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Origin of a restraining bend in an evolving strike-slip system: The Cenozoic As Pontes basin (NW Spain)

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ABSTRACT

The As Pontes basin (12 km^2), NW Iberian Peninsula, is bounded by a double restraining bend of a dextral strike-slip fault, which is related to the western onshore end of the Pyrenean belt. Surface and subsurface data obtained from intensive coal exploration and mining in the basin since the 1960s together with additional structural and stratigraphic sequence analysis allowed us to determine the geometric relationships between tectonic structures and stratigraphic markers. The small size of the basin and the large amount of quality data make the As Pontes basin a unique natural laboratory for improving our understanding of the origin and evolution of restraining bends. The double restraining bend is the end stage of the structural evolution of a compressive underlapping stepover, where the basin was formed. During the first stage (stepover stage), which began ca. 30 Ma ago (latest Rupelian) and lasted 3.4 My, two small isolated basins bounded by thrusts and normal faults were formed. For 1.3 My, the strike-slip faults, which defined the stepover, grew towards each other until joining and forming the double restraining bend, which bounds one large As Pontes basin (transition stage). The history of the basin was controlled by the activity of the double restraining bend for a further 3.4 My (restraining bend stage) and ended in mid-Aquitanian times (ca. 22 Ma).

KEYWORDS **Strike-slip basement fault. Restraining bend basin models. Oligocene-Miocene. Iberian Peninsula.**

INTRODUCTION

Uplifting and subsiding along strike-slip fault zones depend on the geometry of the faults, their spatial arrangement and the fault kinematics (Wilcox et al., 1973; Christie-Blick and Biddle, 1985). In accordance with their orientation and spatial arrangement with respect to the general displacement direction of the blocks separated by the fault zone, bends and stepovers in strike-slip fault zones may give rise to 1) zones with a divergence component, resulting in subsiding areas, or 2) zones with a convergence component, giving rise to uplifting areas developing folds and thrusts (Mann et al., 1984, 1985, Woodcock and Fisher, 1986; Curtis, 1999). Sedimentary basins may form in both cases. In the former case, pull-apart basins form in stepovers, and extensional basins develop along releasing bends. In the latter case, pop-up structures characterize stepovers. Restraining bends cause one block to override the other, and sedimentary basins may develop on the overridden, subsiding block (Crowell, 1976;

Sylvester and Smith, 1976; Steel et al., 1985; Namson and Davis, 1988; Mann et al., 1991).

The influence exerted by the geometry of the faults, their spatial arrangement and the fault kinematics on the evolution of strike-slip systems has been stressed by earlier studies (Wilcox et al., 1973; Crowell, 1976; Christie-Blick and Biddle, 1985). The complexity and variety of situations at diverse scales resulting from the interplay between the faults that make up strike-slip systems was highlighted by the most prominent case studies (Crowell, 1974a and b, 1976; Sylvester and Smith, 1976; Aydin and Nur, 1982; Mann et al., 1983; Royden, 1985; Steel et al., 1985; Schubert, 1986; Cabrera et al., 1988; Sarewitz and Lewis, 1991; Nilsen and Sylvester, 1995). As pointed out by Crowell (1974a and b), fault geometry and/or block motions may change during the evolution of complex strike-slip fault zones. Therefore, the present day configuration of faults and their relation to the sedimentary record, as observed on outcrops, do not reflect the complexity of their structural and sedimentary evolution. Moreover, subsurface data (i.e. well core data base, seismic imaging) often cannot capture the 3D complexity inherent in these systems. To overcome this disadvantage, scaled sandbox models have been employed to simulate and analyze the geometries and the progressive evolution of these kinds of structures and associated basins (Dooley and McClay, 1996, 1997; McClay and Bonora, 2001).

In addition, although a considerable number of very large to small strike-slip systems and their associated basins have been described in outline, there are few detailed descriptions of natural cases regarding the structural evolution of basins in strike-slip fault zones in the literature (Christie-Blick and Biddle, 1985; Mann et al., 1984, 1991; Sarewitz and Lewis, 1991; McBride, 1994; Miller, 1994; Curtis, 1999). The aim of this paper is to present the structural history of the As Pontes basin and to compare it to analogue modelling results. The As Pontes basin formation had been attributed to the geometry of the double restraining bend that bounds the basin at present (Bacelar et al., 1988; Cabrera et al., 1996). However, as will be shown, the restraining bends developed during the later stage of the structural evolution when the basin had undergone a long history.

GEOLOGICAL SETTING

The small As Pontes basin (12 km^2) formed in a NW-SE dextral strike-slip fault zone close to A Coruña, NW Iberian Peninsula, during Late Oligocene and Aquitanian times (Santanach et al., 1988; Huerta et al., 1997). This fault zone is related to the building of the Pyrenean orogen, which extends from Provence, SE France, to Kings Trough in the Atlantic Ocean (Fig. 1). From the Late Cretaceous to Early Oligocene the convergence between Africa and Europe caused the collision between Iberia and Europe resulting in the Pyrenees between France and Spain, a doubly vergent continental collision orogen. To the West of the Pyrenees, along the northern coast of the Iberian Peninsula, the oceanic crust of the Bay of Biscay moderately subducted below the continental Iberian plate (Muñoz, 2002). The subduction started in the Late Cretaceous and was blocked during the Paleogene, the deformation being transferred to the interior of the Iberian plate. Consequently, the large basement-cored uplift of the Cantabrian Mountains, which constitutes the northern margin of the Duero basin, developed because of thrusting over a long ramp connected to a midcrustal detachment (Alonso et al., 1996; Pulgar et al., 1996; 1997; 1999). To the West, this structure splays out in NE-SW sinistral strike-slip faults, and conjugate NW-SE dextral strike-slip faults are located along the coast, further to the West. Both strike-slip systems produce N-S shortening and E-W extension (Santanach, 1994).

A number of small sedimentary basins developed along the aforementioned strike-slip fault zones. The As Pontes basin is located in the Pedroso-As Pontes-Moiñonovo fault zone (As Pontes fault zone henceforth), which extends for 55 km from the coast to Moiñonovo, attaining a maximum width of 10 km. According to Heredia et al. (2004), the As Pontes fault zone extends further to the East and was responsible for significant uplift and relief generation in its northern block.

METHODOLOGY AND DATA BASE

The study of the As Pontes basin was based on a large amount of surface and subsurface data obtained from intensive coal exploration and mining in the basin from the 1960s to the present. The exploration surveys carried out by ENDESA Mina Puentes resulted in detailed mapping (1/2000 to 1/5000 scale) of the Precambrian and Lower Paleozoic basement outcrops and structures around the mine (Fig. 2A). Coal mining in the Oligocene-Lower Miocene basin fill successions, which were exhumed in the successive open pit trenches, also allowed a detailed mapping of the coal bearing sequences (Figs. 2B and 2C). Furthermore, approximately 1400 continuously cored exploration wells reaching the basement were drilled, forming a nearly regular square grid spaced at about 105 m (Fig. 3A). ENDESA Mina Puentes has stored the data obtained from these activities in a comprehensive database that includes detailed lithological and structural core descriptions, maps and geological cross sections. This database was complemented by additional extensive structural and stratigraphic sequence analyses to yield further insight into the relative chronological relationships between the major basement structures and the

