Seismicity and potencially active faults in the Northwest and Central-West Iberian Peninsula

Sismicidad y Fallas Potencialmente Activas en el Noroeste y Centro Oeste de la Península Ibérica

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Abstract

The Northwest and Central-West Iberian Peninsula configure an intraplate area far from the active plate boundaries, where the Variscan basement crops out extensively (Iberian Massif). This area of the Iberian Peninsula has been traditionally considered a seismically stable region; however, it presents a moderate intraplate seismicity which indicates the presence of active structures and the occurrence of potentially damaging earthquakes. The scarcity of Mesozoic and Cenozoic deposits makes very difficult to track the record of the more recent tectonic activity and the characterization of active tectonic structures within the Iberian Massif. Nevertheless the seismic sequences of 1995-1997 in Lugo (5.1 mb; IV) and 2003 in Zamora (4.2 Mw) provided important information about the orientation of the present stress tensor, and the distribution of the hypocenters informed about the rupture geometry of the fault planes. The present work integrates geological, geomorphological, structural, and seismological data in order to define the main potentially active faults in the region. Faults trending NE–SW to N–S are potentially active as strike-slip, in some cases with a reverse component, under a NW-SE to N–S compression.

Keywords: Seismicity, Potentially active faults, Spain, Active tectonics, Neotectonics, Variscan basement

Resumen

El Noroeste y Centro Oeste de la Península Ibérica son parte de una región intraplaca alejada de los bordes de placa sísmicamente activos, donde aflora el basamento varisco (Macizo Ibérico). Esta región de la Península Ibérica ha sido tradicionalmente considera-
da sísmicamente estable; sin embargo, presenta una moderada sismicidad que indica la presencia de estructuras activas y terremotos potencialmente catastróficos. La escasez y dispersión de los depósitos Mesozoicos y Cenozoicos hace difícil identificar la actividad tectónica más reciente, así como la caracterización de las fallas potencialmente activas dentro del Macizo Iberico. Sin embargo la sismicidad de 1995 y 1997 en Lugo (5.1 mb) y de 2003 en Zamora (4.2 Mw) aportó importante información para determinar la orientación del tensor actual de esfuerzos. De igual modo, la orientación de las replicas aportó información sobre los planos de rotura. El presente trabajo integra datos geológicos, geomorfológicos, estructurales y sísmotectónicos para definir las principales fallas potencialmente activas en la región. Las fallas con orientaciones NE-SW hasta N-S son potencialmente activas, bajo un tensor de esfuerzos de NW-SE a N-S, como fallas de desgarre y en algunas zonas con componente inversa.

Palabras clave: Sismicidad intraplaca, Fallas potencialmente activas, España, Tectónica activa, Neotectónica, Basamento varisco

1. Introduction

The North-West and Central-West regions of the Iberian Peninsula are located far away from the seismically active borders of the Iberian microplate (Fig. 1) and have been traditionally considered a stable intraplate area with no significant seismicity. However, seismic sequences of moderate magnitude have revealed the presence of active structures and potentially damaging earthquakes in this region where, in addition, no preparation or seismic education exist to mitigate the risk. Recently, seismicity in intraplate regions has been the focus of scientific studies due to the unexpected and relevant destruction that can be generated by moderate magnitude earthquakes. Examples in the last years are Ungava in 1989, Latur in 1993 and Kutch in 2001 (Adams et al., 1991, Crone et al., 1992, Gupta, 1993). This evidenced the necessity for the revision of the seismic catalogues and active structures in intraplate areas where earthquakes have very long seismic cycles and seismotectonic studies are scarce.

The unexpected intraplate activity in Lugo during 1995-1997, with a maximum magnitude event of 5.1 mb (VI), and Zamora during 2003 with a maximum magnitude event of 4.2 Mw, point out the necessity of a better knowledge of the potentially active tectonic structures were seismicity may occur. In this way, the seismic sequences of Lugo in 1995 and 1997 promoted the revision of the Spanish building design standards (NCSE-94) published just only one year before the Lugo events, and the publication of a new regulation in 2004 (NCSE-2002).

