

# Insights into the “tectonic topography” of the present-day landscape of the central Iberian Peninsula (Spain)

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## Abstract

The landscape of today's central Iberian Peninsula has been shaped by ongoing tectonic activity since the Tertiary. This landscape comprises a mountain ridge trending E–W to NW–SE, the Central System, separating two regions of smooth topography: the basins of the rivers Duero and Tajo. In this study, we explore interrelationships between topography and tectonics in the central Iberian Peninsula. Regional landscape features were analysed using a digital elevation model (DEM). Slope gradients and slope orientations derived from the DEM were combined to describe topographic surface roughness. Topography trend-surfaces inferred from harmonic analysis were used to define regional topographic features. Low roughness emphasizes the smooth nature of the basins' topography, where surfaces of homogeneous slope gradient and orientation dominate. High roughness was associated with abrupt changes in gradient and slope orientation such as those affecting crests, valley bottoms and scarp edges present in the mountain chain and in some deep incised valleys in the basins. One of the applications of roughness mapping was its capacity to isolate incised valley segments. The area distribution of incised rivers shows their prevalence in the east. On a regional scale, the topographic surface can be described as a train of NE–SW undulations or waves of 20 km wavelength. These undulations undergo changes in direction and interruptions limited by N–S-trending breaks. E–W and NE–SW troughs and ridges clearly mark structural uplifts and depressions within the Central System. These structures are transverse to the compressive NW–SE stress field that controlled the deformation of the central Iberian Peninsula from the Neogene to the present. They represent the upper crustal folding that accommodates Alpine shortening. N–S breaks coincide with Late Miocene faults that control the basins' sedimentation. Further, associated palaeoseismic structures suggest the recent tectonic activity of N–S faults in the eastern part of the Tajo Basin. Apatite fission track analysis data for this area suggest the occurrence of a significant uplift episode from 7 to 10 Ma which induced the river incisions appearing in the roughness map. N–S and NE–SW faults could be seismogenic sources for the current moderate to low seismic activity of the east Tajo Basin and southeast Central System. Although N–S fault activity has already been established, we propose its significant contribution to shaping the landscape.

**Keywords:** Digital elevation model; Topography roughness; Topography trend analysis; Central Spain; Tectonics geomorphology; Intraplate deformation

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# 1. Introduction

The landscapes of the intraplate continental domains are the result of long-term interplay between tectonic forces and geomorphic processes (e.g., Roessner and Strecker, 1997; Summerfield, 2000; Burbank and Anderson, 2001). In these areas, compressional tectonic deformation arose from far-field stresses transmitted from the convergent plate borders. These forces can give rise to intraplate mountain chains whose structure and orientation is largely controlled by the pre-existing crust structure and by the orientation of the stress field. This is true of the Iberian plate interior, whose present-day morphostructure is dominated by a mountain range, the Spanish Central System, bounded by two adjacent continental sedimentary basins, the Duero and the Tajo basins, formed during Alpine compressional events related to African and European plate convergence. Before such compression episodes, we can envisage a continental landscape characterised by an ancient smooth surface which will later be folded, tilted and faulted and its river pattern rearranged. Folds and faults created mountain regions and depressed areas trending E–W to NE–SW, to form the mountain range, or Spanish Central System, which extends over 450 km showing a NE–SW trend from Portugal to the Iberian Chain (Fig. 1) and on occasion rises to a height above 2500 m. The average width of the range is some 80 km, separating two sedimentary basins filled with continental materials produced by erosion. Both basins constitute high inland mesetas. Although the tectonic activity that gave rise to these tectonic units started in the Eocene, major tectonic events took place in the Miocene, when the mountain range and basins developed and the landscape's general

features were established. Structural and geological studies indicate this stress field went on to influence the region from the Upper Miocene to recent times as a weak regional stress field (e.g., Capote et al., 1990; De Vicente et al., 1996a; Herraiz et al., 2000).

Present-day regional topographic features are mainly dominated by Alpine block arrangements and some seem to be clearly tectonically controlled. The central Iberian Peninsula is therefore an excellent model for analysing the tectonic record of an intraplate domain landscape. Although the area has been broadly studied in terms of its geomorphological and structural features, only a few studies have dealt with gross topographic features and tectonics (e.g., Cotilla and Córdoba, 2004). This paper examines topography–structure relationships in an effort to evaluate tectonic signatures in the landscape, paying special attention to recent tectonic activity. Topography, defined by elevation data, was analysed by both GIS and trend-surface analysis. Digital data were used to produce a Digital Elevation Model, allowing for rapid characterization of landscapes and the analysis of tectonic structure–topography relationships. By combining slope gradients and slope orientations, we created maps of topography “roughness”, in which incised river valleys are well described. Bearing in mind that uplift is one of the main controlling mechanisms of fluvial incision, “roughness” mapping can be a useful tool for delimiting areas that have been recently tectonically active. In contrast, regional patterns of topography may be described by simple low-order trend surfaces (Doornkamp, 1972; Johansson, 1999). Through trend-surface analysis, we defined a harmonic surface capable of describing both the topographic features and structures that could reflect the relationship between crust relief



P: Pyrenees; EB: Ebro Basin; DB: Duero Basin; IM: Iberian Massif; SCS: Spanish Central System; IB: Iberian Chain; TB: Tajo Basin; B: Betics Cordilleras.

Fig. 1. Geographical and geological setting of the region under study.

and deformation. Topographic analysis plus geological and structural data provided new insights into the possible structural patterns driving crust deformation and landscape construction.

## 2. Geological setting

Interplay between the African and European plates gave rise to the present-day structural and geomorphological configuration of central Iberia. The western part of the Mediterranean was mainly affected by rifting after the Variscan Orogeny. Subsequently, at the northern, northeastern and southeastern borders of the Iberian plate, moderate-to-medium sized Mesozoic sedimentary basins formed. To the west, outside the basins, Mesozoic sediments are thin or even lacking. In the Late Cretaceous, the relative motion of the African and European plates gave way to a convergent regime, under which two mountain chains formed at the active borders of the Iberian plate, The Pyrenees (in the north) and the Betic Cordillera (in the south). In addition, the Iberian Range was created in the plate interior as the result of inversion of the Mesozoic sedimentary basin found in the eastern region of Iberia, and lifted and sunken zones of the Variscan basement gave rise to mountain ranges and basins. One of these basement uplifts (Fig. 1) is the Central System that extends in a NE–SW direction across the centre of the Iberian Peninsula forming a long and narrow mountain range. It consists of a crustal uplifted block bounded by two NE–SW high-angle reverse faults, dipping north at the southern limit and south at the northern boundary. The Variscan basement that outcrops in the Central System is made up of granites and high- to medium grade metamorphic rocks and is overlain in the eastern zone with a thin Mesozoic–Palaeogene cover. The structure of the chain is characterised by E–W alignments and NE–SW uplifted blocks bounded by high angle reverse faults. Where the Mesozoic sedimentary cover has preserved its structure, it consists of basement-core fault-propagation folds (e.g., Sánchez-Serrano et al., 1993; Gómez-Ortiz, 2001). Pre-existing structures in large measure control the location, orientations and displacements of alpine faults (e.g., Vegas and Banda, 1982). Many of these faults limit existing ancient accident blocks (Variscan and late-Variscan) that were reactivated under the alpine stress field. The morphostructure of the Central System is dominated by horsts and grabens, configuring the typical block-mountain physiognomy (e.g., Pedraza Gilsanz, 1994). Refraction seismic studies suggest crust thickening under the chain, where the Moho deepens to 35 km (Suriñach and Vegas, 1988).

