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Finite-element modelling of Tertiary paleostress fields in the eastern part of the Tajo Basin (central Spain)

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Abstract

Three subsequent Tertiary paleostress fields that are deduced from fault-slip data for the eastern part of the Tajo Basin are analyzed by finite-element studies. The modelling results show that maximum horizontal stresses (S_{Hmax}) are mainly controlled by the geometry of the model limits and the boundary conditions applied. The models are used to test two hypotheses on the origin of the Altomira Range. A local stress field responsible for its formation ('Altomira') can be modelled successfully by superposition in time and place of two major paleostress fields ('Iberian' and 'Guadarrama'). Stress trajectories have been modelled with respect to a homogeneous cover and heterogeneous basement to investigate the role of rheological contrasts between different basement blocks on the orientation of the stress field. Results of this kind of modelling suggest a mechanical decoupling between the cover and the basement, especially for the 'Altomira' paleostress field. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

Comparison between results obtained by finite-element stress modelling and observed (paleo)stress data is a mighty tool for the understanding of geodynamic processes. This is specially true where several stress fields (in the case of the Iberian Peninsula, the Tertiary stress fields) controlled by different rheological and structural factors have been described (Simón-Gómez, 1986; Guimerá, 1988; Galindo et al., 1993; De Vicente et al., 1996b). Previous stress modelling results, obtained on theoretical basis, as well as on practical cases (Richardson et al., 1979; Wortel and Cloetingh, 1985; Cloetingh and Wortel, 1986; Grünthal and Stromeyer, 1992; Gölke and Coblentz, 1996), show that certain tectonic processes can be simulated by finite-element modelling. This technique has been applied in different scale models for recent stresses and paleostress data (Meijer, 1995; Janssen, 1996) as well as for deformations on several types of structures (Sassi et al., 1993; Gölke et al., 1994).

The Alpine geological evolution of the interior of the Iberian microplate during the Tertiary is strongly influenced by the presence of large inherited geological structures and by stress transmission from its active borders (Fig. 1): the Pyrenees at the north and the Betics at the south (Sanz de Galdeano, 1996). The tectonic activity at these borders is related to

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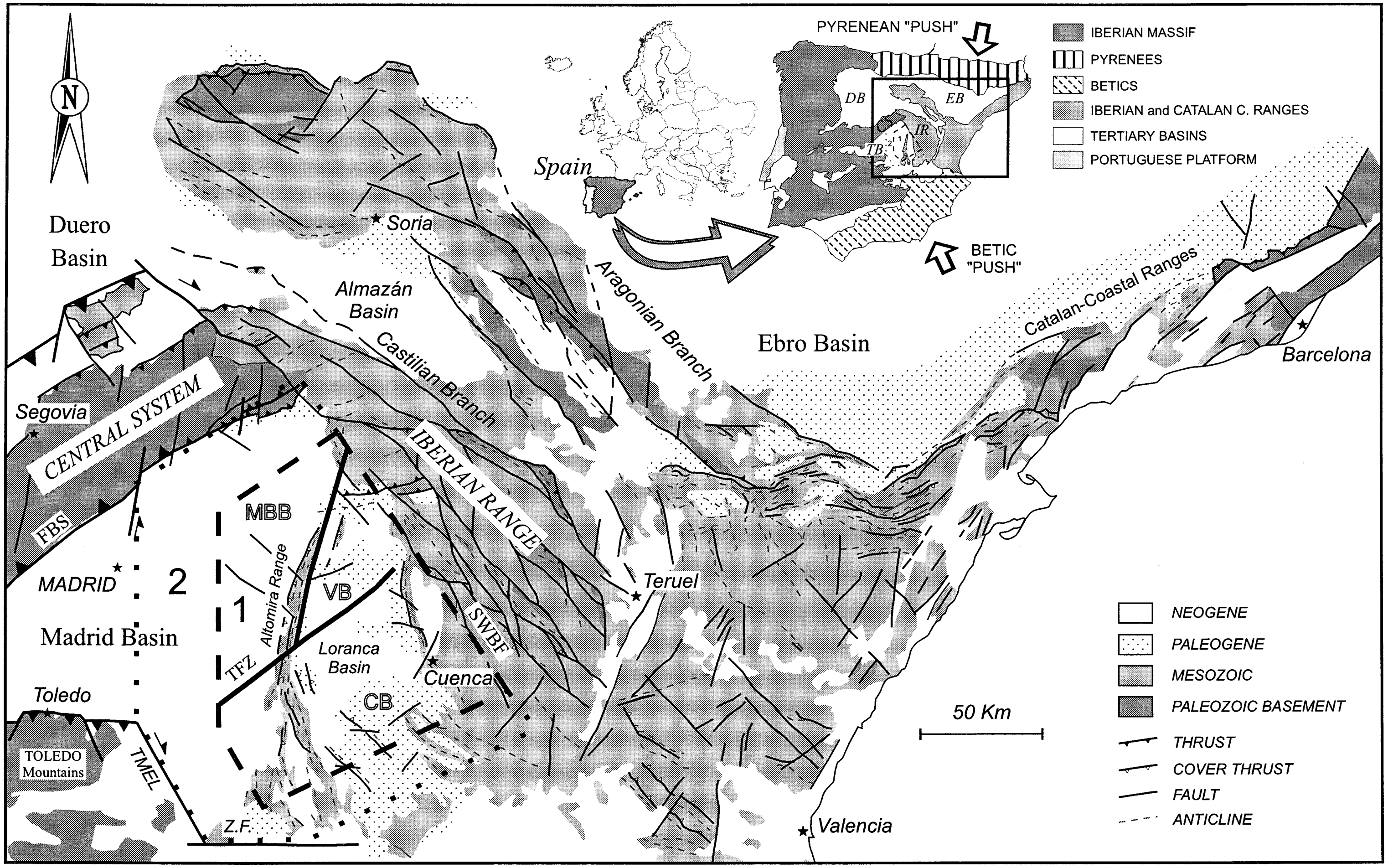

Fig. 1. Geological and geographical location of the study area and finite-element modelling area boundaries. *DB* = Duero Basin; *TB* = Tajo Basin; *Z.F.* = Záncara Fault; *TMEL* = Toledo Mountains eastern limit; *TFZ* = Tarancón Fault Zone; *MBB* = Madrid Basin Block; *VB* = Valdeolivas Block; *CB* = Cuenca Block.

the convergence and lateral displacement between the Iberian, African and Eurasian plates during the Tertiary (Dewey et al., 1989; Srivastava et al., 1990). In the interior of the peninsula, sedimentary basins development (Duero, Tajo and Ebro basins) was controlled by the tectonic activity of its borders. These borders are a set of mountain ranges (the Spanish Central System, Iberian Range, Toledo Mountains, Altomira Range; Fig. 1) that were structured due to the transmitted stresses from the Iberian Peninsula margins. The geometry and characteristics of these deformation belts are strongly subdued to the presence of large crustal faults, which have controlled Mesozoic sedimentation and which have been subjected to inversion tectonics during the Tertiary (Álvaro et al., 1979; Viallard, 1983; Guimerá and Álvaro, 1990). We have studied the eastern part of the Tajo Basin, an area that comprises two Alpine deformation belts (the SW border of the Iberian Range and the Altomira Range) and the Madrid and Loranca Tertiary basins (Fig. 1).

