Geologica Acta, Vol.10, Nº 1, March 2012, 71-80
DOI: 10.1344/105.000001750
Available online at www.geologica-acta.com

# Seismotectonic characterization of the Becerreá area (NW Spain)

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## ABSTRACT

The NW sector of the Iberian Peninsula has been classically considered as a seismically stable area, with only dispersed and low-magnitude activity. Around the village of Becerreá (Lugo) a significant concentration of earthquakes is observed. Since the beginning of instrumental record in 1979, seven seismic crisis have been reported in that zone, including 14 events of magnitude >4 and a larger event of magnitude 5.1$mb_{Lg}$ (VII EMS) in 1997. Even if this seismicity is to be related to the general compressive regime between Africa and Eurasia, the seismotectonic characterization of the area is still controversial, as the different hypotheses considered are based on insufficiently accurate data. New insights to the problem are discussed here, coming from the deployment of a seismic portable network between 1999 and 2002, which has provided new accurate seismic data. The corresponding events are distributed around a subvertical axis, reaching a depth of 12km, and epicentres tend to concentrate beneath the intersection of the main Becerreá fault and secondary, ENE/WSW oriented faults. This intersection structure is thus interpreted as being responsible for the relatively high level of seismic activity over the area.

*KEYWORDS* **Northwest Iberia Becerreá fault. Intraplate earthquakes. Fault interaction. Temporary array.**

## INTRODUCTION

The NW corner of the Iberian Peninsula is an area with low intraplate seismicity, located hundreds of kilometres away from the closest plate boundary. However, this seismicity is noticeable, a significant concentration of earthquakes being located in the SE of Lugo, the so-called Becerreá focus (Fig. 1A). Since 1979 seven seismic crisis were recorded in that area, including up to 14 events of magnitude ≥4 and a main event of magnitude 5.1$mb_{Lg}$ (21 May 1997). In this period, the Spanish National Seismic Network, managed by the National Geographic Institute, has registered more than a thousand events in a 15km-diameter focus (Fig. 2).

The seismic crises of 1995 and 1997 caused an important social alarm in the region. In turn, it has favoured an increase in seismic research, usually focused in the much more abundant seismicity of the southern part of the Iberian Peninsula, arising from the plate boundary between Africa and Europe.

Seismic studies published to date (Capote et al., 1999; Rueda y Mezcua, 2001; Martínez-Díaz et al., 2006, Martín-González, 2006) have considered controversial hypotheses as for the origin of this unusual activity. All these studies considered hypocentral determinations based only on seismic data recorded by the permanent network, which may lack accuracy to properly constrain seismotectonic interpretations, as will be discussed hereafter.

Between 1999 and 2002, several tectonic and geophysical studies were carried out at the NW Iberian Peninsula, on the framework of the Spanish GASPI Project. A portable seismic array composed of up to 24 seismographs was deployed in the area to fulfil the main objectives of this project, which were: i) To recognize the seismically active areas and establish a new seismotectonic zonation (López-Fernández et al., 2004; López-Fernández et al., 2008); ii) to provide new insights about the crustal and upper mantle properties from teleseismic data (Díaz et al., 2006; Díaz et al., 2003); iii) to model the internal crustal structure down to the mantle and its evolution integrating tectonic and geophysical studies (Pedreira et al., 2003; Díaz et al., 2002).

These new seismicity data allowed a higher precision in the hypocentral determination of events, due to the increased number of seismometers and its proximity to the focus.

## GEOLOGICAL AND SEISMOTECTONIC SETTINGS

The present crustal architecture of the NW Iberian Peninsula is a consequence of two subsequent orogenies, the Variscan (Late Palaeozoic) and Alpine (Mesozoic-Cenozoic) ones. The two corresponding domains distinguished in the area are the Variscan Massif and the Meso-Cenozoic sedimentary basins deposited on top of the Variscan basement (Fig. 1B). The Variscan Massif is mainly composed by Palaeozoic rocks, whose structure was acquired during the Variscan orogeny of Western Europe (general E-W compression), and it is divided in four zones (Lotze, 1945; Julivert et al., 1972): Cantabrian Zone, West-Asturian Leonese Zone, Central-Iberian Zone and Galicia-Trás-os-Montes zone.

The alpine cycle in the area is characterized by a general N-S shortening. The result was the partial closure of the Bay of Biscay and the uplift of the Cantabrian Mountains in the northwest of Spain, which constitutes the continuation of the Pyrenees to the West. In the study area the alpine deformation included the reactivation of

