6). Although the IBERSEIS profile does not intersect the Feria granitic outcrop, this high velocity anomaly most probably can be correlated with the granitic body that outcrops 500 m to the S of the trace of the profile (Fig. 1). Therefore, as in the case of La Dehesilla, the tomograms indicate that this granitic body extends at depth from the outcrop to the north beneath the IBERSEIS profile. As in the La Bazana case, the inner part of this anomaly features higher velocities than the outer; therefore, different domains from fresh and unaltered (5800 m/s) to thermally metamorphosed rock (5200 m/s) can be inferred. Good ray coverage exists for this area to a depth of 1200 m, and thus the velocity increase towards the center of the velocity anomaly suggests an onion-like structural configuration for the granitic intrusion.

4.4. Villafranca

In this region, several high velocity zones are displayed in the final velocity model (Fig. 7). A 5800 m/s anomaly is located close to the surface between stations 6050 and 6120. Despite its shallow position no clear interpretation can be provided for this anomaly. A similar situation can be observed between stations 6250 and 6280 where a clear, localized, high velocity anomaly is displayed but its location in depth (from 400 to 800 m) makes an interpretation difficult because it cannot be correlated with any structure in the surface geology. However a sharp lateral discontinuity in velocity at station 6280 is imaged which correlates with a fault mapped at the surface and permits this structure to be traced in depth. In the area surrounding station 6400, a high-velocity anomaly can be correlated with outcropping high-pressure metamorphic rocks. A velocity of 6000 m/s agrees with values expected for amphibolites and retroeclogites (Table 1). In this case, good ray coverage is obtained down to 1500 m.

5. Conclusions

Along the IBERSEIS transect in the Ossa Morena Zone (OMZ) in southwestern Spain, 3D seismic tomography illustrates the correlation of high-velocity anomalies with granites mapped at the surface. Lower Paleozoic granitoids have been imaged as bodies with relatively uniform velocity distribution and average velocity of ~5300 m/s. In contrast, carboniferous granitoids show layered velocity distributions with high velocity cores (~5800 m/s) and lower velocity aureoles next to their margins (~5200 m/s). High velocities within the granites have been associated with fresh volumes of rock, while decreases in velocity are inferred to show altered/fractured zones within granites. Contacts with host rocks feature a negative velocity gradient caused by alteration that usually exists in the neighbourhood of thermal aureoles in granitic intrusions. The La Bazana and La Dehesilla granitic plutons seem to extend to 700 m in depth beneath the seismic profile, while the Feria pluton may reach a depth of as much as 1000 m. In the Villafranca area, some outcropping high-pressure metamorphic rocks are associated with high velocity anomalies (~6000 m/s). Furthermore, a sharp lateral discontinuity correlates with a fault mapped at the surface and enables mapping of this structure in depth. In the La Bazana case, results agree, at the experiment scale, with previous works, which used gravimetric and magnetic techniques to infer the geometry of the granitic pluton. The results obtained in this work demonstrate the success of a methodology rarely applied to the research of plutonic bodies.

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References


