Tertiary basins of Spain
the stratigraphic record of crustal kinematics

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PETER F. FRIEND AND CRISTINO J. DABRIO

(1996)

World and Regional Geology 6

CAMBRIDGE UNIVERSITY PRESS

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CAMBRIDGE
UNIVERSITY PRESS

Published by the Press Syndicate of the University of Cambridge
The Pitt Building, Trumpington Street, Cambridge CB2 1RP
40 West 20th Street, New York, NY 10011-4211, USA
10 Stamford Road, Oakleigh, Melbourne 3166, Australia

First published 1996

Printed in Great Britain at the University Press, Cambridge

A catalogue record for this book is available from the British Library

Library of Congress cataloguing in publication data

Tertiary basins of Spain : the stratigraphic record of crustal
kinematics / edited by Peter F. Friend and Cristino J. Dabrio.
p. cm. – (World and regional geology series)
Includes bibliographical references.
SBN 0 521 46171 5
1. Geology, Stratigraphic – Tertiary. 2. Geology, Structural – Spain. 3. Basins (Geology) – Spain. I. Friend, P.F. II. Dabrio, Cristino J. III. Series.
QE691.T465 1995
551.7′8′0946 – dc20 94-21724 CIP

ISBN 0 521 46171 5 hardback

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Contents

W2 Alpine tectonic framework of south-western Duero basin

J.I. SANTISTEBAN, R. MEDIAVILLA AND A. MARTÍN-SERRANO

Abstract

The tectonic activity in the south-western area of the Spanish Northern Meseta (Ciudad Rodrigo and Duero basins) during most of the Tertiary was determined by a transpressive regime that reactivated Hercynian to Late-Hercynian faults. The record of the Alpine Orogeny is complex because the sedimentary record indicates a compressive regime in the sour e areas coeval with the extensional to transpressive regime indicated by normal or strike-slip faults. This duality is due to the geotectonic position of this area between two compressive areas, the Cantabrian Range and the Central System, and the extensional Atlantic margin.

Introduction

The Duero basin is an intracontinental basin of cratonic type (*sensu* Sloss & Speed, 1974) bounded by mountain ranges that evolved relatively independently during the Tertiary (Fig. 1).

The northern border is the Cantabrian Mountains, made up of Mesozoic and Palaeozoic rocks affected by thrusts and low-angle reverse faults. Its history is related to the Alpine evolution of the Pyrenees.

The eastern border is the Iberian Range that extends between the Pyrenees and the Betics, the main Spanish compressive orogens.

The southern border is the Central System, bounded by high-angle reverse and strike-slip faults of Hercynian to Late Hercynian age, reactivated during Alpine Orogeny.

The western border is the Palaeozoic metasedimentary and igneous rocks of the western Spanish Meseta. It has a relatively passive tectonic history but was affected by the evolution of the Atlantic margin.

South-western border

The south-west corner of the Duero basin is at the junction of two tectonically different borders: one dominated by reverse and strike-slip faults (the southern edge), and the other dominated by vertical, low-magnitude movements (the western border). The morphological expression of the junction area is a half-graben oriented NE-SW, and filled with Paleogene and Neogene sediments; it is referred to as the *Ciudad Rodrigo Graben* ('Fosa de Ciudad Rodrigo').

The 'classic' relative chronology of alpine movements is based upon the assumption that the stratigraphic frameworks of the Duero and Ciudad Rodrigo basins are different. As a consequence, many authors consider that the palaeogeographic and tectonic evolution of these two basins was independent (Jiménez *et al.*, 1983; Corrochano & Carballeira, 1983).

However, detailed mapping by the present authors has revealed similar successions of Tertiary materials in the Duero and Ciudad Rodrigo basins (Fig. 2). This implies that they were connected during the Tertiary and underwent a common evolution (Santisteban *et al.*, 1991; see also Chapter W3).

The Alpine tectonics

Southern border

The southern border of the basin can be divided into two structural domains with different tectonic behaviour during the Alpine Orogeny: the Central System and a series of structures that will be referred to as the Border Massifs (Fig. 3).

The Central System

The evolution of the Central System has been explained in several ways: related to an intracontinental shear zone (Vegas *et al.*, 1986), as a rhombus-graben (Portero & Aznar, 1984), and related to thrust nappes or reverse faults (Warburton & Alvarez, 1989; Babin *et al.*, 1992; Vicente *et al.*, 1992). Diverse stages have been established for the Alpine Orogeny in the northern and southern margins of the Central System (Portero & Aznar, 1984; Vegas *et al.*, 1986; Capote *et al.*, 1990; Calvo *et al.*, 1991; Vicente *et al.*, 1992) (Fig. 3).