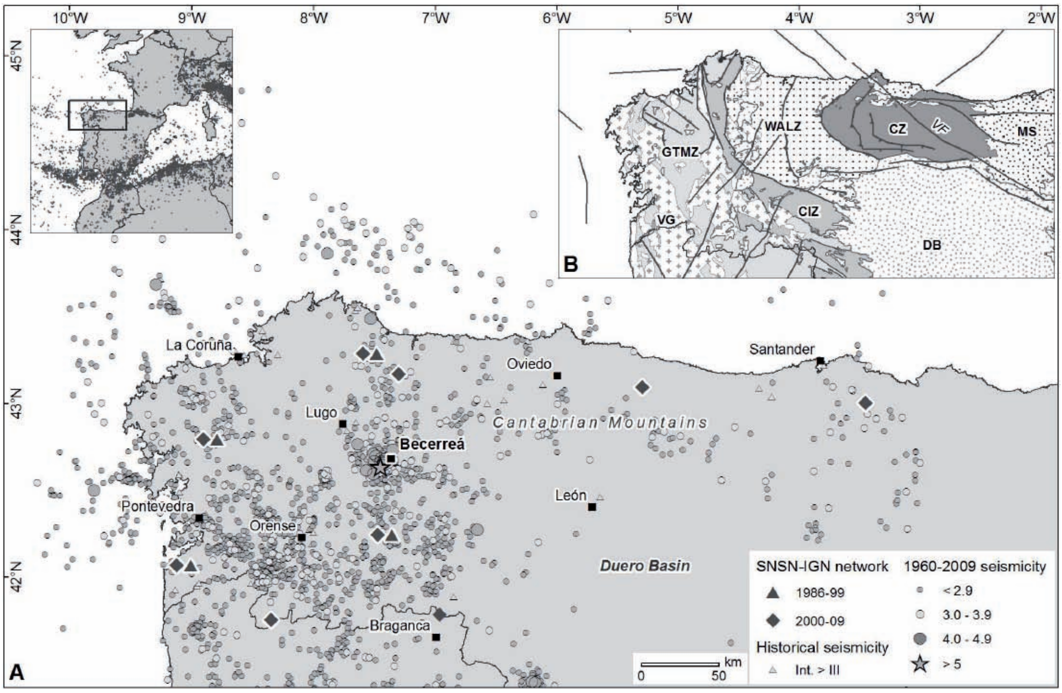

**FIGURE 1** | A) Seismic activity in the NW Iberian Peninsula in period 1960-2009 reported by the Spanish National Seismic Network (National Geographic Institute) and location of the permanent seismic stations. B) Geological scheme of the NW Iberian Peninsula. CZ: Cantabrian Zone, WALZ: West-Asturian Leonese Zone, CIZ: Central-Iberian Zone, GTMZ: Galicia-Trás-os-Montes zone. VG: Variscan granitoids. DB: Duero Basin. MS: Mesozoic. VF: Ventaniella fault.

previous Palaeozoic and Mesozoic structures and the formation of new ones (Alonso et al., 1996; Pulgar et al., 1999).

In the NE sector (Fig. 1B) recent structures show a general E-W and NW-SE strike. In the W sector, a series of uplifted blocks and depressions filled with Mesozoic to recent sediments dominates the tectonic style, with the presence of faults with an overall N-S to NNE-SSW orientation from northern Portugal, NE-SW in the limit with the Cantabrian Cordillera and NW-SE in the north-western part.

The crust in NW Spain shows a preserved variscan structure, with a typical thickness of 30-32km (Díaz and Gallart, 2009). In the Cantabrian zone however, the crust is affected by an important thickening (50-55km) that trends E-W and extends eastwards towards to the Pyrenees as a consequence of the effects of the alpine deformation on the previous extended crust (Pedreira et al., 2003; Fernández-Viejo et al., 1998; Gallastegui et al., 2002).

The study area (SW Becerreá, Fig. 2) is located inside the West-Asturian Leonese Zone, where the crust is divided into upper, middle and lower levels, with a crustal thickness of 32km, and a first order discontinuity at the Moho (Córdoba et al., 1987). The rocks that outcrop in the area are Precambrian (pelites, sandstones and gneisses) to lower Palaeozoic in age (alternating shales, quartzites and sandstones). Cenozoic rocks lay unconformably on top of this basement, and less important Quaternary deposits can also be mapped. The main structures are kilometric anticlinal and synclinal variscan folds verging to the East (Marcos, 1973). Later structures from the alpine cycle are represented by vertical NNE-SSW oriented faults that cut the previous folds. The main one is the so-called Becerreá Fault, which extends for more than 40km in a N30ºE direction, dipping 70-75º to the SE in this segment. Other minor parallel faults, usually associated with Cenozoic deposits in their lower blocks, are also mapped.