In the study area, the existing fault pattern is the result of a long deformational story developed during Variscan and Alpine orogenies. In this type of highly fractured basements the reactivation of previous faults, favorably oriented to the current stress tensor, is the main deformation mechanism, instead of generation of new faults (De Vicente et al. 2007). With low slip-rate faults, and low seismic cycles, the erosion processes are faster than the tectonic processes that generate scarps or other geomorphological evidences of the tectonic activity; therefore they are underestimated. Moreover, faults with strike-slip motion, which do not create great relief and/or sediments associated with their tectonic activity, are likely to be assessed as quiet faults (Villamor et al., 2012). Besides, in this area (Iberian Massif) the scarcity of Mesozoic and Cenozoic deposits make it very difficult to study post variscan tectonic activity (Martín-Serrano et al., 1996; Martín-González, 2009; Antón and De Vicente, 2006). For this reason the study of the recent tectonic activity in these areas must be the result of the integration of geological, geomorphological, structural and seismological data.

The studied region corresponds to the Northwestern and Central-Western part of the Iberian Peninsula covering the NW of Spain and the Western Fringe of the Cenozoic Duero Basin (WCB) (Fig.1). In this paper we perform a tectonic and dynamic analysis of the main seismic sequences occurred in the study area (Anton et al. 2012). We analyze the aftershocks series distribution and the focal mechanisms available in relation to the regional stress state, and possible local stress fields, and we try to determine the fault orientations that are potentially active. We also analyzed the morphological record induced by the recent activity of most active faults in the region, and the most appropriate methodologies to interpret that record.

2. Geological and tectonic setting

The study area predominantly comprises Precambrian and Paleozoic rocks that form the Iberian Massif (Fig. 1). These rocks were mainly deformed and metamorphosed by the Variscan Orogeny (Upper Devonian-Carboniferous in age), and are intruded by igneous rocks, mainly in the western region, during the Carboniferous and Permian times. In the NW Iberian Peninsula, the overall Variscan structure shows an arch-like shape (Asturian Arch) open to the west, where the inner parts of the Variscan Orogen are located (Martínez-Catalán et al., 1990; Arenas and Martínez-Catalán, 2003).

The most recent structures in the NW Iberian Peninsula are associated with the western termination of the Alpine-Pyrenean Orogen relief (Pyrenees in the east and the Cantabrian Mountains in the west) (Gallastegui et al., 2002; Muñoz, 2002; Barnolas and Pujalte, 2004; De Vicente 2007).
and Vegas, 2009; Martín-González and Heredia, 2011a, b) (Fig. 2). The Pyrenees forms the border between Eurasia and the Iberian Peninsula microplate, trending ESE-WNW, and represents a doubly verging continental collision orogen (Choukroune et al., 1990; Muñoz, 1992; Teixell, 1998). The Alpine structures of the Cantabrian Mountains can be divided, based on involved lithologies, age and deformational style, into two regions: the Vasco-Cantabrica (VC) in the E and the Astur-Galaica (AG) in the W (Martín-González and Heredia, 2011b).

In the Astur-Galaica region, the overall Alpine structure is a regional monoclinal flexure that corresponds to the back-limb of a major fault-bend fold related to the Cantabrian Basal Thrust (CBT). This north-dipping basement thrust overturns the Mesozoic-Cenozoic sediments in the south border of the Cantabrian Mountains (Alonso et al., 1996). In the western termination of the CM thrusts there are N-S trending structures (Ibias-Ancares and Rúa-Vilalba structures) (Martín-González and Heredia, 2011a, b) (Fig. 2). These structures partially accommodate the CBT shortening to the north. Therefore, part of the convergence was accommodated by NW-SE faults (Santanach, 1994; Martín-González et al., 2003; Vegas, 2005; De Vicente and Vegas, 2009). These types of movements are also found to the east, in the Ventaniella fault (Cantabrian Mountains) and within the Iberian Chain (e.g. De Vicente and Vegas, 2009; Martín-González and Heredia, 2011b). The compression responsible for these structures is the N-S maximum horizontal stress related with the Pyrenean collision. In Central Iberia, the uplift of the Iberian Chain and the Central System produced an intraplate deformation belt that was also related to the Pyrenean collisional processes, and some left lateral strike slip fault corridors were also developed, as the Bragança-Vilariça and Verín-Vila Real fault corridors or fault systems (Cabral, 1995).