Capote *et al.* (1990) differentiated three faulting episodes or stages, and this is the most generally accepted division:

Iberian Stage: Mean horizontal compression N45-55E that ended with an almost radial distension with the same axis orientation. The age coincides with the

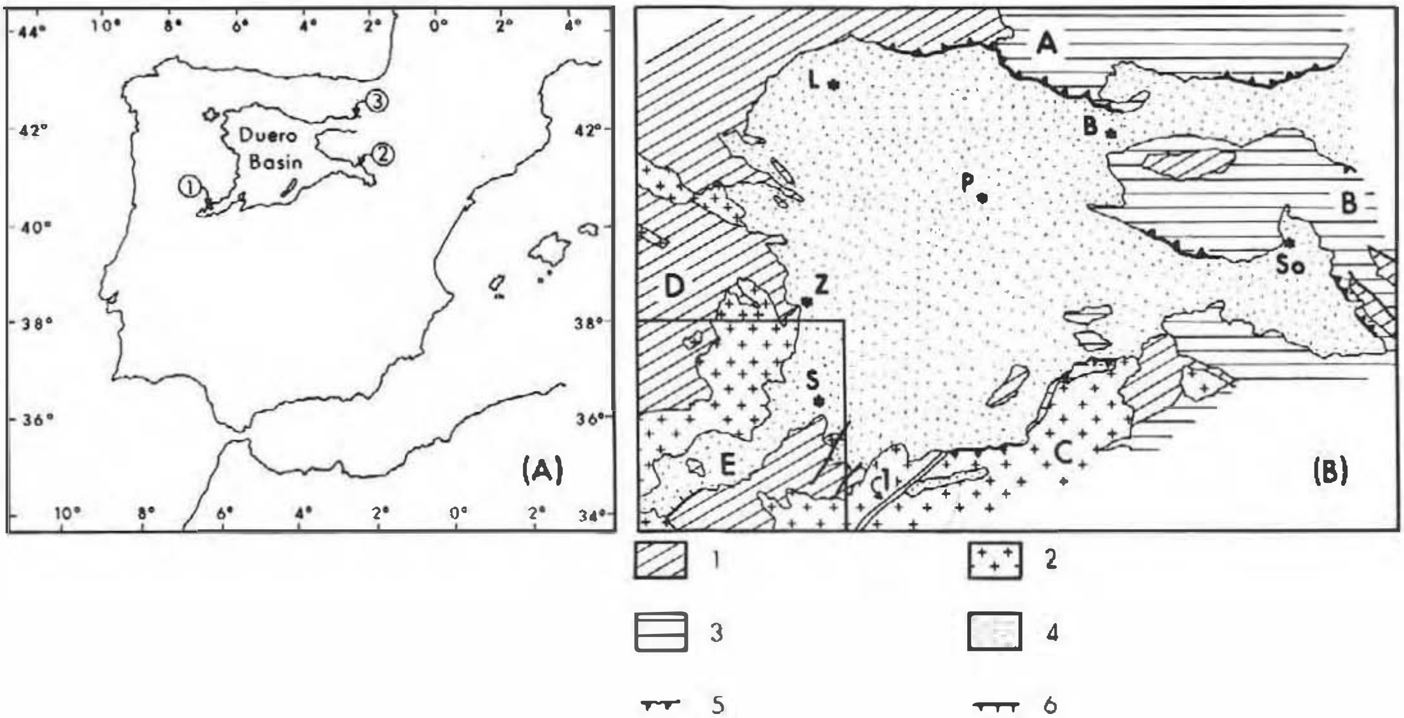

Fig. 1. A. Location map of Duero Basin in the Iberian Peninsula; 1: Ciudad Rodrigo Basin. 2: Almazán Basin, 3: La Bureba Corridor. B. Study area in Duero Basin: L: León, B: Burgos, P: Palencia, So: Soria, Z: Zamora, S: Salamanca; 1: Alentejo–Plasencia Fault, A: Cantabrian Range, B: Iberian Range, C: Central System, D: Western Border. E: Ciudad Rodrigo Basin. Key: Paleozoic, 1: metamorphic rocks; 2: igneous rocks; Mesozoic, 3: carbonates and siliciclastics; Cainozoic, 4: siliciclastics, carbonates and evaporites; Faults, 5: inverse fault; 6: normal fault.