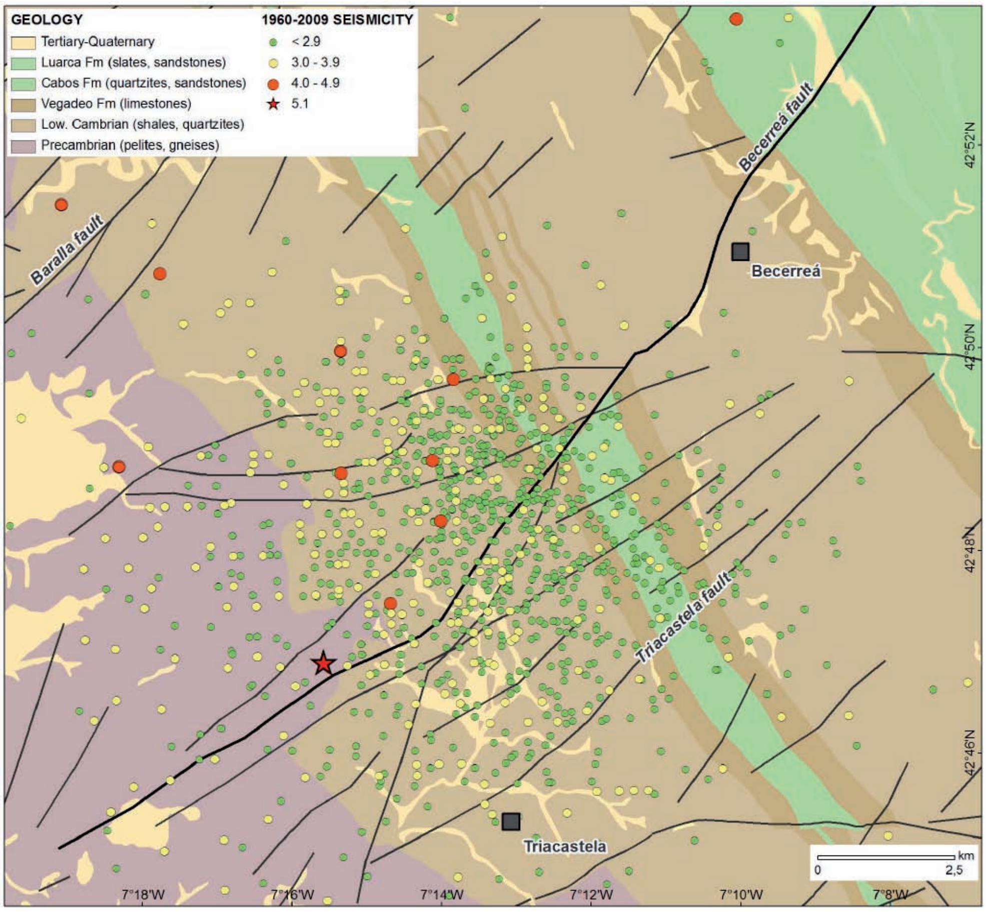

**FIGURE 2** | Seismicity in the study area, during the period 1960-2009, as reported by the National Geographic Institute. Geological units adapted from Marcos (1973).

The present-day geodynamic evolution of the Iberian Peninsula is controlled by the roughly NW-SE oriented convergence between Africa and Eurasia, which occurs at rates of 5-6mm/yr (DeMets et al., 1994; Calais et al., 2003; McClusky et al., 2003; Stich et al., 2006; Serpelloni et al., 2008). This NW-SE compressive regime appears to be constant since the Upper Miocene (De Vicente et al., 1996; Herraiz et al., 2000; De Vicente, 2000; De Vicente et al., 2008).

The distribution of seismicity in the north-western part of Iberia, concerning the area West of longitude 6ºW, is rather disperse (Fig. 1A). However, some particularly active clusters can be identified South of Lugo and southwest of Orense, apparently associated to the alpine structures trending N-S and NNE-SSW (López-Fernández et al., 2004). Activity in the Atlantic margin also appears diffuse (Díaz et al., 2008), with only a few E-W lineations identified, following the old suture line between Iberia and Eurasia. Another cluster of activity is located in the westernmost part of the Cantabrian Cordillera and continental platform, associated to recently active structures that trend NW-SE (Fig. 1B). Eastwards of the Ventaniella Fault and to the south of the Cantabrian Mountain range, at the Duero Basin, the seismic activity is significantly reduced or absent.

In general, seismicity is mostly superficial in the north-western part of Iberia, concentrated in the upper 15km of the crust and of low magnitude.

## SEISMICITY IN BECERREÁ AREA

To better understand the instrumental seismicity pattern in northwest Iberia one should bear in mind that the Spanish seismic network (National Geographic Institute) began monitoring the area in 1979, with only one seismograph. Only by the end of 1986 the number of stations in the area increased to 4 (triangles in Fig. 1A) and later on to 8, between 1999 and 2001 (diamonds in Fig. 1A). The minimum detection threshold was estimated by the National Geographic Institute at magnitudes 3.0-3.5 before 1986-87, and then improved to 2.5-2.8 (Fig. 3). At present, the threshold of recording events is situated at approximately magnitude 2.0 since 2002. In any case, it is important to note the evolution of the annual seismic events reported there (Fig. 3) shows a remarkable activity increase since 1995.

The first instrumental records of seismicity in the focus SW of Becerreá correspond to two earthquakes of magnitude 4.6 and 4.2 in 1979 (Table 1; Fig. 2). There are no records of historical seismicity in the area. Between 1980 and 1995 only one event was recorded. At the end of 1995 two important earthquakes, both of magnitude $mb_{Lg}$=4.6, were followed by a hundred aftershocks (including one of 4.0) and a new earthquake of magnitude $mb_{Lg}$ 4.1 in October 1996.

The main seismic crisis recorded in NW of Spain occurred in 1997. A 5.1$mb_{Lg}$ magnitude earthquake on the 21st of May is the biggest instrumentally registered event in this area until now. Some houses were damaged and other properties destroyed, creating a social alarm in the population of the neighbouring towns, not used to feeling earthquakes of such a magnitude. The hypocenter was located by the National Geographic Institute south of Becerreá, at 13km depth (Fig. 2). Five aftershocks of magnitude >4$mb_{Lg}$ were reported in the next 42 hours. Since then, only one more event of magnitude >4$mb_{Lg}$ has been detected in the area in 2000.