Subsequently, to the south of the CM, the Galacico-Leoneses Mountains (GLM) were emplaced towards the north by north-verging thrusts, causing the erosion of the early foreland basin (western Duero Basin) located in front of the Cantabrian Mountains (Fig. 1). Shortening of the GLM north-verging thrusts was accommodated by NNE-SSW strike-slip faults (e.g. Bragança-Vilariça and Verín-Vila Real corridors), this took place mainly during the Late Miocene and therefore related with the Betic collision (Martín-González et al., 2011). In contrast, the Rías Baixas-Terra Cha Region (RBT) represents the less deformed region of the foreland (Martín-González and Heredia, 2011b) (Fig. 1). Neotectonic activity has been described in the NW Iberian Peninsula related with faulted fluvial deposits and deformed marine terraces (Martínez-Graña et al., 2000; Rodríguez García et al., 2006; Gutiérrez Claverol et al., 2006). Also, complex systems of captures and inversion of the drainage network in Tambre and Xallas rivers (Western Galicia) have been described (Pagés and Vidal Romani, 1997), as well as drainage diversion related to fault activity in El Caurel Mountains (Martín-González, 2009).

To the South and easternmost of the Bragança-Vilariça corridor, is located the region of the Western Fringe of the Cenozoic Duero Basin (WCB) (Figs. 1 and 3). This region is characterized by vast outcrops of uplifted variscan basement. The WCB area consists of uplifted blocks of Precambrian and Paleozoic metamorphic rocks and Pre-Variscan and Variscan granitic rocks within a tectonically complex zone that was intensely deformed during the Variscan Orogeny (Diez Balda et al., 1990).

The WCB region shows a clear fault pattern, with a dominant NNE-SSW trend (e.g. Duero, Almendra, Almeida-Valderaduey faults) (Antón et al., 2010a), which is consistent with the large, neotectonically-active fault systems to the west (Bragança-Vilariça corridor) (Cabral,
seismicity in this area indicates a local N-S oriented of Shmax (Antón et al., 2010a), while regional data show a more NW-SE oriented Shmax (De Vicente et al., 2008).

The whole study area was deformed by extensional and strike-slip brittle faulting during post-Variscan and Alpine times (Arthaud and Matte, 1975; Vegas, 2005; Martín-González et al. 2011). This last brittle deformation was related to the opening of the Atlantic margin in western Iberia during the Triassic and Jurassic (Srivastava et al., 1990) and the far-field effects of the Alpine and current tectonic history of Iberia: convergence at the northern and southern borders (Pyrenees and Betics) (Andeweg et al., 1999; Galindo-Zaldivar et al., 1993; Galindo-Zaldivar et al., 1999; Liesa and Simon, 2009).

3. Seismicity

The analysis of seismic catalogues revealed that in the study area a moderate seismicity occurs. The National Seismic Catalogue, managed by the Instituto Geográfico Nacional (IGN), contains 4,380 historic and instrumental
events in NW Iberian Peninsula (Fig. 4) since the year 1347 until 27th August 2011. The seismic events registered in the study region represent the 8.5% of the total events in the Iberian Peninsula.

In terms of depth and magnitude, 94% of the earthquakes have magnitude value determined and only 56% have hypocenter solution. 97% of the seismicity occurs in the upper crust, with hypocenter depths lower than 15 km. (Fig. 4). 90% of the earthquakes have magnitudes lower than 3.5 mb.

3.1. Lugo seismic sequences (Sarria-Triacastela-Becerreá)

The recent seismicity recorded is mainly located in SW of Galicia, in Lugo (1995 and 1997, Lugo sequences, 5.1 mb), south of the Cenozoic depression of Sarria. At this area, NNW vergent thrusts joint NE-SW strike-slip fault corridor (Martínez-Díaz et al., 2006; Martín-González et al., 2006) (Fig. 2).