The Duero and Tajo basins are two large Cenozoic continental basins filled mainly with siliciclastic sediments at the margins and evaporites in central areas, showing an endorheic arrangement. Basin infilling was controlled by lifting of the Central System. Depocenters occur close to the chain boundaries, with infill thicknesses up to 3000 m (Querol, 1989; Aroservice, 1964; Gómez-Ortiz et al., 2005). The sedimentary infill of the Duero basin can be broadly grouped into a pre-orogenic Late Cretaceous to Palaeocene sequence, a syn-orogenic sequence including Eocene–Oligocene sediments and a post-orogenic sequence of Miocene–Quaternary age (e.g., Mediavilla et al., 1996; Santisteban et al., 1996; Armenteros et al., 2002). The opening of the Atlantic around the Late Neogene saw the end of the basin's endorheic character, with the Tertiary sedimentary infill stage being replaced by the present erosional state of the basin. The mean altitude of the basin is 800 m. This relief is characterized by smooth shapes, flat or gently rolling surfaces. In eastern and southern zones of the area examined, both surfaces show a mean elevation of about 1100 m. In the eastern area, a plateau appears, constructed on lacustrine limestones (Miocene–Pliocene), which represent the end of the endorheic sedimentary cycle (Mediavilla et al., 1996; Santisteban et al., 1996). To the south, at the boundary with the Central System, a piedmont links the mountain chain to the basin interior.

Seismic and borehole data show that Palaeogene pre-orogenic deposits constitute most of the Tertiary sediments of the Tajo Basin. Syn-orogenic Neogene materials (mainly Miocene) attain a mean thickness of 800 m (Junco and Calvo, 1983). Based on the tectono-sedimentary units defined for the Miocene (Junco and Calvo, 1983), it can be inferred that the Spanish Central System was largely built up in the Miocene. Moreover, the sedimentary record points to the Middle Miocene for the main tectonic uplift event (Calvo et al., 1996; De Vicente et al., 1996b). Tertiary sediment thickness and basement top depth under the Duero and Tajo basins suggest a structural uplift of 3 to 4 km (Querol, 1989; De Vicente et al., 1996a; Gómez-Ortiz et al., 2005). The mean altitude of the basin is 600 to 700 m. In the eastern zone, the landscape is typified by the “Paramo” surface (mean elevation 1100 m), which is also a plateau constructed on lacustrine limestones (Miocene–Pliocene) that represent the end of the endorheic sedimentary cycle. As in the Duero basin, close to the Central System in the N and NE, vast alluvial piedmont deposits have developed from mountain reliefs (e.g., Pérez González, 1994). The topography in the south is characterised by smooth modelling of valleys and hills.



The Spanish Central System ends abruptly towards the east against the Iberian Chain, another alpine mountain range (Fig. 1). This chain was built up during the Palaeogene, before Central System rising, and has NW–SE trending structures where deformation mainly involves the Mesozoic cover. The link to the Iberian Chain is characterised by several NW–SE strike-slip faults, which probably moved like transfers (dextral movement) of the reverse faults that uplifted the Spanish Central System (e.g., De Vicente et al., 1996a).

### 3. Digital elevation model and topographic and structural features

Landform features and elevations were mapped for a thorough analysis of structure–topography relationships. Mapping gave rise to a digital elevation model, or DEM, elaborated in the frame of the construction of a geographic information system.

We obtained elevation information from 1:50,000 Spanish topographic maps, including 20 m contour intervals as well as spot elevation heights. Topography was generated by manual digitisation. Rough data were

refined to eliminate height and position errors. A regular grid was calculated into a  $250 \times 250$  m cell using kriging as the interpolation method, according to a linear variogram model without drift. This cell size allowed us to capture the essential features of the landscape and avoid introducing noise along river valleys and areas of smooth topography.

The quality of the surface generated was assessed in two stages (cf. Sánchez-Serrano, 2000). First, we compared input contours to calculate contours by visually checking the correctness of the morphology. In a second step, height accuracy was quantitatively evaluated using reference data. At the map control points, the surface root mean square error of height was  $\pm 12$  m, a value in the  $<5\%$  range of the grid cell-size (Felicísimo, 1994), indicating acceptable height accuracy for the generated surface.

We used the tools implemented in the GIS: Idrisi Kilimanjaro, to prepare a shaded-relief image of the study area (Fig. 2). As shown in Fig. 2, the Central System is a straight and narrow mountain range, 40 to 80 km wide, on which ridges rise abruptly over a piedmont etched on ancient rocks with a rolling morphology

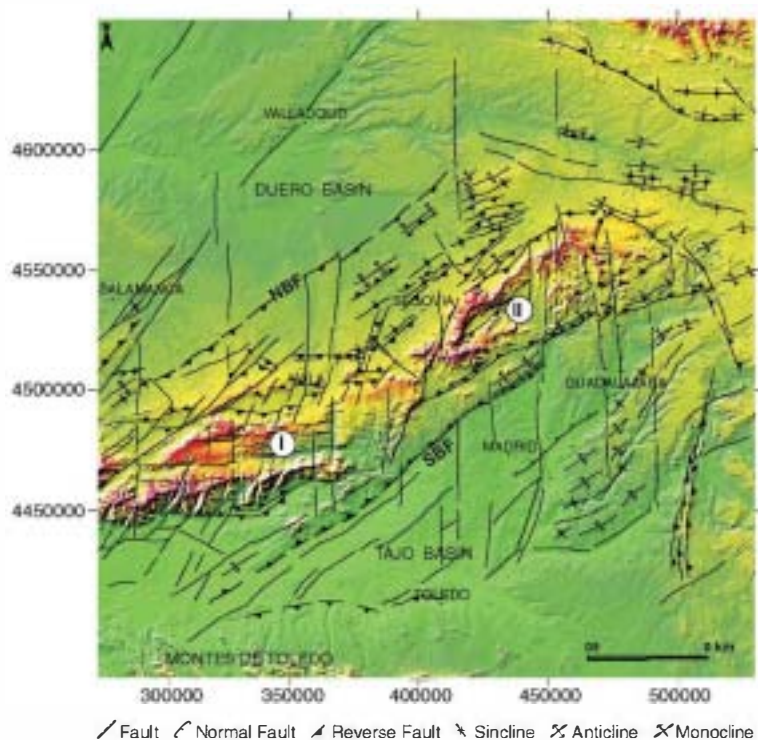


Fig. 2. Digital elevation model of central Spain. The image is a shaded-relief representation of the topography, as if illuminated by a light source in the northwest at an elevation of  $30^\circ$ . Highest elevations are coloured red. Two domains, Gredos and Guadarrama, can be distinguished in the Spanish Central System according to the dominant orientation of mountain alignments. The structural sketch of the area is superimposed on the DEM. Landform orientations conform structural features. UTM coordinates (m), Zone 30. For interpretation of the reference to colour in this figure legend, the reader is referred to the web version of this article.