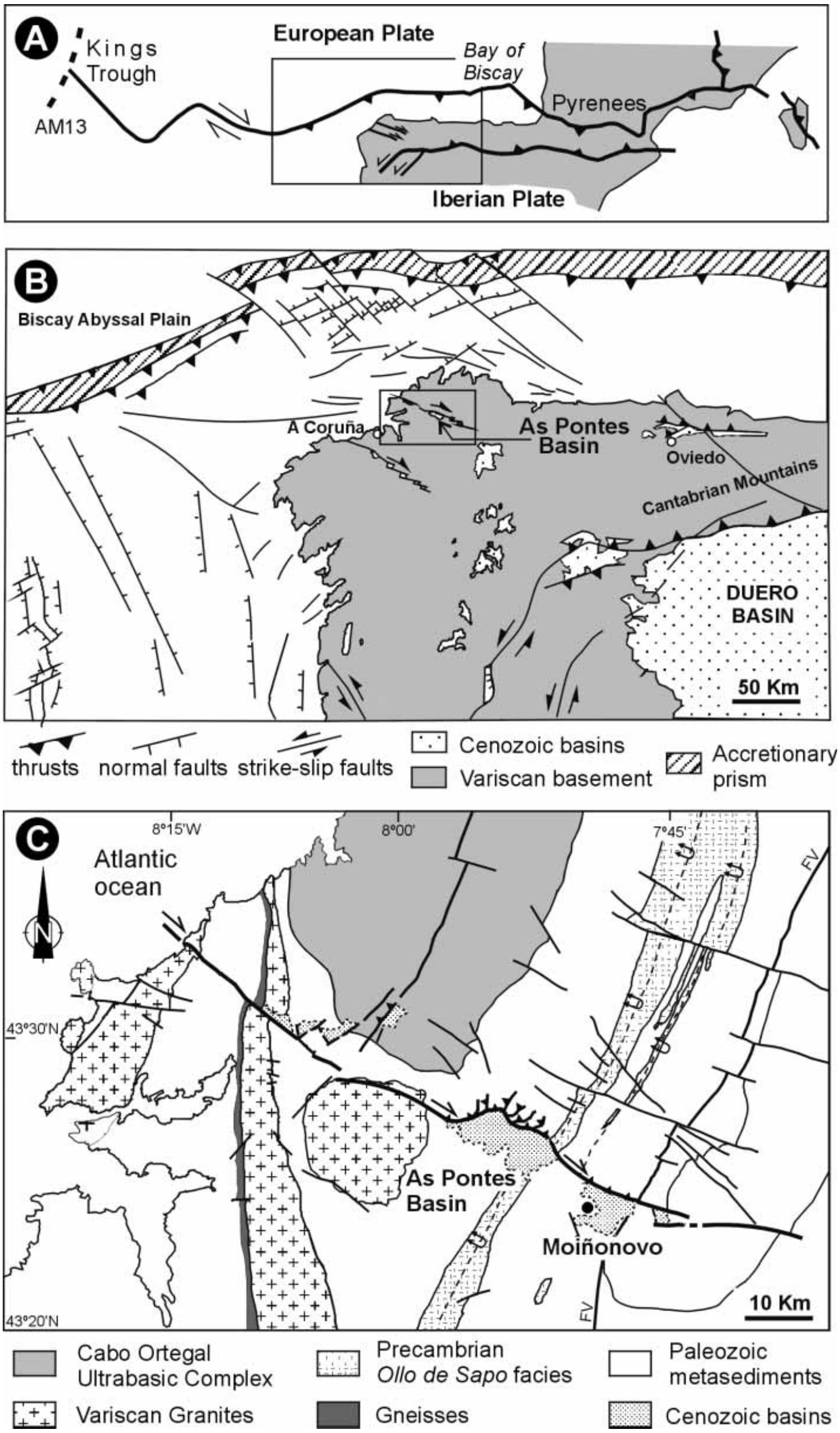


FIGURE 1 **Location and geological setting of the As Pontes basin. A) Pyrenean convergent margin stretching from SE France as far as magnetic anomaly AM 13. B) Major tectonic characteristics of NW Iberia. C) The As Pontes strike-slip Fault Zone.**

syntectonic, coeval, basin infill. All the available stratigraphic and structural information was used to determine the geometric relationships between tectonic structures and stratigraphic markers and to perform the structural analysis and basin evolution reconstruction, including the structure kinematics.

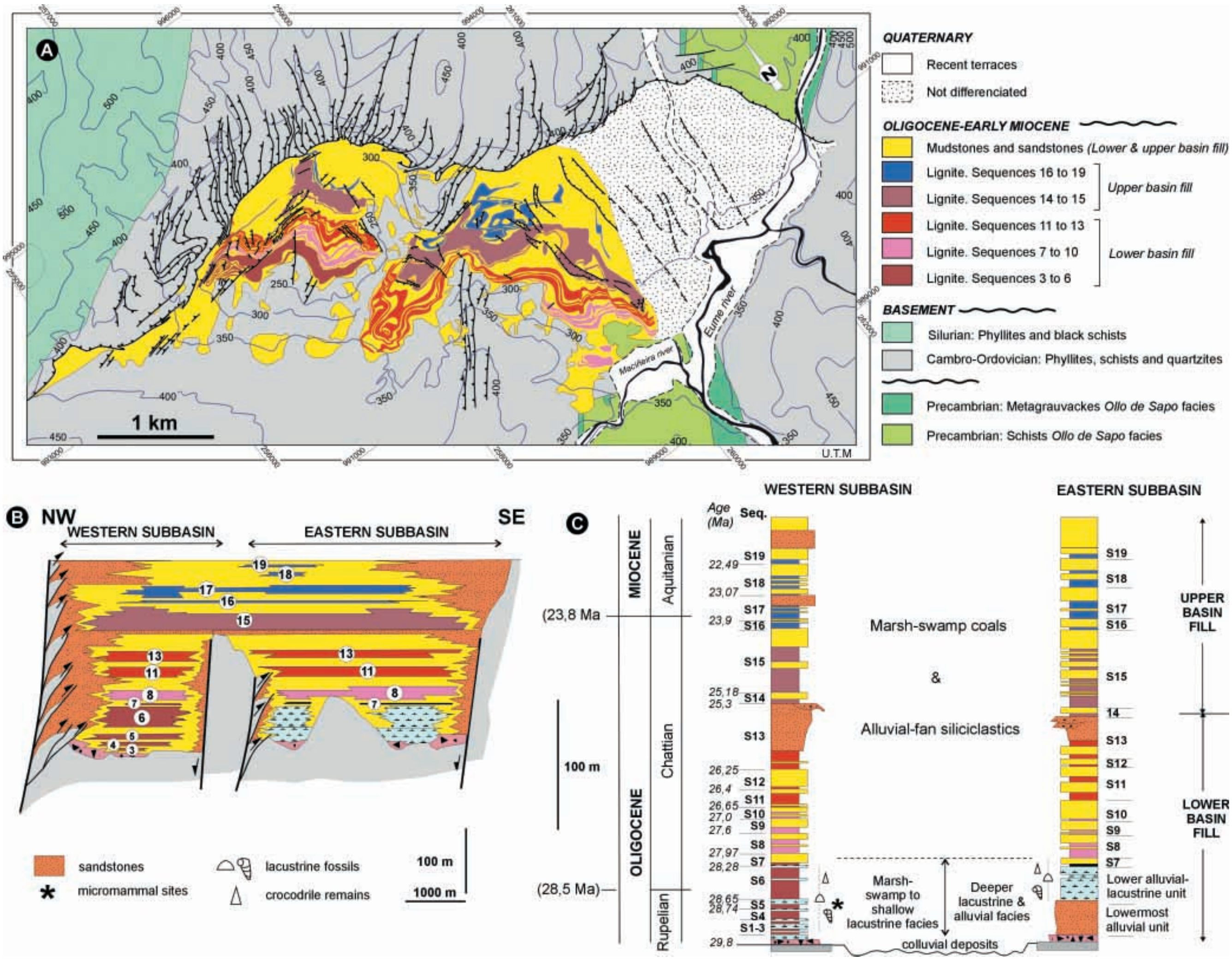


FIGURE 2 | **Overall features of the As Pontes Basin. A) Geological map of the basement surrounding the basin and of the open-pit outcrops of the basin fill in 1997. Based and modified from mapping data provided by the Geological Office of ENDESA Mina Puentes. B) Stratigraphic panel of the basin fill showing the eastern and western subbasins and the major coal-alluvial sequences. C) Synthetic stratigraphic logs of the eastern and western subbasin fills with indication of the chronology of bottom of the coal-alluvial sequences (based on Huerta et al., 1996, 1997, and on Ferrús, 1998).**

THE AS PONTES BASIN

The As Pontes basin is the largest basin in the As Pontes fault zone. It extends for 8 km in a NW-SE direction and its width varies between 1.5 and 2.5 km (Fig. 2). The basin is asymmetric. Along its southwestern margin the sedimentary fill onlaps the substratum, which descends progressively towards the northwestern margin, where the basin is bounded by two gentle double restraining bends of the main fault (Bacelar et al., 1988). The Cenozoic-basement isobath map shows that the basin is formed by two subbasins separated by a threshold (Fig. 4).

The basin was developed on the Variscan basement made up of gneisses, schists, quarzites and, mainly, phyllites. This basement is characterised by a multiphase deformation, which shows a strongly penetrative cleavage dipping 40º to 70º to the NW (Arce Duarte et al., 1975; Fernández et al., 1975; Aller and Bastida, 1996). The cleavage bends to a more E-W trend close to the main fault (Manera et al., 1979). Moreover, in this area, the basement shows a major NNE-SSW antiform, cored by cropping out Precambrian gneisses (Ollo de Sapo facies), that crosses the southeastern part of the basin and constitutes a marker for the lateral displacement of the As Pontes strike-slip fault (Fig. 4). The subcrop map of the basin shows approximately a 1 km long dextral separation of the strongly dipping (>70º) southeastern limb of the antiform along the main fault, the relatively large N-S normal faults bounding the subbasins to the East, and a large number of small south-directed thrusts (Ferrús, 1998).

