3D geometry, structure and formation of the Duero basin within the Pyrenean Orogen geodynamic scenario

Geometría 3D, estructura y formación de la Cuenca del Duero en el contexto geodinámico del orógeno Pirenaico

P. Granado[1], O. Ferrer[1], M. Butillé[1], J. A. Muñoz[1], E. Roca[1], J.C. Ballesteros[2], A. Giménez[2], R. A.Vallejo[2] and P. González[2]

1 Geomodels Institut de Recerca, Departament de Geodinàmica i Geofísica, Facultat de Geologia, Universitat de Barcelona (UB), Martí i Franquès s/n, 08028 Barcelona, España. pablomartinez_granado@ub.edu
2 ENDESA Generación S.A., Subdirección I+D. C/ Ribera del Loira 60, Planta 0 E. 28042 Madrid, España

Abstract: The Duero foreland basin is characterized by a large synformal geometry formed by the lithospheric flexure and northward subduction of the Iberian crust underneath the Cantabrian-European crust. Basin structure is represented by high-angle faults that involve both basement and cover units, and that did not generate large amounts of horizontal displacement. The northern deformation front is represented by a series of S-directed faults that probably sole into middle-lower crustal levels. Growth strata within the basin interior indicate that basement faulting occurred during the uppermost Cretaceous to Paleocene, previous to the onset of the foreland stage, while the Orogen uplift and the northern deformation front activity took place mainly between the Eocene-Oligocene, locally protracting until Miocene times. The Duero Basin behaved as an orogenic scale buttress due to the lack of an inherited Late Jurassic-Early Cretaceous extensional architecture associated with the opening of the Bay of Biscay. Hence, most of the Alpine contraction had a major impact where Mesozoic extension was more important, like the North Iberian Margin and the system of Mesozoic extensional basins of the Pyrenean rift.

Key words: Duero Basin; subduction; North Iberian Margin; lithospheric extension; continental contraction.

Resumen: *La Cuenca Cenozoica del Duero es una cuenca de antepaís que presenta una geometría de gran sinclinal formado por la flexión litosférica y la subducción de la corteza Ibérica bajo la corteza Cantábrico-Europea. La estructura interna de la cuenca está representada por fallas de alto ángulo que involucran a basamento y cobertera, sin haber generado grandes desplazamientos horizontales. El frente orogénico septentrional está representado por una serie de fallas dirigidas al sur que se enraizarían en la corteza inferior-media. Las relaciones tectónica-sedimentación muestran que las fallas del interior de la cuenca fueron activas durante el Cretácico superior-Paleoceno, previamente a la etapa de antepaís, mientras que el levantamiento del Orógeno y la actividad del frente de deformación se produjo durante el Eoceno-Oligoceno, localmente hasta el Mioceno. La Cuenca del Duero se comportó como un contrafuerte de escala orogénica al carecer de una arquitectura extensiva previa heredada del* rifting *Jurásico Superior-Cretácico Inferior asociado a la apertura del Golfo de Vizcaya. La contracción Alpina se focalizó allí donde la extensión Mesozoica fue más importante, como en el Margen Nor-Ibérico y el sistema de cuencas extensivas Mesozoicas del rift Pirenaico.*

Palabras clave: *Cuenca del Duero; subducción; margen Nor-Ibérico; extensión litosférica; contracción continental.*

INTRODUCTION

The development of foreland basins is ultimately related to an orogenic system and associated tectonic forces that result in the bending of the lithosphere. The Cenozoic Duero basin is located in the N of the Iberian plate (Fig. 1) and developed during the collision between the Iberian and Eurasian plates. Deep geophysical imaging and modeling have demonstrated the northward down bending of the middle-lower Iberian crust underneath the Cantabrian-European one as a result of roughly N-S convergence (Fernández-Viejo, 1997; Gallastegui, 2000; Pedreira, 2004; Fig. 2). The geometry, internal structure and sedimentary fill of the Duero basin strongly differ to that of the easterly Ebro foreland basin. Such discrepancy is the ultimate consequence of the inherited architectural controls exerted by Late Jurassic to Early Cretaceous rifting that lead to the opening of the Bay of Biscay. Rifting related extreme extension was focused along the North Iberian Margin, where mantle and lower crustal rocks became exhumed (Roca et al., 2011), while progressive smaller amounts of extension took place eastward in the Basque-Cantabrian Basin and along the Pyrenean rift system. The Duero basin remained as an almost undisturbed 'cratonic' block where a series of transgressive-regressive cycles were deposited during the Cretaceous. The only evidences of Mesozoic extension and related sedimentation are known to be located to its easternmost margins where Triassic units were deposited.