and small residual relieves. It consists of E–W to NE–SW alignments of mountain and intramountain basins, where Mesozoic and Tertiary sediments are preserved. Maximum elevations exceed 2200 m, the average being 1150 m. Minor ranges of the Central System are mostly linear features, with main crests on structural uplifts (e.g., Birot and Solé Sabarís, 1954; Pedraza Gilsanz, 1994). Two domains can be differentiated according to the orientation main landforms: a western domain, the Gredos domain, oriented E–W; and an eastern domain, denoted the Guadarrama domain, with a clear NE–SW direction. The Gredos domain consists mainly of granites, while in Guadarrama, metamorphic rocks predominate, especially at its eastern end. The contact between both domains develops on a surface of gentle relief, from which a straight mountain range rises up to 1000 m in height.

Along the chain, main water divide and summit line positions change. To the west in Gredos, both run close to the southern border, while to the east in Guadarrama, they run close to the northern border. Many peaks are flat-topped and are probably the remnants of exhumed surfaces, unlevelled under alpine deformation and uplifted to a height close to 2000 m (Schwenzner, 1937; Pedraza Gilsanz, 1978; Garzón Heydt, 1980; Fernández García et al., 1993).

The basins' drainage pattern is characterised by NE–SW, N–S and NW–SE orientated valleys. Top basin infill is marked by a high surface (mean elevation ~1050 m) linked towards the east to the Iberian Chain. In eastern areas of the basins, incised valleys cross these surfaces. The Duero River follows the central axis of its own basin and its southern tributaries run into it following a straight N–S trend. On the contrary, the drainage of the Tajo Basin is clearly asymmetric and its main stream, the Tajo River, follows the southern basin border.

Fig. 2 shows the structural map of the study area overlying the DEM. Note the similar orientations of topographic forms and structures. Topography highs, namely sierras, correspond to uplifted blocks. Between the sierras, tectonic depressions form narrow corridors where small basins developed. A thin succession of Cenozoic sediments fills these basins. Corridors are also the place of straight valleys consequent with the mountain chain trend. In the Gredos domain, both topographic features and structures exhibit an E–W orientation while in the Guadarrama, NE–SW trending dominates. To the east of the Central System, where a thin Mesozoic cover is preserved, NE–SW folds of half-wavelength 5 to 10 km are conformable with topography. This is particularly observable in the Duero basin,

where these folds interrupt the gentle top-infilling surface of this basin (Fig. 2).

Two main reverse-faults bound the Central System mountain chain: the northern border fault (NBF), a south dipping structure, and the southern border fault (SBF), which dips north. The NBF is a blind structure with no morphological expression on topography. It runs north of the last Mesozoic cover outcrops of the Central System. A strong gravity gradient due to the density contrast between the basement rocks and Cenozoic sediments is associated with the NBF and this feature was used to draw its trace in Fig. 2 (Mezcua et al., 1995; Gómez-Ortiz, 2001). The SBF is also related to a strong gradient, but also exhibits a well developed escarpment. Here, the southernmost basement outcrops can be correlated to the SBF (e.g., Racero, 1988) (Fig. 2). Basin depocenters occur close to both faults, i.e., close to the Central System topographic limits and Tertiary sediments reach a thickness of up to 3 km at these depocenters. As mentioned in Section 2, taking into account cover-basement discordance, a maximum vertical displacement of 4 km can be estimated (e.g., Querol, 1989; Vegas et al., 1990; De Vicente et al., 1992; González-Casado and De Vicente, 1996).

Faults and folds are not so conspicuous inside the basins. Mappable structures like E–W and NE–SW trending folds that deform the Late Miocene limestone beds are mainly observable in the eastern part of both basins. There are also N–S faults that coincide with straight valley paths. These faults offset Neogene sediments and in some cases they have associated palaeoseismic structures (e.g., Giner-Robles, 1996; De Vicente et al., 1996a; Silva et al., 1997).

Tectonic structures appear to control regional topography features in the study area. Drainage network analysis and trend-surface analysis were then used to investigate the landscape tectonic record.

#### 4. Topographic surface roughness and incised valleys

Among topographic features, rivers are extremely sensitive to tilting and uplifting (e.g., Merritts et al., 1994; Holbrook and Schumm, 1999; Burbank and Anderson, 2001; Keller and Pinter, 2002) and the distribution of incised valleys may provide data on uplifted block location. Fault scarps and incised valleys can be characterised by a sharp and abrupt slope gradient and slope orientation variation at the top of hillsides. If we combine two descriptive variables such as slope gradient and slope orientation (aspect) to compare topographic surface characteristics between neighbouring areas,

terrain topography irregularity or “roughness” can be assessed. As a result, entrenched stream reaches and hillside scarps are sharpened. Both variables are easily measurable in a DEM. To obtain an image of “roughness” based on slope gradient and slope orienta-

tion, we used a simple method that is easily implemented in a raster type GIS. The standard deviation of the slope gradient and slope orientation was calculated for a neighbourhood of  $3 \times 3$  cells. Since a N-S orientation could be  $0^\circ$  or  $360^\circ$ , a transformation must be made.