The most important structural characteristic of the study area is the presence of a 100-km-long thin-skinned fold-and-thrust belt with a N–S trend and a W vergence: the Altomira Range. This fold-and-thrust belt developed under a regional N–S shortening parallel to the range direction, which makes its origin arguable. The origin of the Altomira Range has been basically interpreted in two ways: (a) after Guimerá (1988), the Pyrenees, the Iberian Range and Catalan Coastal Ranges were structured under the same N10ºE regional compression, resulting from the collision of the Iberian and Eurasian plates; in view of this model, the Altomira Range is an oblique ramp of the Iberian Range foreland fold-and-thrust belt of the Pyrenean orogen (Guimerá and Álvaro, 1990); (b) as a lateral extrusion of the Mesozoic cover to the west at the foreland of both the Pyrenees and Betics, produced by the superposition of both regional compressions (Muñoz-Martín et al., 1994).

In both hypotheses, the tectonic stresses that generated the Altomira Range must have been influenced by previous structures in the Hercynian basement and in the cover, as well as by the Mesozoic sedimentary architecture itself (Van Wees et al., 1995).

The aim of this study is to investigate, through a series of finite-element models, the Tertiary paleostress fields deduced from the Mesozoic and Cenozoic cover at the eastern part of the Tajo Basin (Muñoz-Martín and De Vicente, 1996). Special attention has been drawn to the boundary conditions, which have to reflect the main geological structures of central Iberia. The results of these stress orientation models can provide valid data to discuss the origin of different paleostress fields and associated structures, as well as its relation with the tectonic activity at the northern and southern margins of the Iberian Peninsula (Pyrenees and Betics). The possible presence of reorientations of the stress trajectories in the basement with regard to the cover, caused by the presence of basement blocks with different rheological characteristics, has also been studied during the modelling. Mechanical decoupling could be caused by the presence of a detachment level (Triassic Keuper facies) between the cover and the basement.

2. Geological setting and Tertiary paleostress fields

The eastern part of the Tajo Basin reflects a complex Tertiary geological evolution, with a large variety of active structures, whose evolution and kinematic chronology is recorded by the deformation history of the deformation belts and the sedimentary infill of the Tertiary basins (Calvo et al., 1993; De Vicente et al., 1996a). The most important characteristics of the two deformation belts in this area (the Iberian and Altomira ranges) and of the Madrid and Loranca Tertiary basins is described in order to put the paleostress data and the developed finite-element models into a larger framework.

The Iberian Range (Fig. 1) is an intraplate range with an overall NW–SE trend whose origin and geometry is related to the presence of NW–SE-trending basement faults, that controlled sedimentation in the Iberian Basin during the Mesozoic, and which were inverted during the Tertiary (Álvaro et al., 1979). At the Iberian Range, the Mesozoic sedimentary cover has a thickness of several thousands of metres, and the presence of plastic Lower to Middle Triassic rocks (Keuper facies) allows us to distinguish between a detachable cover formed by Jurassic, Cretaceous and Tertiary materials and a basement consisting of Paleozoic and lower Triassic materials (Álvaro et al., 1979; Viallard, 1983). This Hercynian basement crops out at the Iberian Range in spindle (or almond) shaped massifs, stretched in a NW–SE direction parallel to the chain, usually limited by high dip faults with lateral movement (Guimerá and Álvaro, 1990). The tectonic activity of the Iberian Range presents two main different stages for the Tertiary. (1) In a first stage (Oligocene) the range acted as a dextral transpressive zone located at the foreland of the Pyrenees orogen (Guimerá and Álvaro, 1990; Salas and Casas, 1993). (2) During the Middle–Late Miocene the eastern part of the range acted as a dextral transpressive limit of the Central Spanish System, clearly related to the formation of the Betics (De Vicente et al., 1996a). This dextral movement is also expressed at the southern border of the Almazán Basin, by the development of abundant transpressive structures (Bond, 1996).

The Altomira Range (Fig. 1) is a west-verging fold-and-thrust belt that only affects the Mesozoic cover. Geophysical data (Querol, 1989; Perucha et al., 1995) show that the basement below the Upper Triassic (Keuper) evaporitic facies is not involved in the compressive structures that appear at the Altomira Range and Loranca Basin. Inherited basement structures, however, controlled the location of the cover deformation, as well as the vergence and the lateral extension of the thrusts. The presence of fractures in the basement that are oblique to the cover thrusts, produces a series of transfer zones developed in the cover that separate zones with different structural characteristics, and control sedimentation in the Tertiary basins (Rodríguez-Aranda, 1995; Rodríguez-Aranda et al., 1995). In this general scheme two different sectors can be distinguished, which are separated by a NW–SE fracture zone that affects the basement (the Tarancón Fault Zone; Capote, 1983). At its northern half part, the Altomira Range presents peculiar structural properties, such as a straight trace in a N–S to N20ºE trend and deformation condensed in one or two narrow anticlinories. At its northern surficial termination, the Loranca and Madrid basins join together due to the cushioning of the compressive structures (Figs. 1 and 2).

From the Tarancón Fault Zone to the south, the folds and thrusts rotate in an anticlockwise sense in a NW–SE direction parallel to the Iberian Range. This change in orientation of the structures is favored by transfer zones that developed in the cover on the top of NE–SW- to E–W-trending basement faults (Figs. 1 and 2).

The Madrid Basin (Fig. 1) is an intraplate basin whose infilling is formed by a sequence of Tertiary continental sediments that is clearly related to different tectonic activity of its borders (the Spanish Central System, Altomira Range, Iberian Range and Toledo Mountains; Calvo et al., 1989; De Vicente et al., 1996a). A series of progressive unconformities of Late Oligocene and Early Miocene age developed in relation to the emplacement of the Altomira Range folds and thrusts. These unconformities allow to date the onset and stages of activity of Altomira Range structures. From Middle Miocene on, alluvial sediments from the Spanish Central System onlap the compressive structures of the Altomira Range, showing a low tectonic activity of this range during this period and thus indicating an upper age limit of major deformation in the Altomira Range.

The Loranca Basin (Fig. 1) is an intraplate basin filled up with mainly Oligocene–Lower Miocene continental sediments, whose deposition was controlled by the folds and thrusts of the Altomira and Iberian ranges (Díaz-Molina et al., 1989). The main basin infill phase occurred during the Late Oligocene and Late Miocene with a series of alluvial fans whose apexes are located to the south of Cuenca and at the Iberian Range (Díaz-Molina et al., 1989; Díaz-Molina and Tortosa, 1996).