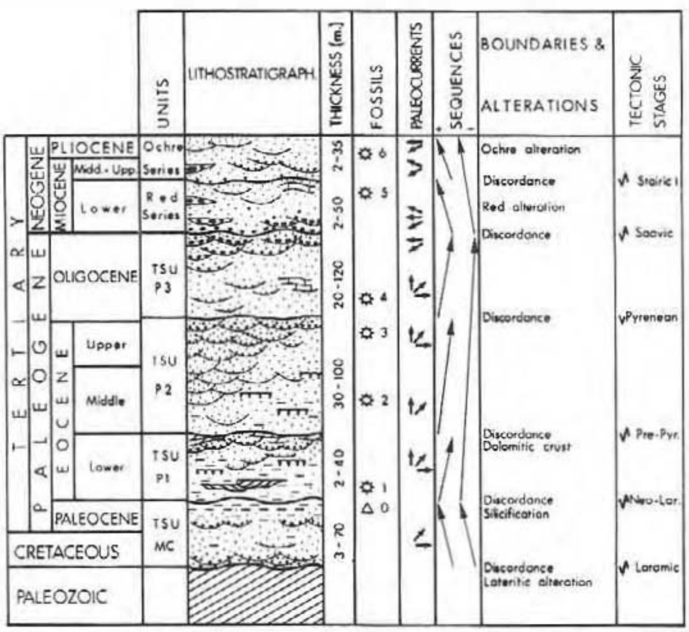

Fig. 2. Tertiary units of SW Duero Basin. Fossils, 0: Absolute age (Kr/Ar) 58 Ma (Blanco *et al.*, 1982), 1: Sanzoles and Avedillo (Zamora), 2: Teso de la Flecha (Salamanca) and Corrales II (Zamora), 3: Molino de Pico and San Morales (Salamanca), 4: Camino Fuentes and El Molino (Ciudad Rodrigo Basin), 5: El Guijo (Salamanca), 6: Benavente (Zamora). (Modified from Santisteban *et al.*, 1991.)

Oligocene–Early Miocene boundary, but movements affected Paleogene sedimentation more generally.

Guadarrama Stage: Maximum horizontal compression N140–155E that diminished with time. It took place in the Early–Late Miocene boundary (intra-Aragonian *sensu stricto*) and was responsible for the present reverse horst–graben structure.

Torrelaguna Stage: This was a minor phase with compression N160–200E, probably related to the previous one, Late Miocene to Quaternary.

The dates of these stages were deduced from the sediments of the closest basins affected by the faulting. This raises some doubts, particularly about the northern border of the Central System, because there is controversy concerning the age of sediments affected by the reverse faults of the Guadarrama Stage. Some authors (Corrales, 1982; Portero *et al.*, 1982; Corrochano *et al.*, 1983) consider these sediments as Early–Late Miocene, whereas others (Olmo & Martínez-Salanova, 1989; Santisteban *et al.*, 1991; see Chapter W3) consider them as Oligocene in age (Fig. 2). The last dating implies that the Iberian Stage was pre-Oligocene (possibly at the Eocene–Oligocene boundary, i.e. the Pyrenean phase of Brinkmann, 1931) and the Guadarrama Stage was Oligocene Early Miocene (the Saavic phase of Brinkmann, 1931).