Several interpretations have been proposed to explain the origin of this activity. All of them are based on the event locations reported on the National Geographic Institute's seismic catalogue, the accuracy of which largely depends on the variable, and limited network coverage. Capote et al. (1999) associated it with the Baralla fault, located 10km west of Becerreá (Fig. 2). Rueda and Mezcua (2001) proposed the existence of a NNE-SSW thrust fault at a depth of 15km which does not crop out, and that would rotate in this area towards a NNW-SSE position. Martínez-Díaz et al. (2006) related the seismicity with a southeast N30ºE fault parallel to the Baralla reverse fault.

## ANALYSIS OF GASPI NETWORK DATA

A portable seismic array composed by up to 18 portable stations was installed in NW Spain (GASPI

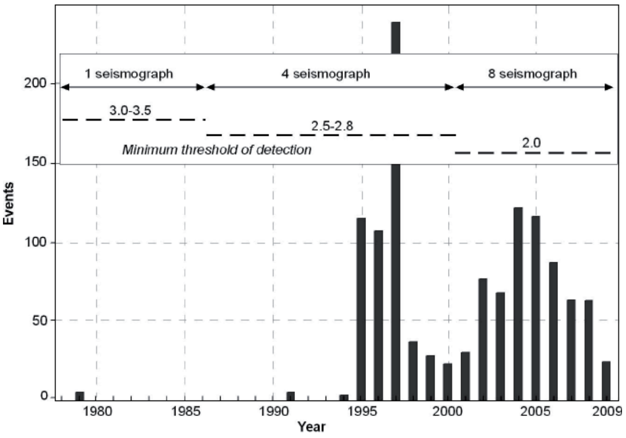

**FIGURE 3** | Time distribution of seismicity (National Geographic Institute catalogue) in the Becerreá area, during the period 1979-2009. Minimum detection thresholds estimated by the National Geographic Institute.

**TABLE 1** | Catalogue of magnitude >4 events in the Becerreá area (National Geographic Institute Spanish network)

| N° | Date | Origin time | Longitude | Latitude | Depth | Int. (MSK) | Mag. ($mb_{Lg}$) | Type(1) |
|---|---|---|---|---|---|---|---|---|
| 1 | 15-02-1979 | 10:11:59 | 42.760 | -7.368 | 10 | V | 4.6 | M |
| 2 | 18-12-1979 | 05:47:34 | 42.888 | -7.163 | 20 | VI | 4.1 | M |
| 3 | 29-11-1995 | 23:56:28 | 42.817 | -7.303 | 9 | V-VI | 4.6 | M |
| 4 | 24-12-1995 | 14:29:21 | 42.860 | -7.315 | 15 | V-VI | 4.6 | M |
| 5 | 24-12-1995 | 18:19:53 | 42.835 | -7.253 | 9 | III-IV | 4.0 | A |
| 6 | 29-10-1996 | 19:38:04 | 42.830 | -7.228 | - | V | 4.1 | M |
| 7 | 21-05-1997 | 23:49:45 | 42.817 | -7.233 | 9 | V | 4.1 | F |
| 8 | 21-05-1997 | 23:50:45 | 42.783 | -7.258 | 13 | VI | 5.1 | M |
| 9 | 22-05-1997 | 00:02:51 | 42.740 | -7.307 | 2 | - | 4.3 | A |
| 10 | 22-05-1997 | 00:17:19 | 42.848 | -7.293 | 17 | - | 4.9 | M-A |
| 11 | 22-05-1997 | 01:32:35 | 42.908 | -7.443 | 21 | - | 4.1 | A |
| 12 | 22-05-1997 | 05:06:52 | 42.807 | -7.232 | 9 | - | 4.3 | A |
| 13 | 23-05-1997 | 18:14:42 | 42.793 | -7.243 | 9 | III-IV | 4.4 | A |
| 14 | 30-01-2000 | 15:03:06 | 42.815 | -7.254 | 11 | III | 4.1 | M |

(1)Type of event: M = main, F = foreshock, A = Aftershock.

project), in subsequent deployments from April 1999 to January 2002 (Fig. 4A). Taking into account the location of the permanent seismometers (National Geographic Institute), the distribution of portable instruments was planned to better characterize the present-day seismicity of the region and to study the crustal structure with seismic methods based on teleseismic recordings. Three different models of digital dataloggers were used: Reftek, Lennartz-Marslite and Lennartz-Mars88, equipped with GPS synchronization, and Lennartz Le20s and Le5s three-component seismometers, with flat frequency response broadened up to 20 and 5 seconds respectively. Twelve stations worked in continuous mode (sampling rate of 50 sps), whereas Lennartz-Mars88 instruments used a triggered algorithm.

To extract the events, a STA/LTA detection algorithm was applied to the continuous data sets. An event was retained whenever it triggered over a minimum of 3 different stations in a 8s interval. Finally, we compiled a complete catalogue including events not catalogued by the permanent network and new hypocentral relocations of the events previously catalogued by the National Geographic Institute.