2.1. Tertiary paleostress fields

The different paleostress fields for this region that have been modelled in this study have been reconstructed by Muñoz-Martín and De Vicente (1996) from more than 3000 fault-slip data, measured on 78 sites in Mesozoic, Tertiary and Quaternary rocks (Fig. 2). The stress inversion method used in order to obtain paleostress tensors is the one developed by Reches et al. (1992), while the smoothed S_{Hmax} trajectory maps have been constructed following Lee and Angelier (1994). According to these data Muñoz-Martín and De Vicente (1996) have deduced three paleostress fields, that differ with respect to their ages, their principal stress axes directions and the different activated structures along the east-

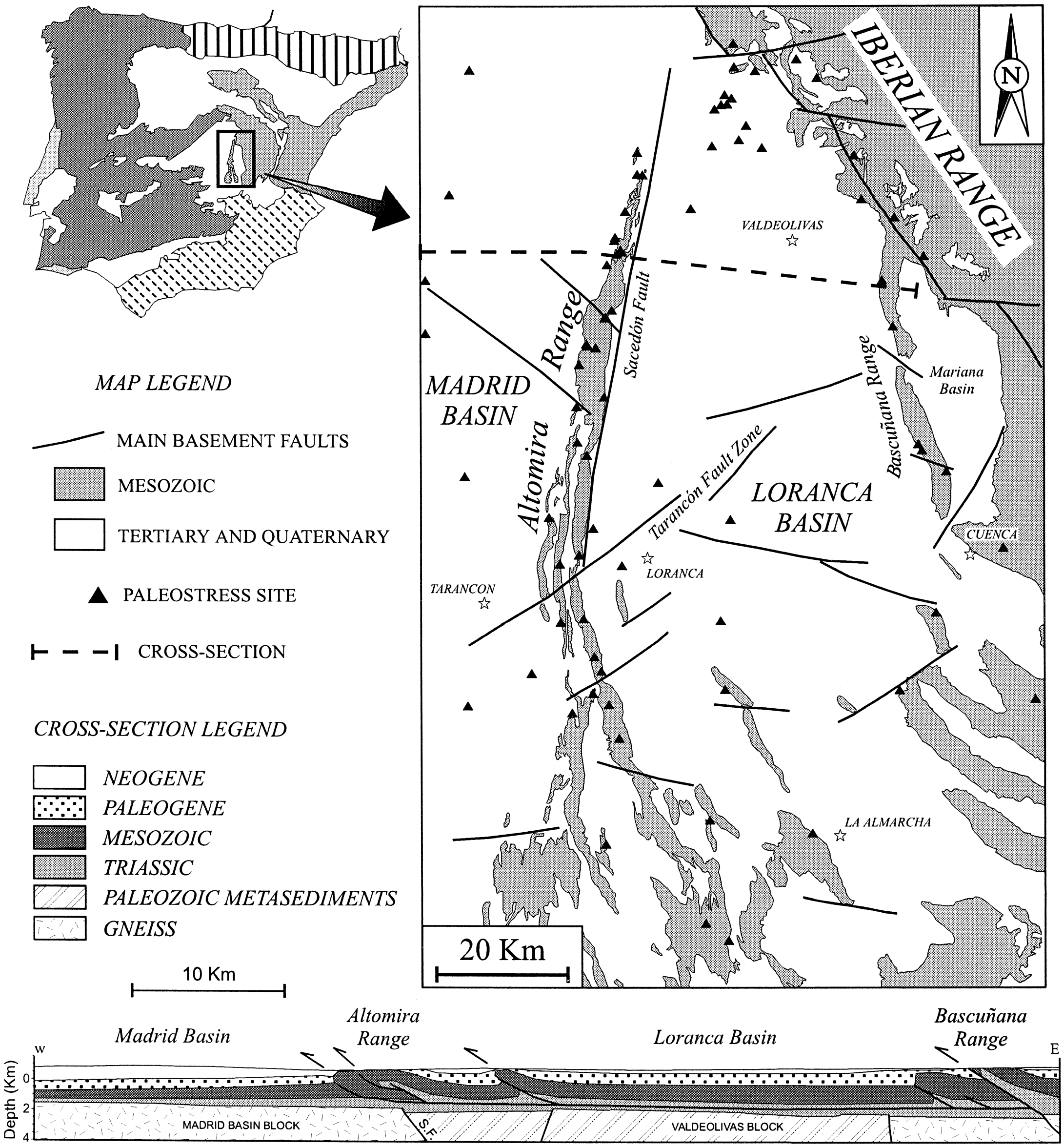

Fig. 2. Upper panel: paleostress data sites and main basement faults deduced from geophysical data. Lower panel: simplified geological profile of the general structure deduced from structural and geophysical data (Perucha et al., 1995; Muñoz-Martín, 1997), and differentiated basement blocks, separated by the Sacedón Fault (*S.F.*).

ern part of Tajo Basin. The most recent stress field, called 'Guadarrama', is compatible with present-day stress trajectories deduced from earthquake focal mechanisms for the centre of the Iberian Peninsula (De Vicente et al., 1996b), and with recent stress data deduced in Morocco and western Europe (Müller et al., 1992; Medina, 1995).

2.2. 'Iberian' paleostress field (Oligocene, Fig. 3)

The compressive paleostress field can be characterised by a regional strike-slip stress tensor in transpressional regime, with σ_1 horizontal oriented to N55ºE, vertical σ_2 and a stress ratio $R = 0.2$ $(R = (\sigma_2 - \sigma_1)/(\sigma_1 - \sigma_3))$. This paleostress

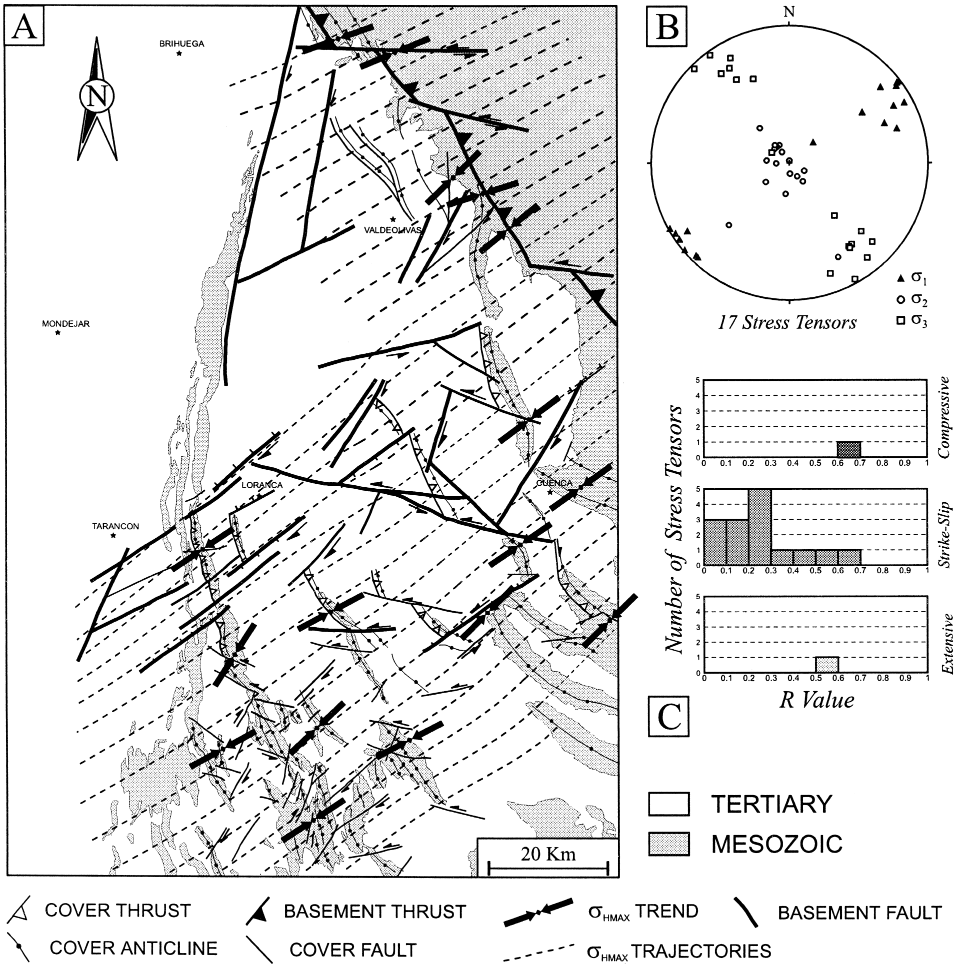

Fig. 3. (A) Paleostress and S_{Hmax} trajectory maps of 'Iberian' paleostress field (Oligocene). (B) Main axis orientations. (C) R value histograms.