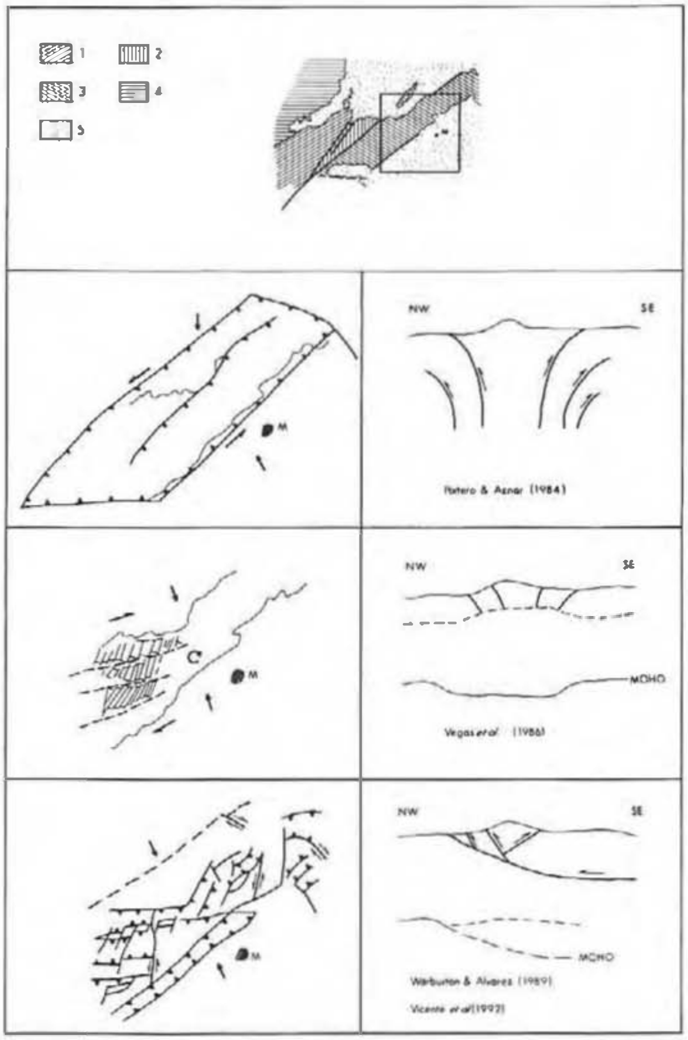

Fig. 3. Previous interpretations of the structural development of the Central System. The upper diagram shows the location of the main geologic zones: 1 – Border Massifs, 2 – transition zone, 3 – Central System (*sensu stricto*), 4 – Western Border, 5 – Tertiary deposits (Duero and Tajo basins). The lower three pairs of diagrams compare three different interpretations of the structural development of the area, with structural outline maps on the left, and cross-sections on the right (from Portero and Aznar, 1984; Vegas *et al.*, 1986; Warburton and Alvarez, 1989; and Vincente *et al.*, 1992).

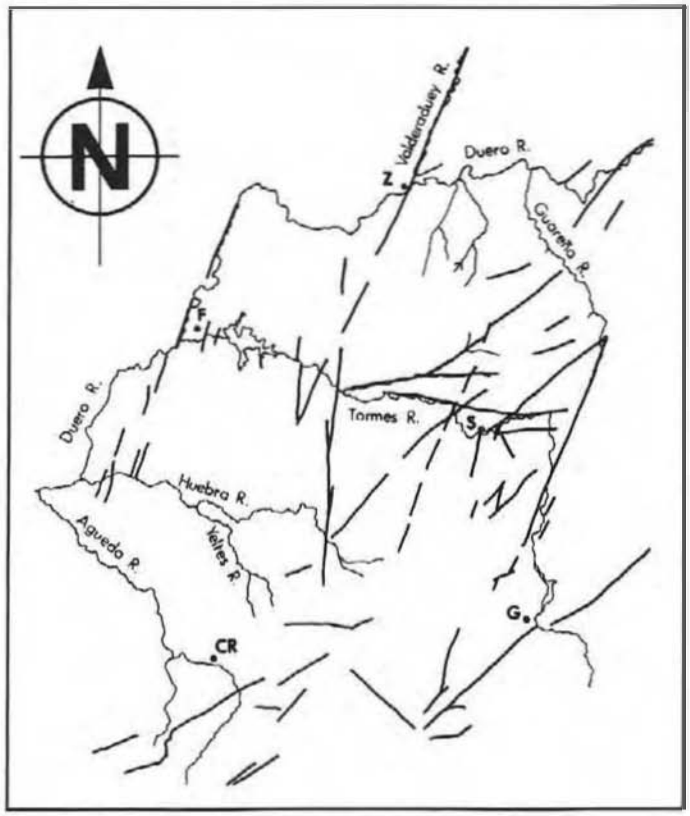

Fig. 4. Faulting sketch of Western Duero Basin deduced from field work and teledetection studies. Z: Zamora, F: Fermoselle, S: Salamanca, CR: Ciudad Rodrigo, G: Guijuelo. (From Santisteban *et al.*, in press.)

The Border Massifs

In the north-western side of the Central System a few Palaeozoic structural highs pertaining to the southern border of Duero basin have survived (Fig. 3). The structure of these massifs is quite different from the Central System *sensu stricto*.

They are bounded by normal or strike-slip faults with dominantly vertical movements and a configuration of horsts and grabens that extends NE–SW. These fault-blocks were horizontally displaced by faults trending NNE–SSW and they are also bounded by WNW–ESE faults (Fig. 4).