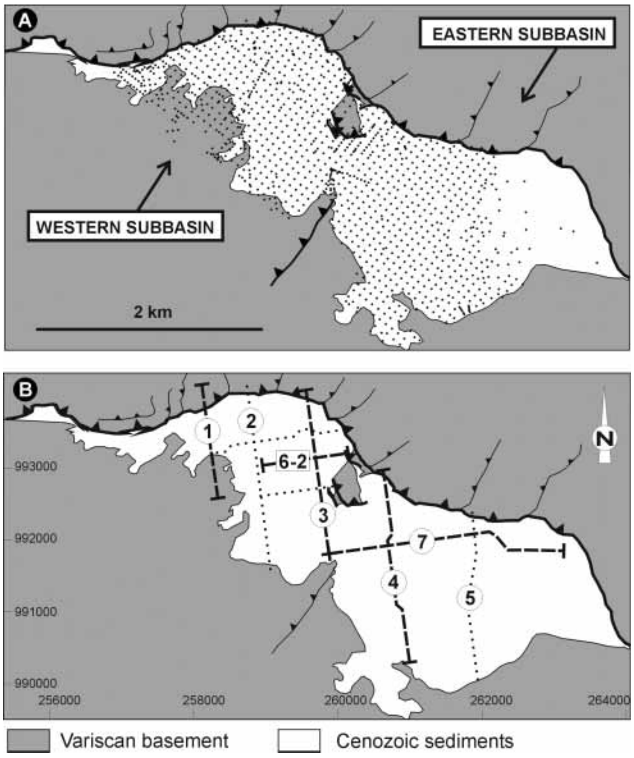


FIGURE 3 **Distribution of the sources of available information on the structure and stratigraphy of the As Pontes basin. A) Coal exploration and exploitation well grid. B) Structural cross sections.**

Depositional framework and Stratigraphy

Basin depositional systems

The sedimentary fill of the As Pontes basin attains a thickness of 400 m in the NW corners of both subbasins. This basin fill resulted from the interplay between alluvial fan, lacustrine and marsh-swamp sedimentation, and consists of major siliciclastic facies assemblages, interfingered with significant brown coal seams and minor carbonate deposits. Several lithostratigraphic (Bacelar et al., 1988; Cabrera et al. 1995, 1996; Ferrús, 1998; Fig. 2), biostratigraphic (López et al., 1993; Cabrera et al., 1994) and magnetostratigraphic (Huerta et al., 1996, 1997) studies have enabled detailed stratigraphic subdivision and accurate dating of the basin fill (Ferrús, 1998).

Mainly mudstone, minor sandstone and very minor conglomerate make up the alluvial fan successions. The widespread mudstone and sandy mudstone facies indicate that these systems were fed predominantly by fine grained sediments owing to the rock composition of the catchment (major phyllites and schists and minor quartzites and gneisses; Barsó et al., 2000, 2003; Sáez et al., 2003). The textural and sedimentological features of these alluvial fine-grained facies indicate that mud flows and more diluted, concentrated flash flows were the main depositional processes on the fan surfaces. More diluted aqueous flows (e.g. sheet flows, channelized flows) resulting in water laid sand-dominated deposits were more restricted.

The lacustrine assemblages attained their maximum development in the eastern basin zones, in the earlier stages of the basin evolution, and consist of cyclically arranged shallow lacustrine mudstones and carbonates, and deeper lacustrine laminated mudstones and carbonate-clay rhythmites (Cabrera et al., 1995; Sáez and Cabrera, 2002).

The brown coal and coaly mudstone facies were deposited in marsh-swamp zones closely related to the distal-marginal alluvial mud flats. The coal seams and the related coaly mudstone beds range from a few cm up to several tens of m in thickness and are often laterally widespread (from several hundred m up to a few km).

The interfingering and vertical transitions between coal and alluvial deposits record the settling, spreading, retreat and final obliteration of the coal generating environments. This evolution is closely related to coeval opposite alluvial fan trends of retreat and spreading, respectively (Fig. 2). Successive composite coal-alluvial sequences resulted from the spreading and retreat pulses of the alluvial-fan systems and attained diverse thickness and spread during the diverse evolutionary stages of the basin. These stages resulted mainly from tectonosedimentary changes that modified the silicilastic sediment contribution and the basin subsidence rate (Ferrús, 1998).

The top of the basin fill is affected by an erosion surface. It has been estimated that approximately 60 m of sediments were eroded (Ferrús, 1998).

Stratigraphic subdivision and correlation

The coal bearing basin fill has been split into 19 composite coal-alluvial sequences (Fig. 2C). Each sequence includes (1) a lower basin margin restricted alluvial fan assemblage that interfingers basinward with coal bearing and coal-dominated successions, characterised by laterally extensive, continuous coal seams; and (2) an upper basinward spread alluvial-fan assemblage almost exclusively made up of siliciclastics.

Extensive correlation surfaces are easily recognized and traced in the inner basin zones, where coal deposits are widespread and can be used as stratigraphic markers. These correlation surfaces can be traced towards the marginal basin zones, combining the use of marker beds with sequential trend analysis. Although some correlation surfaces could not be precisely traced as far as the most marginal basin zones, where coarse-grained alluvial deposits dominated, a fairly accurate correlation was obtained.

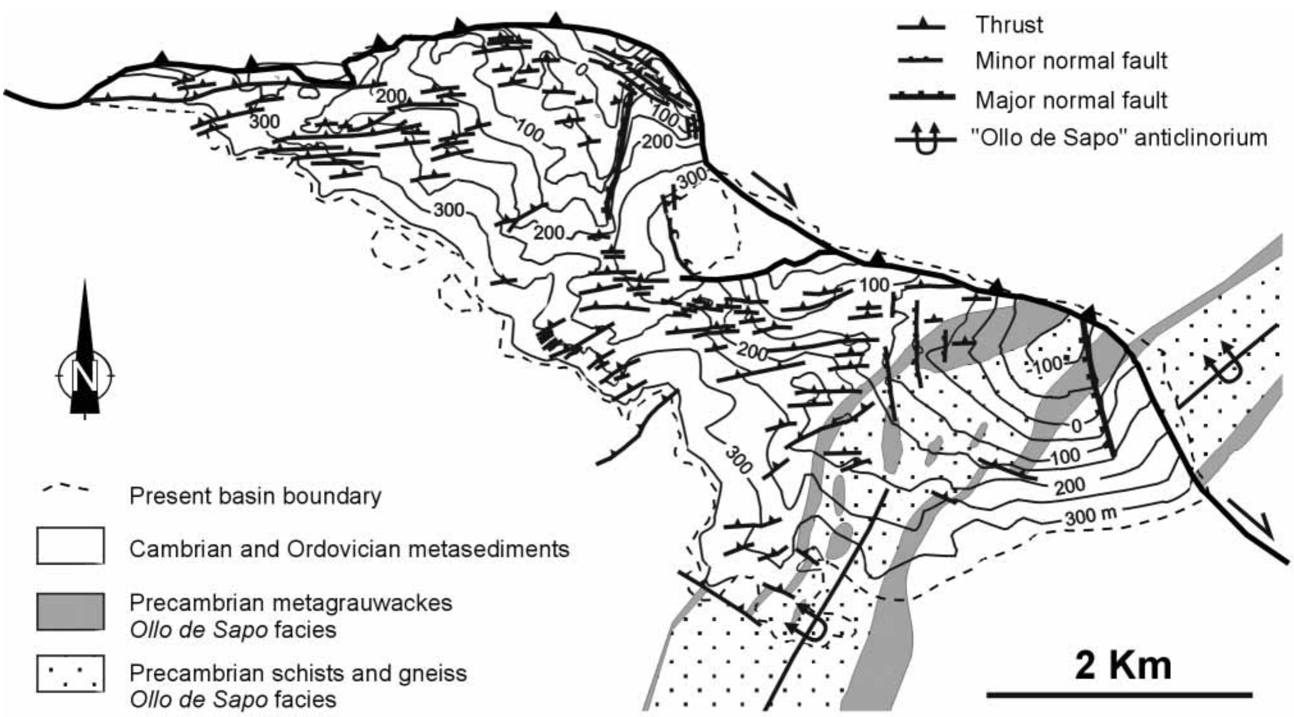


FIGURE 4 **Sub crop map, isobath (topographic, sea level datum in meters) and structural map of the As Pontes basin basement.**

The dense grid of exploration wells together with the occurrence of the laterally extensive coals and coaly mudstones enables us to obtain a fairly precise stratigraphic correlation from the inner to the marginal basin zones (Figs. 2B, 2C and 3A). Likewise, it is possible to determine the geometric relationships between the basement tectonic structures and the stratigraphic markers. Moreover, the available lithostratigraphic (Bacelar et al., 1988; Cabrera et al., 1995, 1996; Ferrús, 1998) and magnetostratigraphic data (Huerta et al., 1996, 1997) indicate that the correlation surfaces are isochronous or nearly isochronous (Ferrús, 1998). Thus, the As Pontes basin constitutes a unique natural laboratory for improving our understanding of the kinematic evolution of a strike-slip restraining bend basin, from the nucleation of its earliest structures until its mature stages.

Structure

The As Pontes basin is characterised by the coeval generation of compressive and extensional structures during its early structural history. The most conspicuous structure is the strike-slip fault, whose two gentle double restraining bends bound the basin to the NE. This fault has an important thrust component to the N of both sub-basins, where the fault has an E-W orientation. A system of south-directed thrusts affects the northern margin of each subbasin. N-S trending normal faults define the eastern limits of the subbasins. This structural assemblage is consistent with N-S shortening and E-W extension.