field activated several structures that affect the Mesozoic cover and reactivated basement faults in the Iberian Range (Fig. 3). In the study area active structures associated with this paleostress field are mainly NW–SE-trending NE-dipping thrusts and dextral (NNE–SSW) and sinistral (ENE–WSW) strike-slip faults (Muñoz-Martín, 1997). Deformation related to this paleostress field is restricted to the SW border of the Iberian Range and to the southern half of the study area. The northern boundary of this deformation in the interior of Loranca Basin is marked by the SW–NE-trending Tarancón Fault Zone (Figs. 1 and 3). The origin of this paleostress field must be related to the collision with Eurasia along the northern limit of the Iberian microplate generating the 'Pyrenees-push' from the north (Guimerá and Álvaro, 1990). This regional stress field experienced a counterclockwise rotation of the S_{Hmax} south of reactivated NW–SE-trending crustal faults in the Iberian Range (Simón-Gómez, 1984) that controlled sedimentation at the Iberian Basin during the Mesozoic. (Álvaro et al., 1979; Guimerá and Álvaro, 1990).

2.3. 'Altomira' paleostress field (Upper Oligocene–Lower Miocene; Fig. 4)

A stress field in the context of a general transpressional regime, with a N100ºE-trending horizontal σ_1,

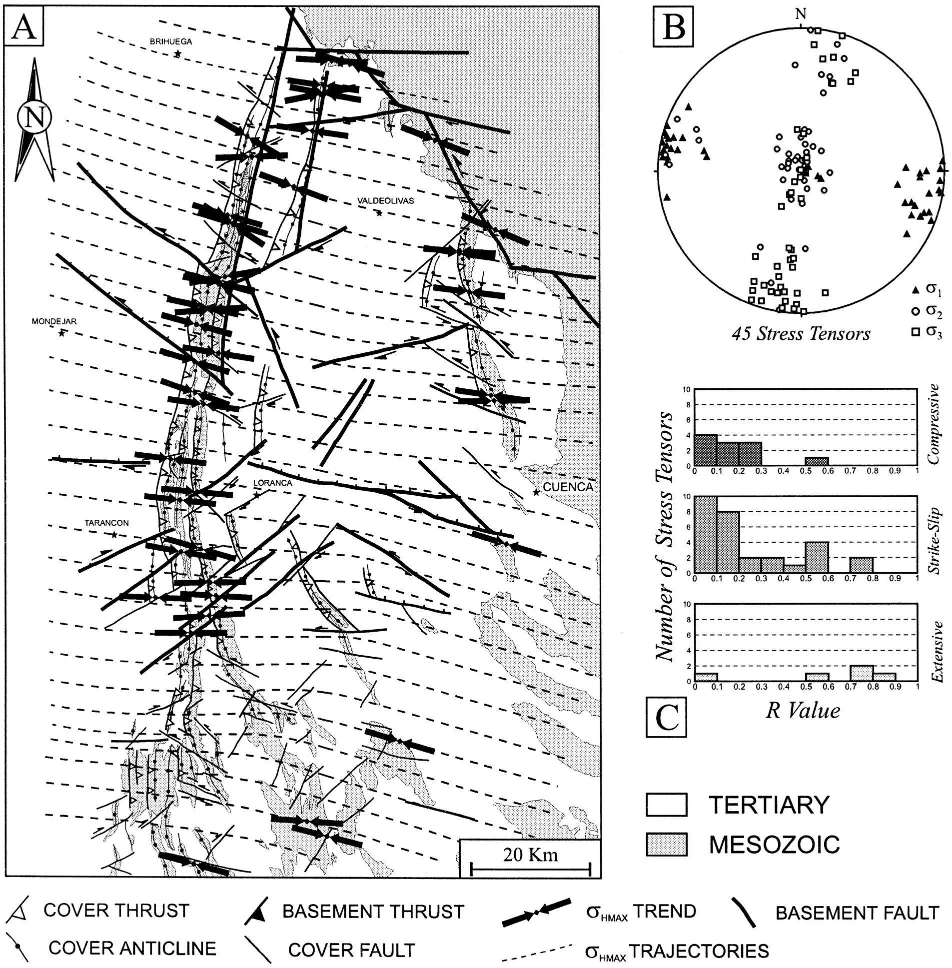

Fig. 4. (A) Paleostress and S_{Hmax} trajectory maps of 'Altomira' paleostress field (Upper Oligocene–Lower Miocene. (B) Main axis orientations. (C) R value histograms.

a vertical σ_2 and a mean $R = 0.13$, is interpreted to be responsible for the structuring of the northern and westernmost sectors of Altomira and Bascuñana Ranges (Fig. 4). Active structures affected by this stress field are N–S- to N20ºE-trending thrusts and associated folds, and ENE–WSW dextral and WNW–ESE sinistral strike-slip faults (Fig. 4). The smoothed S_{Hmax} trajectories are homogeneous and only present a small clockwise rotation at the SE part of the study area. The shortening associated with thrusting imposed by this stress field, reaches a maximum close to the north of the Tarancón Fault Zone (Muñoz-Martín and De Vicente, 1998). Microstructural analysis shows that this stress field reactivated the main structures that developed under the 'Iberian' paleostress field in the southern half of the study area. The 'Altomira' paleostress field has a Late Oligocene–Early Miocene age deduced from the age of syntectonic sediments related to Altomira Range thrusts (Díaz-Molina and Tortosa, 1996), and from the fact that compressive structures of the Altomira Range are sealed by Middle and Upper Miocene sediments (Calvo et al., 1989; Rodríguez-Aranda, 1995). Spatial distribution of deformation related to this paleostress field basically coincides with the study area. Fault data assigned to this stress field have been measured in Jurassic, Cretaceous and Paleogene rocks of the Altomira Range and the SW border of the Iberian

Range, as well as on Lower Miocene sediments of the Madrid and Loranca basins.