Seismic activity in the area of Sarria-Triacastela-Becerreá began in 1995 with two earthquakes of magnitude 4.6 mb (November 29 and December 24, 1995) and their associated aftershocks. In May 1997 a second series followed the former, beginning with an earthquake of magnitude 5.1 mb (http://www.ign.es/ign/es/IGN/SisCatalogo.jsp).

The 1995 sequence was composed by two subseries. The first one began with a 4.6 mb earthquake on November 29th, 1995, followed by a series of aftershocks, up to 37 during the same day. Their frequency decreased rapidly in 20 days, following the Omori law (Martínez-Díaz et al., 2006). The second subseries began with another 4.6 mb earthquake on 24th December of that year and was followed by a series of aftershocks of lesser importance. In 1996 and part of 1997 the recorded events did not exceed the magnitude 4.1 mb. In the 21th May, 1997 a 5.1 mb earthquake started the second seismic sequence. This earthquake was preceded by a premonitory of magnitude 4.2 mb, only 59 seconds before the main event. After that, a large series of 106 aftershocks took place in 24 hours, one of which reached magnitude 4.5 mb. The sequence of aftershocks decayed according to the Omori law within the thirty following days.

The 1997 sequence has a significant southeastward migration in relation to the 1995 sequence. Moreover, the position of the epicenters of the major earthquakes and the temporal sequence of the events has been interpreted as triggering mechanisms between the main events (Martínez-Díaz et al., 2006).

From 1994 to 2005, 25 focal mechanisms have been calculated in the Lugo area (Herraiz et al., 1998; Rueda and Mezcua, 2001; Harvard, 2001; Pondrelli et al., 2002; Stich et al., 2003; López et al., 2004b). Only fifteen been long strictly to the seismic crisis of 1995 (Herraiz et al., 1998; Rueda and Mezcua, 2001) and 1997 (Herraiz et al., 1998; Rueda and Mezcua, 2001; Harvard, 2001; Pondrelli et al., 2002; Stich et al., 2003), all of them summarized in Fig. 5. In this figure, are also displayed twelve focal mechanisms calculated by the IGN (Institute responsible for the Spanish Seismic Network) (Rueda and Mezcua, 2001), three mechanisms from the SIGMA project (Herraiz et al., 2000) of the three largest events of the 1995 sequence, two mechanisms of the biggest events of the 1997 sequence calculated by Harvard CMT Project, one mechanism of the 1997 series calculated by Pondrelli et al. (2002), and two mechanisms form Stich et al. (2003). The later five focal mechanisms were calculated by the Centroid Moment Tensor method (CMT). There are also other focal mechanisms solutions from the same area recorded from 1999 to 2002, offering us valuable information about the active faults in the area (López et al., 2004a and 2004b).

There are important differences between the published focal mechanisms solutions. For example, the first event of the second series (1997) has a reverse type solutions following the data from Rueda and Mezcua (2001), while other authors propose extensional type solutions (Stich et al., 2003). The same discrepancy exists between the mechanisms calculated for the first 4.6 magnitude event in the 1995 series (Fig. 5) (Herraiz et al., 2000, Rueda and Mezcua, 2001). It is not the scope of this work to discriminate or assess which is the best published solution. Therefore an analysis with all the solutions has been made. The published solutions can be gather in two groups, solutions indicating left-lateral strike slip faulting with reverse component trending NE-SW to NNE-SSW, and solution indicating normal faults trending NW-SE. The focal mechanisms calculated with a more accurate seismic network installed after the seismic sequences of Lugo (López et al., 2004a and 2004b) are in agreement with strike-slip faulting with reverse component.

Despite the different focal mechanism solution published, the maximum horizontal compressive stress for the region is consistent in all of them. With all the focal mechanism of the Lugo seismic sequence, a NW-SE shortening is observed (Martín-González, 2005). Using a larger number of focal mechanisms including the whole Northwest Iberian Peninsula, González-Casado and Giner (2000) obtained the same NW-SE direction, which is in turn the same solution of Rueda and Mezcua (2001).