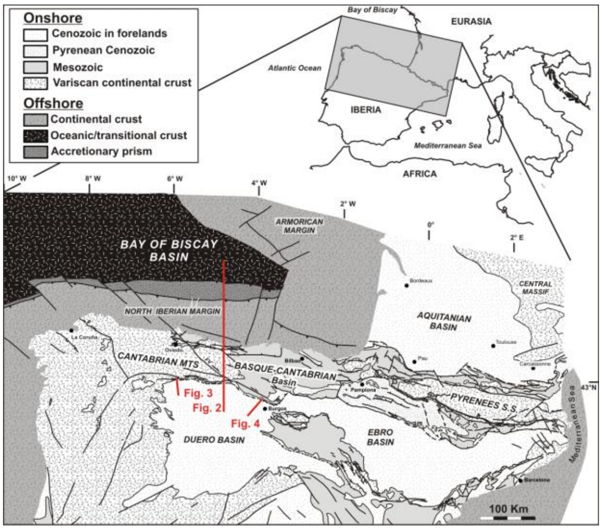

FIGURA 1. *Location of the Duero basin. FV: Ventaniella Fault. Modified from Muñoz (2002).*

Previous studies have mainly dealt with the deformation pattern along the northern orogenic front along with the deep crustal structure of the Northern Iberian Margin (Fernández-Viejo, 1997; Gallastegui, 2000; Roca et al., 2011). In this work, the geometry and structure of the basin are illustrated from the interpretations of 2D seismic lines (Fig. 2). Inferences from them help constraining the geodynamic evolution of the North Iberian Margin and the Western Pyrenean Orogen.

WESTERN LIMIT TO IBERIAN CRUST SUBDUCTION

As foreland basins are directly linked with flexure and subduction of plates, the boundaries of basins must also be approximately coincident with those of their relating plate subduction systems. The Pyrenean Orogen and Duero basin subduction system has been located from the compilation of various geophysical datasets (Muñoz, 2002; Pedreira, 2004 and references therein). The subduction system roughly strikes E-W following the structural trend of the Pyrenean Orogen. The consequences of Alpine convergence and subduction are expressed by the crustal thickening inferred underneath the Cantabrian Mountains, where Moho depths reach *c.* 45 km (Fernández-Viejo, 1997). Geophysical data suggests that the western limit of crustal thickening, and Iberian crust subduction, might be imposed by the NW-SE striking structural trend of the Ventaniella and related offshore fault system (Fig. 1).

DUERO BASIN GEOMETRY AND STRUCTURE

The Duero basin forms part of the whole orogenic system. It presents a large synformal geometry (Figs. 2), with a short steeply dipping to overturned northern monocline that has been locally telescoped by S-directed thrusts, and a much larger shallowly dipping southern limb. The Cenozoic fill is characterized by a regional low-angle unconformity that marks the onset of the foreland stage starting around Eocene times.

In the northwestern sector of the basin, the deformation is mainly located within the N limb of the synform (Fig. 3). Structures are represented by roughly EW-striking N-directed high-angle basement-involved reverse faults with associated fault-propagation folds. These faults affect the Mesozoic cover and cut across most of the Cenozoic sequences. These faults can be trace out of the basin and correlated with E-W to ENE-WSW striking reverse faults that place the Pre-Cambrian basement on top of the Albian-Cenomanian