The border massifs preserve the best record of the alpine deformation of this area (Jiménez, 1972; Jiménez, 1973; Corrochano *et al.*, 1983). (Figs. 5 and 6A). Accordingly to Brinkmann's (1931) nomenclature the tectonic stages of this area are:

- Laramic phase (Late Cretaceous–Paleocene): faulting of basement affected by the Mesozoic lateritic weathering profile.
- Neo-Laramic phase (Paleocene–Eocene): high-angle faults (NNE–SSW, NE–SW and E–W) bring together Hercynian and Cretaceous–Paleocene rocks. Tilting of these sediments towards NE. There are normal, strike-slip and some, scarce, E–W reverse faults with small displacement.
- Pre-Pyrenean phase (Early–Middle Eocene): tilting and sinking of Lower Eocene sediments towards N and NE due to NE–SW and E–W normal and normal–strike-slip faults.
- Pyrenean phase (Upper Eocene–Oligocene): great reorganisation of the basin related to a stage of fault reactivation and major uplift of the borders of the basin. The horst and graben structure also affected sedimentary basin. After this time these fracture areas are indicated by slight subsidence. The newly created structural highs were never covered (buried) by younger sediments.

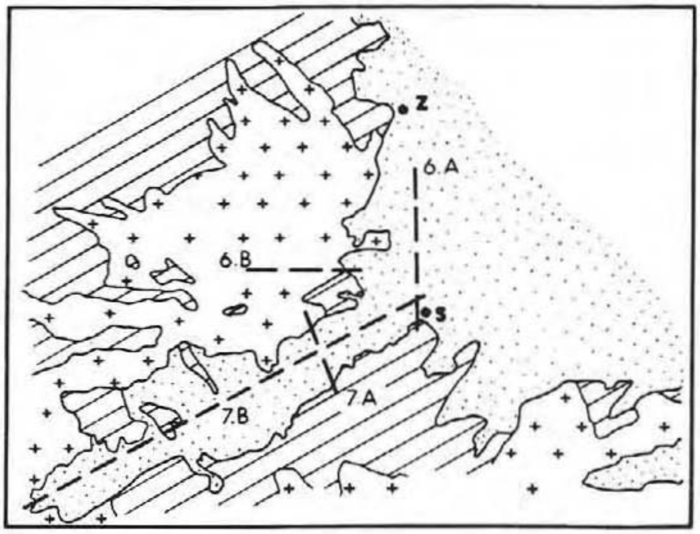

Fig. 5. Location of cross-sections in Figures 6 and 7.

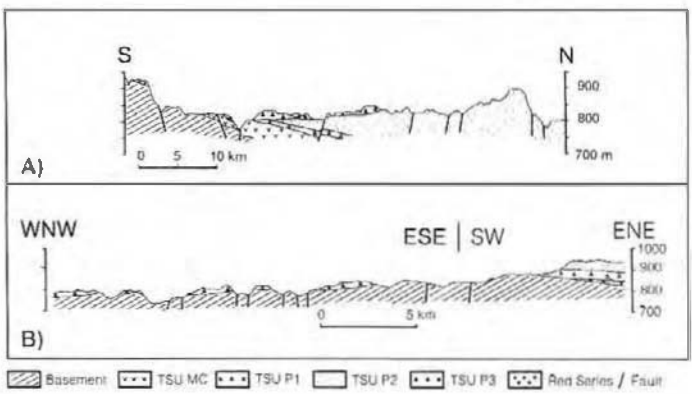

Fig. 6. A. S–N cross-section from Border Massifs towards Duero Basin. Note the horst located at N which serves as palaeo-threshold along the Oligocene and Neogene (modified from Santisteban *et al.*, 1991). B. W–E cross-section of Western Border: TSU P3 sediments are located in lower positions than previous units and are tilted towards the west in relation to NNE–SSW faults.

- Saavic phase (Oligocene–Early Miocene): movements of NE–SW and E–W normal faults that modified the basin extension and tilted previously defined blocks. NNE–SSW faults lowered blocks towards the west. Major uplift in the eastern and south-eastern areas generated a configuration very close to the present.
- Stairic phase (Early–Late Miocene, Pliocene): small extensional phenomena that lowered blocks towards the west.

The western border

This border has been considered inactive due to the scarcity of Tertiary deposits allowing the recognition of alpine movements, and the fragmentation of the old, plain landscape.

However, detailed study of small Tertiary sedimentary outcrops and weathering profiles has revealed at least three tectonic stages of post-Paleocene, pre-Oligocene and post-Oligocene ages. Related vertical displacements are about 100 m (Figs. 5 and 6B).

The first faulting stage affected igneous and metamorphic rocks with a superimposed lateritic weathering profile and silicification processes of Mesozoic age, related to the top of MC tectonosedimentary unit (MC TSU of Fig. 6), (Upper Cretaceous Paleocene). Elsewhere, these faults are fossilised by the sediments of the P1 TSU (Lower Eocene); fault movements can be dated as Paleocene–Early Eocene. However, it may be argued that this is actually the result of a double faulting process (pre-Paleocene and Paleocene–Early Eocene).