A number of structural cross-sections forming an orthogonal net were drawn to study the compressive structure of the northern margins and the normal faults that define both subbasins (Ferrús, 1998). One set of sections is parallel to the shortening direction (approximately N-S) and the other one is parallel to the extension direction (approximately E-W). Some of these sections will suffice to illustrate the main characteristics of the As Pontes basin structure (Fig. 3B).

Sedimentary evidence of tectonic activity

Owing to its syntectonic character, the As Pontes basin fill was deeply affected by the evolution of the basin-related tectonic structures. As a consequence, the coal-alluvial sequences display significant changes in thickness and lateral spreading and show different relationships with the tectonic structures. This enables us to date and determine the evolution of these basement structures. The following criteria have been useful to establish the structural history of the basin.

1) Increasing thickness towards a fault provides evidence of the activity of this fault during sedimentation. The most prominent case of the thickness changes is the one observed between sequences 1 and 10 (Figs. 5A and 5B). The basin fill thickness increases eastward, towards the N-S normal faults and wedges westward and southward with the development of an extensive basement onlap. This is mainly due to the activity

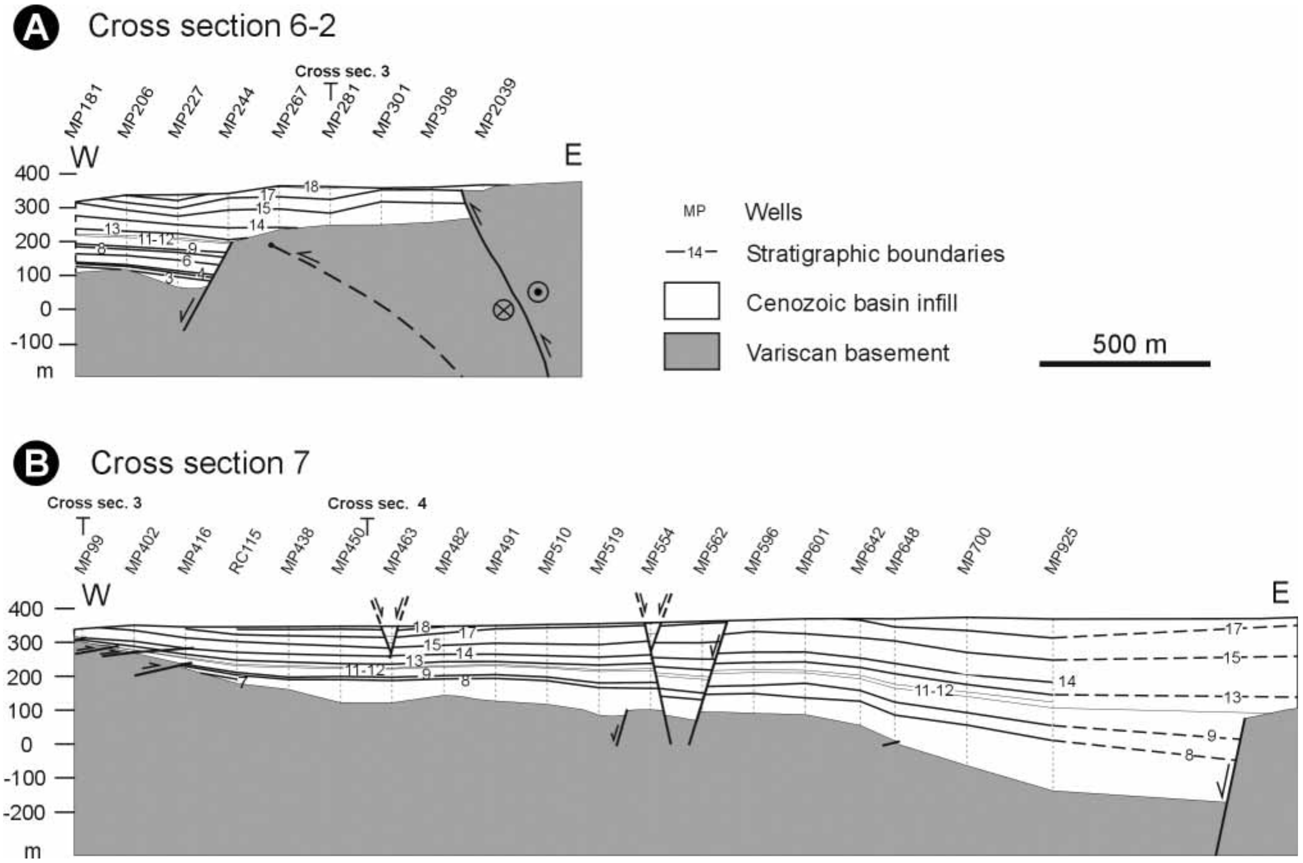


FIGURE 5 | **Cross sections showing the main normal faults in the As Pontes basin and their relationships with the main stratigraphic markers A) Cross-section 6-2. B) Cross-section 7 (see Fig. 3 for location).**

of the N-S normal faults, which tilted the basement in both subbasins. Albeit with less intensity, the thickness of the low basin fill increases towards the E-W thrusts (Figs. 6A to 6C), confirming the coeval activity of these thrusts and the normal faults. As a result, the maximum sediment thickness occurs at the toe of the northern ends of the normal faults, near their convergence with the E-W thrusts.

2) Very subtle thickness changes related to the development of small growth strata systems reveal the development of local structural culminations caused by thrusts located in the subbasins, resulting in supra-attenuated folds (central part of Fig. 6C).

3) Onlapping and overlapping the reliefs created by the faults and the sealing of these faults by the coal-alluvial sequences yield evidence of the cessation of fault activity. The N-S normal faults were completely overlapped by the basin infill during sedimentation of sequences 11 to 13 (Fig. 5). The onlapping-overlapping of the E-W thrust to the North of the subbasins show that they became inactive following a hindward sequence (see southern part of cross-section 3 and northern part of cross-section 4; Figs. 6A to 6C).

The thrusts

The thrust systems located to the North of both subbasins show similar geometry, despite their separate development (Fig. 6). To the West of each system, where the thrust trend is close to E-W, the thrust angle is low, and the N-S horizontal shortening produced by thrusting reaches the highest values (Table 1). Towards the East, their trend progressively changes to NW-SE, and the thrust-angle and the dextral component of their transport direction increase (Ferrús, 1998). The thrust system related to the western subbasin links with the main strike-slip fault to the West, whereas the eastern one joins the main strike-slip fault to the East (Fig. 1C).

Both thrust systems started with the formation of a main thrust in the sense that the thrust accumulates the highest amount of thrusting for each system (i.e. 700 m and 600 m for the western and eastern thrust systems, respectively). Starting from that thrust, two different sequences developed. On the one hand, a number of successive thrust sheets piled up following a break-back sequence (sensu McClay, 1992). Each new thrust cuts younger stratigraphic horizons, nucleates in the hanging-wall of the preceding thrust, and shows a higher dip than