Phase-picking and seismogram analysis was performed with SAC2000 (Seismic Analysis Code) program (Goldstein and Minner, 1996). First hypocentral determinations were carried out using the inversion program Hypo71 (Lee and Lahr, 1975). The P-wave velocity model used in the hypocentral inversion is composed by 5 homogeneous layers (Layer 1: 0-3km, Vp=5.5km/s; Layer 2: 3-12.5km, Vp=6.0 km/s; Layer 3: 12.5-22km, Vp=6.2km/s; Layer 4: 22-30km, Vp=6.7km/s; Vmantle=8.0km/s) derived from the seismic refraction models available in the region (Córdoba et al., 1987; Pulgar et al., 1996; Fernández-Viejo et al., 1998, 2000; Ayarza et al., 1998). A mean Poisson's ratio of 0.25 is assumed to infer the S-wave velocity model.

In order to determine the magnitudes for all the earthquakes detected, we used the relationship between total signal duration and epicentral distance proposed by Lee and Lahr (1975) for local earthquakes:

$$MD = -0.87 + 2 \log(T) + 0.0035D$$

Where T is the total signal duration in seconds and D the epicentral distance in kilometres. Although other estimates of the magnitude could achieve greater accuracy, we opted for this calculation, considering it sufficiently accurate for the objectives of the study and the seismic particularities of this area. In any case, differences regarding the magnitude estimated by the National Seismic Network ($mb_{Lg}$) and our estimates, which do not exceed in 0.2 for all events recorded by both arrays.

As a first step, we identified the artificial events (mainly quarry blasts) present in our dataset, using the classical procedure (Street et al., 2002) that analyses features as lower frequency content, a well developed dispersive wave train, a large P and S-wave amplitude, and repetition of times and locations. After excluding those artificial events (that represent 80% of the total number of events in this area which has a significant mining activity), and considering only those locations with RMS<0.3, the final catalogue consists of 185 earthquakes located in the epicentral zone (Fig. 4B).

A comparison of epicentral locations considering either the National Geographic Institute or the whole of the datasets (National Geographic Institute+GASPI) has been attempted and is illustrated in Figure 4C. A marked