2.4. 'Guadarrama' paleostress field (Middle Miocene–Present)

This paleostress field is responsible for a major part of the formation of the Spanish Central System during Middle–Late Miocene (De Vicente, 1988; Capote et al., 1990), and is compatible with the present-day stress field, deduced from earthquake focal mechanisms (De Vicente et al., 1996b). In the study area the 'Guadarrama' stress field is identified as a strike-slip regime, with a constant N155°E-trending horizontal σ_1 and an R value around 0.33 (Fig. 5). Main structures activated by this stress field are NW–SE dextral and NNE–SSW sinistral strike-slip faults. Fault data assigned to this stress field have been measured on Jurassic to Quaternary sediments. In several sites it has been proved that previous weakness planes (faults, bedding planes, etc.) have been reactivated as strike-slip faults by this stress field (Muñoz-Martín, 1997). S_{Hmax} trajectories are very homogeneous within the study area, and extend to the north and to the west, covering the Spanish Central System (De Vicente et al., 1996b). The origin of this paleostress field is related to the transmission of stresses from the southeast due to the ongo-

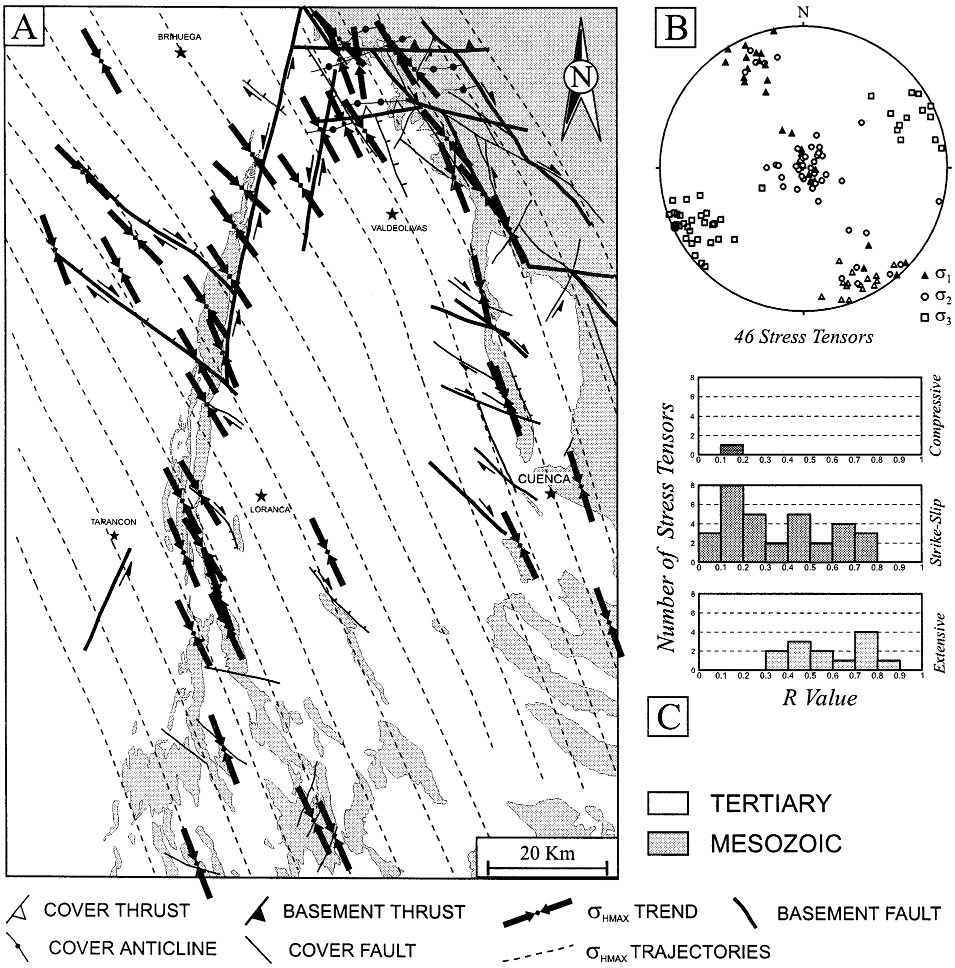

Fig. 5. (A) Paleostress and S_{Hmax} trajectory maps of 'Guadarrama' paleostress field (Middle Miocene–Present). (B) Main axis orientations. (C) R value histograms.

ing convergence between Africa and Eurasia/Iberia building up the Betics (Galindo et al., 1993; De Vicente et al., 1996b).

2.5. Structure of the eastern part of the Tajo Basin

Balanced geological cross-sections extending from the Madrid Basin to the Iberian Range across the Altomira Range indicate a maximum shortening of 18% (16 km) in the central part of the study area, close to the north of the Tarancón Fault Zone (Muñoz-Martín, 1997). Seismic reflection profiles (Querol, 1989) and gravity data (Perucha et al., 1995; Muñoz-Martín, 1997) allow to constrain the basement structure under the Madrid and Loranca Tertiary basins and show that basement is not involved in the compressive deformation of the Altomira Range. This finding is in contrast to what occurs in the Iberian Range. Nevertheless, basement faults produced a stepped basement geometry that seems to control the location and lateral extension of the thrusts in the cover, which are developed upon the detachment level (Fig. 2). Geophysical data reveal the presence of a large normal fault in the basement located under the Altomira Range thrusts (Sacedón Fault, Figs. 1 and 2). Both this fault and the westward disappearance of plastic Keuper facies along a N–S edge in the proximity of the Altomira Range, must have played an important role in the nucleation of the deformation (Van Wees et al., 1995). Combination of both factors has probably determined the straight trace of the northern half of the Altomira Range.

Geophysical data enable us to define a series of blocks in the basement under the Mesozoic–Tertiary cover, with different lithological and structural characteristics (Querol, 1989; Perucha et al., 1995; Muñoz-Martín, 1997). In this way, three main blocks have been defined in the study area: the Madrid Basin Block, the Valdeolivas Block and the Cuenca Block (Figs. 1 and 6). The Madrid Basin Block consists of granitic and gneissic rocks with a low fracture density. The Valdeolivas Block is formed by Paleozoic metamorphic rocks that are characterised by a higher fracture density. Finally, the Cuenca Block has a heterogeneous composi-

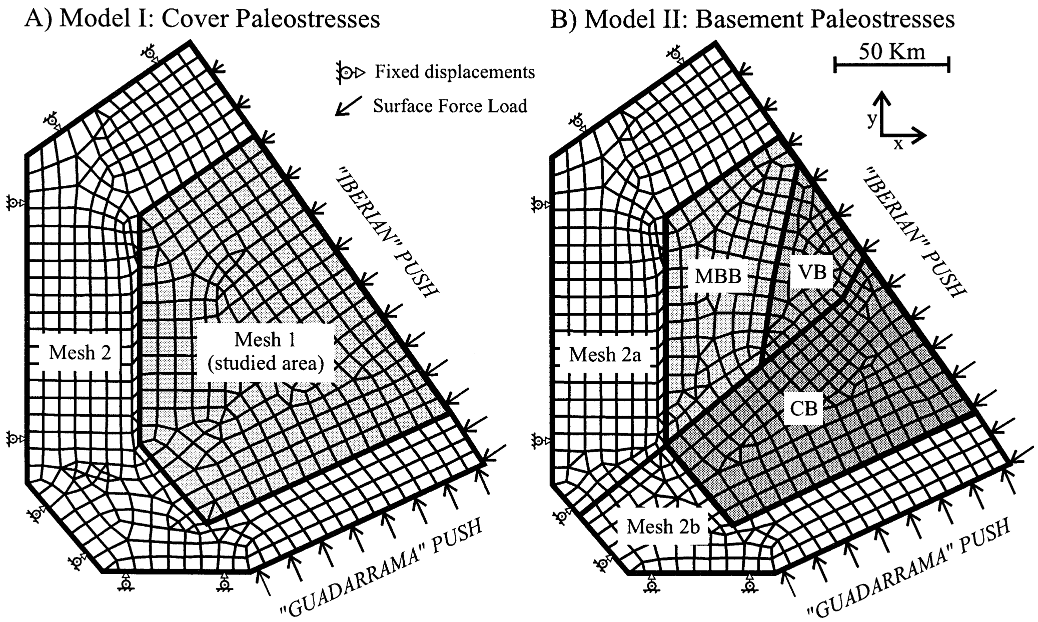

Fig. 6. Finite-element meshes and boundary conditions for both models: (A) Model Group I — cover paleostresses; (B) Model Group II — basement paleostresses. *MBB* = Madrid Basin Block; *VB* = Valdeolivas Block; *CB* = Cuenca Block. Arrows show the surface force loads applied on the model boundaries in order to generate both regional stress fields: Iberian and Betic compressions. Mechanical parameters used for the modelling are listed in Table 1.