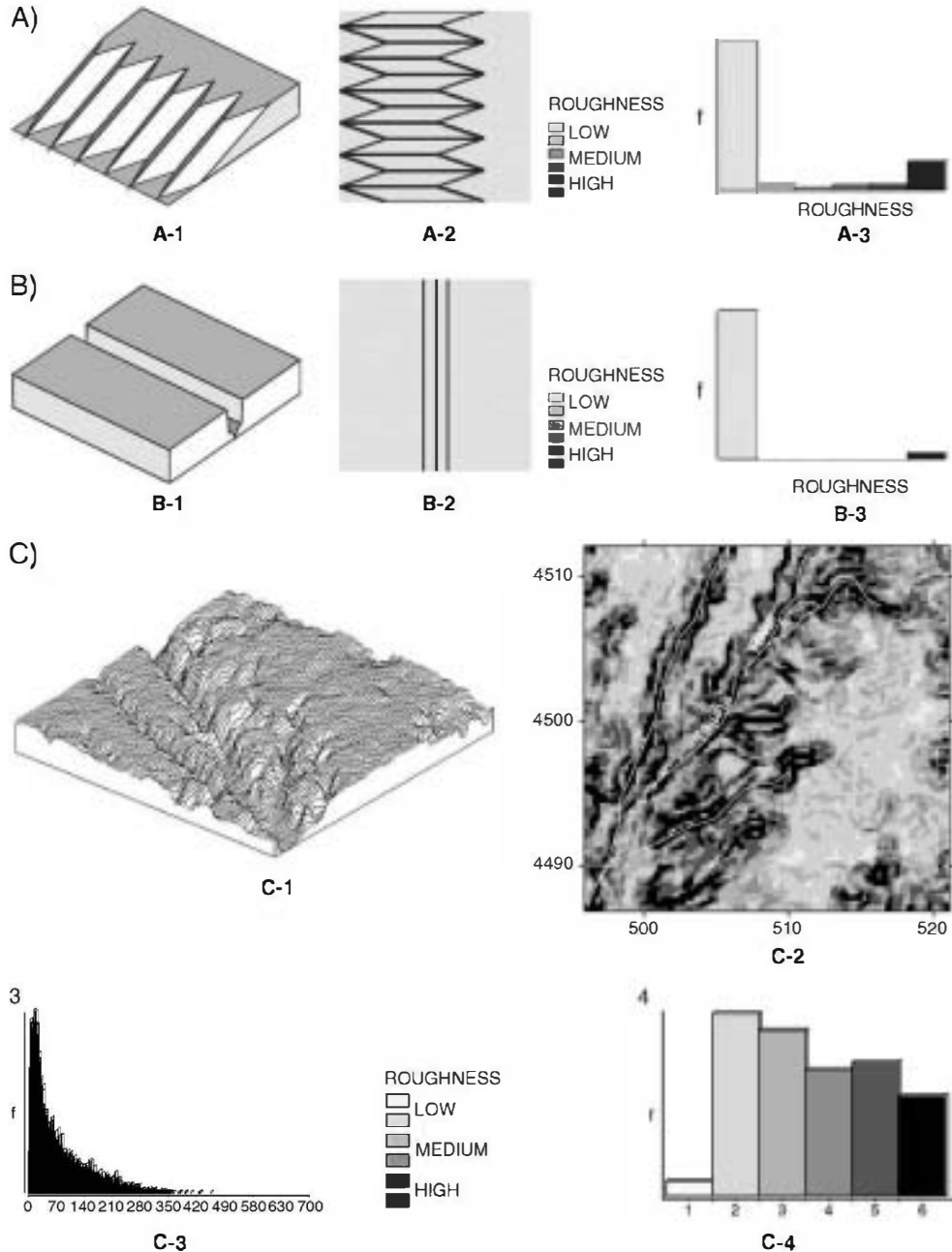


Fig. 3. Roughness analysis of two simple theoretical forms, and a small area in the eastern part of the study region (inset C in Fig. 4). Block diagram (A-1; B-1), roughness map (A-2; B-2) and histogram of roughness classes (A-3; B-3) are shown in each case. High roughness values describe slope ruptures located in valleys and crests. Case C illustrates the roughness of the Tajuñar river valley, an incised valley in the Tajo Basin that runs through a smooth topography. Dark grey narrow bands indicating high roughness map high surface limits, surfaces built on hard rocks such as the Upper Miocene lacustrine carbonates of the Tajo Basin. C-1: Three-dimensional model; C-2: Classified roughness map (resolution, 250 m. UTM coordinates m, Zone 30); C-3: Frequency histogram of the roughness image before classification and C-4: Frequency histogram of the classified image.



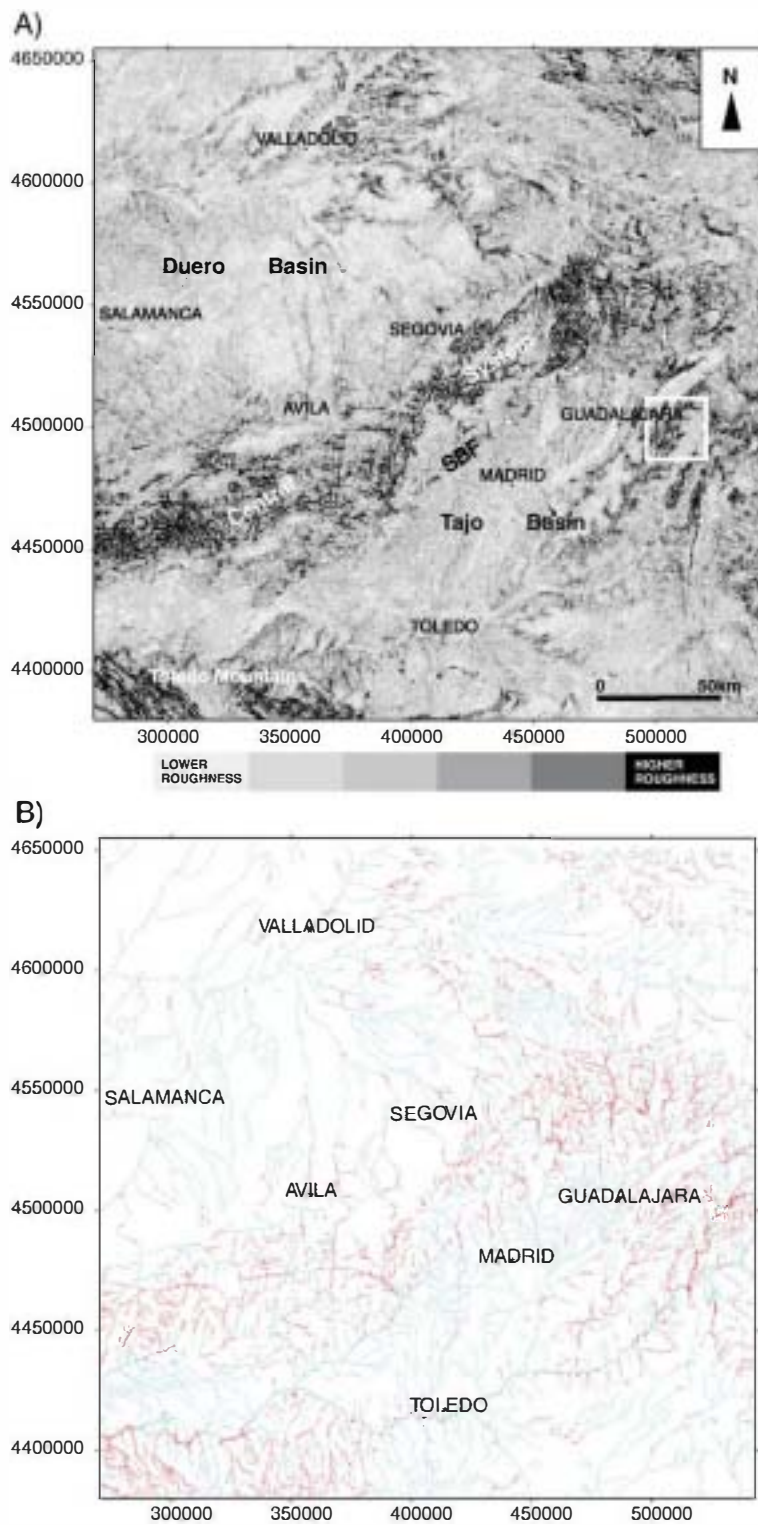


Fig. 4. (A) Roughness image of the study area. Bands of high roughness define crests and incised valleys, characterising the mountainous relief of the Central System, Toledo Mountains and Iberian Range. Low roughness values characterise the basins. The white box fits the area of Fig. 3C. BSF: South border fault (white dashed line). (B) From the roughness map, a map of incised rivers segments marked by red lines was derived. In the eastern region, incised rivers predominate in the basins and mountain ranges. For interpretation of the reference to colour in this figure legend, the reader is referred to the web version of this article.