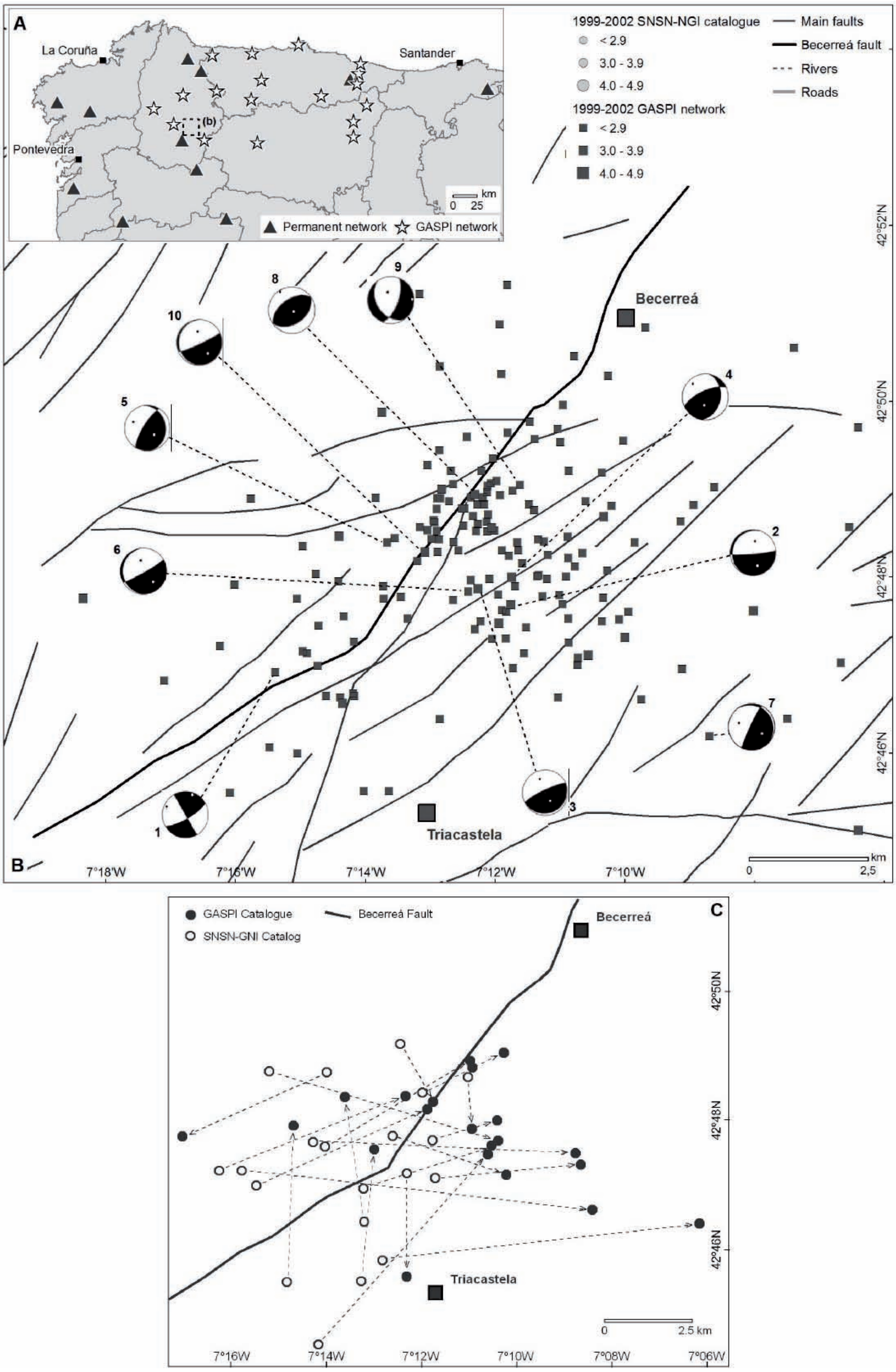

**FIGURE 4** | A) Site location of the temporal GASPI seismic array and the Spanish national seismic network. B) New epicentral locations and focal mechanisms (Table 2) derived in this study during the period 1999-2002. C) Comparison between the locations after permanent and temporary networks (higher magnitude events recorded during the period 1999-2002).

focusing is observed when using the complete dataset, as well as a clear eastwards shifting of epicentres, as a consequence of the situation of permanent sites, mostly westward from the seismic foci. Epicentral differences may exceed 10km in some cases.

Approximately 65% of the 185 retained events (121) are previously uncatalogued earthquakes, not reported by the permanent seismic network. All events were located in the upper 12km of the crust with magnitudes ranging between 1.6 and 3.5. The minimum detection level in the zone covered by the temporary array had an approximated magnitude of 1.6.

Focal mechanisms were also calculated whenever possible. P-wave polarity was used to derive focal solutions for the earthquakes with the best azimuthal coverage. In some cases, it was necessary to use composited mechanisms due to the reduced number of readings available. In these cases groups of consistent earthquakes were defined, taking into account the geostructural characteristics of origin zone. The final results were 10 focal solutions (Table 2, Fig. 4B) that were obtained using the program FPFIT (Reasenberg and Oppenheimer, 1985) with the same velocity model as for the location procedure. For these events, a maximum error of 2km in epicentral location and 3km in depth is estimated.

## SEISMOTECTONIC INTERPRETATION

The new set of seismicity data complements the data from the permanent seismic network and shows the highest density of epicentres in the SW of Becerreá, inside a relatively small area of 25km$^2$, with a sub-circular morphology (Fig. 4B). The epicentral area appears better constrained and greatly reduced with respect to previous studies based on the national network catalogue, which may be biased by the dominant westward location of the closer permanent stations with respect to the active foci. Fault systems in this area are disposed with a predominant orientation NE-SW to ENE-WSW, being the Becerreá Fault (N30E) the main structure and possibly the principal seismogenic source.

The calculated focal mechanisms display two types of dominant solutions (Fig. 4B) corresponding to vertical and oblique-thrust faulting. Only two events have a different focal solution, one normal and the other strike-slip faulting. Both cases should correspond to local structural adjustments needed to accommodate the main movement observed. All the solutions obtained have one nodal plane oriented from N10ºE to N85ºE, which is compatible with the main trend of the fault traces. In general, within this tectonic context, the results are consistent with previous solutions derived by Herraiz et al. (2000) and Rueda and Mezcua (2001).

The new seismic events with the best quality (GAP<200, RMS<0.15, Hypo-71 quality A-B; in total 67 events) have been relocated using the Double-Difference technique (Waldhauser and Ellsworth, 2000; Waldhauser, 2001), which allows a more accurate image of the seismicity (Fig. 5). The relative location of pairs of events in the double difference (DD) algorithm minimizes the influence of the velocity model, and decreases the errors produced by the use of 1-D velocity model, which does not accurately reflect the real 3D structure of the area. Considering the limited number of events, to solve equations we follow the SVD (singular value decomposition) method, which estimates the least square errors by computing proper covariances. In this case, mean errors were 0.5km in epicentral location and 1.9km in depth; in any case, always less than 1.5 and 3.5 respectively.

The hypocentres are distributed around a subvertical axis, reaching a depth of about 12km (Figs. 5, 6) and thus