Sediments of the younger P3 TSU (Oligocene) are located in topographically lower positions to the west of the previous units due to NNE–SSW and NE–SW fault systems. These structures extend to the Valderaduey faulting zone (Martin-Serrano, 1988). Igneous rocks often show S–C structures, related to these movements, that record normal displacements (Diez Montes, pers. commun., 1992). The distribution of sediments of the P3 related to these faults, and the displacement of faults by other fault systems show that these movements are of pre-Oligocene age.

The last tectonic movements recorded here lowered blocks including Tertiary sediments towards the west, i.e. away from Valderaduey fracture zone. Two stages can be differentiated: a first subsidence of the sediments of P3 TSU towards the east, followed by rotation (tilting) of blocks and subsidence to the west. A minimum age cannot so far be given to these movements because of the absence of younger deposits. They are thought to be of post-Oligocene age.

The Ciudad Rodrigo Basin

This is a half-graben bounded to the south by a main NE–SW fault. In fact, this is not a single fault but a parallel system cut by a conjugate (secondary) NNE–SSW system that displaces the main system. There are also scarce NW–SE and WNW–ESE faults that displace the fault (Figs. 5, 7A and 7B). The basin border therefore has a complex structural history.

The high-angle dip of the fault planes makes it very difficult to determine the true components of movement. Gracia Plaza *et al.* (1981) and Jiménez & Martín-Izard (1987) described strike-slip components, whereas Alonso Gavilan & Polo (1986–87) found normal components. The accumulated vertical displacement amounts to 300 m (Jiménez & Martín-Izard, 1987). components have been found so far.

The first Alpine movements in the Ciudad Rodrigo Basin, supposed to be of the Laramic phase, caused domes trending NE–SW (Mingarro *et al.*, 1970). Eocene cannot be clearly identified due to the lack of previous sediments.

The Ciudad Rodrigo Basin was generated in the Early Eocene by the activity of the fault forming the southern boundary.

At the Eocene Oligocene transition, new reactivation of faults

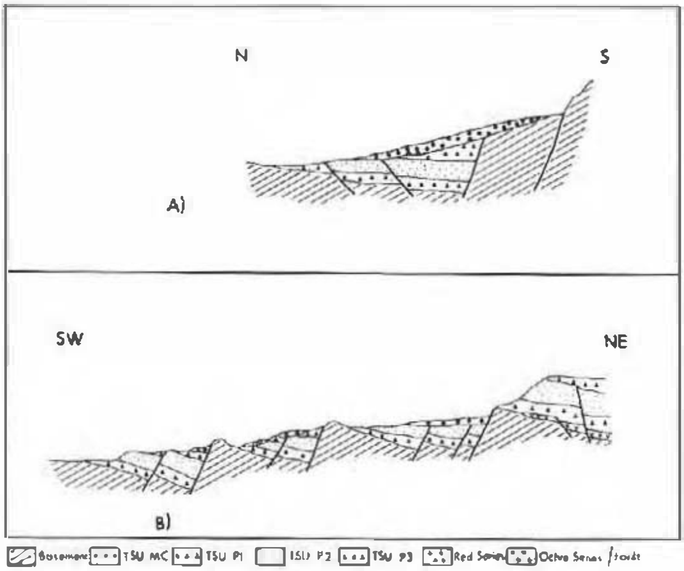

Fig. 7. Schematic cross-sections of the Ciudad Rodrigo Basin. A. N–S section showing the asymmetrical infill of the basin in relation to its southern border. B. SW–NE section showing the westward deepening of the basin. Fault dips are exaggerated.

lowered the northern blocks and the basin depocentres shifted towards the north.

A new reactivation at the Oligocene–Miocene boundary (the Saavic phase of Brinkmann, 1931) modified again the extent of the basin. Unlike other basins of the Hesperic Massif there was no sedimentary tectofacies developme

immediately after faulting. The basin deposits were not genetically related to the faults, which were buried rapidly after their movement.

Neogene alpine activity took place in the western and central areas of the basin. The main Neogene phase took place between the deposition of the Red (Lower Miocene) and Ochre Series (Middle Miocene–Pliocene). Then, a reactivation of NNE–SSW faults caused vertical movements of several tens of metres. Several faulting stages have been recorded in the eastern areas, where they break the top of the Red Series. The age of these movements cannot be established, but they show normal-dextral displacement (Gracia Plaza *et al.*, 1981).