First, original orientations are measured from  $0^\circ$  to  $180^\circ$  and then from  $180^\circ$  to  $0^\circ$  (instead of  $180^\circ$  to  $360^\circ$ ). Second, original orientations (measured from  $0^\circ$  to  $360^\circ$ ) are rotated  $90^\circ$  in a clockwise direction ( $90^\circ\text{E}=360^\circ$ ) and then the first transformation is applied. Thus, two superimposed maps are obtained. Each cell value is the maximum value for both maps. The assumption made is that only the difference in slope orientation between neighbouring cells is relevant to roughness estimations.

Each cell of the slope and slope orientation maps were multiplied by each other to obtain a topography variance map. A value is estimated for each cell ( $250 \times 250$  m), which is a quantitative variable and depends on neighbouring cells. The final result is a map of roughness

values that range between 0 and a maximum value, which depends on the maximum slope gradient and slope orientation variation. The interpretation of results is difficult, so empirical classification was undertaken. Slope orientation and gradient values were reclassified to establish three roughness intervals: low, intermediate and high. Sharp and abrupt changes in slope orientation and slope gradient describe a high roughness surface. Otherwise, low roughness values denote a surface characterised by a homogeneous slope gradient and orientation. Fig. 3 provides roughness values for a few simple theoretical cases and roughness analysis. These theoretical examples imagine parallel crest sets, an incised valley and scarps of different extension. They illustrate extreme ends of roughness: areas of homogeneous slope

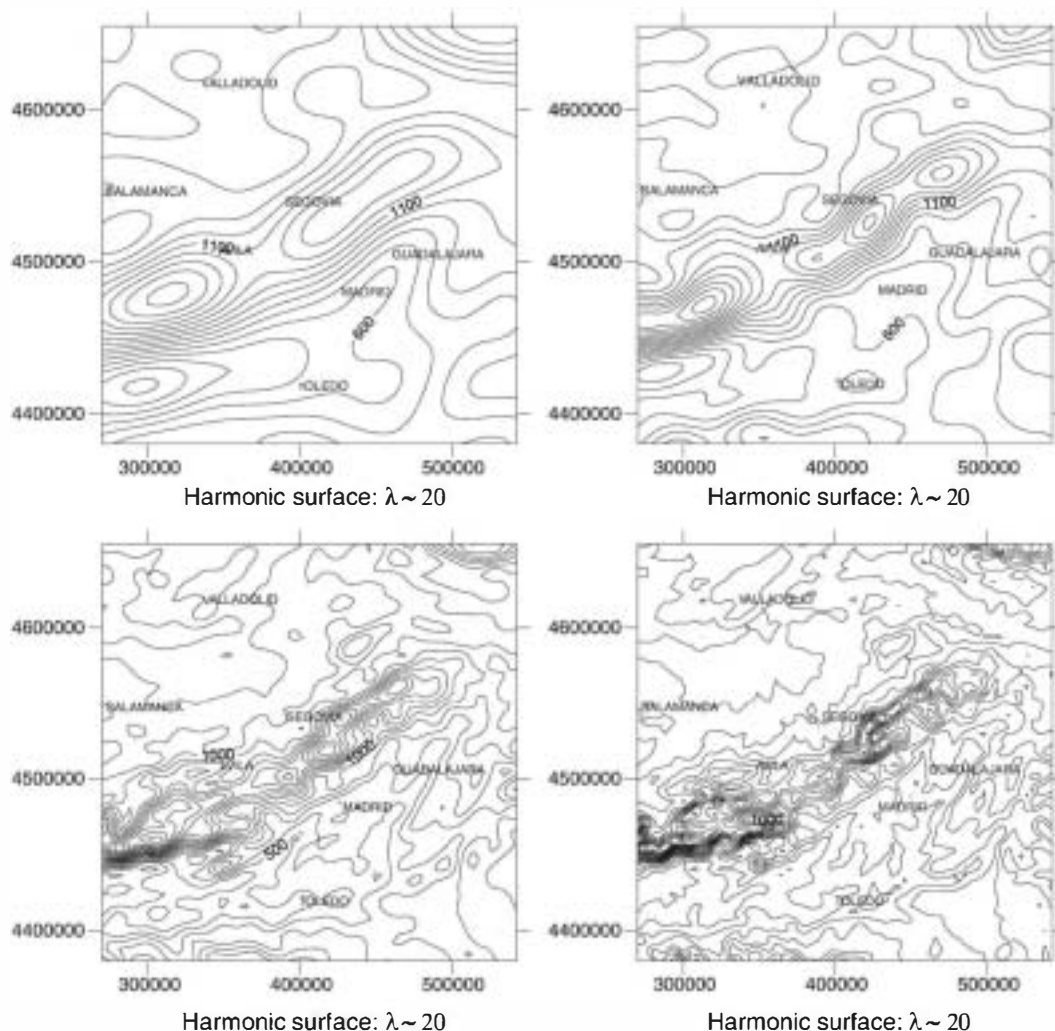


Fig. 5. Harmonic surfaces of wavelengths 80, 40, 20 and 10 km. The long wavelength harmonic surfaces show the main forms of the landscape: the mountain chain and basins. Drainage patterns in the Central System and the Duero and Tajo basins are best described by the 20 and 40 km harmonic surfaces, which well-represent uplifted and depressed zones. UTM coordinates m, Zone 30.



orientation and slope gradient and narrow bands that represent abrupt changes in slope gradient and slope orientation.

Fig. 3A, case C, is a real case illustrating the roughness of the Tajuña river valley, an incised valley located in the Tajo Basin running through a smooth topography plane. Linear black areas denote slope ruptures located in the valley bottom at the upper edge of the valley slope where it meets with high surface limits, surfaces built on hard rocks such as the Upper Miocene lacustrine carbonates of the Tajo and Duero Basins. Before classifying roughness values, the frequency histogram indicated high dispersion, which after roughness classification, was grouped as 6 values.

#### 4.1. Topographic surface roughness and incised valleys of the study area

The same rule was followed to obtain the roughness map for the study area (Fig. 4A). From the histograms, 6 classes were established and grouped as low, intermediate and high roughness. Classification emphasizes

smoother topographies. In Fig. 4A, the light grey areas correspond to the lowest roughness topographic surface of the Tertiary basins' relief, especially prominent in the Duero Basin. Over these low roughness regions, narrow dark grey zones indicating higher roughness appear. They map high surface limits, surfaces built on hard rocks such as the Late Miocene lacustrine carbonates of the Tajo and Duero Basins. Low roughness is restricted to small intermountain basins in the Central System where high roughness values predominate. Dark grey linear features mainly represent summit lines, scarps and deep incised valley floors.

