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Main morphotectonic characteristics of Asturias, Spain

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RESUMEN

Asturias es parte de uno de los cuatro mesobloques morfotectónicos que constituyen el macrobloque Septentrional (Número 9) de la placa Ibérica. El esquema de regionalización territorial fue obtenido sobre la base de la metodología de Rantsman (1979) empleando distintos métodos géologo-geofísicos y geomorfológicos. Se distinguen en la cartografía de Asturias unidades territoriales (1 mesobloque de montaña, 8 bloques, 208 microbloques y 668 nanobloques), morfoalineamientos (cantidad/orden: 1/2, 1/3, 10/4, 35/5 y 77/6) y nudos morfotectónicos (cantidad/orden: 2/3, 11/4, 31/5 y 86/6). La cantidad de morfoestructuras delimitadas aumenta, signicativamente, de oeste a este. Al nivel del orden de bloque se distingue muy bien una diferenciación transversal de las unidades territoriales y de los morfoalineamientos, que se interpreta como una expresión de la heterogeneidad litosférica. Existe una buena relación entre las morfoestructuras y la sismicidad, destacando que la mayor actividad está en los bloques aledaños a Oviedo y en las partes norte y este. El sector marino es manifiestamente sismoactivo.

PALABRAS CLAVE: Asturias, España, morfotectónica, Península Ibérica.

ABSTRACT

Asturias is part of one of the four morphotectonic mesoblocks that make up the Northern macroblock (Number 9) of the Iberian plate. The framework of territorial regionalization was developed on the basis of the methodology of Rantsman (1979) using different geologic-geophysical and geomorphological methods. The territorial units (1 mountain mesoblock, 8 blocks, 208 microblocks and 668 nanoblocks), morphoalignments (quantity/order: 1/2, 1/3, 10/4, 35/5 and 77/6) and morphotectonic knots (quantity/order: 2/3, 11/4, 31/5 and 86/6) can be distinguished in the cartography of Asturias. The number of well defined morphostructures increases, significantly, from west to east. At the block level, a very well defined transverse differentiation of the territorial units and morphoalignments is noticeable. This differentiation is interpreted as an expression of the region's lithospheric heterogeneity. There is a clear relationship between morphostructures and seismicity, especially with respect to the higher activity found in the blocks adjacent to Oviedo and the northern and eastern regions. The oceanic sector is decidedly seismically active.

KEY WORDS: Asturias, Spain, morphotectonics, Iberian Peninsula.

1. INTRODUCTION

Asturias is a territory with an area of 10.565 km^2 situated in the northern part of the Iberian Peninsula (IP) (Figure 1). It is limited on the west by Galicia, on the east by Cantabria, on the south by Castilla León and on the north by the Cantabrian Sea (Figure 2). Asturias has a mountainous geography and is greatly influenced by the sea. Its most important population centres with the exception of Oviedo are on the coast or very close to it. From the point of view of current geodynamics, it is wholly located in an intraplate zone. The crust type is continental although there is oceanic crust in its immediate vicinity.

This is the third work in a series that attempts to report results concerning neotectonic movements for the IP based on the principles of morphostructural analysis (Cotilla and Córdoba, 2003, 2004) and also to offer an alternative to explain the relationship of seismicity and tectonics. These principles were elaborated by Guerasimov (1946) and later developed by Mescheriakov (1966) and Rantsman (1979), among others. Its theorectical basis is the "geostructure - morphostructure - morphosculpture" triad, constructed on the basic genetic principle of relief development, which considers that relief is the result of the reciprocal action of endogenic and exogenic processes.

Previous morphostructural studies on the IP produced three maps: 1) Large structural groups (Terán *et al*., 1994), 2) Tectonic frameworks (Capote and De Vicente, 1989), 3) A tectonic structural framework by A. Ribeiro (Baptista, 1998). An independent work, the SIGMA project, (Herraiz *et al*., 1998) was able to place Asturias inside the tectonic region of the Cantabrian Range. Two seismotectonic maps (Rey Pastor, 1956; Instituto Geográfico Nacional, 1992) have not been commented in earlier works.

Alekseevskaya *et al*. (1977) found that morphostructural maps are the basic starting point for the study of many geophysical problems. One objective of morphostructural analy-

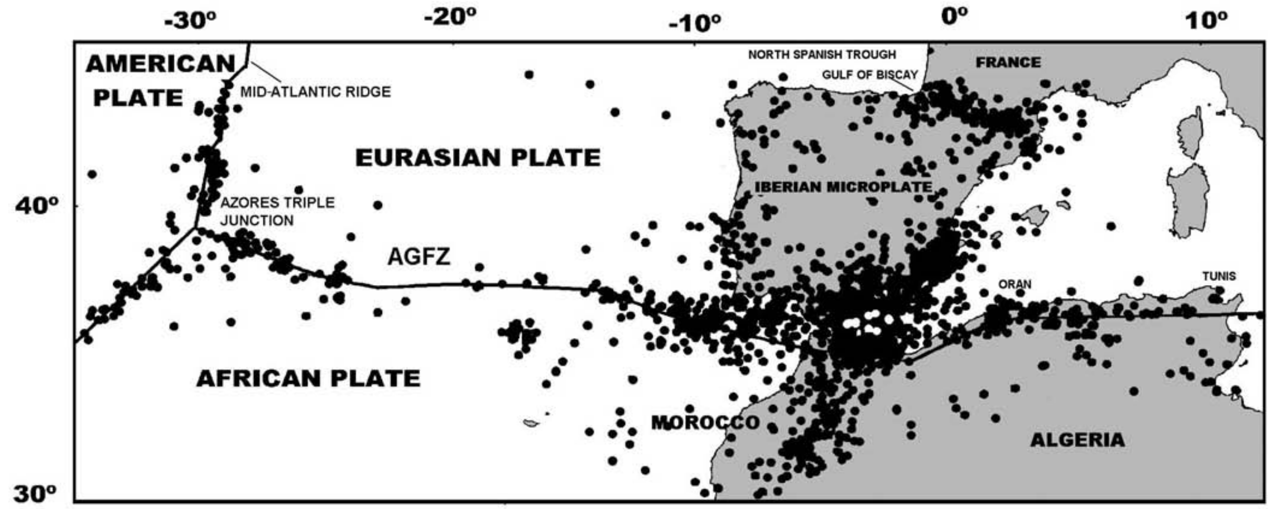

Fig. 1. Sketch map showing the epicentres, the largest lithospheric plates (American, African and Eurasian), the main boundaries of the plates, the triple junction of the Azores, and the Iberian microplate. [AGFZ= Azores –Gibraltar fault zone; black lines = tectonic weakness lines; black circles = epicenters. Adapted from Baptista (1998)].

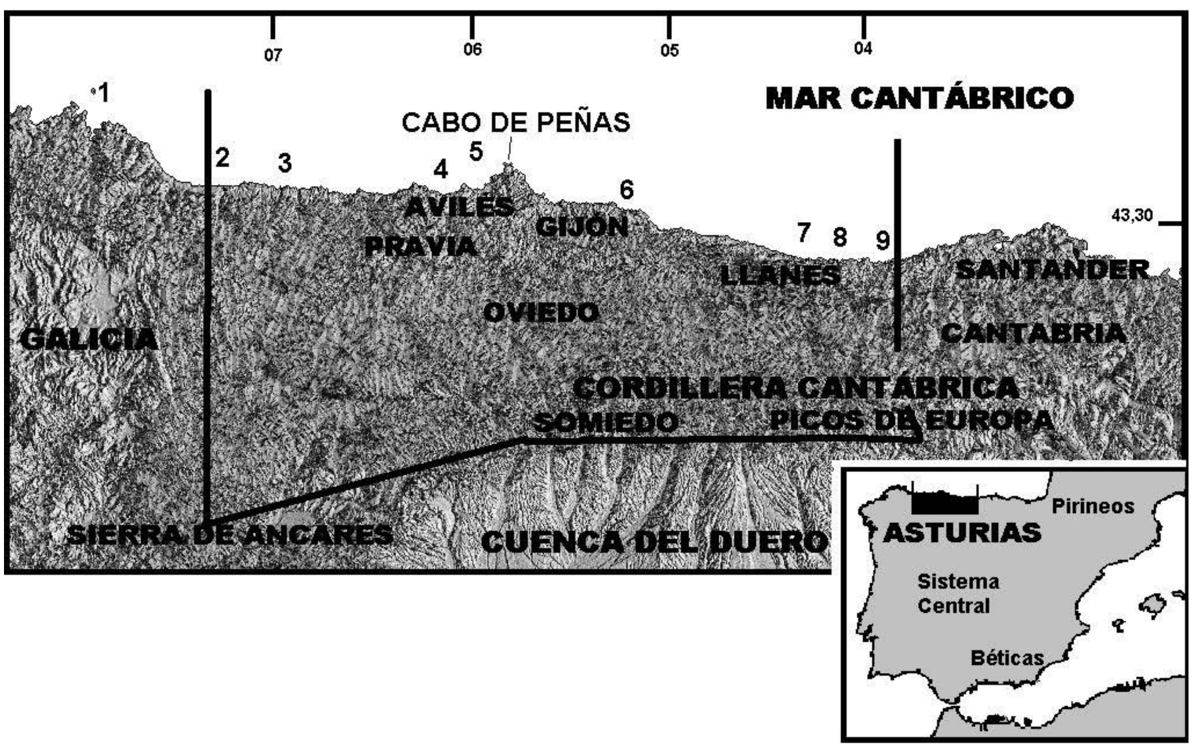

Fig. 2. Location of Asturias in the Iberian Peninsula. Digital relief image of Asturias. [1- Vivero, 2- Ría de Ribadeo, 3- Ría de Navia, 4- Ría de Pravia, 5- Ría de Avilés, 6- Ría de Villaviciosa, 7- Ría de Santiuste, 8- Ría de Tina Mayor, 9- Ría de Tina Menor.]