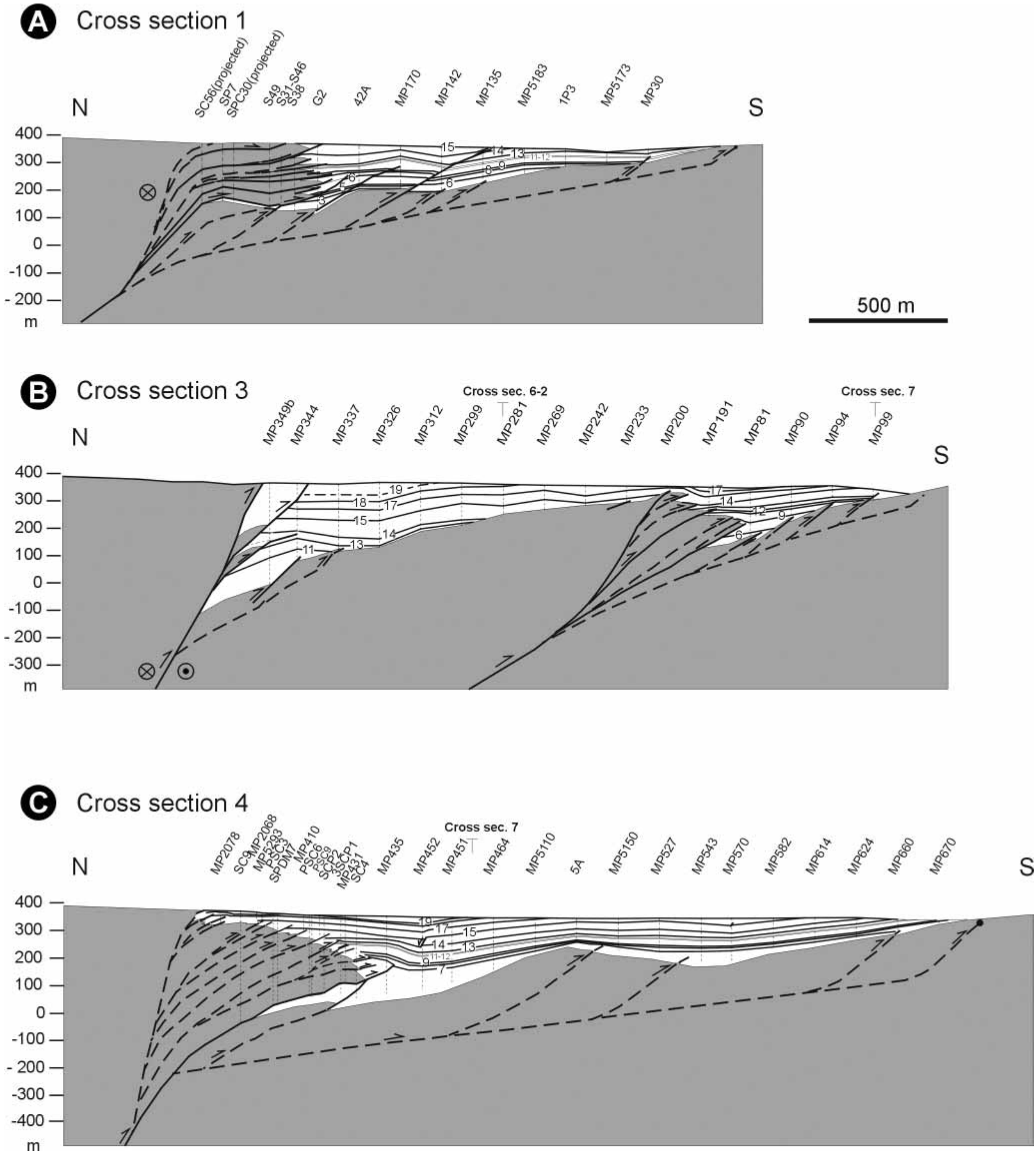


FIGURE 6 **Cross sections showing the main thrusts in the As Pontes basin and their relationships with the main stratigraphic markers. A) Cross-section 1. B) Cross-section 3. C) Cross-section 4 (see Fig. 3 for location).**

the preceding one (Fig. 6C). The successive thrusts branch at depth from the main fault plane. On the other hand, coevally with the development of the break-back thrust sequence, albeit with some delay, south-directed thrusts with trends varying between E-W and NE-SW propagate to the South in a roughly forward-breaking sequence. The emplacement of the northernmost thrusts of this sequence causes the culmination shown by the thrust sheets of the break-back sequence (Fig. 6C).

Minimum amounts of N-S horizontal shortening and vertical displacement component were estimated directly from the horizontal and vertical separation of the basement/infilling boundary for each individual thrust along each cross-section (Ferrús, 1998). The amount of N-S horizontal shortening caused by the western thrust system clearly diminishes from West (cross-section 1) to East (cross-section 3) (Table 1). The thrust system of the eastern subbasin progressively vanishes westward in the threshold that separates both subbasins. In this way, the N-S shortening due to thrusting is small near its western end (cross-section 3), increases in its central part (cross-section 4), and diminishes again towards its eastern end (cross-section 5) joining the main strike-slip fault. The amount of shortening due to the thrusts that cause the culmination of the back-breaking pile (cross-section 1, Fig. 6A) are not included in this estimation given that no precise data were available for these lower thrusts. The vertical component of displacement for each thrust-system is minimum where the thrusts trend E-W and maximum where the thrusts become parallel to the main strike-slip fault (NW-SE) and the dip of the thrust planes increases (Table 1).

Although the general thrust trend is slightly oblique with respect to the regional trend of the pervasive Variscan cleavage, the dip of both structures is northward, and, locally, thrusts planes coincide with the Variscan cleavage. The exclusive south-vergence of the thrusts was probably controlled by the Variscan anisotropy.

The normal faults

The eastern border of the western subbasin is defined by only one N-S trending normal fault, which dips 60º to the West. This fault reaches its maximum vertical displacement (200 m) at its northern end. The vertical displacement peters out towards the South. Sediments from the middle part of the basin fill sealed this fault when its activity ceased (cross-section 6-2, Fig. 5A).

The basement of the eastern subbasin is disrupted by a set of N-S normal faults, whose dips range between 60º and 75º (cross-section 7, Fig. 5B). The vertical displacement of the easternmost fault, the most prominent, is nearly 200 m, whereas the displacements of the rest of the faults do not reach 50 m, diminishing towards the West. Some of these normal faults define small N-S oriented grabens. These faults were active in several episodes according to the separations evidenced by different correlation horizons and by the alluvial and lacustrine facies distribution in the lower part of the basin fill (Sáez and Cabrera, 2002). Some of these normal faults affect the whole basin fill, whereas others are sealed by sediments belonging to the lower or to the middle part of the sedimentary basin infill.

TABLE 1 **Range of values for N-S horizontal shortening and for vertical displacement.**

Cross section	N-S shortenning (m)		Vertical displacement (m)	
	W sub-basin	E sub-basin	W sub-basin	E sub-basin
1	1140		250	
2	515		380	
3	470	450	455	230
4		815		420
5		335		340

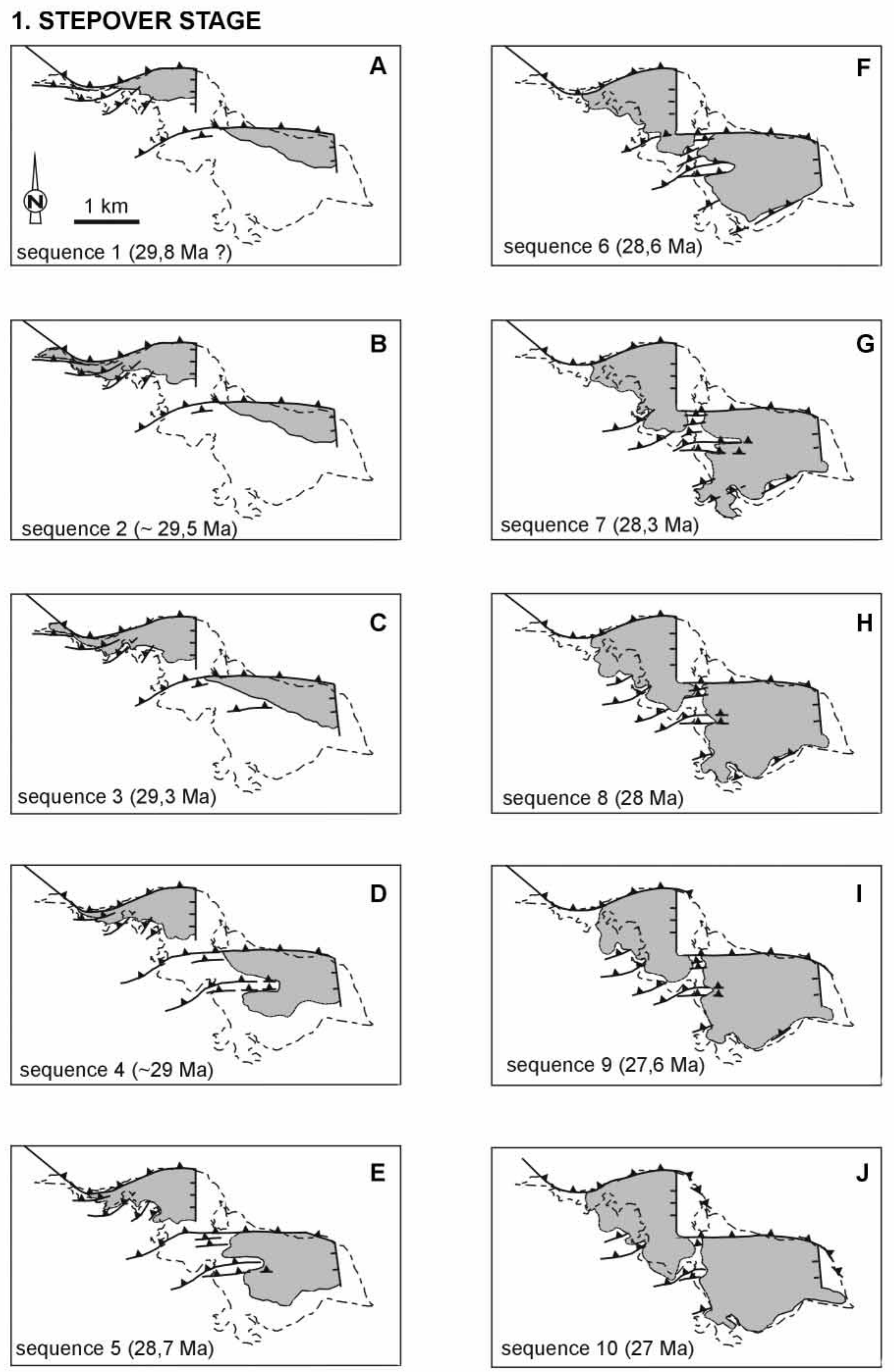
The double restraining bend

The double restraining bend is the most striking structural feature in map view since it was the last to form. It envelops the whole basin along its north-eastern margin, joining the NW-SE main strike-slip fault segments that merge from the NW and SE ends of the basin, thus constituting part of the main As Pontes fault. Along the stretches where the restraining bend trends approximately E-W, this main fault coincides with the uppermost thrusts of the break-back sequences related to both subbasins described above. As a result, the whole structure, the main fault and the thrust pile depict an asymmetric, south-vergent positive flower structure. The NW-SE trending fault segment between both thrust systems corresponds to a late short-cut, which left the westernmost part of the eastern subbasin thrust system inactive. The dip of the As Pontes fault along the double restraining bend is interpreted to change progressively from nearly vertical, where its trend is NW-SE (strike-slip), to approximately 30º N where it trends E-W (thrust).