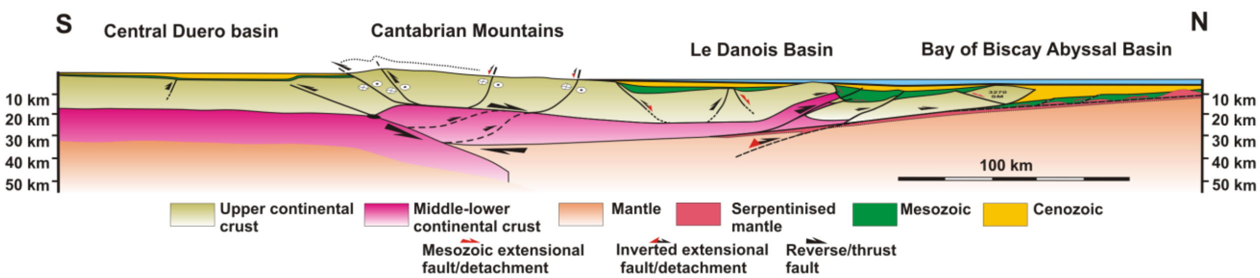

FIGURE 2. *Lithospheric cross section along the Duero basin, Cantabrian Mountains and offshore region. Compiled and modified from Gallastegui, 2000; Pedreira, 2004; Roca et al., 2011.*

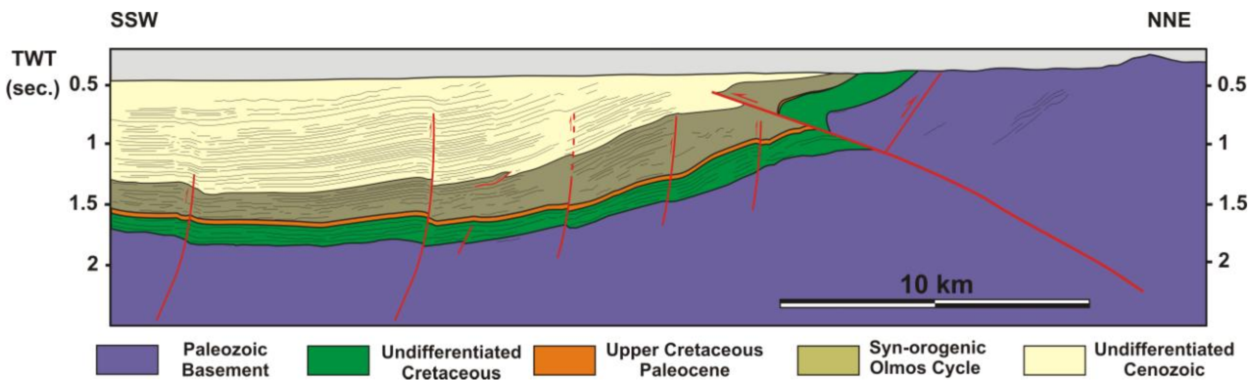

FIGURE 3. *Interpretation from a series of NNE-SSW trending seismic sections across the North Western sector of the Duero basin (seismic data is not shown due to confidentiality agreement).*

Utrillas Formation. In the North Central sector, deformation is focused on both limbs of the Duero synform. To the N, it is represented by the blind roughly E-W striking S-directed crustal scale Campillo Fault, and to the S, by a series of roughly E-W striking N-directed basement-involved faults. The southern fault system has associated contractional growth strata wedges that have remained preserved underneath the foreland basin regional unconformity. Growth strata associated to the Campillo Fault indicate a late activity (Gallastegui, 2000). In the northeastern sector of the basin the deformation pattern and the basin configuration are slightly different. Triassic units reported in commercial drill intersections indicate an inherited Mesozoic extensional architecture. The structural configuration in this sector is represented by two major basement-involved structures, i.e., the San Pedro and the Iglesias structural highs (Hernaiz and Solé, 2000). These structures strike roughly NW-SE to E-W, are N-directed and have associated growth strata wedges (Fig. 4). They are separated by the Sasamón Through, which occupies an intermediate position between the Duero and Ebro basins. It hosts the thickest syn-orogenic sequence of the basin. Uplift and erosion of Upper Cretaceous units at both structural culminations have been observed (Fig. 4).