sis is the elaboration of interdisciplinary criteria to determine the zones with the greatest probability of the occurrence of earthquakes (Chigariov, 1977). Gvishani *et al*. (1987) applied this to the Pyrenees, considered to be related to the Cantabrian Chain. A full exposition of this methodology is found in Cisternas *et al*. (1985) and Cotilla and Córdoba (2004).

The relationship of seismicity to intersection or fault crossings (Herraiz and Lázaro, 1991; Sanz de Galdeano and

López Casado, 1988; Cotilla and Córdoba, 2003) has been used previously for the IP. Nevertheless, until now there has not been a systematic study to prove or refute this hypothesis. Thus the present study tries to do it for the Asturias region, a zone of low level of seismic activity.

2. METHODS

The application of structural – morphostructural methods in morphotectonic research allows one to reach an understanding of the differentiated character of the geotectonic evolution of the morphostructures of a territory. At the same time it explains the heterogeneous growth of its morphostructural complexes, including the determination of the relief, of the structural - tectonic elements and of the tectonic deformations of the geomorphological levels. In this way it is possible to establish the principal limits of the territorial (or morphotectonic) units, the active lineal elements and their intersections, from a morphochronological perspective. In this sense, Dumitrashko and Lilienberg (1954) demonstrated the existence of the morphostructure - recent tectonic movements - seismicity interactions and defined the general structure of morphostructural research.

The criteria and principles of morphostructural classification are a diverse and numerous set of seismicity interactions and defined standards (Cotilla *et al*., 1991; Jain, 1980). However, there is a fundamental set of field methods and measurements (qualitative and quantitative) which in general is synthesized by Filosofov (1960) and González *et al*. (2003). They permit the analysis and interpretation of: 1] topographic scale maps : a] numerous (1:50.000 1:100.000) and of aerial photographs, b] medium and small (1:500.000-1:1.000.000) maps and satellite images and photographs; 2] bathymetric maps; 3] morphometric relief maps (using mapmaking techniques or outlines: hypsometric, with maximum and minimum quotas, vertical (DV) and horizontal (DH) dissection, slope angles (averages and maximums), potential intensity of fluvial erosion (IPEF), morphoisohypsis, isobaths, difference of isobaths, etc.); 4] lineal elements of relief at different scales (direction and magnitude); 5] the hydrographic grid (rivers, watersheds and basins); 6] of the geological, tectonic and geophysical characteristics (including seismicity). Not only were the gradient of the vertical neotectonic movements and the influence of the exogenous processes ascertained (Hernández *et al*., 1990; Cotilla *et al*., 1997), but also it was determined that it is possible to distinguish the three main relief categories used in morphotectonic methodology: 1) territorial units (blocks of different rank); 2) border zones between them (morphoalignments); 3) areas of interaction between the morphoalignments (intersections and knots).

The cartographical coverage of the IP, and Asturias in particular, is extensive and well documented. There are quite reliable topographic maps at 1:50.000-1:1.000.000 scale; also the aerial photography map with approximately 1:10.000-1:60.000 scale is very good quality. There are at least two precise, "user-friendly" digital relief resources that considerably assist with the morphographic analysis of the regions. The geologic maps are 1:50.000 - 1:1.000.000 scale and the borehole catalogue (trenches and wells data) is also useful for the purposes of our research.

In addition to the methods discussed in the previous paragraphs to identify and characterize neotectonic movements, Cotilla *et al*. (1991) and González *et al*. (2003) recommend using the following: A) fluvial (Cox, 1994; Hack, 1973; Korzhuev, 1979; Merrits and Herterbergs, 1994; Sherve, 1966; Strahler, 1957) {1) The coefficient of sinuosity (Ks = relationship between the straight-line measurement and the curve measurement of the lineal relief elements [rivers, divides, coastlines, etc.]); 2) The factor of significant slope change in watersheds and rivers (FCcr); 3) The symmetry/asymmetry index of the fluvial basins along their divides and along their fluvial channels (IScf / IAScf); 4) The index of the shape and orientation of the basins (IFcf / IOcf); 5) the factor of the visual change of the basins (Fcec)}; B) Hypsometric-Fluvial {1) The potential intensity of fluvial erosion (IPEF); 2) The elevation/number of intersection of rivers index (Iai); 3) The orientation/length of river index (Iol)}.

A detailed analysis of the fluvial networks also implies the definition and hierarchical classification of watershed divides (González *et al*., 1988). In general, these lineal relief elements reflect very well the neotectonic activity of a region. The analysis of the watershed should not be limited to a small area or region, but rather should be expanded to a high taxonomic level. Cotilla *et al*. (1991) consider that divides (parteaguas, P) can be differentiated into a well-ordered hierarchy using a principal, higher level or order. This principal order is evident when the divide unambiguously defines great fluvial basins (i.e. the Atlantic basin), and is denominated Principal Divide of the First Order (Parteaguas Principal de Primer Orden, PPPO). The level immediately below is the Principal Divide of the Second Order (PPSO), that runs without interruption from the PPPO to the coastline. In the basins there are always more than one PPSO, but they always comprise smaller areas than a PPPO. From this PPSO one can draw a greater number of dividing lines, the Principal Divides of the Third Order (PPTO), and in consequence a greater number of basins (of smaller areas) appear. The procedure is similar for inferior categories. The Principal Divides separate into Secondary Divides, which instead of flowing into the ocean flow into rivers. There is a relationship between the extension of a basin and the order of the divide. Evidently, when describing basins with this hydrographic categorization method, different combinations of divides of different orders can occur.

Another useful complement to morphostructural studies is the methodology of Krestnikov (1987) based on the hypothesis of the existence of geomorphological levelled spaces (or surface levelling) (Jain, 1980). Theoretically, these are found in the highest parts of mountain systems and are characterized by their almost horizontal or lightly sloped inclination toward the edges of the mountain chains. In general, levelled surfaces constitute concentric and stepped groups, like staircases, that join marine and fluvial terraces with higher altitudes. It is common to assume that the highest levels are the oldest in the system and that they correspond to watershed dividing lines. In the great majority of cases this regular arrangement is disturbed by the action of erosion, leading to the creation of isolated peaks. Levelled surfaces generally do not have sediments, which are necessary for adequate dating. Using the altimetric values of the levelled surfaces and their spatial relationship it is possible to estimate the size of their neotectonic movements (vertically). In a similar way, using data from deep geological boreholes, the mobility and extent of rise and fall of a region can be established. The procedure for determining neotectonic movements with this methodology is simple. On a geological map, we see the formations of the neotectonic period and on the topographic map we find the highest isolines. On the latter, the boreholes with the pertinent data is found for the selected period. Using all of this information, estimates of the movements are made and the findings are represented in the form of isolines. Consequently, when drawing conclusions, these results should be compared and contrasted with the overall results reached by methods described in the preceding paragraphs without ignoring the horizontal dynamic (González *et al*., 1988). In an analogous way, Gladfelter (1971) carried out a study of the Spanish Central System (Sistema Central Español).

The territorial units of the IP are divided into six ranks (megablock, macroblock, mesoblock, block, microblock and nanoblock), (Cotilla and Córdoba, 2004). The first (megablock) is the largest territory, has experienced only one type of orogenic process and despite having different defining relief features has only one type of geodynamic behaviour in the current stage of geological evolution. This territorial unit corresponds to the Iberian microplate, or plate, (the Iberian megablock for the authors). At the same time, to subdivide this unit into others of inferior rank (macroblock, mesoblock, block, microblock and nanoblock) the following evidence must be considered: the maximum elevations of the mountain ranges, character of the composition and orientation of the largest relief elements; direction of the tectonic movements; etc. In particular, the macroblock is distinguished, fundamentally, by the type of orogenic process and by tectonic characteristics on a large scale. On the other hand, the mesoblock (evidently a part of the macroblock) is distinguished by the predominant type of relief, the averages of the relief parameters and the pattern of the relief elements. The differentiation of the blocks (always contained in the mesoblocks) is accomplished looking at the neotectonic history and the singularities of the relief parameters. Microblocks and nanoblocks are marked by the quantitative characteristics of the relief elements they contain, totally or partially.