The analysis of the spatial distribution of hypocenters shows that they apparently define a plane striking NNE-SSW with a dip of ~ 80° towards the SE, extending to a depth around 15 km. In the second crisis, the pattern of distribution does not appear so clear and its dispersion is
could be grouped as follows:

1. The NE-SW strike slip faults with some reverse component (Vilachá, Ferreiros, Baralla, Becerreá, Lóseo and Loureiro faults).

The Focal Mechanisms calculated after the seismic crisis indicates the existence of a great variety of solutions, which apparently indicate a readjustment of many structures. In general, the 1997 seismic crisis has been identified as triggered by the first series on 1995. This triggering effect is only justifiable if the fault of the first sequence is a NE-SW left lateral strike-slip fault with reverse component (Martínez-Díaz et al., 2006).

much larger, but there is a clear spatial migration of hypocenters, indicating a reactivation of several faults located further southeast of the first (Martínez-Díaz et al., 2006).

Despite the significant contradictions between the focal mechanisms calculated for the area there are some common aspects. In the first series, the focal mechanisms identified by different authors indicate the existence of a common nodal plane with minimum differences, oriented NNE, with left lateral movement. Focal mechanisms of the second series, one of the nodal planes is again similar to that observed in the first series. Although, in this case, the strike slip component is lower (Fig. 5).

Looking at the structures mapped in the area (Figs. 3 and 5), the faults that better fit the mechanisms solutions
3.2. Orense seismic sequences (Celanova)

Since the 90’s a significant seismicity has been recorded in the Orense region. Events reach a magnitude of 3.8 mb and the years with seismicity particularly intense were 1998, with 96 events (maximum magnitude of 3.6 mb), and 2005, with 108 events (maximum magnitude of 2.8 mb). The most notable increase in the number of events...
occurs after the crisis of Lugo in 1997. Seismicity can be grouped in three zones. Although there has been an event at a depth of 33 km, maximum depth does not exceed 26 km and is concentrated around 7 km (Fig. 6).

In the 1980-1990 decade, earthquakes were scarce and they were concentrated around the basin of Xinzo de Limia (Sandias) (Fig. 6). In the 1990-2000 decade seismicity started west of Celanova with a NNE-SSW trending distribution. In the 2000-2010 decade the magnitude of the events decreased but the number increased. The seismicity in Celanova continues, trending NNE-SSW, and another crisis started east of Mondariz. Broadly speaking, seismicity seems to migrate towards SW. In depth events seem to fit a NNE-SSW trending plane strongly dipping to SE (Fig. 6).

The distribution of epicenters (Fig. 6) and hypocenters (section WNW-ESE, b-b’ in Fig. 6) seems to be orientated in NE-SW planes. They fit with the main faults which are NE-SW strike-slip faults (Fig. 6). Regionally they correspond to the Orense and Lugo-Chantada fault corridors (Fig. 2 and 6). Northward, the Orense fault corridor links with the faults that are the responsible for the
Sarria-Triacastela-Becerrea seismicity (Figs. 2, 5). The connection of the structures in a NE-SW fault corridor, and the temporal migration of the seismicity can be interpreted as the southwest migration of the activity following these NE-SW corridors (Fig. 6).

3.3. The western fringe of the Cenozoic Duero Basin and the “Muelas del Pan” seismic sequences.

Data compilation of instrumental seismic activity for the WCB (http://www.ign.es/ign/es/IGN/SisCatalogo.jsp; Stich et al., 2003) provides important information in relation to the moderate active deformation of this intraplate area and the currently active tectonic stresses.

The IGN catalog contains 189 earthquakes registered in the WCB area, since the year 1831 to August 2011, corresponding magnitudes ranging from 0.8 to 5.2 mb (Fig. 3). The majority of the events are in the depth range from 1 to 15 km, which is characteristic of brittle deformation in the upper crust of continental intraplate areas. Only 10 events are in the depth range from 15 to 23 km. The location of most of the registered events have a RMS value lower than 0.75.