**TABLE 2** | Focal parameters calculated during the period 1999-2002

| Nº | Date | Hour | Long. W | Lat. N | Depth (km) | MAG | NL[1] | Nodal plane A | | | Nodal plane B | | | P axis | | T axis | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Azm | Dip | Rake | Azm | Buz | Rake | Azm | Dip | Azm | Dip |
| 1 | 09-19-1999 | 02:44 | 7 15.33 | 42 47.07 | 2.27 | 2.0 | 5 | 60 | 75 | -180 | 330 | 90 | -15 | 284 | 11 | 16 | 11 |
| 2 | 06-20-1999 | 04:44 | 7 11.67 | 42 47.78 | 10.57 | 2.9 | 9 | 85 | 85 | -80 | 201 | 11 | -153 | 6 | 49 | 166 | 39 |
| 3 | 08-01-1999 | 05:08 | 7 12.17 | 42 47.97 | 7.84 | 3.5 | 7 | 65 | 10 | 90 | 245 | 80 | 90 | 335 | 35 | 155 | 55 |
| 4 | 08-01-1999 | 05:10 | 7 11.65 | 42 48.09 | 8.14 | 3.1 | 6 | 10 | 35 | 40 | 245 | 68 | 118 | 315 | 19 | 194 | 57 |
| 5 | 08-14-1999 | 11:09 | 7 13.56 | 42 48.52 | 7.37 | 2.6 | 6 | 350 | 20 | 50 | 212 | 75 | 103 | 291 | 29 | 140 | 58 |
| 6 | 09-11-1999 | Comp.1 | 7 12.32 | 42 47.94 | 7.00 | 2.7 | 14 | 60 | 85 | -80 | 176 | 11 | -153 | 341 | 49 | 141 | 39 |
| 7 | 09-23-1999 | 19:57 | 7 08.65 | 42 46.24 | 9.4 | 2.4 | 6 | 205 | 85 | 100 | 321 | 11 | 27 | 286 | 39 | 126 | 49 |
| 8 | 02-25-2000 | Comp.2 | 7 12.19 | 42 49.04 | 2.80 | 3.2 | 8 | 55 | 40 | -90 | 235 | 50 | -90 | 145 | 85 | 325 | 5 |
| 9 | 05-03-2000 | 23:43 | 7 11.49 | 42 49.14 | 8.21 | 2.6 | 6 | 20 | 65 | -60 | 146 | 38 | -137 | 333 | 59 | 89 | 15 |
| 10 | 09-07-2000 | 08:24 | 7 13.10 | 42 48.30 | 7.43 | 2.5 | 7 | 65 | 86 | -80 | 181 | 11 | -153 | 346 | 49 | 146 | 39 |

(1)NL: Number of readings. Azm: azimuth; Composited 1: 19:13 – 21:01; Composited 2: 02:02 – 02:04

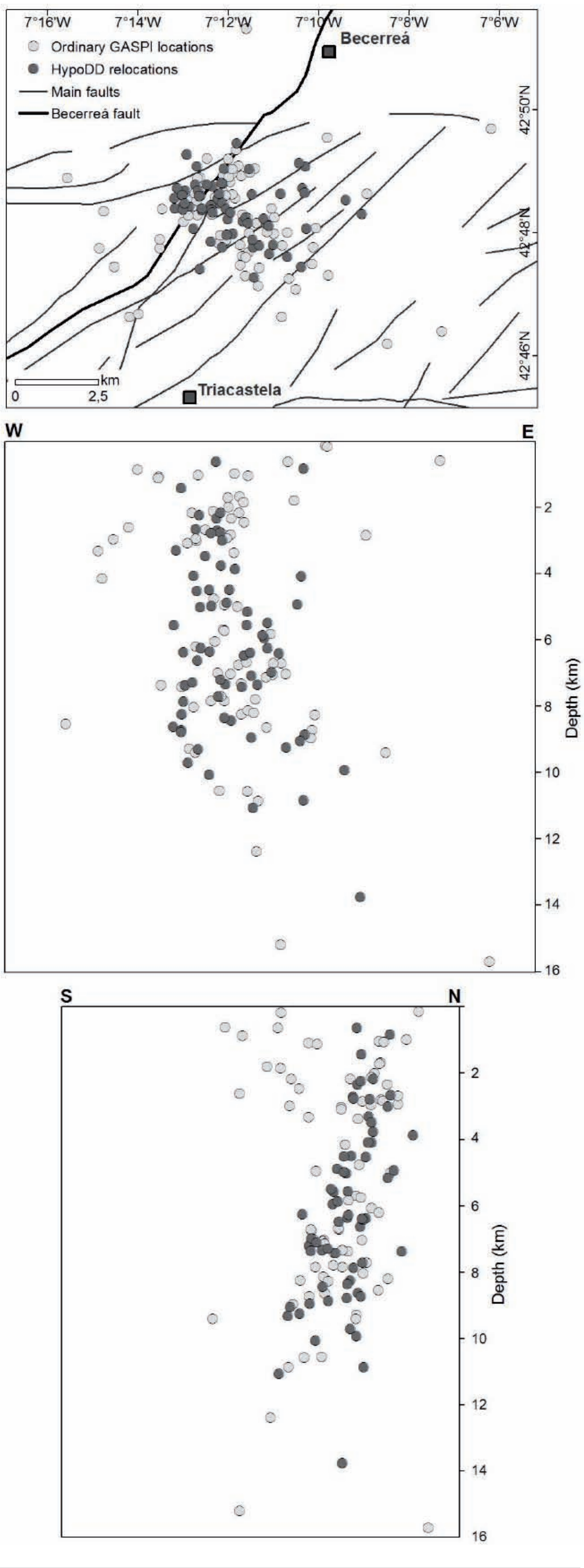

**FIGURE 5** | Relocation of the original best quality events of the GASPI network catalogue (1999-2002) using the "Double-Difference Earthquake Location" technique, and E-W and N-S cross sections.

remaining near the surface. This geometry can only be explained in this tectonic context by the existence of a fault intersection zone (probably the Becerreá fault with other minor ENE-WSW oriented structures).

This type of intersections constitutes a first order structural discontinuity in the propagation of the main fault movement, controlling the nucleation and barrier to seismic events. The accumulated tensions are generally solved as small movements, but can have some moderate events when punctual stress is built in response to the barrier formed by the second structure to the main movement. The slight dispersion of events at the surface can be attributed to the structural readjustments that accommodate the main movement along the Becerreá fault.