Lineal relief zones are termed morphostructural alignments (morphoalignments, alignments or lineaments). They subdivide into ranges according to the hierarchy of the units they separate. They can also be classified according to their direction as longitudinal and transverse - diagonal. Evidently, they are lines of tectonic weakness (LDDT) and in consequence they are associated with tectonic movements. The structures that are the expression of the most recent tectonic activities are classified as first rank when they possess a width greater than 50 km and a length of more than 1000 km (i.e. the limit of the Africa – Eurasia plates) (Alekseevskaya *et al*., 1977). Along their path, they may have modifications in the morphology and the kinematics. A morphostructural alignment might not necessarily correspond with the fault marked on the tectonic map; but this does not signify that it is not associated with seismic activity (Alekseevskaya *et al*., 1977; Gvishiani *et al*., 1987).

Longitudinal lineaments are approximately parallel to the principal relief features. In general they represent the limits of the relief features that appear as systems of long narrow blocks. The transverse alignments, on the other hand, are those structures that cross and cut (generally at the ends) at sharp angles to the blocks. Morphostructural blocks are those places where there is an intersection between two or more morphoalignments. In the majority of the cases, the knots form because of the intersection of longitudinal and transverse-diagonal morphoalignments, though they can appear because of the convergence of various alignments. For the purposes of the first stage of research, by definition, a knot has a circular shape and a much greater width (~20 km) than an alignment. The radius for the knots on the IP is 25 km and is in agreement with the results obtained from the formulas of Riznichenko (1976) of seismic events up to M=6. The knots are interesting elements, not only because the reactivization of longitudinal faults occurs there, given their intersection with the transverse ones, but also because there is a greater probability for earthquakes to occur there (Gabrielov *et al*., 1996; Liu *et al*., 1999; Schenkova *et al*.,1995; Zhidkov *et al*., 1975). In fact, the knots are the area of greatest tectonic weakness (Arsovsky and Hadzievsky, 1970; Assinovskaya and Solovyev, 1994; Riznichenko, 1992).

Evidently, research with a morphotectonic basis method uses results from other authors in similar fields. Some of these results are re-evaluated to adapt them to the requirements or objectives of the investigation. Taking this into account, one must consider data from geodynamics, geology, geomorphology, tectonics and geophysics, from the regional and local level. This avoids duplication of effort and saves time when carrying out the research.

3. GEODYNAMIC FRAMEWORK

The following summary was developed fundamentally on the basis of these works: Dewey *et al*. (1989), Grimand *et al*. (1982), Le Pichon and Sibuet (1971), McKenzie and Morgan (1968), Mezcua *et al*. (1980, 1983, 1991), Olivet *et al*. (1984), Roest and Srivastava (1991), Srivastava *et al*. (1990), Udías *et al*. (1989), Udías and Buforn (1991), Vegas (1985), Williams (1975) and Zitellini *et al*. (2001).

The Azores – Gibraltar active fault zone (AGFZ) marks the western boundary between the African and Eurasian plates (Figure 1). Many authors assume that these plates have been converging for the past 53 My. At the western end of this plate boundary, the relative plate motion is mainly considered divergent. A triple junction tectonic system is located in this area. At about –17ºW the AGFZ is quite diffuse and suggests that the Hayes – Atlas fault constitutes the plate boundary. Seismic activity for the Mediterranean region is associated with the mentioned tectonic contact between the African and Eurasian plates. A well-defined end band of seismic activity is observed between the Azores Triple Junction and the Gulf of Cádiz but is quite diffuse from the Strait of Gibraltar to the east. In this last region the existence of very deep and intermediate depth seismic activity is well known, 640 km and 120 km, respectively. Such data has been used served as the basis for developing an original and unique model for the region known as delamination. Several other models are applied to the region, but the authors consider delamination to be the most appropriate.

This plate boundary is rather simple, separating ocean-ocean convergence and lacking a Benioff zone. Nevertheless, several studies show the complexities of the seismotectonic pattern of the mentioned plate boundary zone. The P- axes have a predominantly N-S to NW-SE orientation. The Eurasia-Africa plate boundary is characterized by an east-west trend and extends from the Azores Triple Junction into the Mediterranean Sea. East of Madeira Islands an oblique plate convergence is apparent, demonstrating the presence of a wide transpression zone across the Alboran Sea up to the Tell Atlas Mountains (Northern Africa).

The Iberian plate, located at the northern part of the mentioned tectonic line, is bordered by two Alpine foldbelts, the Pyrenees to the north and the Betic Cordilleras to the south (Figure 2). These active belts separate the IP from, respectively, the rest of Eurasian plate and the African plate.

Outline of the geology and tectonics

The following references have been used in this summary: Alonso *et al*. (1996), Álvarez Marrón and Pérez Estaún (1978), Álvarez-Marrón *et al*. (1996, 1997), Boillot and Capdevila (1997), Capote and De Vicente (1989), Charpal *et al*. (1978), Choukrone *et al*. (1989), Dallmeyer and Gil Ibarguichi (1990), Dallmeyer *et al*. (1991), Espina *et al*. (1996), Fernández Viejo (1997), Fernández-Viejo *et al*. (1998), Grimand *et al*. (1982), Gutiérrez (1982), Hirt *et al*. (1992), Hoyos Gómez (1989), Instituto Geológico y Minero de España (1974, 1977), Instituto Tecnológico y Geominero de España (1989), Leponier and Martínez García (1990), Martínez García (1981, 1983), Matte (1991), Pérez-Estaún and Bastida (1990), Pérez Estaún *et al*. (1988, 1991, 1994), Perroud (1982), Ries *et al*. (1980), Seguet and Daguières (1986), Van Calsteren (1977), Williams and Ficher (1984) and Ziegler (1988).

From a geological point of view, four different types of rocks emerge on the IP (Figure 3): 1) Precambrian, deformed before the Palaeozoic; 2) Palaeozoic rocks deformed by Hercynian orogenesis; 3) Mesozoic and Tertiary, deformed by Alpine orogenesis; 4) Mesozoic and Tertiary, not deformed by Alpine orogenesis. The regions marked as postorogenic Palaeozoic, not deformed by Hercynian orogenesis, comprise a very limited part of the outcrops. The degree of individuality of these groups is not equal. In fact, the Precambrian terrain has been incorporated into the Hercynian chain, so it is found to appear only in the form of rocks making up this mountain chain. Also it can be stated that the IP has two principal parts: 1) a segment of the European Hercynian chain; 2) a segment of the Alpine system. The so-called Iberian Hercynian domino (bookshelf faulting), although it breaks the surface in many places, is also hidden in large part by Mesozoic and Tertiary formations that form platforms of table land or show variable deformation. This deformation reaches its maximum importance in the Iberian Chain, which can be considered a chain of intermediate rank. Superimposed on all these formations is a tectonic system of fractures of Cenozoic antiquity, autonomous with respect to the preceding structures. This system of fractures is in reality a part of the system that affects Western Europe and is seen principally as a group of tectonic trenches.

The Hercynian chain crops out along a long stretch of the western half of the IP, forming the Iberian or Hesperico Massif, which is in direct relation to the nuclei of Palaeozoic material of the Iberian Chain, although the outcrops are not continuous. Also, outcrops of Palaeozoic rocks deformed in the course of Hercynian orogenesis exist in the Catalan Coastal Range, in the axial zone of the Pyrenees and in the internal zones of the Betic Range, although these nuclei are more difficult to situate inside the general framework of the Hercynian chain. In contrast it is easier to set up a basis for the study of the Iberian Massif, which can be divided into a concrete number of zones that correspond to elongated units parallel to the direction of the Hercynian structures. These zones essentially have a paleogeographic meaning. So the variations in thickness and facies take place principally in a transverse direction, while longitudinally there is greater