The topographic fabric is somehow influenced by lithology. In the west and central part of the chain, where igneous rocks extensively outcrop, topography is smoother than towards the eastern end where metamorphic rocks, mainly slates and quartzites, give rise to a more incised relief. This relationship is clearly illustrated at the southern limit of the zone, at the Toledo Mountains, where Palaeozoic quartzite bars are marked by linear zones, or bands, of high roughness. In the Duero and Tajo basins, the lithological character of the

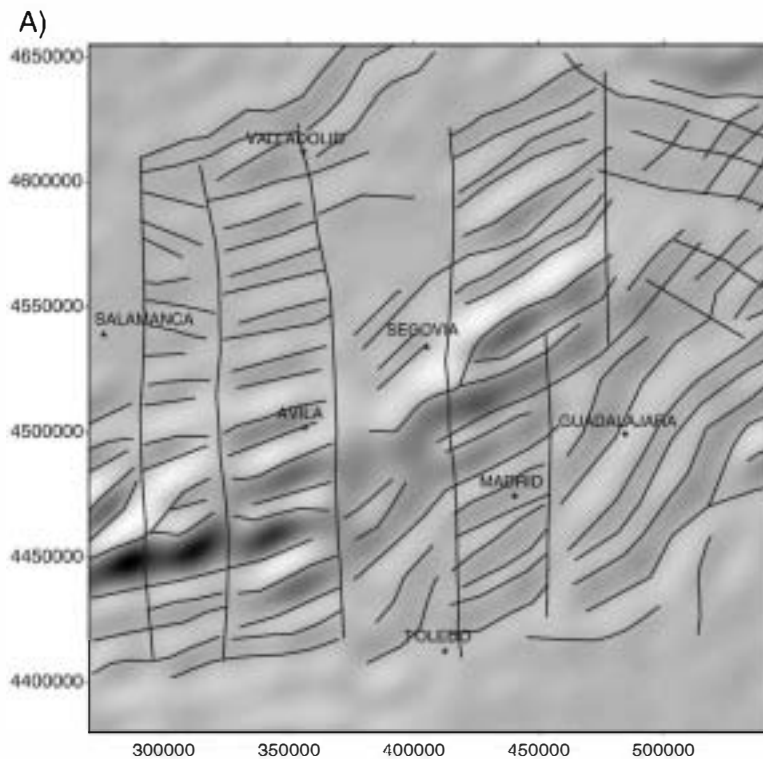


Fig. 6. (A) On a regional scale, a harmonic surface of 20 km wavelength describes the main features of the topographic surface of the Central System and Tertiary basins. The shaded image shows the main pattern of the harmonic surface comprised of E-W to NE-SW wave trains, laterally bound by N-S accidents. Waves are attenuated towards the north, in the Duero Basin. (B) The topographic profiles of the digital elevation model (solid line) and harmonic surface (broken line) show differences between the two topographies. The harmonic surface represents a smoother topography, yet still marks depressed and uplifted zones.

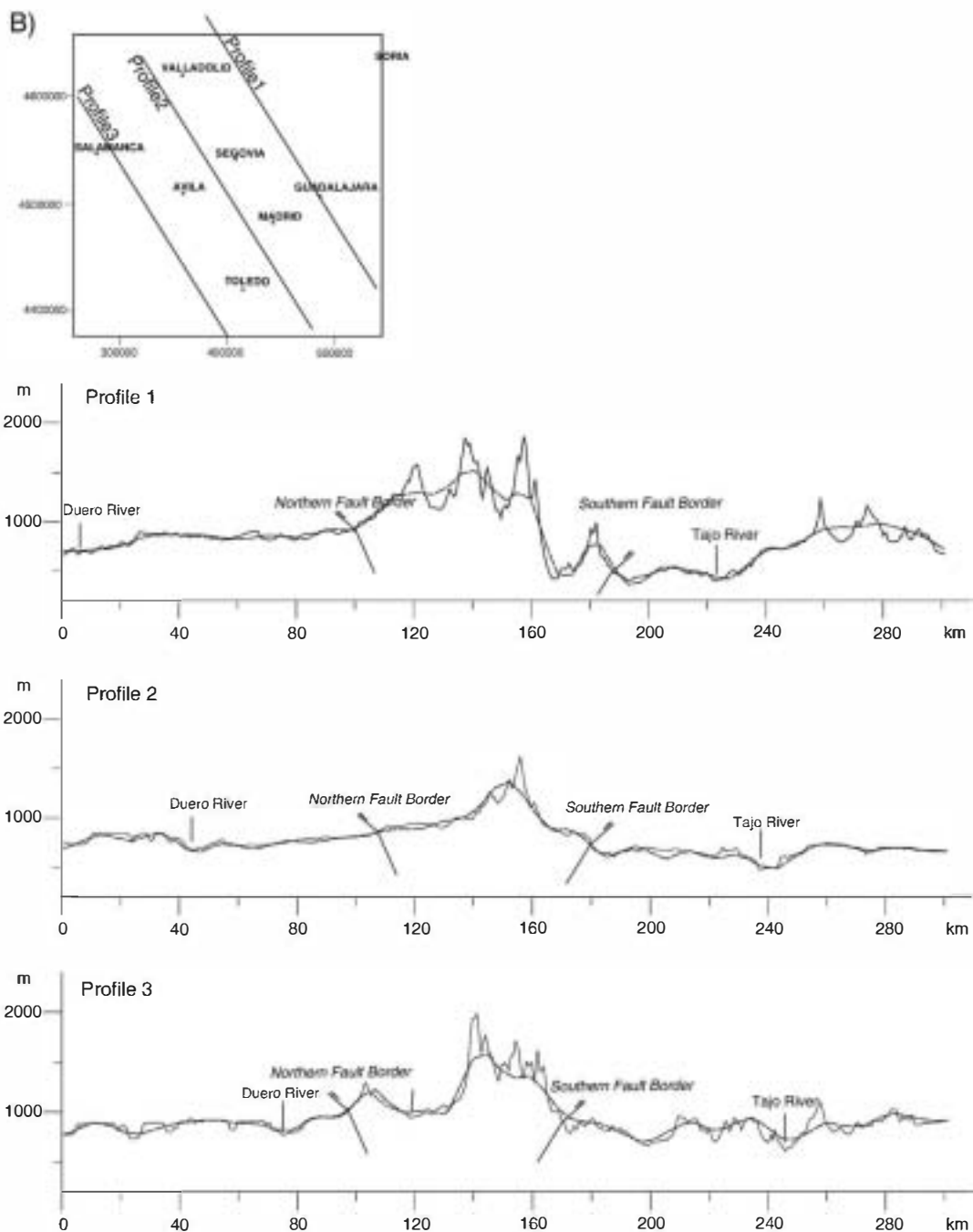


Fig. 6 (continued).

tertiary substratum, quite homogeneous but incoherent, gives rise to a gentle landscape of flat or rolling planes cut by wide, slightly entrenched river valleys.