The maximum magnitude seismic events (5.2 MD, Mezcua y Martínez Solares, 1983) correspond to earthquakes that occurred close to in Zamora in 1961. The spatial distribution of epicenters shows an important cluster in the Muelas del Pan-Villalcampo area, where 114 earthquakes have been recorded since 1995. In this area, two seismic sequences with events magnitudes higher than 3.4, occurred in 2001 and 2003 (Fig. 7). The distribution of the events of the seismic sequence could be related the Esla fault. This fault is a NNE-SSW trending segment where the Esla River is deeply incised (Antón et al., 2011). In this region NNE-SSW lineations are well recognized (Figs. 3 and 7).

The largest sequence was recorded in 2003 and started with a 3.8 Mw event in January 12th 2003, followed by 15 aftershocks in 2 days. On January 23nd 2003, another event of 4.2 Mw occurred and was followed by 7 aftershocks in the next 2 days. On January and February 2003, 58 seismic events occurred in this area (Fig. 7).

The two main earthquakes occurred in January 2003, with magnitudes (Mw) 3.8 and 4.2 respectively. It was possible to determine well-constrained focal mechanisms from moment tensor solutions (Stich et al., 2003) (Fig. 7). These are typical strike-slip faulting solutions with a NNE-SSW trending (N7º-12ºE) nodal plane (Antón, 2004; Antón and De Vicente, 2006; Antón et al., 2010a). These focal mechanisms seem to indicate that the Esla fault system, with an average N10°E trend, is moving as a left lateral strike slip structure under the present regional N-S to NW-SE compression (Antón et al., 2010b). From this evidence, NNE-SSW faults located to the west, like those from the Bragança-Vilariça, Verin-Vila Real and Orense fault corridors, should also be moving as left-lateral strike-slip faults with some reverse component.

4. Geomorphological evidences of recent tectonic activity

Throughout the entire study area several geomorphological evidences of the presence of recent tectonic activity have been recognized, as exemplified below:

4.1. NE-SW trending strike-slip faults in Galicia

NE-SW strike-slip faults are potentially active in the NW Iberian Peninsula. A representative fault of those is the Ferreiros fault, which has been studied in detail. We may evaluate the fault kinematics after the establishment of the regional drainage network. The Ferreiros fault is a left lateral strike-slip fault with a horizontal offset of 800 m on Variscan markers. This fault belongs to the fault system that limits the Cenozoic deposits of the Sarria depression (Fig. 2). Ferreiros fault diverts channels with NW-SE trend. There are four main channels that are deflecting when crossing the fault. More than fifteen channels can be identified in the south block (downstream) but only four of these channels can be continued upstream and the rest are beheaded streams. Moreover, ridges that divide the channels became offset by Ferreiros fault (Fig. 8).

The whole displacement of the Ferreiros fault has been balanced in order to know whether all the displacement has occurred when the drainage network was established. After removing the offsets of the Variscan marker the drainage fits again. Therefore, the fault horizontal displacement has occurred after the drainage was established. Unfortunately no data about drainage ages are available to estimate slip rates.

4.2. El Bierzo depressions

El Bierzo Cenozoic depressions are filled with detritic and carbonated sediments which are in turn, deformed by E-W and ESE-WNW thrusts (Fig. 9). The largest basin is the Ponferrada basin, which is drained by the Sil river which flows from NE to SW and is deflected towards the west in the southern limit of the basin. The main channel has terraces exclusively on its right bank (Fig. 9),
and on the northern side of the basin the drainage pattern develops a parallel pattern flowing towards the SSW and shows a relevant asymmetry, depicting that the main channel is displaced southwards.

Topographic profiles have been executed across the basin. They show that the depression has a gentle slope towards the south and presents terraces only in the right (north) bank of the main channel, evidencing a southwards tilting of the basin. This tilting can be explained by the effect of the north vergent thrusts that limit the depression on its southern side and uplift the Aquilianos and Teleno Mountains (2100 m) which are younger than the south vergent thrust (Martín-González et al., 2011) (Fig. 9).