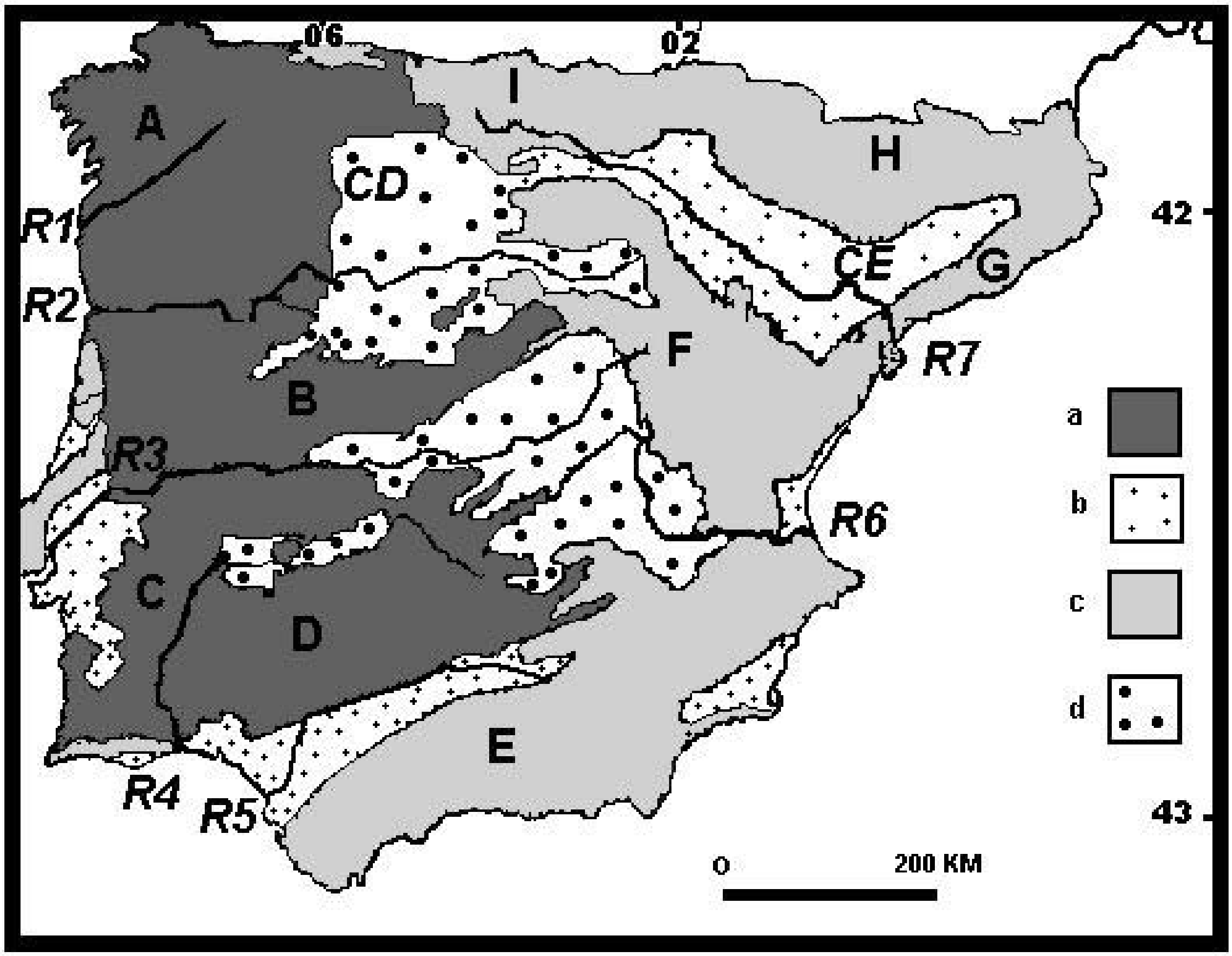

Fig. 3. Morphostructural map of the Iberian Peninsula. [Mountain Ranges: A- Macizo Gallego, B- Cordillera Central, C- Montes de Toledo, D- Sierra Morena, E- Cordilleras Béticas, F- Cordillera Ibérica, G- Macizo Catalán, H- Pirineos, I- Cordillera Cantábrica; Rivers: R1- Miño, R2- Duero, R3- Tajo, R4- Guadiana, R5- Guadalquivir, R6- Júcar, R7- Ebro; Structural units: a- Hercynian massif, b- Terciary basins, c- Alpine borders, d- Peripheric basins, e- Alpine mountains. Modified of Terán *et al*. (1994).]

consistency. Nevertheless, not only are the facies and the thickness characteristics of each zone, but there are also differences from the point of view of structure, of metamorphosis, magmatism and metalogenesis.

Considered as a whole, the Iberian segment of the Hercynian range has a bilateral symmetry. This symmetry manifests itself principally in: 1) the existence of opposing vergences; 2) the presence of great extensions of more modern terrain in the two most external zones (Cantabrian and Sub-Portuguese) in contrast with the oldest terrains (Lower Palaeozoic and Precambrian nuclei) that in great part form the other zones. However, this symmetry is not perfect, given that important differences exist between the two branches of the range.

The Cantabrian Zone (Figure 4) forms the nucleus of the arc (Asturian fold) that comprise the Hercynian structures in the northern part of the Iberian Massif. The western limit of this zone forms a strip of Precambrian rocks that compose the nucleus of the Narcea antiform. The other limits are imposed by the Mesozoic - Tertiary layer and by the sea. Although the Palaeozoic succession is found to be incomplete, in this zone all the systems are represented to a greater or lesser degree, with a great variety of lithologies. The foundation of the Palaeozoic succession is observed only along the length of the Narcea antiform, which lies discordantly on Precambrian material. Above this discordance is found a concordant succession, although with some stratigraphic gaps, up to the Lower Cambrian. In the Upper Carboniferous there are various discordances, but of diverse im-

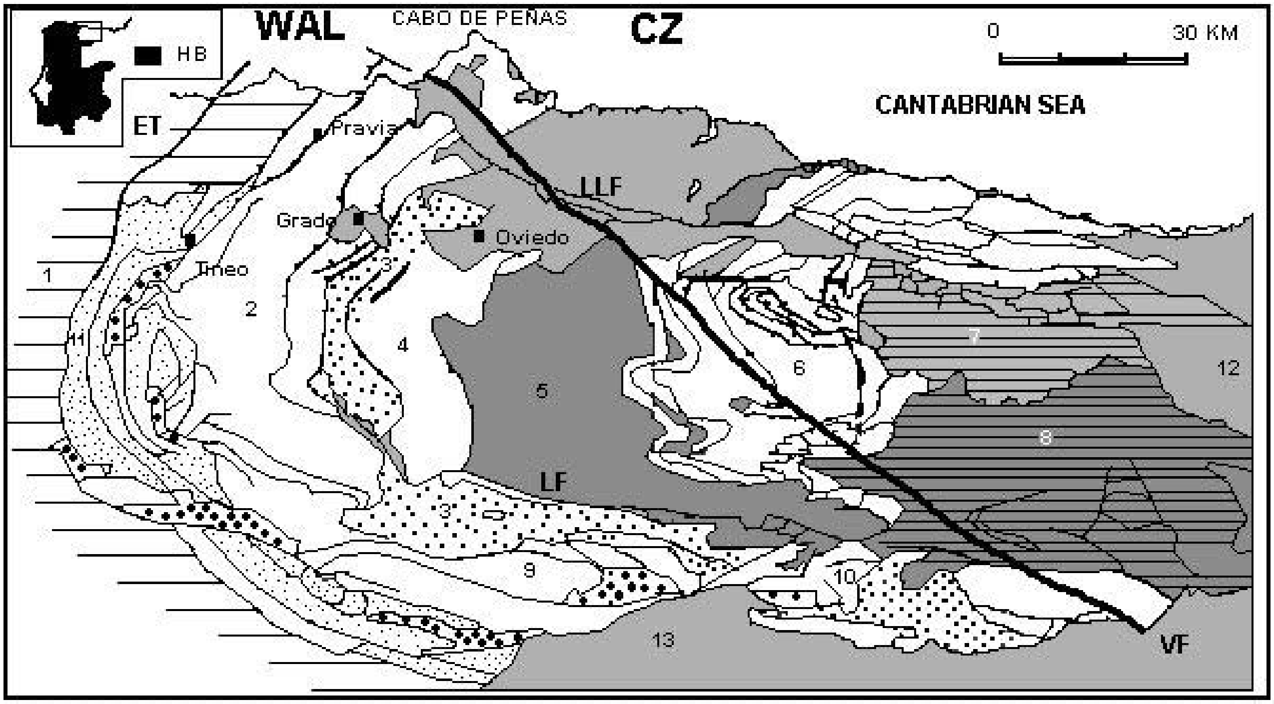

Fig. 4. Geological scheme of Cantabrian zone. [1: Zona Asturoccidental-Leonesa, 2: Unidad de Somiedo, 3: Unidad de La Sobia-Bodón, 4: Unidad del Aramo, 5: Cuenca Carbonífera Central, 6: Región del Ponga, 7: Picos de Europa, 8: Unidad del Pisuerga-Carrión, 9: Unidad de Correcilla, 10: Esla, 11: Cangas de Narcea, 12: Cuenca Vasco-Cantábrica, 13: Cuenca del Duero. CZ= Cantabrian Zone; ET= Espinar thrust; HB= Hercynian Belt in Western Iberia; LF= León fault; LLF= Llanera fault; VF= Ventaniella fault; WAL= Western Asturias-León Zone. Modified of Instituto Geológico y Minero de España, 1974].

portance. From the tectonic point of view, the deformation took place very close to the surface, without metamorphosis and except for part of the Pisuerga – Carrión region, practically without schistosity or with a very local schistosity. Under these conditions, the anisotropy due to the stratigraphy and the lithological differences, and the corresponding contrasts in ductility, exert an important control on deformation. In a general sense, one can distinguish some initial tangential type structures and other later structures, represented by generally vertical folds of axial planes. The strata and flakes were folded later on. Only in a limited area (the northern part of the region) do they consist of sharply vergent or prostrate structures. The strata and flakes were folded later. Magmatic activity in the Cantabrian Zone is scarce, although the existence of volcanism that starts in the Middle Cambrian and continues intermittently to the Suliric has been found. Plutonism is practically nonexistent (or minimum), found only in very small, post-tectonic stock structures, close to the Narcea antiform.