From this map, segments of incised valleys were isolated along river courses. Fig. 4B shows incised stream reaches in red (black in the paper version). As may be noted in this figure, one of the main features of

the method used is that it allows us to easily generate an image of stretches of incised rivers in areas of gentle relief. Incised rivers predominate in the southwestern and eastern zones of the study area. In the Central System, incised valleys dominate, irrespective of basement lithology. Isolated linear incised valley segments as well as the distribution of incised valleys provide

clues on recent tectonic activity. Linear valleys are related to faulting. In the Gredos domain in the western part of the chain, N–S and E–W linear valleys coincide with mapped faults. Short incised valley segments occur along faults transverse to streams, and, as mentioned above, a good example can be found in streams incised when they cross the southern border fault scarp (Fig. 2, SBF). Incised rivers predominate in the eastern zone of the study area, the Central System and Toledo Mountains. As later discussed in Section 6, this feature is probably related to the recent tectonic uplift of some basement blocks, as has been suggested by apatite fission tracks analysis (Sell et al., 1995; De Bruijne and Andriessen, 2002).

## 5. Trend-topographic surface analysis

One of the aims of this paper was to assess gross topographic features related to tectonic structure. From a regional standpoint, main topographic features can be described by low wavelength harmonic surfaces (e.g., Rayner, 1972; Johansson, 1999). We used the MATLAB 6.5 R13 software package to perform the analysis. The map extends 400 km in N–S and E–W directions. Data were gridded every 4000 m by kriging. The grid size allowed us a first surface smoothing. Using the GTOPO30 DEM, a 100 km fringe was established around our own elevation data, before Fourier transforming to avoid edge effects due to the periodicity assumption in the Fourier transform.

Fig. 5 provides contour maps of several harmonic surfaces estimated from topographic data. These represent some of all the possible harmonic surfaces that describe the regional trends in the topographic data. Harmonic surfaces of wavelengths 80 km and 40 km, provide a very smooth view of topography also reflecting the main regional features of the study area. The mountain range is well defined as are the basins' main drainages. Even harmonic surfaces of wavelengths 20 and 10 km reflect the main topographic features on a regional scale within the chain and basins. Differences between eastern and western domains and the positions of water divides and intramountainous basins are well represented. Main valleys are shown within basins. Relationships between troughs and rivers or grabens and ridges, and mountain alignments of 20 km harmonic surface wavelengths fairly accurately reflect mountain alignments, intramountainous depressions and main river valleys parallel to the Central System. Among all the harmonic surfaces, we think this one represents a regional topographic surface of the study area and describes its main topographic features. The

NW artificially shaded image shows the main pattern of the harmonic surface of wavelength 20 km. These wave trains show up clearer on the Central System alignments (Fig. 6). The harmonic surface shows E–W to NE–SW undulations related to highs and lows. Undulations change in direction following the mountain alignment trend. As seen in Fig. 6A, undulations extending into the basins are much better defined in the Tajo than the Duero basin. Indeed, the undulation amplitude is below 100 m in the central part of the Duero Basin and practically disappears thereafter. A further outstanding feature of this shaded enhanced surface, is the presence of other linear N–S oriented structures bounding the domains characterised by undulations of different amplitude and orientation. The main strike shift coincides with the change in structural orientation between the Gredos and Guadarrama domains.

Since we are dealing with a mathematical surface, undulation axis locations might not exactly coincide with topographic highs and lows, but in our case they were highly related. The degree of correlation between the two surfaces is reflected by the 3 topographic profiles of true relief and harmonic surfaces shown in Fig. 6B. The north and south border faults of the Central System are drawn in the profiles. Good agreement may be observed between the highs and lows of both surfaces, especially in the case of main valleys and mountains. However, some deviations from the original topographic surface were noted. Positive deviations occurred in summit alignments, areas of locally more resistant bedrock or mount relict (Fig. 6B). Negative deviations were observed in the deepest valleys.

As well as gross topographic features, the 20-km wavelength harmonic surface marks structural uplifts and tectonic depressions in the Central System. This relationship is not so evident in the basins where vertical displacements along faults are minor and sedimentation infill in depressed blocks obscures tectonic topography. Bearing in mind today's periodic nature of deformation structures of Central System crust deformation, we can envisage a NE–SW uplifted and depressed block in the Duero and Tajo.

Faults and folds in the eastern part of the basins coincide with trend analysis undulations. Moreover, some N–S discontinuities coincided along their course with incised rivers and geologically mapped faults (Fig. 2).

## 6. Discussion

Our topography analysis results indicate a strong link between topography and tectonics. In fact the gross present-day topography of the central Iberian



Peninsula can be described as a “tectonic topography” (Fig. 2). Two aspects of our results warrant attention: first of all, we should ask ourselves which topographic elements could be related to previous tectonic activity; and secondly, we should consider what may be inferred about crust deformation from the trend-analysis results.

DEM analysis and derived topography roughness mapping revealed intense river incision in the Central System and in the eastern part of the study zone, suggesting a probable recent uplift event. River incision could be in part controlled by an isostatic response to mountain chain building, especially considering that chain formation has been accompanied by crust thickening (Suriñach and Vegas, 1988; Gómez-Ortíz et al., 2005) and therefore some—if not all—of the fluvial incision could be the result of uplifts linked to tectonic activity.

Constraints on vertical motions are provided by apatite fission-track studies. These studies provide evidence for an initial Late Eocene to Early Oligocene uplift phase associated with compressional deformation, a significant cooling event during the Middle Miocene, and rapid cooling from the Early Pliocene (5 Ma.) onwards (Sell et al., 1995; De Bruijne, 2001; De Bruijne and Andriessen, 2002). During the younger cooling event, uplift and erosion reach up to 6 km in the eastern Central System, at the Guadarrama domain (De Bruijne and Andriessen, 2002). From fission track data we can suggest that recent uplift events are responsible for the intense incision of the drainage network, not only of the eastern part of the Central System, but also in the eastern part of the Duero and Tago basins, as shown in the incised rivers maps (Fig. 4B). Present tectonic activity is reflected by a low seismicity. The instrumental earthquake distribution of the area examined shows epicentres related to the NE–SW trending Central System’s south border fault, which could be considered slightly seismogenic (De Vicente et al., 1996a) and, probably, to N–S faults and beyond the chain in the NE quadrant of the Tago Basin. A geodesy technique, Very Long Baseline Interferometry (VLBI), also predicts present-day uplift of the Central System at about 1 mm/year (NASA Goddard Space Flight Center VLBI Group, 1999). These data suggest that despite being of low intensity, recent and present tectonics control relief evolution.