Later movements into the basin acted during the Late Miocene–Pliocene (Moreno, 1991) and until the Quaternary. However, their importance and magnitude are less and they clearly indicate extension.

The Duero Basin

The Tertiary sediments of the Duero basin *sensu stricto* show features that indicate a close relationship between tectonics and sedimentation. These features are fractures and anomalous thicknesses of sediments related to buried fault systems (Figs. 5 and 6A).

Upper Cretaceous to Paleocene sedimentation took place in a low-relief landscape with irregular topography and a well-developed weathering profile.

A younger episode of faulting broke up this homogeneous pattern. This is observed only in the margins of the basin.

During Early–Middle Eocene times, the basin tilted towards the east and north-east. Although the surface expression of the faults was not strong, there were notable differences of subsidence related to deep faults.

In the transition from Late Eocene to Oligocene times a system of horst and graben was generated, and tilting to the east and north-east took place again.

A small fault episode, and the beginning of tilting to the west, were recorded at the Oligocene–Early Miocene boundary.

After that time, faulting took place that was related to almost radial extension. These were the intra-Miocene and Plio-Quaternary faulting episodes that were characterised by tectonic subsidence towards the west.

Tectonics and sedimentation

The evidence for all these tectonic movements was preserved in the stratigraphic framework of the basin. It is noteworthy that the climatic curve records increasing aridity, while sedimentary successions show a coarsening-upwards trend related to the progressive uplift of source areas. Similarly, changes of palaeogeography in successive units coincide with lines of possible tectonic origin. Also, areas of subsidence tend to be defined by lines parallel to the main faults.

Palaeodrainage patterns are most useful in interpreting the tectonic evolution. Channels tend to flow parallel to fault strikes but, when they flowed at right angles to fault lines, river deposits fossilised the faults. The geometry of the resulting units is almost tabular and this is considered as an indication of very limited tectonic activity. Thus, we consider that tectonic activity has been recorded as changes of palaeogeography related to subsidence or local faulting in the sedimentary basin. In contrast, the largest tectonic movements occurred near the source areas far away to the south.

Synthesis

Tectonic stages

From this work we can differentiate the following faulting episodes (according to Brinkmann's, 1931, nomenclature) (Fig. 2):

- Cretaceous–Paleocene: progressive uplift of the Hesperic Massif due to N–S compression (Laramic phase).
- Pre-Eocene: reactivation of NE–SW and NNE–SSW normal to strike-slip fault systems. ENE–WSW extension (Neolaramic phase).
- Early Eocene–Middle Eocene: fault favoured lowering towards the NE. Near radial extension (Pre-pyrenean phase).

- Late Eocene–Oligocene: generation of NE–SW horst-graben systems bounded by E–W faults and displaced by NNE–SSW ones. Major uplift of borders and source areas and reorganisation of the sedimentary basin. ENE–WSW extension (Pyrenean phase).
- Oligocene–Early Miocene: gentle sinking towards the north and west favoured by small slip normal faults. E–W extension (Saavic phase).
- Early Miocene–Middle Miocene: westward sinking favoured by N–S faults. E–W extension (Stairic I phase).
- Late Miocene–Recent: continued, pulsating, sinking towards the west. Near radial extension (Stairic II and following phases).

Geodynamic setting and evolutionary model

We propose an evolutionary model for this area of the Duero and Ciudad Rodrigo Basins as follows:

Uplift of the Hesperic Massif at the end of the Late Cretaceous, as a result of the convergence of Iberia and Eurasia. Since then until the Late Oligocene–Early Miocene the approach was recorded as compressive pulses (Paleocene–Early Eocene, Early Eocene–Middle Eocene, Late Eocene–Oligocene) directed NNE–SSW. These movements have been recorded in the sedimentary record as a coarsening-upwards macro sequence, composed of coarsening-upwards TSUs, reflecting the progressive uplift of the southern source areas.

The Iberian and Euroasiatic plates welded together in the Miocene and, since that time, behaved as a single plate. The compression due to the convergence of the African plate caused the last uplift and modification of the Central System and southern borders of the Duero Basin.

Extension has dominated in the basin since Miocene times, causing small changes such as little morphological scarps and modifications of the river drainage pattern.

This scheme covers all the main normal and strike–slip faults developed during the whole of the Tertiary. To understand this let us consider the position of the area in relation to the main Tertiary plate boundaries. Two areas of lithospheric convergence, the Pyrenees and the Betic Ranges, limited to the N and S the Iberian peninsula (Fig. 8). The western boundary was the divergence area of the Mid-Atlantic Ridge, whereas the eastern one was the compressive chain of the Iberian Range. This pattern generated an area of minimum compression to the west that underwent extension during most of Tertiary times (Proença Cunha & Pena dos Reis, 1992).