Adjoining the preceding zone we find the Western Asturias – León Zone (Figure 4). It borders the two antiforms whose centre appears in the Precambrian, and there are also Cambrian and Ordovician materials and to a lesser degree Silurian ones. To the east is the Narcea antiform, with Precambrian slate in its centre, and to the west is the antiform in whose centre the porfiroid formation known as the Ollo de Sapo appears. Precambrian slate also appears in the centre of the great prone fold of Mondoñedo. From a tectonic point of view, the deformation is accompanied by metamorphosis and schistosity. In general terms, metamorphosis increases in intensity from east to west. The tectonic style shows essentially similar folds, with superposition of various phases of folding. Here first there were strike-slip tectonics followed by folding tectonics that deform the former structures, creating folds with retro-separation or near vertical, axial surfaces.

One of the features found when making a E-W profile of the northwest part of the IP is the presence of extensive areas where foliations and lineations are subhorizontal or form wide synforms, that are separated by narrow antiforms bordered by normal and slip-strike faults. Structures of the first type are seen across greater part of the Cantabrian Zone and the Central part of the western Asturias - León Zone. Meanwhile structures of the second type are represented by the Narcea antiform. The tracts with subhorizontal or slightly sloped structures have been linked to crustal detachments on a grand scale. They are probably due to basal overthrusts where overlapping systems of observable lineations are seen on the surface. The antiforms are related to the piling up of links in the lower part of the sedimentary section and in the base and probably are situated in places that have an important lack of crustal continuity in periods of pre-Neogenic development. That is, when the zone evolved as a stable, eastern edge during the Early Palaeozoic.

On the continental platform of Asturias, the Cretacian series are deformed by a first phase of deformation, erosion and covered unevenly by Upper Eocene. Meanwhile the Mesozoic terrain was eroded a second time at the end of the Oligocene. In general the structures have an E-W orientation and are contemporary to the paroxysm of the deformation in the Pyrenees (Palaeocene - Upper Eocene). In the region of Asturias and the Basque Country the new structures are: horst and graben types and large synclines and anticlines, respectively. This is the deformation which is responsible for the greater part of the structures that appear on the continental shelf. After subaerial erosion there is a new discordance due to the transgression of the Lower Miocene. The folds, the horst and graben created at the end of the Oligocene were affected in the Neogene by transverse movements NW-SE, N-S or NE-SW, on which submarine canyons were built (i.e. Avilés, Llanes and Torrelavega). These structures constitute some of the most outstanding features of the submarine relief.

In our study region there are two important basins, the Duero and the Oviedo ones. The Duero basin is defined by three Alpine mountain ranges that surround it: 1) the Cantabrian Mountains on the north; 2) the Iberian Chain on the east; 3) the Central system on the south. This basin is a wide endorheic Tertiary basin whose northern margin is formed by an assemblage of alluvial forms developed at the foot of the southern slope of the Cantabrian Mountains. As we said before, the northern margin of the Duero basin is the foreland basin situated ahead of the mountain front. Then, the Oviedo basin, behind the dorsal uplifted wall, can be interpreted as a piggyback basin developed from the tectonic inversion of the Llanera extensional fault and minor uplift. The sedimentary record of Oviedo basin is incomplete, with a maximum preserved thickness of approximately 400 m. The northern margin of the basin consists of a fringe of small coalescent alluvial fans of poorly efficient transport power with radii of up to 4-5 km. The sediments of the Oviedo basin are generally tilted slightly northward. In both basins a wedge of nonmarine sediments prograded from the basin margin during Alpine deformation.

General characteristics of the relief

This summary has made use of the following studies: Asencio Amor (1970), Asencio Amor and Nonn (1964a, 1964b), Asencio Amor and Teves Rivas (1966), Bertrand (1971), Cueto (1930), Farías and Maquínez (1995), Fernández Martínez (1981), Fernández Rodríguez *et al.* (1997), Gladfelter (1971), Gómez de Llanera and Royo Gómez (1927), González *et al.* (1996), Hernández Pacheco and Asencio Amor (1959a, 1959b, 1960a, 1960b, 1963, 1964), Hernández Sampelayo (1949), Hoyos Gómez (1989), Instituto Geológico y Minero de España (1971), Jiménez (1997), Jiménez Sánchez (2000), Llanera and Royo (1927), Llopis Lladó (1954), Martínez García (1981), Muñoz Jiménez (1982) and Terán *et al.* (1994).

The northern edge of the Iberian Peninsula (Figure 3) is continental and originated in the Mesozoic during the opening of the Bay of Biscay. Later it was affected by the Alpine convergence between the Iberian and European plates. This is very noticeable on the eastern side of the Peninsula, where the intracontinental orogenesis of the Pyrenees is located. This edge is characterized by very important lateral variations that affect not only the crust and upper mantle but also the continental – oceanic transitional domains. The "V" shape of the Biscay Bay shows that it is one of the annexes of the rift system of the North Atlantic. This northern edge of Iberia has a narrow continental shelf (30-40 km) that continues to an abyssal plane ~4.500 m deep with a continental slope 10-15 km wide.

The Cantabrian Range is made up of a mountainous ridge of alpine origin, parallel to the Cantabrian coastline, which from maximum altitudes of 2600 m (Cerredo 2648 m, Peña Vieja 2615 m, Sierra del Cordel 2064 m, Peña Santa de Castilla 2596 m y Naranjo de Bulnes 2518 m) rapidly descend northward to the coast (over 40 - 45 km), or delimit the narrow strip of the seaboard region. The Cantabrian Range has been defined as folded chains of intermediate type. To the south it demarcates the limit of the Duero basin (Tertiary), to the west and southeast the Hesperico Massif (Hercynian plane) and to the east zones lifted by the tectonics of the compression in the Hesperico Massif. It is similar, in this sense, to the Sierra Morena and the Cordillera Ibérica.

The Cantabrian coast displays a clear and well-defined latitudinal alignment, which is related to the alpine tectonic accidents that compartmentalize the blocks, both the continent as well as the continental edge. At the same time, a coastal sector of unique characteristics corresponds to each morphostructural unit. Thus, it can be stated that structural and lithological factors have had a strong influence on the formation of the indented coastline. It is a young, indented coast, dominated by high cliffs, with few beaches and coves (Table 1). Along the shoreline, marine platforms are scarce or nonexistent. Three are found in the west (altitude): 1) +25 - 30 m, 2) +15 - 18 m, 3) +5 - 6 m. In the central zone (Avilés - Cabo de Peñas - Luanco) the following are found (altitude): 1) +70 - 80 m, 2) +50 - 60 m, 3) +30 - 35 m, 4)