tion, and is characterised by a dense fracture network with large vertical offsets. Boundaries between these blocks are formed by two important fracture zones in the basement: the Sacedón Fault between the Madrid Basin and Valdeolivas Block, and the Tarancón Fault Zone between these two and the Cuenca Block (Figs. 1 and 6).

3. Finite-element models of paleostress fields

To model the observed paleostress fields and test the possibility of mechanical decoupling between cover and basement, the following approach has been applied.

(1) Model Group I: modelling of the stress trajectories for the Mesozoic cover in which the fault-slip data have been obtained. A 2D elastic plate with constant mechanical properties has been assumed for which we modified (a) the external geometry according to different geological boundaries, and (b) the boundary conditions of the model limits till for all of the three stress fields mentioned above; the modelled stress trajectories fit the observations.

(2) Model Group II: modelling of the stress trajectories for the basement. Once we have found boundary conditions for which the modelled stress trajectories for the cover are similar to the observed ones, we applied the same boundary conditions to a plate with the same external geometry but subdivided into three areas with different mechanical characteristics. The objectives of this model group are, firstly, to test the effect of assigning different mechanical properties to the different basement blocks on the stress trajectories and, secondly, to investigate whether this will give rise to indications for mechanical decoupling between the Mesozoic cover (mechanically homogeneous) and the basement (less homogeneous). Differences in the modelled stress-trajectories between basement and cover might point to such a decoupling, favored by a detachment level. These sorts of decouplings have been described in other thin-skinned fold-and-thrust belts as the Jura Mountains (Becker, 1989). Unfortunately, there are no paleostress data from the basement in the study area, and therefore, the results of the second model group cannot be proved, unlike the results obtained for the cover.

3.1. Model geometries

The geometry and boundaries of both model groups are shown on Figs. 1 and 6. Mesh 1 corresponds to the area where paleostress data have been obtained and is also the area where the modelling results will be shown. Due to the long distance between the study area and some of the most important geological boundaries of the centre of the peninsula, it has been necessary to build a second mesh (Mesh 2) surrounding the first one, to make the mesh limits coincide with the main geological structures. The model has been built in plane (2D plane stress elements), assuming an elastic mechanical behavior and considering the stress sources as pressures (Surface Force Loads). Calculations have been carried out with the ANSYS (Swanson Analysis Systems, Inc.) finite-element package and the used mechanical parameters are shown in Table 1. The modelling results of the stress trajectories are shown for Mesh 1. The stress magnitudes are not shown because the stress inversion methods provide only relative main axes magnitudes and orientation, but not their absolute values.

In order to establish the model geometry and its boundary conditions, kinematics and geometry of the main geological structures of the centre of the peninsula have been taken into account (Figs. 1, 2 and 6). Although different starting geometries have been tried, the model that fits the paleostress data in the cover best, corresponds to the model which it boundary coincides with the main geological structures of

Table 1
Mechanical properties of the elements assigned to each mesh area on the finite-element models

Area	Poisson coefficient, υ	Young modulus, E (GPa)
Model I — homogeneous plate (cover)		
Mesh 1	0.25	8.00
Mesh 2	0.25	8.00
Model II — basement plates		
Madrid Basin Block	0.25	8.00
Valdeolivas Block	0.25	5.00
Cuenca Block	0.25	4.00
Mesh 2a	0.25	8.00
Mesh 2b	0.25	4.00

the centre of the Iberian Peninsula (Figs. 1 and 6). Once the model geometry and the mesh elements are defined, different boundary conditions were applied on the limits. This process has been repeated until the model results fit the observed 'Iberian' and 'Guadarrama' paleostress fields. These two stress fields have been used to constrain the definitive model geometry and boundary conditions, due to the fact that both present a regional character. Therefore, their origin is less arguable than the 'Altomira' stress field. The paleostress sources have been applied at the Iberian Range SW border fault ('Iberian' push) and at the SE boundary of Mesh 2 ('Guadarrama' push; Figs. 1 and 6). The latter has been applied from outside of Mesh 1, because its origin is far away from the study area, at the Betic Ranges. Once both regional stress fields were modelled successfully, we tried to model the 'Altomira' intermediate stress field, taking into account two possible origins: a push from the north-northeast ('Pyrenean push' as it is suggested by Guimerá and Álvaro, 1990), and a superposition of both regional pushes (Muñoz-Martín et al., 1994). For the latter case both regional field stress sources were applied and their relative magnitudes were modified till the modelled trajectories fit the observations.

In order to model the basement paleostress trajectories (Model Group II), Mesh 1 was subdivided in three different areas keeping the mean element size (Fig. 6B). Mechanical behavior of the three areas corresponding with the above-described basement blocks, has been considered elastic and homogeneous, values of the Poisson coefficient (ν) and the Young modulus (E) have been assigned according to their geological characteristics (Table 1). Since a model always is a simplification of reality, the more general objective of this simple model is checking if the contrast among materials with different mechanical properties is able to produce significant changes on the stress trajectories, with respect to a mechanically homogeneous material with the same boundary conditions.

4. Paleostress field model results

The S_{Hmax} trajectory maps obtained by modelling of the homogeneous elastic plate (Model I, Fig. 7) are very similar to the ones obtained from fault-slip data (Figs. 3–5). Model results show very regular S_{Hmax} trajectories, although some minor perturbations and rotations with respect to the observations can be observed. The two factors that have been relevant in order to fit the model results to the geological data have been the model boundary geometry, the variation of the surface force load magnitudes and the position of the applied loads. On the contrary, values of mechanical parameters, as well as absolute values of applied stresses have influenced the magnitudes of the stress components obtained during the modelling, but not their orientation. The most important results obtained during the achievement of both model groups are described next.

4.1. Results of Model Group I (paleostress in the cover)

4.1.1. Modelled 'Iberian' stress field (Fig. 7A)

A surface force load has been applied directly on the Iberian Range SW border fault. In order to fit the model to the data, a reduction to the north of the compression magnitude along the eastern boundary has been necessary (from 10 MPa at the southern side of the boundary decreasing to 5 MPa at the northern limit). In the case of a constant 10 MPa surface load along the eastern boundary, significant extensional stresses perpendicular to the Spanish Central System Southern Border Fault appear in the northern part of the model whereas these have not been found in the geological record. This decrease of the compression can be justified by the cushioning of the Iberian Range compressive structures and by the absence of paleostress data compatible with this field to the north of the Tarancón Fault Zone. The modelled S_{Hmax} trajectories present a slight clockwise rotation towards the W boundary of the study area in agreement with the observed paleostress directions. This rotation seems to be related by the presence of N–S-trending faults at the centre of the Madrid Basin (Fig. 1; De Vicente et al., 1996a).