AGE OF DEFORMATION

The analysis of growth strata packages, their distribution along the basin and styles of contractional deformation across the Duero basin have provided basin formation age constraints. Growth sediment wedges deposited on top of Upper Cretaceous (Maastrichtian?) carbonates and preserved below the regional unconformity (Fig. 3) indicate the onset of contractional deformation occurred within the basin interior in uppermost Cretaceous-Paleocene times. Outcropping growth strata along the northern orogenic front and in the Cantabrian Mountains indicate that deformation started during Middle Eocene times and probably protracting until Middle Miocene, with the main orogenic deposits hosted within the Sasamón Trough being Oligocene in age (Hernaiz and Solé, 2000).

DISCUSSION AND CONCLUSIONS

The deformation pattern and the amount of contraction in the Duero basin contrast with those occurring in the offshore region (Fig. 2) and in the Ebro foreland basin. Offshore, Late Jurassic-Early

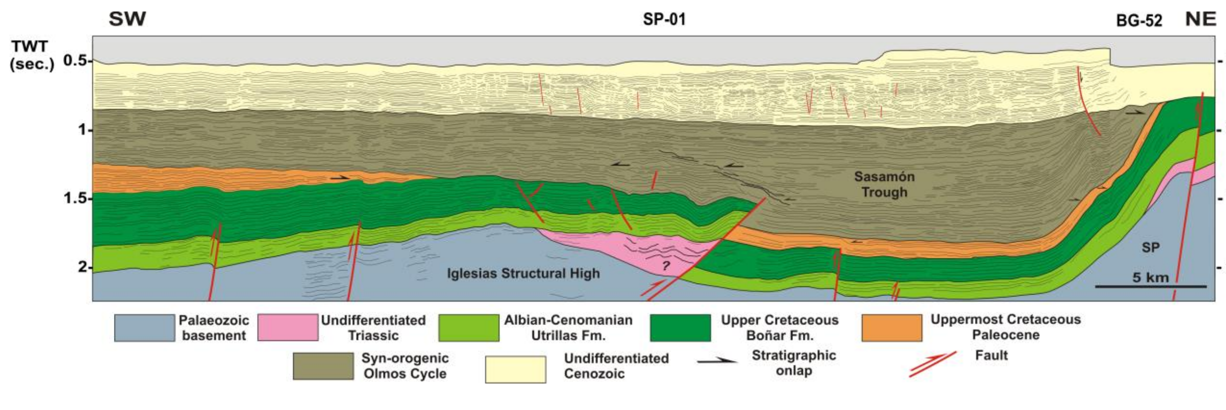

FIGURE 4. *Interpretation from a series of NE-SW trending seismic sections across the North Eastern sector of the Duero basin. The interpretation shows the Iglesias and the San Pedro Structural high, separated by the Sasamón Trough (seismic and well data are not shown due to confidentiality agreement).*

Cretaceous extensional basins have been inverted and an accretionary prism has developed (Álvarez-Marrón et al., 1996; Roca et al., 2011 and references therein). This is the ultimate consequence of the structural inheritance of the Late Jurassic to Early Cretaceous rifting. Moreover, the Present Day structure demonstrates that most of the orogenic shortening has been accommodated offshore. Deformation within the Duero basin, as represented by high-angle basement-involved faults, produced small amounts of horizontal shortening. Their associated growth strata indicate a late Cretaceous-Paleocene activity, roughly coeval with the onset of deformation in the North Iberian Margin, and hence before the beginning of the foreland stage. The Duero basin has thus remained as a partially undeformed 'cratonic block' and could be seen as an orogenic scale buttress. Such evolution contrasts with that of the central and eastern parts of the Pyrenean orogen and Ebro Basin, where the Early Cretaceous extensional basins have been inverted and incorporated into salt-detached S-directed and shallowly-dipping thrust sheets with associated piggyback basins. These differences have been fundamentally controlled by the along strike changes in the Mesozoic extensional architecture along with the existence of the regionally deposited Triassic evaporites. Such detachment-prone level has favored the development of the mentioned shallowly-dipping easy slip thrusts sheets toward Ebro foreland basin. The transition between the Duero and Ebro basins can be observed along the Sasamón Trough, as it occupies an intermediate position (Fig.1). Such structural transition can be appreciated in the structural style of the Iglesias High: a large N-directed basement-involved structure that generated an emergent thrust front as evidenced by the erosion of the Cretaceous units and associated unconformities (Fig. 4).