Table 1

Shapes and elements of the relief and landscape of Asturias

Nº	Type	Denomination
1	Capes	Blanco, Busto, Cebes, de Aguilera, de Arnao, de Conchinquina, de Doria, de Lumere, de Mar, de Novellana, de Oteiro, de Peñas, de Salinas, de Tablizo, de Ubiambre, Fontanella, Lastres, Playón de Bayas, Prieto, San Agustín, Torres, Vidio
2	Inlets	Engaramanda, de Bañuguez, de la Conejera, de España, de Novales, de Purión, de Santa María del Mar, del Gordo
3	Isles	de Arnielles, de Pancha, de Poo, del Castro de Ballota El Palo de Poo, La Deva
4	Beaches	de Aguilar, de Moledo, de la Estaca, de la Jerra, de los Molinos
5	Points (Headlands)	Aguamía, Bajo de Carreros, Barchinas, Bonaya, Borona, Canto de Palo Verde, Carreras, Castrello, Coin, de Aranzón, de Bañugues, de Barro, de Campiello, de Caravia, de Caranques, de Castellón, de Castro de Bellota, de Celorio, de Cerro Sancho, de Cudillero, de Cuernos, de Espasa, de El Maste, de Jani, de Lastres, de Merón, de Nueva, de Ñora, de Pendueles, de Penote, de Quintana, de Ribadesella, de Rodiles, de Sabión, de San Antonio, de San Antolín, de San Lorenzo, de San Pedro, de Santa Ana, de Serín, de Tazones, de Torbas, de Vega, de Villanueva, de Villar, de Xivares, de la Atalaya, de la Corbera, de la Entonada, de la Franca, de la Isla, de la Rosca, de la Silla, de la Vaca, de las Llastras, de las Poleas, de las Rubias, de los Cabrerizos, del Aguión, del Altar, del Arenal, del Barco, del Bozo, del Caballo, del Camboredo, del Olivo, del Pedrón, del Sarello, del Socollo, El Castro, El Gaviotero, El Pico, El Rego, El Sol, Engaramadura, Formigosa, Gabiares, Gouñín, La Centolleira, Mal Perro, Melín Beciella, Misiera, Mohosa, Mulleres, Nocedal, Percebera, Picón, Piedra del Rayo, Vidrias, Romanela
6	Rias	de Áviles, de Navia, de Pravia, de Ribadeo, de Ribadesella, de Santuste, de San Vicente, de Tina Mayor, de Tina Menor, de Villaviciosa
7	Rivers	Aller, Cares, Dera, Deva, Eo, Gueña, Mier, Nalón, Nausa, Navia, Nervión, Noreña, Norta, Pas, Piloña, Sella,
8	Mountain ranges	(> 1000 m): del Acedo, de Aramé, de Begega, de Bonzón, de Caniella, de Carangas, Cazarnosa, de la Cabra, de Conforcos, del Crepón, de Cuera, de Dagueño, de Degaña, de Giblaniella, Ibollo, de los Lagos, Muriellos, de Pandermueles, del Pando, del Palo, de la Pilarilla, Oballo de Peña Ventana, de Quintana, de la Serranita, de Tablado, de Tinero, Valledor, de la Verde, de la Zarza, Picos de Europa, Cordal de (Berdocedo, Bustariega, Carrocedo, la Mesa, Murias, Ponga, Sorbia), Serranía de las Fuentes de Invierno, Cordillera de los Llanos, Monte de Raneiri (< 1.000 m): de Abedular, Ablaniego, de Adrado, de Anieva, de Aramó, de Aves, de Beza, de Bodanaya, de Braña Jual, de Buset, de Caniza, de Cañal, Carondio, de la Casonera, de la Ceniscada, Cocón, de Corteguero, de Covalier, de la Cubeta, de la Cuesta, de Escapa, de Faces, de Fontebona, de Nedrina, de Perlumes, de Pesquerín, de Porta, de San Isidro, de San Mamés, de San Roque, Santa Ana, de Sellón, Silvallana, de Soldepuestas, Sollera, de Tineo, de las Traviesas, de los Vientos,

+15 - 20 m, 5) +5 - 6 m, 6) +2 - 2,5 m, 7) +1,5 m. At the same time, the system of beach dunes is scarcely developed, the majority of the stretch of dunes situated to the west and north-east. Their age corresponds to the Upper – Holocene Pleistocene.

The coast can be divided into three sectors: 1) where the coast is generated on masses of granite; 2) where two related environments coincide, respectively, with the two zones of the second morphostructural units (one western and the other eastern). In the western sector the coast is developed over Palaeozoic slates and quartzites, whose structures are perpendicular to the coast and create a siliceous coast where the quartzites, due to their greater resistance to erosion, produce the capes (ej. the de Bustos, Vidio and de Peñas). To the east of Gijón, in the eastern region, the coast is fundamentally carved into calcareous material of the Mesozoic era (Villaviciosa - Ribadesella) and the Palaeozoic (Ribadesella - Llanes), with a few interruptions of siliceous Mesozoic (Rodiles) or Palaeozoic extensions (San Antolín). In this eastern region the structures are noticeably parallel to the coastline. In the Ribadesella - Llanes stretch a large part of the rias and coves where rivers empty have a carstic origin; 3) comprising the rest of the Cantabrian coast, composed of Mesozoic materials, above all calcareous rock, with large structures parallel or almost parallel to the sea. It is in this sector where the rias of greatest width are found (Santander, Santoña - Laredo and Nervión).

The Quaternary model of the Cantabrian region is of an especially erosive type, with an sharp climatic influence, in which the rates of erosion greatly surpass those of sedimentation. Nevertheless, the inlets and present day estuaries are related to the postglacial rise of the sea level, and function as river mouths. Some typical features like shoreline sandbars and arrow shaped deposits are found there. Periglacial deposits occupy quite a large area on the Cantabrian Coast, and are found all along the coast on abrasion platforms and even still forming a layer on marine deposits (in Laredo and Castro Urdiales, in Santander). There are fluvial and coluvial deposits in Santander, and in the Cubas River, a terrace of 10 m.

The fluvial network of Asturias (Figures 5A, 5B, 5C, and 5D) is short and steeply sloped. The Nalón river is the longest and drains the largest area. This river, in central part of its course has the following terraces: I) Lower Pleistocene [1) +85 - 80 m, 2) +60 - 50 m]; II) Lower - Middle Pleistocene [3) + 40-35 m]; III) Middle Pleistocene [4) +32 - 24 m, 5) +20 - 15 m]; IV) Upper – Holocene Pleistocene [6) +5

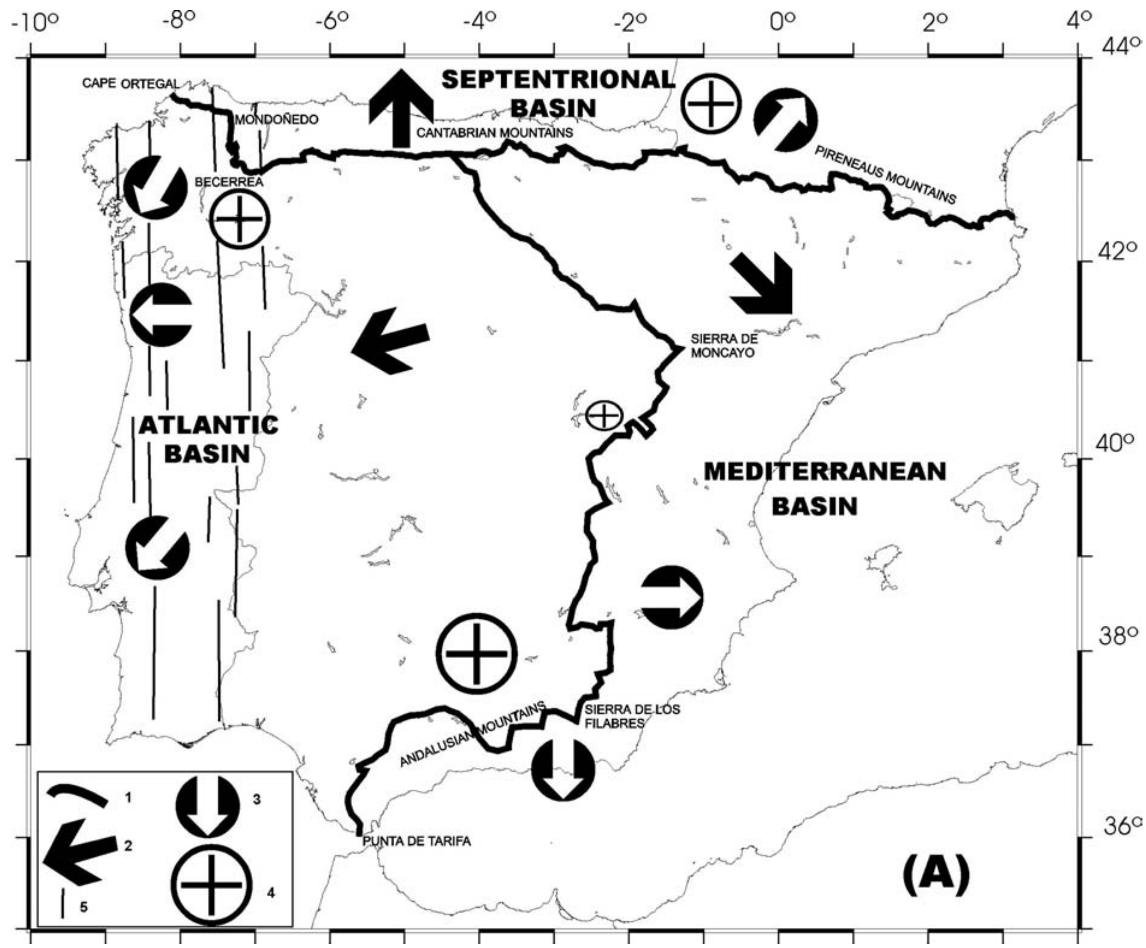

Fig. 5. Hydrographic characteristics of the Iberian Peninsula. [{A) Fluvial network scheme of the Iberian Peninsula. 1: Principal Watershed; 2: main directions of the largest basins; 3: local directions of secondary basins; 4: rising zones; 5: selected alignments}; {B) Sketch of the main watersheds in Asturias. Continuous line = PPPO; discontinuous line = PPSO; black points = PPTO; largest basins: 1: north, 2: south; northern basins: A=Eo, B=Navia, C=Narcea-Nalón, D=Sella, E=Della}; {C) Scheme of IPEF data. 1: 0,1-0,29; 2: 0,3-0,49; 3: 0,5-0,69; 4: 0,7-0,79; 5: 0,8-0,95}; {D) Fluvial network of Asturias and surroundings. Rivers: 1=Eo, 2=Navia, 3=Narcea, 4=Nalón, 5=Sella.} See Table 10.]