4.1.2. Modelled 'Guadarrama' stress field (Fig. 7C)

When applying a constant surface load force of 10 MPa directly to the southern border of Mesh 1 the results show inhomogeneous stress trajectories and extensional stresses associated with the Toledo

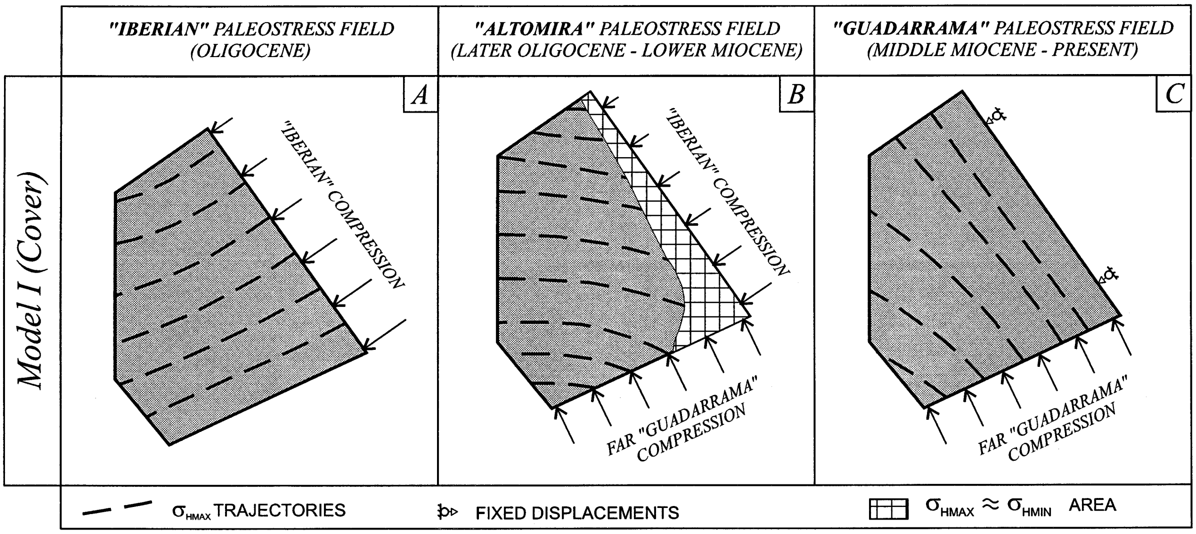

Fig. 7. S_{Hmax} trajectory results for Mesh 1 in Model Group I (cover). The 'Iberian' compression has been applied directly on the eastern boundary of the model. 'Guadarrama' compression has been applied from the southern limit of Mesh 2. Superposition of 'Guadarrama' and 'Iberian' compressions result in the 'Altomira' stress field. See text for explanation and compare with S_{Hmax} trajectories maps obtained from fault-slip data (Figs. 3–5).

Mountains' eastern border (Fig. 1). Since both have not been observed, the surface load force has been shifted to the edge of Mesh 2, 50 km southward, to fit the model results to the data. This stress source located at the southeast of the study area is compatible with a Betic origin. Allowing motion parallel to the Iberian Range SW border fault is justified because this area behaves basically as a dextral strike-slip zone during the Neogene (De Vicente et al., 1996b; Bond, 1996). The presence of an anticlockwise rotation of the modelled S_{Hmax} trajectories with regard to the microstructural data at the southwest of the study area could have been balanced by a N–S compression deduced at the Toledo Mountains (Martín and De Vicente, 1995). This fact has not been checked on the models due to the absence of paleostress data between the Toledo Mountains and the study area.

4.1.3. Modelled 'Altomira' stress field (Fig. 7B)

In order to test both hypotheses on the origin of the Altomira Range described in the introduction, two different approaches have been undertaken with the aim to predict S_{Hmax} trajectories similar to the observed 'Altomira' paleostress field.

(a) Locating the surface load forces at the Iberian Range SW border fault, we tried to arrive at the observed E–W paleostress field. We were not able to model the observed stress field, even if we changed the geometry and the boundary conditions of the model in a way that improved the fit slightly but is not very realistic from a geological point of view.

(b) Superposing of the two regional compressions that yielded the best results for the 'Iberian' and 'Guadarrama' regional fields, keeping their relative magnitudes intact. The result of this first approach showed a good fit for the southern half of the model, but it did not coincide with the geological data in the northern part of the study area. To obtain a better fit between model results and observations, we changed the magnitudes of the applied surface load forces. The best fit was obtained by reducing the 'Iberian' compression at the northern part of the model (with a magnitude gradient along the Iberian Range from 10 MPa at the south to 1 MPa at the northern Mesh 2 boundary) and a constant Betic compression of the same magnitude as used to model the 'Guadarrama' paleostress field. These conditions imply that the Betic push was constant and came from the southeast, while the intensity of the 'Iberian' stress field was starting to diminish during the formation of the Altomira Range (Late Oligocene–Early Miocene).

The 'Altomira' stress field modelling results indicate an elongated band, increasing to the south in width and adjacent to the eastern boundary of Mesh 1, where the main horizontal stress magnitudes are very similar ($S_{Hmax} = S_{Hmin}$; Fig. 7B). This area could correspond to the eastern boundary of the 'Altomira' stress field spatial distribution. The S_{Hmax} orientation seems to have rotated anticlockwise from this boundary to the northeast, getting a NE–SW orientation (compatible with the 'Iberian–Pyrenean' compression). This is suggested by microstructural studies at the northeast of the study area (García-Cuevas et al., 1996). Both the observed and the modelled paleostress field present very constant N100E-trending S_{Hmax} trajectories, except for the area south of the Tarancón Fault Zone, where the S_{Hmax} trajectories have a few degrees clockwise rotation. This fact suggests that from the study area boundary to the south, the 'Altomira' stress field has changed to a NW–SE compression related to the Betic chain. Microstructural studies located to the south of the study area (Vegas and Rincón, 1996), have not detected the presence of an E–W compression, while NW–SE and NE–SW compressions do appear along the Tertiary. It is, however, very likely that for different times the superposition of these two major stress fields has led to similar local stress fields in other areas of the centre of the Iberian Peninsula.

4.2. Results of Model Group II (paleostress in the basement)

4.2.1. Modelled 'Iberian' stress field (Fig. 8A)

The most important effect caused by mechanical inhomogeneities in the basement is a clockwise rotation in the north of the study area, which does not appear in the results for an elastic homogeneous plate (Fig. 8). This rotation is produced by the presence of the Sacedón Fault, that is the boundary between a homogeneous and strong basement (Madrid Basin Block) and a weaker one under the Loranca Basin (Valdeolivas Block). On the southern part of Mesh 1, there are some minor clockwise S_{Hmax} trajectory rotations along the Tarancón Fault Zone.