Another fact supports the different behaviour of the western and eastern areas: the eastern Central System was the locus of marine and coastal sedimentation during Late Mesozoic and Early Tertiary times whereas, at the same time, the Western Central System was an uplifted, terrestrial realm. According to this, the eastern areas experienced a more pronounced uplift during Alpine Orogeny than the western ones.

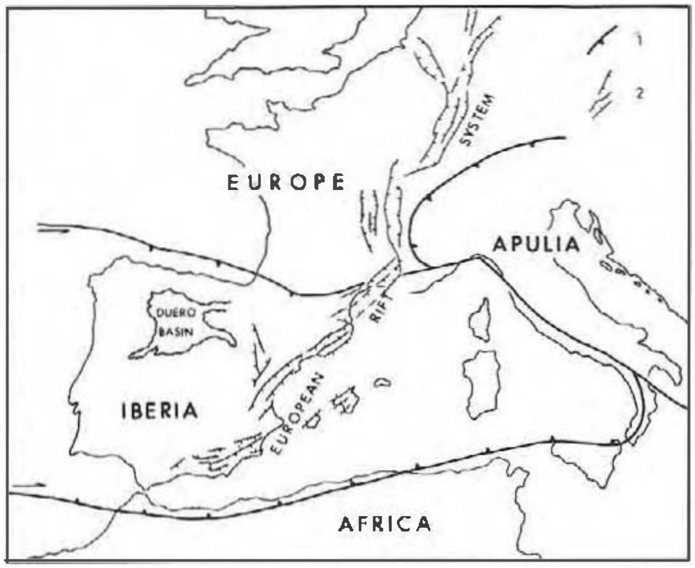

Fig. 8. Relative position of Iberian Peninsula and Duero Basin relative to main plate boundaries. N and S limits (Pyrenees and Betics) are compressive domains which acted during the Tertiary. This situation led to an W–E extensional regime in western Iberia.

According to the previous reasoning, we propose a hypothesis based on Simón Gómez (1984, 1990):

(a) Maximal compression occurs to the east of the basin (Pyrenees, Iberian and Betic Ranges). This might produce an arcuate deformation of the stress field so that western areas showed compression directions oblique to main faults. This could generate a transpressive regime.

(b) Changes in relation and/or direction of stress related to a crustal irregularity (like the Alentejo–Plascencia fault).

(c) Coeval compressive and extension fields. Extension prevailed in the study area. This hypothesis implies a change in stress relationships but does not require a change in stress direction.

(d) Thrust erosion simultaneous with its positioning (as proposed by Beaumont *et al.*, 1992) and passive behaviour of the Duero basin. Under these constraints, lithospheric overload produced a frontal furrow and a marginal ridge (dome) that favoured vertical instead of tangential movements. Forces acting on a faulted substratum reactivated older fault lines as 'normal' faults. In support of this hypothesis, geophysical data show a crustal thickening in the Central System and thinning towards the north-west (Martín Escorza, 1990; Babín *et al.*, 1992).

However, these are merely hypotheses and they now need to be tested by new studies.

Conclusion

The south-western area of the Spanish Northern Meseta (Ciudad Rodrigo and Duero basins) is characterised by tectonically active south and south-western boundaries and a relatively tectonically passive western border.

The tectonic activity in the area during most of the Tertiary was determined by a transpressive regime that reactivated Hercynian to Late-Hercynian faults, newly created faults are scarce. The main faulting stages have strike–slip to normal components. Brittle response of the crustal materials favoured faulting instead of folding. However, sedimentary units show a coarsening-upwards trend related to accelerated uplift of the source areas located to the south and south-east. This evidence indicates a compressive regime for areas located towards the east (Central System) during Paleogene times. Neogene deposition records extensional regimes.

The tectonic activity strongly changed the morphology and boundaries of this area generating and modifying systems of horsts and grabens.

There is a complex record of the Alpine Orogeny in the area, because the sedimentary record indicates a compressive regime in the source areas, coeval with an extensional to transpressive regime indicated by normal or strike–slip faults. This duality is due to the geotectonic position of this area between two compressive areas, the Cantabrian Range and the Central System, and the extensional Atlantic margin.

The south-western Duero Basin is considered to have been a moderately active area of cratonic type (*sensu* Sloss & Speed, 1974). It occupies an intermediate position between the largest areas of deformation of the Iberian Plate.

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