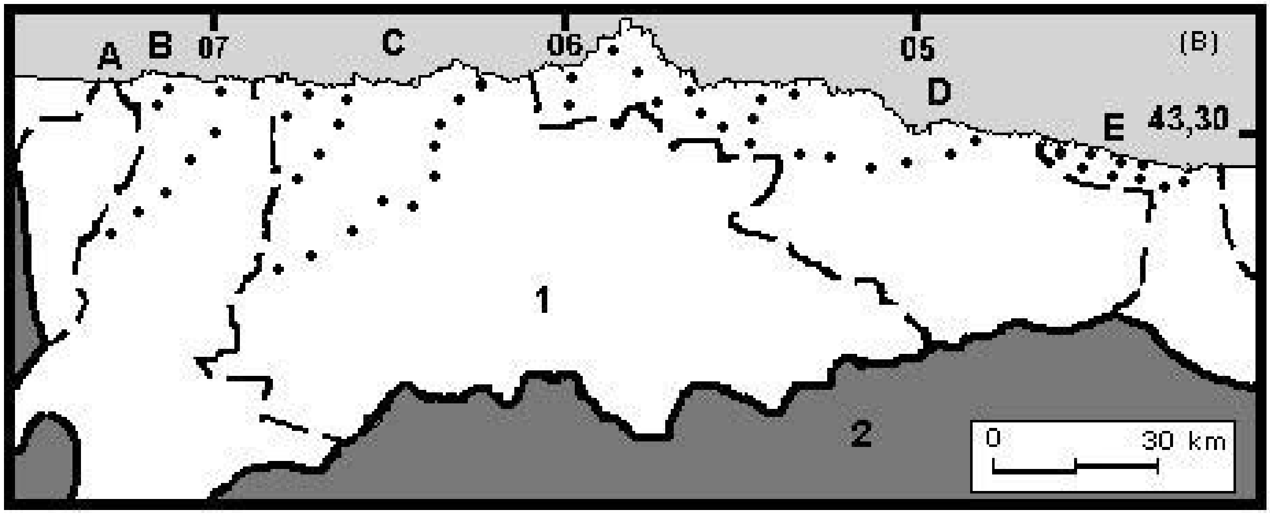

Fig. 5B.

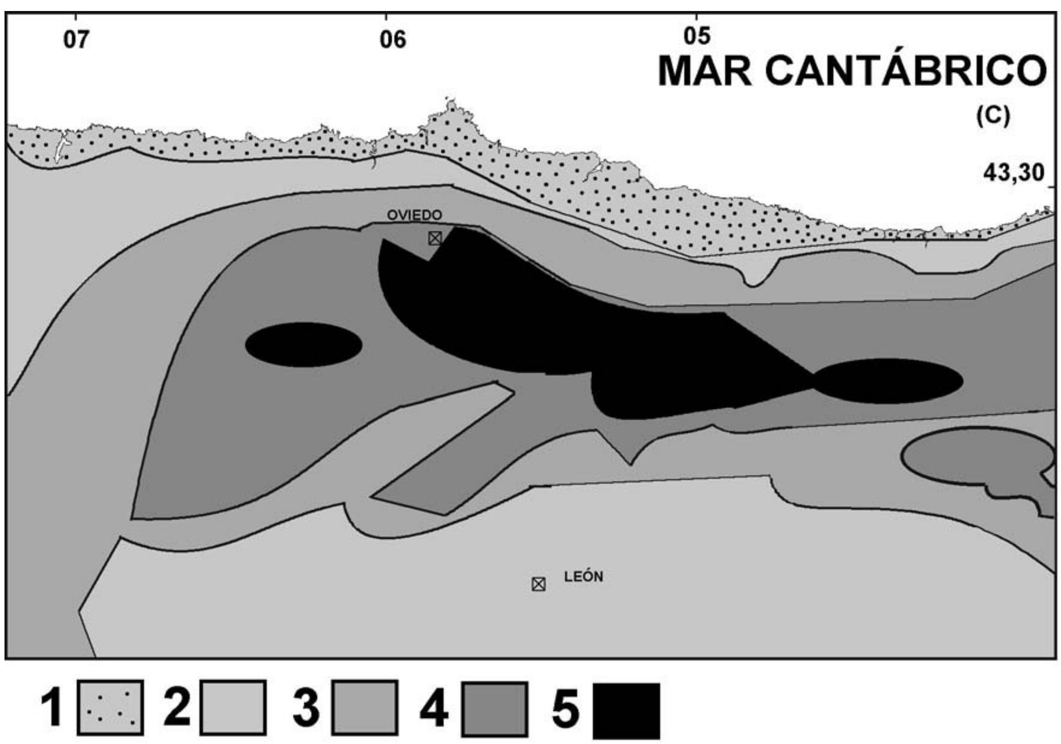

Fig. 5C.

m, 7) +2 m]. The divide of surface water in this zone separates the so-called "Wet and Green Spain" (the Atlantic face of the Cantabrian range) and "Dry Spain" (the Meseta).

Another outstanding geomorphological feature on the Cantabrian coast is the existence of a surface or series of surfaces of abrasion (Rasas or Sierras Planas), located at an elevation of 100 - 200 m (Cabo de Torres, Cabo de Peñas, Cabo de Vidio, and from the zone of Ribadesella - Llanes and Cabo Mayor). In the Torrelavega region there are a series of these worn surfaces. The most consistently level and oldest surface is found between La Tina Mayor and the Sella

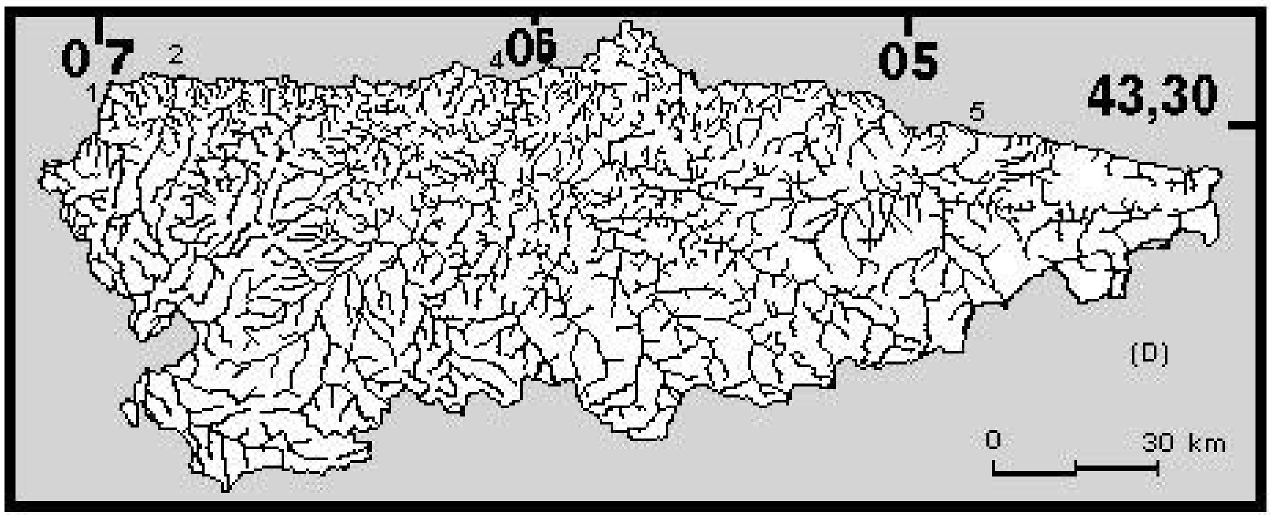

Fig. 5D.

River at an altitude of 220 m. Going north towards the de Pimago and del Pechón ranges it descends to 180 m and disappears to the east so that San Vicente de la Barquera and Santander (in Cantabria) have lower altitudes and better preserved surfaces. Farther to the east of Santander, between Laredo and Castro Urdiales, fragments just 50-60 m high appear over Aptian limestone. This formation is better preserved in the western shoreline, made of siliceous substrate, than in the rest of the calcareous composition. This flat ground is slightly sloped toward the Eo river, in the western part, starting from the Cabo de Peñas. One can assume its origin is related to the action of the sea. The previously noted altitudes for the present day would have been similar to those during the Upper Pliocene.