Structural history of the basin

The integration of all the aforementioned data led to the drawing of a series of palinspastic maps corresponding to most (18) of the 19 sequences that show the main active faults and the extension of the preserved sedimentary area for each sequence (Fig. 7).

The basin history began around 30 Ma ago (late Rupelian, just before the beginning of the Chattian) with the formation of two separate small basins caused by similar structural associations in an underlapping stepover (Figs. 7A to 7J, stepover stage). An E-W initial thrust ends to the East against a N-S fault, which acted as a transfer fault with respect to the thrusts of the hangingwall and affected the footwall as a normal fault. To the West, the thrust of the eastern basin vanishes gradually. There are no sufficient data to affirm that the thrust of the western basin was connected to the West with the NW-SE strike-slip fault. Immediately, thrusts in break-back sequences formed at the hangingwall of the initial thrusts,


1. STEPOVER STAGE
A
N
1 km
sequence 1 (29,8 Ma ?)
F
sequence 6 (28,6 Ma)
B
sequence 2 (~ 29,5 Ma)
G
sequence 7 (28,3 Ma)
C
sequence 3 (29,3 Ma)
H
sequence 8 (28 Ma)
D
sequence 4 (~29 Ma)
I
sequence 9 (27,6 Ma)
E
sequence 5 (28,7 Ma)
J
sequence 10 (27 Ma)

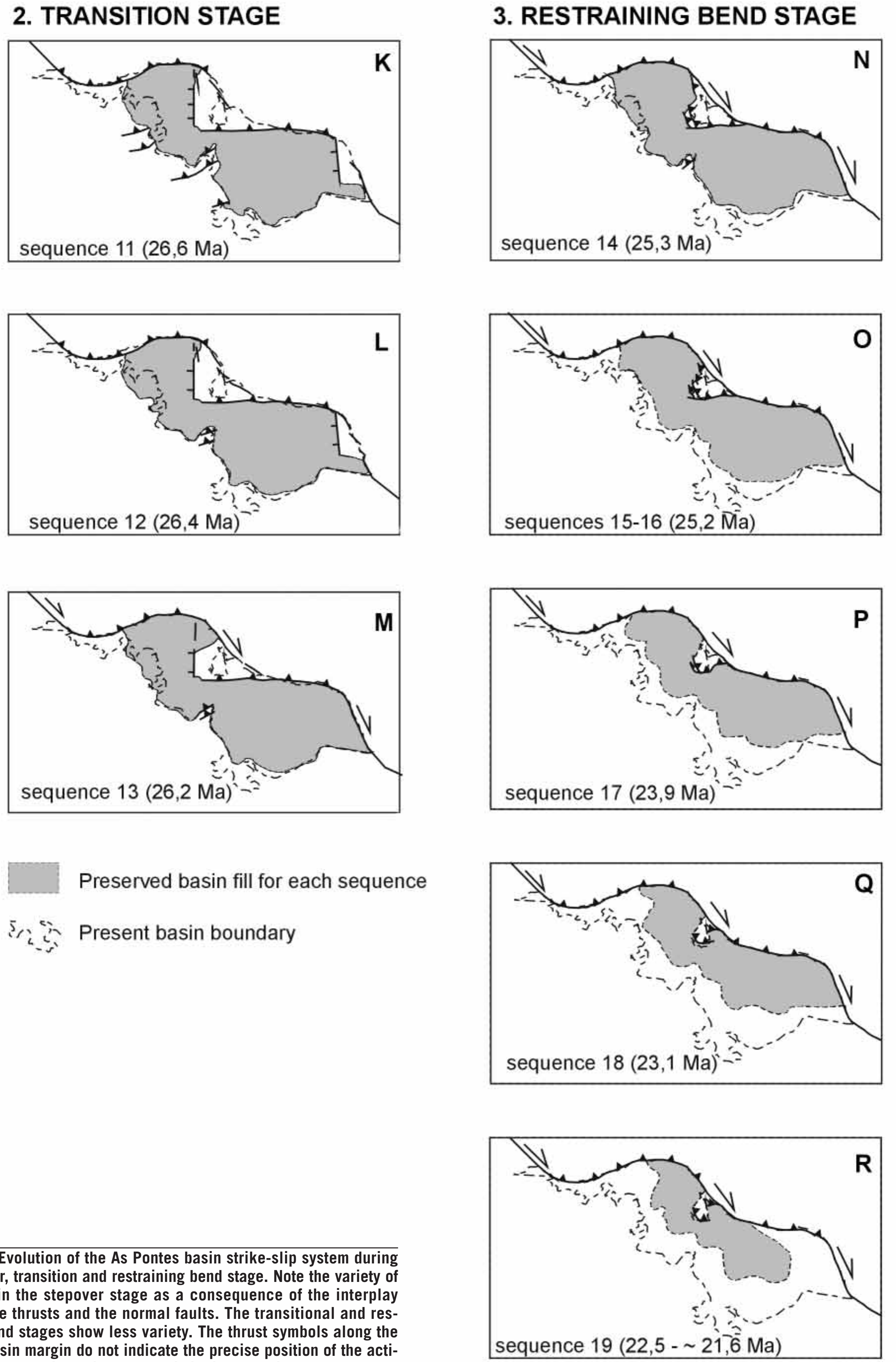


FIGURE 7 **Evolution of the As Pontes basin strike-slip system during the stepover, transition and restraining bend stage. Note the variety of situations in the stepover stage as a consequence of the interplay between the thrusts and the normal faults. The transitional and restraining bend stages show less variety. The thrust symbols along the northern basin margin do not indicate the precise position of the active thrusts in each time slice, due to limitation resulting from scale.**

and the normal faults grew towards the South causing the coeval southward propagation of the subsidence. As a consequence, positive reliefs, which fed the detritic sedimentation, rose to the North of the basins. The maximum subsidence was located in the vicinity of the junction between the N-S normal faults and the E-W thrusts, where the maximum deposit accumulation also occurred. The coal-alluvial sequences onlapped the Variscan basement towards the SW. Coevally with the break-back thrust sequence, albeit with some delay, thrusts also propagated towards the South in a forward breaking sequence. The emergence of some of these thrusts generated local supra-attenuated structural culminations that gave rise to internal basin fill unconformities (sequences 7 to 10). This structural-sedimentary pattern (two small separate basins bounded by thrusts and normal faults) lasted until sequence 10 (27 Ma). At 28.6 Ma (sequence 6) the normal fault of the western basin owing to its southern propagation, reached the thrust, which bounds the eastern basin to the North. The sediments overlapped the western part of this thrust system. The threshold surface that emerged between both basins gradually decreased in size.

Between 26.6 and 25.3 Ma, three coal-alluvial sequences (11 to 13) were deposited while the structural pattern began to change (Figs. 7K to 7M, transition stage). The large normal faults became inactive. The sedimentary sequences onlapped the fault scarp and the faults were overlapped by the basin infill. The onlap of the western normal fault began from the North and progressed southward, whereas the sealing of the eastern normal fault commenced at its southern end and progressed towards the North. At the same time, the western thrust system propagated to the SE, bounding the extending basin to the NE, and the strike-slip fault located to the SE of the As Pontes basin propagated towards the NW, damming the expanding basin to the East. The double restraining bend was being formed. During this time both subbasins coalesced, and the sedimentation area of the single As Pontes basin remained fairly stable.

Between 25.3 and 22(?) Ma, the late basinal history is characterised by the occurrence of a short-cut that linked both northern thrust systems (Figs. 7N to 7R, restraining bend stage). Thus, the structural-sedimentary history of the earlier stepover finished with the birth of the double restraining bend that linked the previously separated strike-slip faults and made up the northern As Pontes basin margin. The sequences 14 to 19 are thicker in the basin zones close to the northern margin than to the South. The maximum basin fill thickness also occurs in the zones situated above the intersection of the formerly active normal faults and the E-W thrusts. An apparent offlap of the upper coal-alluvial sequences on the underlying basin infill seems to reveal a persistent restriction of the depositional area towards the northern basin margins during this time. However, the erosional surface on top of the basin infill and the approx 60 m missing sediments (Ferrús, 1998) prevent us from determining the evolution of the sedimentary area during the late basin history. The thickness of the estimated eroded deposits on top of the coal beds of sequence 19 would represent 0.5 Ma and, therefore, the basin history would reach mid-Aquitanian times.