All these tectonic activities were produced in a collision regime under a stress field whose maximum horizontal shortening direction during the Cenozoic shows a main trend NNW–SSE to NW–SE. Palaeo-stress maps indicate a variation in the orientation of the maximum horizontal shortening direction to NNE–

SSW in the Upper Eocene (when the Pyrenees and Iberian Range formed) and NW–SE from the Upper Miocene (Betic Cordillera formation and intraplate deformation) to the present (e.g., De Vicente et al., 1996a; Herraiz et al., 2000; Andeweg, 2002; Jabaloy et al., 2002; De Vicente et al., 2004). Fig. 7 shows the tectonic units of the Iberian Peninsula and adjacent areas, and indicates the orientations of the undulations derived from trend-surface analysis and the mean orientation of the stress field from the Miocene to the present. The orientations of the Betic Cordillera, Central System and these undulations are evidently transverse to the compression and the outcome of deformation. In the absence of a Mesozoic cover with stratigraphic discontinuities marking the deformation geometry, we used the original pre-Alpine smooth topographic surface as the reference surface to evaluate crust deformation and interpreted the undulations as crust folds. Based on our harmonic analysis, we can suggest that folds of different wavelengths developed. Best correlations between harmonic surface and main structures corresponded to the 40 km and 20 km wavelengths. In our opinion, this last wavelength exhibits good agreement with structural highs and lows and characterize crust deformation at a regional scale. Assuming a crust rheology similar to that of today’s crust—a wet granite-quartzite rheology—folds could involve the first 6 to 8 km (Tejero and Ruiz, 2002). Recently, some authors have proposed lithospheric folding to explain deformation in the Iberian intraplate domain (e.g., Cloetingh et al., 2002; Vegas, 2004). Cloetingh et al. (2002) obtained wavelengths of about 50 km from numerical models of lithosphere deformation. This wavelength is close to ~40 km harmonic surface but higher than the ~20 km proposed by us to describe regional structure and control regional topographic features. These could represent different wavelength folds generated during a compressive tectonic event.

Apart from the folds, the trend-surface analysis revealed the existence of N–S alignments limiting domains whose folds showed a different longitudinal orientation. Many of these alignments coincide with the occurrence of pre-Alpine faults in the Variscan basement and control longitudinal fold train development and fault displacement, bounding topographic and structural domains with different orientation. These clearly coincide with previously mapped faults in the Miocene deposits of the Tago basin and are also related to straight fluvial valley reaches and, probably, already controlled former drainage rearrangements. N–S fault movements are well documented in the Tago basin, where late Miocene sedimentation is controlled by N–

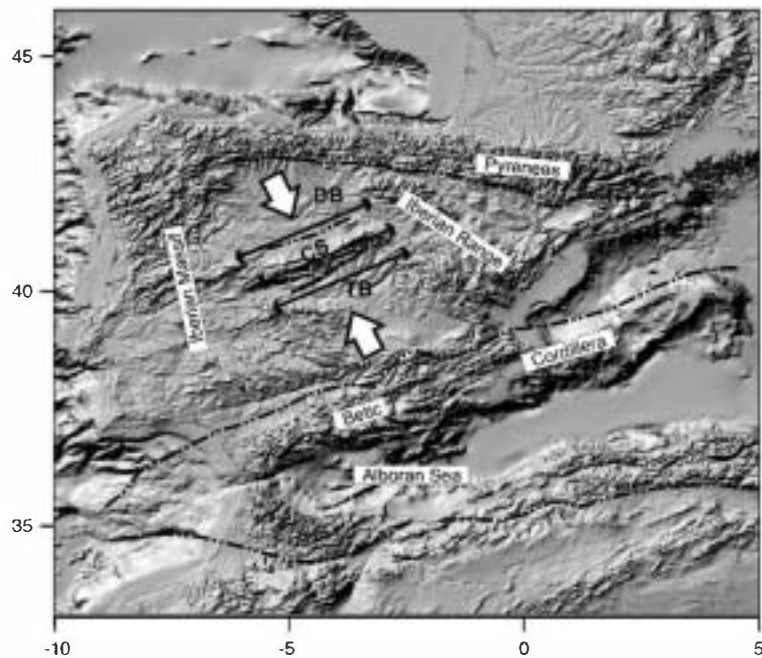


Fig. 7. Digital relief-shaded image showing the principal tectonic elements of the Iberian Peninsula. The northeastern and southern sectors comprise the following Alpine chains, from north to south: the Pyrenees, the Iberian Range and the Betic Cordillera. Moreover, within the Iberian Massif, Alpine reliefs are found that mainly uplift the Variscan basement such as the Central System. Arrowed lines indicate the main trend of undulations inferred from the trend-surface analysis. They show a NE-SW orientation, similar to that of the Betic Cordillera, transverse to the maximum horizontal shortening direction (white arrow). CS: Central System. DB: Duero Basin. TB: Tajo Basin. Geographic coordinates.

S faults (Calvo et al., 1996; De Vicente et al., 1996b). Further, Quaternary alluvial deposits in N-S valleys contain soft-sediment structures, interpreted as palaeo-seismic structures related to a period of intense tectonic activity in the Middle Pleistocene (Giner-Robles, 1996; De Vicente et al., 1996a; Silva et al., 1997).

## 7. Conclusions

The main findings of our topographic analysis of the central Iberian Peninsula based on a DEM and trend-surface analysis are:

- A "roughness" image was generated from the DEM using slope gradients and orientations. Areas of high roughness were related to abrupt changes in slope orientation such as those that occur in valley bottoms. This variable served to discriminate incised valley segments, indicating their predominance in the east of the study area. River incision appears to record a considerable uplifting episode—more intense in the eastern area of the study area—that occurred from the Pliocene to the present.
- Regional topographic features can be described by NE-SW wave trains of some ~20 km wavelength. Waves are longitudinally interrupted and change in

direction, differentiating domains limited by N-S breaks.

- NE-SW undulations run transverse to the stress field (maximum compressive horizontal axis oriented NW-SE) that controlled the deformation of the interior Iberian plate throughout the Neogene to the present. These undulations may be related to ~20 km wavelength crustal folds that accommodate shortening. The nucleation and evolution of these structures may be conditioned by pre-existing structures reactivated in Alpine and recent times.
- N-S structures are faults that clearly controlled Late Miocene sedimentation and river patterning. Associated seismites suggest recent tectonic activity in the eastern part of the Tajo Basin. N-S and NE-SW faults could be seismogenic sources for today's moderate to low seismic activity of the eastern Tajo Basin and southeastern Central System. Although N-S fault activity has already been established, we propose its significant contribution to landscape generation.

This investigation emphasizes the considerable effects of tectonic movements on the morphological development of the Iberian intraplate domain. Our results highlight the need for topographic data analysis as a complement to neotectonic and recent tectonics



studies applied to regional tectonics, even when dealing with areas of low tectonic activity or those in which geomorphic processes have masked the signs in the landscape left behind by tectonics. Future tectonic and geomorphological studies will provide data on the dynamic tectonic processes that have shaped the landscape of the central Iberian Peninsula.

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