4.3. The Western Fringe of the Cenozoic Duero Basin

In the WCB, systematic analysis of structures affecting the Cenozoic sediments shows how they are coincident with fault trends related to the present stress field (Antón,
Fig. 7.- Esla fault area, seismicity and focal mechanisms. Epicenter distribution and hypocenters location showing a possible fault plane orientation. Location in Fig. 2.

Fig. 7.- Zona de la Falla del Esla, sismicidad y mecanismos focales. Distribución de epicentros y localización de hipocentros, que muestran las posible orientación del plano de falla. Localización en Fig. 2.
Faults mostly trending N-S to NE-SW are dissecting Cenozoic deposits and inducing vertical displacement, sinking westwards (Villar-Alonso et al., 2000).

An important neotectonic feature within the WCB is the asymmetry in the fluvial deposits distribution, common to most of the N-S and NW-SE trending streams (Fig. 10a, b and c). Lateral migration of fluvial deposits give place to asymmetric valleys showing gentle western and southwestern slopes, where glacis deposits are present, with opposite steeper margins. Some examples occur in the northeastern part of the area, where NW-SE, N-S and E-W streams (Fig. 9b) show deposits restricted to the western and southern margins, respectively. Southernmost of the Oblea river (Fig. 10b) a N-S structure is conditioning the fluvial asymmetry, with sediments only present in the western margin. Asymmetry in Quaternary fluvial deposits and lateral migration of valleys seems to be related with an E-W to ENE-WSW extension (Antón, 2004) resulting in block tilting to the east, also described by other authors (Escuder et al., 2000; Santisteban et al., 1996). This process is mostly conditioned by N-S to NW-SE trending faults (Fig. 10e).

Other field observations, such as faults with a clear Cenozoic activity, e.g. Golpejas fault (Fig. 10d) among others, support the presence of a transpressive shear zone, formed by two conjugate faults systems trending ~ N30ºE and ~ N140ºE, that conditioned the contact between Paleozoic metamorphic rocks and lower Eocene sediments (Santisteban and Martín-Serrano, 1991).

5. Potentially active faults

The seismic activity recorded during the historical and instrumental periods in the study region can be considered moderate; although it is noteworthy that in 1997 was recorded in Lugo one of the largest magnitude earthquake (5.1 mb) occurred in the instrumental period of the Iberian Peninsula. The epicentral locations show a scattered
distribution but with some clusters associated with larger seismic sequences (Fig. 4). The spatial distribution of seismicity concentrates on lineaments that match with neotectonic faults trending NE-SW. The seismicity seems to migrate southward following these trends as evidenced by the seismicity increase in Orense after the seismic crisis of Lugo.

The distribution of seismicity at depth (see histogram in Fig. 4) indicates that over 80% of the seismicity is concentrated in the upper 25 km of crust. This is consistent with a rheology controlled by the mechanical nature of an intraplate crust (highly rigid). This behavior combined with the highly fractured Variscan basement has been argued to explain some seismic sequences as triggered seismicity by the stress transfer mechanisms, in which earthquakes can trigger another of similar magnitude on faults located nearby.

In this study, we define potentially active faults as faults that can move under the “current tectonic regime” (Muir-Wood and Mallard, 1992). The current tectonic regime is the period in which the tectonic stresses have remained constant, for the Northwest and Central Iberian Peninsula we will consider that the current tectonic regime starts at least in the Middle Miocene (Srivastava et al., 1990; Andeweg, 2002).