The maximum N-S shortening due to cumulative thrusting attained a minimum of 1140 m and corresponds to a shortening rate of 0.25 mm yr^{-1}. This was achieved mainly in the stepover and the transition stages (ca. 4.5 Ma). The maximum cumulative vertical displacements caused by thrusting north of each subbasin were 455 and 420 m for the western and eastern subbasins, respectively. These values give us an idea of the currently eroded positive relief that rose in the compressive stepover. The 200 m maximum vertical displacement along the two main normal faults occurred during the stepover stage (3.4 Ma), and corresponds to an average vertical slip rate of 0.06 mm yr^{-1}. The dextral displacement along the restraining bend can be estimated at approximately 1000 m representing a strike-slip rate ranging from 0.2 mm yr^{-1} (if transition and restraining bed stages are considered) to 0.3 mm yr^{-1} (if only the restraining bend stage is taken into account). These strike-slip rate values correspond to a N-S slip-component, parallel to the thrust shortening and of 0.1 and 0.15 mm yr^{-1}, respectively.

CONCLUDING REMARKS

1. The small size of the As Pontes basin together with the surface and subsurface data base affecting almost the whole basin makes it an excellent natural laboratory for determining the geometric relationships between tectonic structures and stratigraphic markers in order to reconstruct the evolution of the structures involved in the basin history.

2. The double restraining bend that bounds the As Pontes basin is the end stage of the structural evolution of a compressive underlapping stepover, where the basin was formed. The basin and the positive reliefs to the North did not result from the activity of a pre-existing double restraining bend along the As Pontes fault. By contrast, the restraining bend formed after the basin and associated reliefs had already undergone a long structural, erosive and sedimentary history.

3. The coeval development of E-W thrusts and orthogonal N-S normal faults in the As Pontes underlapping stepover is related to N-S shortening and coeval E-W extension. Thrusting was responsible for uplifting to the North of the basin, whereas normal faulting caused basin subsidence. The location of the normal faults may have

been determined by the overburden due to the development of the thrust imbricates. The presence of these N-S normal faults buried by the sedimentary fill and not observable on the surface accounts for the relative importance of the basin subsidence and extension with respect to the total deformed area in a compressive stepover.

4. The asymmetry of the compressive structures -the wide, asymmetric positive flower structure with exclusive south vergence of thrusts- was controlled by the Variscan basement foliation, which dips northward.

5. Two main stages, which are separated by a short transition, can be distinguished in the As Pontes basin evolution. a) Stepover stage. During this stage two small basins developed in the underlapping stepover. Both basins were bounded by thrusts to the north and normal faults to the east. This stage lasted ca. 3.2 Ma. b) Transition stage. For 1.3 Ma, the strike-slip faults that defined the stepover grew towards each other and reached the thrusts, forming the double restraining bend that bounds the single As Pontes basin with two subbasins. c) Restraining bend stage. This last stage, which is characterised by the activity of the double restraining bend, lasted a minimum of 2.9 Ma. Since the eroded upper basin-fill deposits may represent 0.5 Ma history, both the stepover and the restraining bend stages probably had a similar duration, the total history of the basin lasting approx 8 Ma.

6. The slip-rates of the faults involved in the evolution of the underlapping stepover of As Pontes ranges between 0.2 mm yr^{-1} (which corresponds to the strike-slip fault during the restraining bend stage) and a maximum of ca. 0.3 mm yr^{-1} (which corresponds to thrusting during stepover and transition stages, the minimum horizontal shortening being 0.25 mm yr^{-1}).

Analogue models have simulated the earlier geometries and the progressive evolution of strike-slip systems (Dooley and McClay, 1996, 1997; McClay and Bonora, 2001). Nevertheless, the limitations inherent in this modelling approach do not allow the reproduction of some significant aspects of the structural evolution of strike-slip systems (e.g. previous anisotropy of the deformed rocks). Thus, well documented studies of recent and ancient cases could provide a supplementary approach since they show factors that are not considered in these analogue models. From this perspective, the As Pontes basin case shows how difficult it can be to infer the early structural evolution of strike-slip related structural systems from their present day outcropping configuration. A comparison between some of the results obtained from the analogue models by McClay and Bobora (2001) and the observations resulting from the As Pontes case study underline a number of significant differences.

a) In these analogue models, base plates, which simulate the basement, designed in such a way as to produce restraining strike-slip stepovers, form the offset fault system at the base of the model. The sedimentary cover is simulated by a homogeneous sandpack with different colour layers (McClay and Bonora, 2001). The experiments model the structures that form in the cover over an isotropic basement affected by a strike-slip fault with diverse stepover geometries. The case of As Pontes is radically different, since it shows the formation of restraining bends starting from an underlapping stepover in a metamorphic basement devoid of sedimentary cover, displaying a penetrative anisotropy defined by a monoclinal foliation.

b) The experiment modelling structures that form on a basement underlapping restraining stepover results in a double-vergent pop-up structure made up of reverse-oblique faults with opposite dips giving rise to a fairly symmetric flower structure (fig. 4 in McClay and Bonora, 2001). This contrasts with the compressive end structure of As Pontes, which is a wide, asymmetric flower structure, all of whose reverse and oblique-reverse faults dip in the same direction as the regional foliation.

c) The coeval development of E-W thrusts and N-S normal faults at As Pontes during the stepover stage has no equivalent in the published analogue models. Likewise, the relatively extensive subsiding areas at As Pontes related to normal faulting, giving rise to the basin, are also absent in the experiments. These features indicate a deformation field with horizontal shortening and extension perpendicular to the shortening. Models do not simulate such deformation fields.

Summing up, the case of As Pontes provides new insights into the structural evolution of intracontinental strike-slip systems, namely the formation of restraining bends in basement as an evolved stage of underlapping compressive stepovers preceded by the formation of thrusts and normal faults. Moreover, this case study also highlights the importance of the pre-existing anisotropy in the attitude of the faults that form during this process.

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REFERENCES

Aller, J., Bastida, F., 1996. Geology of the Ollo de Sapo antiform unit to the south of the Cabo Ortegal Complex (NW Spain). Revista de la Sociedad Geológica de España, 9, 83-102.

Alonso, J.L., Pulgar, J.A., García-Ramos, J.C., Barba, P., 1996. Tertiary basins and Alpine tectonics in the Cantabrian Mountains (NW Spain). In: Friend, P.F., Dabrio, C.J. (eds.). Tertiary basins of Spain. The stratigraphic record of crustal kinematics. Cambridge University Press, 214-227.

Arce Duarte, J.M., Fernández Tomás, J., Álvarez Menéndez, J.M., López García, M.J., Capdevila, R., 1975. Mapa Geológico de España, Scale 1:50.000, segunda serie, nº 23, Puentes de García Rodríguez. Madrid, Instituto Geológico y Minero de España, Memoria explicativa, 32 pp.

Aydin, A., Nur, A., 1982. Evolution of pull-apart basins and their scale independence. Tectonics, 1, 91-105.

Bacelar, J., Alonso, M., Kaiser, C., Sánchez, M., Cabrera, L., Sáez, A., Santanach, P., 1988. La cuenca terciaria de As Pontes (Galicia): su desarrollo asociado a inflexiones contractivas de una falla direccional. II Congreso Geológico de España, Simposios, Granada, Sociedad Geológica de España, 113-121.

Barsó, D., Cabrera, L., Marfil, R., Ramos, E., 2000. Evolución de la procedencia y redes de drenaje de la cuenca continental de As Pontes. Geotemas, 1, 151-154.

Barsó, D., Cabrera, L., Marfil, R., Ramos, E., 2003. Catchment evolution of the continental strike-slip As Pontes basin (Tertiary, NW Spain): constraints from the heavy mineral analysis. Revista de la Sociedad Geológica de España, 16, 73-89.

Cabrera, L., Roca, E., Santanach, P., 1988. Basin formation at the end of a strike-slip fault: the Cerdanya Basin (eastern Pyrenees). Journal of the Geological Society of London, 145, 261-268.

Cabrera, L., Jung, W., Kirchner, M., Sáez, A., 1994. Crocodilian and paleobotanical findings from Tertiary lignites of As Pontes Basin (Galicia, NW Spain). Courier Forschungsinstitut Senckenberg, 173, 153-165.

Cabrera, L., Hagemann, H.W., Pickel, W., Sáez, A., 1995. The coal bearing Cenozoic As Pontes Basin (NW Spain): Geological influence on its coal characteristichs. International Journal of Coal Geology, 27, 201-226.

Cabrera, L., Ferrús, B., Sáez, A., Santanach, P.F., Bacelar, J., 1996. Onshore Cenozoic strike-slip basins in NW Spain. In: Friend, P.F., Dabrio, C.J. (eds.). Tertiary basins of Spain. The stratigraphic record of crustal kinematics. Cambridge, University Press, 247-254.