Becerreá focus is situated at the confluence of two tectonic regional domains, where the N-S structures change eastwards to the E-W ones. Interference patterns, such as termination of the E-W and NNE-SSW faults and interaction with folds have been recognized on the surface. In this context, the interaction between differently oriented structures may condition the fault kinematics, favouring the apparition of asperities in the active structures of the NNE-SSW trending area. These zones of structural weakness favour at the same time the concentration of stresses and control the development of the low magnitude seismicity.

The earthquakes recorded between 1999 and 2002 are distributed around a subvertical axis, reaching a depth of about 12km (Figs. 5, 6) and thus remaining near the surface. We propose a model of intersecting faults (Becerreá fault and other minor ENE-WSW oriented structures) to explain this distribution. This intersection constitutes a first order structural discontinuity for the propagation of movement along the main fault that controls the nucleation of seismic events. The accumulated tensions are generally solved by small movements. In addition, other moderate events may also occur due to the barrier effect formed by the second structure to the main movement. The slight dispersion of events at the surface may be attributed to the structural readjustments that accommodate the main movement along the Becerreá fault.

It must be noted that there are a number of examples of low seismicity areas away from plate boundaries where the seismic distribution is clearly correlated with the intersection of structures (see as example Talwani, 1999; Yamini-Fard et al., 2006). The fault intersections in the Becerreá zone will therefore create a weakened area where the regional intraplate deformation is released as low to moderate continuous seismic activity, as it has previously been described in similar areas (Talwani, 1999; Pascal, 2002).

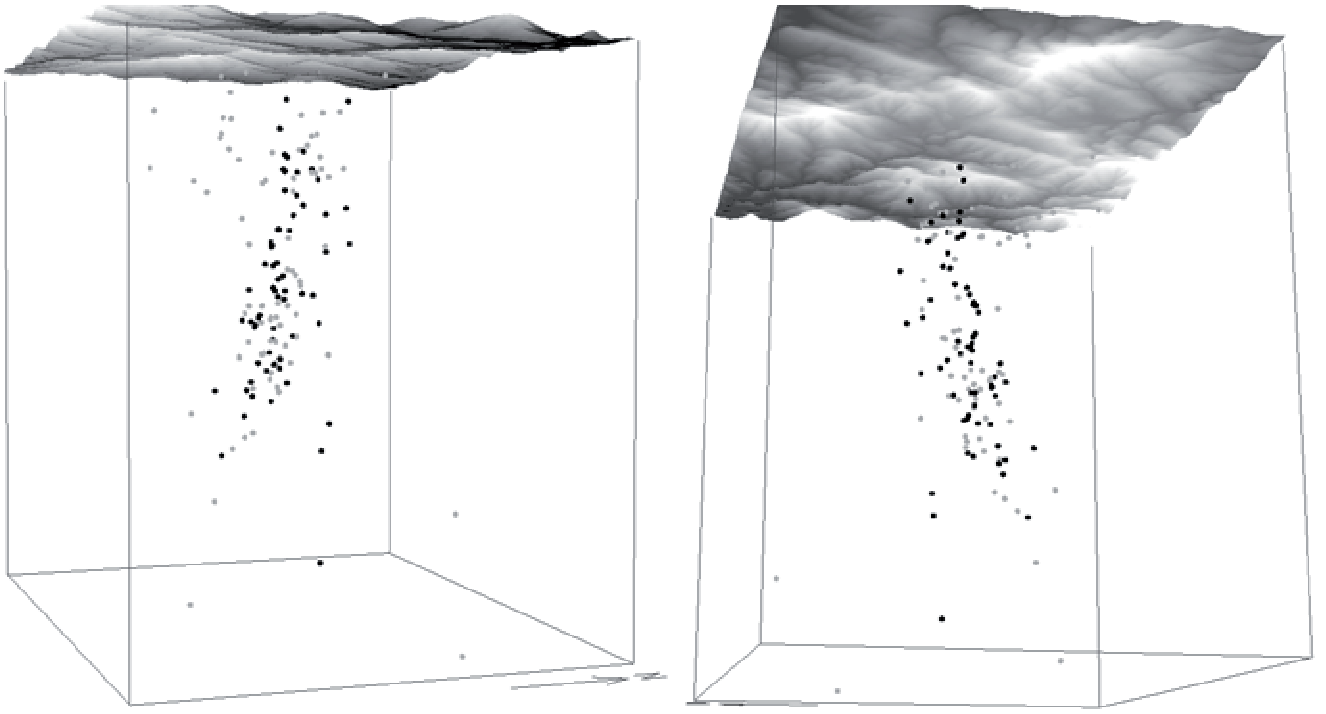

**FIGURE 6** | 3D representation of the Hypocenter Double-Difference (HypoDD) relocated events. Ordinary GASPI locations are shown in light gray.

## ACKNOWLEDGMENTS

This work was carried out with the support of the GASPI (AMB98-1012-C02-02) and MARCONI (REN2001-1734) projects from the Spanish Ministerio de Ciencia y Tecnología. We would like to thank the responsible of the SNSN- National Geographic Institute databases for sharing the seismic data used in this study. Supported by the Consolider-Ingenio 2010 Programme, under project CSD2006-0041, "Topo-Iberia".

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**Manuscript received June 2010;**
**revision accepted April 2011;**