Taking into account that the horizontal maximum compression calculated in the NW Iberian Peninsula is NW-SE (Srivastava et al., 1990; Andeweg 2002), the best orientated structures (among those recognized in the region) that have significant activity are: 1.-The NE-SW strike-slip faults with a reverse component (as hypocenters distribution, field observation and focal mechanism solutions indicate). 2.-The younger NE-SW thrusts of the Caurel Mountains and the Galaico-Leoneses Mountains (as field observation and some focal mechanism solutions indicate) 3.- The NW-SE normal faults (as some focal mechanism solutions indicate) (Fig. 2). Those groups of structures can be potentially seismogenic faults (Fig. 11). However, the two first groups explain better the seismic sequences analyzed formerly and they agree with the previous sismotectonic studies (González-Casado and Giner, 2000; Rueda y Mezcua, 2001; López et al., 2004a; Martin-González et al., 2006; Martinez-Díaz et al., 2006) that pointed out NE-SW fault moving with a strike-slip movement with reverse component, as the seismogenic faults. Moreover, the strike-slip faults are conspicuous in the region, and long corridors are present running NE-SW, supporting the thesis that these corridors are the most probable seismogenic faults in the region. Those corridors are grouped in three main corridors or fault systems: Orense, Lugo-Chantada y Caldelas (Fig. 2). The main seismic sequences (Lugo and Orense sequences)

are related to faults belonging to the Orense corridor. These corridors penetrate in Portugal and have the same orientation as the Bragança-Vilarica fault corridor, which has a slip rate of 0.2-0.5 mm/a (Cabral, 1989 and 1995; Rockwell et al., 2009; Cabral et al., 2010), the Verin-Vila Real fault corridor, and some segments of the Alentejo-Plasencia fault (Villamor, 2002) (Figs. 11 and 2).

To the South, the WCB has relatively flat relief at a mean elevation of 750 m above sea level, but is affected by large-scale fractures dominated by N-S to NNE–SSW left-lateral strike-slip faults (Antón et al., 2010a). However, the relevance of the fracture pattern in the WCB is highlighted, among others, by the fluvial network dis-
distribution. Main streams orientation (such as the Agueda, Duero, Esla and Valderaduey rivers) (Fig. 11) is conditioned by the fault pattern as abrupt changes in main trunk direction and incision distribution reveal (Antón and Muñoz Martín, 2007; Antón et al., 2011).

In the WCB, N-S to NE-SW main faults seems to be responsible for the seismicity recorded in the area. The main example is the Esla fault where moderate seismicity, with magnitudes up to 4.2 Mw, occurs. Moment tensor focal mechanisms (Stich et al., 2003) evidence the seismogenic activity of an N10° trending left lateral strike slip fault moving under a N-S to NW-SE oriented maximum horizontal compressive stress.

Moreover, asymmetries in fluvial deposits distribution and lateral migration of valleys revealed faults movements during the Cenozoic or/and in the Quaternary. Structures controlling the deposits distribution asymmetries are mostly oriented NW-SE to N-S (Antón, 2004).
Fig. 11.- Sketch showing the fault orientations and faults that are potentially active under the current stress field.

Fig. 11.- Esquema mostrando las orientaciones de las fallas que son potencialmente activas bajo el tensor actual de esfuerzos.

6. Conclusions

The North-West and Central-West Iberian Peninsula correspond to intraplate regions located far away from the seismically active borders of the Iberian Peninsula. However, seismic sequences of moderate magnitude (5.1 mb) have revealed the presence of active structures and potentially damaging earthquakes in this region.

After the analysis of the spatial distribution of seismicity and focal mechanisms, faults trending NE-SW to N-S seem to be the responsible for most of the present seismicity.

Geomorphological and structural evidences of recent tectonic activity have been identified in tilted terraces, asymmetries in fluvial deposits distribution and drainage affections. Theses evidences are due to strike-slip faults trending NE-SW and N-S, and to northwest verging thrusts. All these structures can be reactivated under the inferred present stress field.

In the NW Iberian Peninsula the seismicity seems to be oriented following NE-SW fault corridors (e.g. Orense fault corridor) and the seismicity increased in Celanova (Orense) after the seismic crisis of Lugo indicating a southward migration of the activity.

Taking into account the horizontal maximum compression, and the evidences of recent activity, the potentially active structures are: 1) NE-SW to N-S strike slip faults; 2) Thrust trending NE-SW to ENE-WSW with NW vergence (Fig. 11).

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