4.2.2. Modelled 'Guadarrama' stress field (Fig. 8C)

These results present the smallest deviation with regard to the observed paleostress field, in other words, to the results for the cover. This is due to the fact that the Tarancón Fault Zone is oriented perpendicular to the general S_{Hmax} trend. The Sacedón Fault is oriented oblique to the general S_{Hmax} trajec-

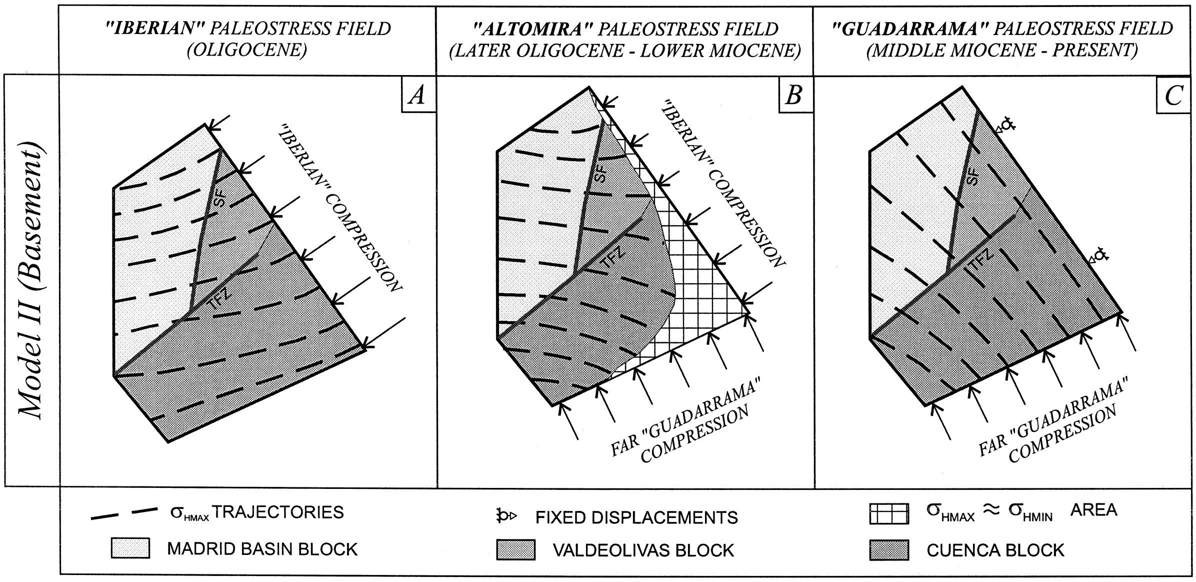

Fig. 8. S_{Hmax} trajectory results for Mesh 1 in Model Group II (basement). Boundary conditions are the same as the ones used for Model Group I (Fig. 7. See text for explanation and compare with S_{Hmax} trajectory maps obtained from fault-slip data (Figs. 3–5). *SF* = Sacedón Fault; *TFZ* = Tarancón Fault Zone.

tories, but is too far away from the stress origin and too close to the model's northern limit to originate significant rotations of the stress trajectories.

4.2.3. Modelled 'Altomira' stress field (Fig. 8B)

This is the model that presents the largest deviation from the elastic homogeneous plate model adapted for the cover. N100ºE-trending S_{Hmax} trajectories, located from Sacedón Fault Zone to the west, rotate anticlockwise to a NE–SW orientation in the north part of Mesh 1. On the other hand, the boundary between the Cuenca Block and the Valdeolivas and Madrid Basin blocks defined on Mesh 1, produced a clockwise rotation along the Tarancón Fault Zone. These combined effects generate a less regular modelled S_{Hmax} trajectory map than the one generated for an elastic and homogeneous plate. In any case, a N100ºE-trending S_{Hmax} trajectory zone appears in the main part of the area where the Altomira Range is developed in the cover.

5. Discussion and conclusions

The construction of simple finite-element models to study the orientation of stress fields as an effect of changing boundary conditions, has allowed us to reproduce the observed Tertiary compressive paleostress fields, deduced from fault-slip data from the cover of the eastern Tajo Basin. The results of the finite-element stress models confirm the idea that the geometry of the structures and of the model boundaries play a definitive role on the intraplate stress orientation, as it is suggested in several previous papers (Cloetingh and Wortel, 1986; Bada et al., 1998). In this way, the modelled S_{Hmax} orientation of all three paleostress fields is strongly influenced by the most important crustal faults in the central peninsula (i.e. Central Spanish System southern border and Iberian Range SW border faults). Moreover, the relative magnitudes of the boundary compressive loads significantly affect the modelling results (i.e. to simulate the compressions transmitted to the interior of the plate by the Pyrenean and Betic collisions).

From a geodynamic point of view, the fact that is has been necessary to diminish the relative intensity of 'Iberian' compression with regard to 'Guadarrama' compression in order to generate the 'Altomira' paleostress field, implies a tectonic chronology in which the Altomira Range was active after the Iberian Range. This confirms previous similar results based on microstructural analysis (Muñoz-Martín and De Vicente, 1996) and on the architecture of the basin infill (Calvo et al., 1989; Díaz-Molina and Tortosa, 1996). It has not been possible to obtain E–W-oriented stress trajectories through the application of stresses solely from the Iberian Range, not even by less realistic geometries and boundary conditions. These results contradict the hypothesis about the origin of the Altomira Range postulated by Guimerá and Álvaro (1990), for which the Altomira Range would be an oblique ramp of the transpressive structures of the Iberian Range, which constitutes the foreland of the Pyrenean orogen. The modelling results presented in this paper support the hypothesis that the 'Altomira' paleostress field is a local stress field, generated by spatial and temporal superposition of both major paleostress fields originated at the Pyrenees and Betics (Muñoz-Martín et al., 1994). These regional stress fields were transmitted from the northern and southern borders towards the interior of the Iberian microplate, generating a fold-and-thrust belt oblique to both regional compressions during the Oligocene–Early Miocene. This extrusion of the cover to the west formed the Altomira Range and has been controlled by inherited Hercynian structures in the basement, as well as by the presence of a significant stratigraphic detachment level (Upper Triassic Keuper facies). Parallelism between the Sacedón Fault, that controlled Triassic sedimentation, and the approximate location of the western border of the Upper Triassic plastic facies, suggests that these are related to each other and have played an important role in the nucleation of compressive structures at the Altomira Range (Van Wees et al., 1995; Muñoz-Martín, 1997).

Regarding the results of the basement stress models, some significant stress reorientations with respect to the sedimentary cover modelling results have been obtained. These are explained in terms of variations of the elastic parameters assigned to the basement blocks. The stress reorientations are most important for the 'Altomira' paleostress field model, because of the location and orientation of the boundaries between the blocks with respect to the general S_{Hmax} trend. In general, the effect of mechanical boundaries is most significant if they make a small angle with respect to the general stress field. In any case, an area with N100ºE-trending S_{Hmax} appears on the larger part of the study area. Model Group II results suggest that a decoupling between sedimentary cover and basement could have occurred, if the geological boundary conditions were similar to the ones used in the model. This decoupling would develop on the detachment level formed by the Triassic Keuper facies. Nevertheless, this decoupling seems to be less important than the one detected at the Jura Mountains (Becker, 1989). This fact may be related to the higher stress magnitudes and/or lower spatial constraints imposed by geological structures at the Jura Mountains.

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