Christie-Blick, N., Biddle, K., 1985. Deformation and basin formation along strike-slip faults. In: Biddle, K.T., Christie-Blick, N. (eds.). Strike-slip deformation, basin formation, and sedimentation. Society of Economic Paleontologists and Mineralogists Special Publication, 37, 1-34.

Crowell, J.C., 1974a. Origin of late Cenozoic basins in southern California. In: Dickinson, W.R. (ed.). Tectonics and Sedimentation. Society of Economic Paleontologists and Mineralogists Special Publication, 19, 292-303.

Crowell, J.C., 1974b. Sedimentation along the San Andreas Fault, California. In: Dott Jr., R.H., Shaver, R.H. (eds.). Modern and Ancient Geosynclinal Sedimentation. Society of Economic Paleontologists and Mineralogists Special Publication, 19, 292-303.

Crowell, J.C., 1976. Implications of crustal stretching and shortening of coastal Ventura basin, California. In: Howell, D.G. (ed.). Aspects of the geologic history of the California Borderland. Pacific Section American Association of Petroleum Geologists Miscelaneous Publication, 24, 365-382.

Curtis, M.L., 1999. Structural and kinematic evolution of a Miocene to Recent sinistral restraining bend: the Montejunto massif, Portugal. Journal of Structural Geology, 21, 39-54.

Dooley, T., McClay, K., 1996. Strike-slip deformation in the Confidence Hills, southern Death Valley fault zone, eastern California, USA. Journal of the Geological Society of London, 153, 375-387.

Dooley, T., McClay, K., 1997. Analog modeling of pull-apart basins. American Association of Petroleum Geologists Bulletin, 81, 1804-1826.

Ferrús, B., 1998. Análisis de cuenca y relaciones tectónica-sedimentación en la cuenca de As Pontes (Galícia). Doctoral thesis, Universitat de Barcelona, 351 pp.

Fernández, F., Piera, T., Peinado, M., Menéndez, J., Gómez, J., Capdevila, R., 1975. Mapa Geológico de España, Scale 1:50.000, segunda serie, nº 22, Puentedeume. Madrid, Instituto Geológico y Minero de España. Memoria explicativa, 45 pp.

Heredia, N., Rodríguez-Fernández, L.R., Vegas, R., de Vicente, G., Cloething, S., Giner, J., González Casado, J.M., 2004. Cadenas cenozoicas del Noroeste peninsular. In: Vera, J.A. (ed.). Geología de España. Madrid, Sociedad Geológica de España, Instituto Geológico y Minero de España, 619-621.

Huerta, A., Parés, J.M., Cabrera, L. Ferrús, B., Sáez, A., 1996. Datación magnetostratigráfica de la cuenca terciaria de As Pontes (Galicia, NW de España). Geogaceta 20(5), 1021-1024.

Huerta, A., Parés, J.M., Cabrera, L. Ferrús, B., Sáez, A., 1997. Magnetocronología de las sucesiones cenozoicas de la cuenca de As Pontes (La Coruña, Noroeste de España). Acta Geologica Hispanica, 32, 127-145.

López-Martínez, N., Fernández, M.T., Peláez, P., de la Peña, A., 1993. Estudio paleontológico en las cuencas terciarias de Galicia. Revista de la Sociedad Geológica de España, 6(3-4), 19-28.

Manera, A., Barrera, J.L., Cabal, J.M., Bacelar, J., 1979. Aspectos geológicos de la cuenca terciaria de Puentes de García Rodríguez (provincia de La Coruña). Boletín Geológico y Minero, 45, 451-461.

Mann, P., Hempton, M.R., Bradley, D.C., Burke, K., 1983. Development of pull-apart basins. The Journal of Geology, 91, 529-554.

Mann, P., Burke, K., Matumoto, T., 1984. Neotectonics of the Hispaniola: Plate motion, sedimentation and seismicity at a restraining bend. Earth and Planetary Science Letters, 70, 311-324.

Mann, P., Draper, G., Burke, K., 1985. Neotectonics of a strike-slip restraining bend system, Jamaica. In: Biddle, K.T., Christie-Blick, N. (eds.). Strike-slip deformation, basin formation, and sedimentation. Society of Economic Paleontologists and Mineralogists Special Publication, 37, 211-226.

Mann, P., Tyburski, S.A., Rosencrantz, E., 1991. Neogene development of the Swan Island restraining-bend complex, Caribbean Sea. Geology, 19, 823-826.

McBride, J.H., 1994. Investigating the crustal structure of a strike-slip "step-over" zone along the Great Glen fault. Tectonics, 13, 1150-1160.

McClay, K.R., 1992. Glossary of thrust tectonics. In: McClay, K.R. (ed.). Thrust Tectonics. London, Chapman & Hall, 419-433.

McClay, K., Bonora, M., 2001. Analog models of restraining stepovers in strike-slip fault systems. American Association of Petroleum Geologists Bulletin, 85, 233-260.

Miller, R.B., 1994. A mid-crustal contractional stepover zone in a major strike-slip system, North Cascades, Washington. Journal of Structural Geology, 16, 47-60.

Muñoz, J., 2002. The Pyrenees. In: Gibbons, W., Moreno, T. (eds.). The Geology of Spain. London, The Gelogical Society, 370-385.

Namson, J.S., Davis, T.L., 1988. Seismically active fold and thrust belt in the San Joaquin Valley, central California. Geological Society of America Bulletin, 100, 257-273.

Nilsen, T.H., Sylvester, A.G., 1995. Strike-slip basins. In: Busby, C.J, Ingersoll R.V. (eds.). Tectonics of sedimentary basins. Cambridge MA, Blackwell Science, 425-457.

Pulgar, J.A., Gallart, J., Fernández-Viejo, G., Pérez-Estaún, A., Álvarez-Marrón, J., ESCIN Group, 1996. Seismic image of the Cantabrian Mountains in the western extension of the Pyrenean belt from integrated reflection and refraction data. Tectonophysics, 264, 1-19.

Pulgar, J.A., Alonso, J.L., Espina, R.G., Marín, J.A., 1999. La deformación alpina en el basamento varisco de la Zona Cantábrica. Trabajos de Geología, 21, 283-294.

Pulgar, J.A., Pérez-Estaún, A., Gallart, J., Álvarez-Marrón, J., Gallastegui, J., Alonso, J.L., ESCIN Group 1995. The ESCIN2 deep seismic reflection profile: a traverse across the Cantabrian Mountains and adjacent Duero basin. Revista de la Sociedad Geológica de España, 8, 383-394.

Royden, L.H., 1985. The Vienna basin: a thin skinned pull-apart basin. In: Biddle, K.T., Christie-Blick, N. (eds.). Strike-slip deformation, basin formation, and sedimentation. Society of Economic Paleontologists and Mineralogists Special Publication, 37, 319-338.

Sáez, A., Cabrera, L., 2002. Sedimentological and paleohydrological responses to tectonics and climate in a small, closed, lacustrine system: Oligocene As Pontes Basin (Spain). Sedimentology, 49, 1073-1094.

Sáez, A., Inglès, M., Cabrera, L., de las Heras, A., 2003. Tectonic-palaeoenvironmental forcing of clay-mineral assemblages in nonmarine settings: the Oligocene-Miocene As Pontes Basin (Spain). Sedimentary Geology, 159, 305-324.

Santanach, P., 1994. Las Cuencas Terciarias gallegas en la terminación occidental de los relieves pirenaicos. Cuadernos Laboratorio Xeolóxico de Laxe, 19, 57-71.

Santanach, P., Baltuille, J.M., Cabrera, Ll., Monge, C., Sáez, A., Vidal-Romaní, J.R., 1988. Cuencas terciarias gallegas relacionadas con corredores de fallas direccionales. II Congreso Geológico de España, Simposios, Granada, Sociedad Geológica de España, 123-133.

Sarewitz, D.R., Lewis, S.D., 1991. The Marinduque intra-arc basin, Philippines: Basin genesis and in situ ophiolite development in a strike-slip setting. Geological Society of America Bulletin, 103, 597-614.

Schubert, C., 1986. Origin of the Yaracuy basin, Boconó-Morón fault system, Venezuela. Neotectonics, 1, 39-50.

Steel, R., Gjelberg, J., Helland-Hansen, W., Kleinsphen, K., Nottvedt, A., Rye-Larsen, M., 1985. The Tertiary strike-slip basins and orogenic belt of Spitsbergen. In: Biddle, K.T., Christie-Blick, N. (eds.). Strike-slip deformation, basin formation, and sedimentation. Society of Economic Paleontologists and Mineralogists Special Publication, 37, 227-264.

Sylvester, A.G., Smith, R.R., 1976. Tectonic transpression and basement-controlled deformation in San Andreas fault zone, Salton Trough, California. American Association of Petroleum Geologists Bulletin, 60, 2081-2102.

Wilcox, R.E., Harding, T.P., Seely, D.R., 1973. Basic wrench tectonics. American Association of Petroleum Geologists Bulletin, 57, 74-96.

Woodcock, N.H., Fisher, M., 1986. Strike-slip duplexes. Journal of Structural Geology, 8, 725-735.

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