On a larger scale, the uplift experienced by the Cantabrian Mountains could be explained as the result of middle-lower crustal thickening and tectonically driven upward extrusion (Jones et al., 2005). Such mechanisms of crustal thickening could be achieved by duplexing at middle-lower crustal levels and/or by distributed deformation occurring by ductile vertical stretching within the lower crust (Butler and Mazzoli, 2006). Such shortening has been, at least partially, accommodated in the upper crust by crustal-scale transpressional brittle faulting in the Cantabrian area (Fig. 2). The uplift and erosion of the Cantabrian Mountains is therefore related with a deep seated process of crustal thickening and would be age-constrained by the Eocene-Oligocene growth strata wedges preserved along the orogenic front and observed in seismic data.

ACKNOWLEDGEMENTS

The authors would like to acknowledge ENDESA Generación S.A. I+D for providing the funding and datasets. Also the *Secretaría d'Universitats i Recerca del Departament D'Economía i Coneixement de la Generalitat de Catalunya* is thanked for the funding provided to the Geodynamics and Basin Analysis Research Group (Group de Recerca Consolidat GGAC 2009SGR1198.

REFERENCES

Álvarez-Marrón, J., Pérez-Estaún, A., Dañoibeitia, J.J., Pulgar, J.A., Martínez-Catalán, J.R., Marcos, A., Bastida, F., Ayarza Arribas, P., Aller, J., Gallart, A., González Lodeiro, F., Banda, E., Comas, M.C., Córdoba, D. (1996): Seismic structure of the northern continental margin of Spain from ESCIN deep seismic profiles. *Tectonophysics* 264, 153-174

Butler, R.W.H. and Mazzoli, S. (2006): Styles of Continental Contraction: A review and Introduction. En: *Styles of Continental Contraction.* (R.W.H. Butler y S. Mazzoli Eds.), Geol. Soc. Am. Spec. Paper 414, 1-10.

Fernández-Viejo, G. (1997): *Estructura cortical de la Cordillera Cantábrica y su transición a la Cuenca del Duero a partir de datos de sísmica de refracción/reflexión de gran ángulo.* Tesis Doctoral, 316 pp. Universidad de Barcelona-CSIC

Gallastegui, J. (2000): Estructura cortical de la Cordillera y Margen Continental Cantábricos: Perfiles ESCI-N. *Trabajos de Geología,* 22: 1-221

Hernáiz, P.P. y Solé, J. (2000): Las estructuras del diapiro de Salinas de Rosío y del Alto de San Pedro-Iglesias y sus implicaciones en la evolución tectónica de la transversal burgalesa de la cordillera Vasco Cantábrica-Cuenca del Duero. *Revista de la Sociedad Geológica de España*, 13: 471-486

Jones, R.R., Holdsworth, R. E., McCaffrey, K.J.W., Clegg, P., Tavarnelli, E. (2005): Scale dependence, strain compatibility and heterogeneity of three-dimensional deformation during mountain building: a discussion. *Journal of Structural Geology,* 27: 1190-1204

Roca, E., Muñoz, J.A., Ferrer, O., Ellouz, N. (2011): The role of the Bay of Biscay Mesozoic extensional structure in the configuration of the Pyrenean orogen: Constraints from the MARCONI deep seismic reflection survey. *Tectonics*, 30 TC2001 doi:10.1029/2010TC002735

Pedreira, D. (2004): Estructura cortical de la zona de transición entre los Pirineos y la Cordillera Cantábrica. Tesis Doctoral, 343pp. Univ. de Oviedo, 2004

Muñoz, J.A. (2002): The Pyrenees. En: *The Geology of Spain* (W. Gibbons y M.T. Moreno, eds.). Geological Society, London, 370-385.