In general, the orography of the north of the IP is associated with the regularity of the mountain ranges and altitudes due to its E-W alignment and its compactness. At the same time the geological composition and the resultant relief features are diverse. It should be noted that in the western Asturian sector there is a recurrence of some of the morphological features of Appalachian type found in Galicia. High eroded surfaces develop on a succession of regular folds, running east and characterized by a succession of rocks of very different resistances, such as quartzites and slates, aligned perpendicularly to the coast. In the eastern sector, however, in the extension near Santander, the Mesozoic cover is better preserved, thanks to the progressive sinking of the Palaeozoic shelf. This shelf would have constituted the edge of the continental slope during the Secondary. This lithology favours the configuration of domes and synclinal holes framed by slopes.

In the whole of the Cantabrian orography (Cordillera Cantábrica) three sectors can be distinguished: 1) the Asturian Massif, made up of Palaeozoic materials folded and broken by latitudinally oriented trenches, which continue to the surroundings of Llanes; 2) the mountains of Santander, which are alpine type, and are made of Mesozoic limestone, with softly folded structural forms; 3) the threshold of the Basque Country, which is formed by Mesozoic terrain, but with a predominance of markedly folded marly facies and flysh.

The structural relief created by the monoclinal flexure of the Cantabrian area is evident in the present relief. The present-day watershed is not far from the upper dorsal culmination wall hinge that must have represented the initial watershed in the beginning of the uplift of the mountain range. The winding trace of the present-day watershed results from the different erosion rates undergone by the lithological units of the basement, although the overall trace is E-W. The area, whose elevation is over 1200 m, has many summits ranging between 1800 m and 2000 m.

As was previously mentioned, Asturias, according to the morphotectonic classification made by Cotilla and Córdoba (2004), is part of the Northern macroblock (Number 9) (Figure 6, Table 2). The limits of the Northern macroblock are the following alignments: A7 in the western part, A8 on the southern flank, A9 on the northwest and A2 on the east, and the Cantabrian Sea on the north. This structure is relatively regular, but its eastern side is larger than its western side and its southern border has both an E-W and a NE tendency. In fact, Asturias is defined as a mountain mesoblock parallel to the coast, but with the passing of time it is becoming smaller and narrower to the east. In Tables 3, 4 and 5 there is a collection of data of all of these elements. It is very significant from the tectonic point of view in the Northern macroblock that 2nd order knots (34 and 31) are situated in the two extremes of the A8 alignment. This territorial units contains 23% of the general fracturing related with the IP. It is the most fractured, followed by Macroblock 1 (Southern)= 17% and Macroblock 5 (Coastal) = 15%.

Geophysics: gravimetry, geomagnetism and seismic data

The basis of this outline is principally taken from the following studies: Álvarez-Marrón and Pérez-Estaún (1978), Álvarez-Marrón *et al*. (1996, 1997), Ardizone *et al*. (1989), Ayarza Arribas (1995), Banda *et al*. (1995), Charpal *et al*. (1978), Choukroune *et al*. (1989), Córdoba (1998), Córdoba *et al*. (1987, 1988), Fernández-Viejo *et al*.(1998), Hirt *et al*. (1992), Lalaut *et al*. (1981), Mezcua and Benarroch (1996), Pérez-Estaún *et al*. (1994), Perroud (1982), Pulgar *et al*. (1996), Ries *et al*. (1980) and Van Casteren (1977).

Some years ago, Spain developed a program for Seismic Studies of Iberian Crust to study the northern part (ESCIN) (Figure 7). Two deep seismic reflection profiles on land (ESCIN-1 and ESCIN-2), two offshore (ESCIN-3 and ESCIN-4) and several refraction/ wide-angle reflection profiles were carried out. Specifically, five seismic on land and marine surveys (ESCIN-1, -2, -3, -4, and IAM-12) were developed in order to study the Northern Iberian Continental Margin (Cantabrian Mountains and their transition to the adjacent Duero foreland basin, the platform margin offshore Asturias and the platform margin to the northwest of Galicia).

The E-W reflection ESCIN-1 profile showed the thin-skinned tectonic style of deformation in the Cantabrian Zone. Different seismic responses at middle and lower crustal lev-

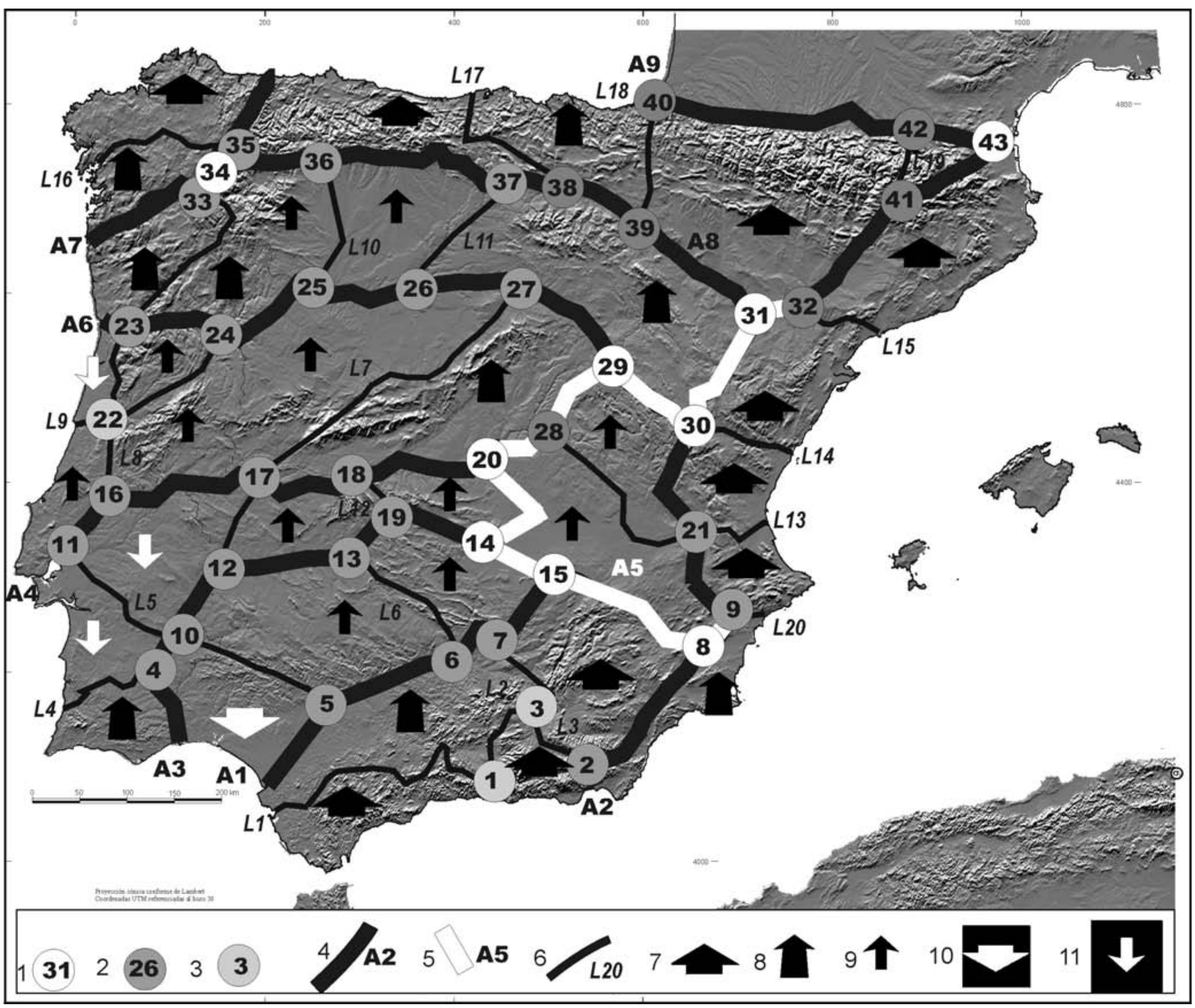

Fig. 6. Simple representation of the Iberian megablock. [Original scale 1:1.000.000. {1, 2, 3: knots of second – fourth order; 4, 5: lineaments of second order; 6: lineament of third order; 7, 8, 9: uplifting (very active, active and weak); 10, 11: downthrow (very active and weak.)} See Tables 3, 4 and 5].

Table 2

Data on the Septentrional macroblock

Area (x10 km²)	Number of Mesoblocks	Blocks	Microblocks	Nanoblocks
88,1	4	694	981	1.273

els in the foreland thrust and fold belt area (Cantabrian Zone) and hinterland area (Narcea antiform) suggested that Variscan tectonics strongly affected deep-crustal levels in the hinterland areas, whereas they remained undeformed beneath the foreland.

The effect of the recent Alpine tectonics on the Variscan crust was studied by a N-S seismic transect along the Cantabrian Mountains and their transition to the: 1) northern Iberian Continental Margin (ESCIN-4); 2) Duero foreland basin (ESCIN-2). In the latter profile (65 km long) it was possible to observe that the crust changes from sub-horizontal beneath the Duero basin to north-dipping beyond the mountain front. The Moho is identified at about 35 km inland and deepens to about 60 km, ending abruptly at the shoreline. And according with the ESCIN-4 the continental Moho is at a depth of ~29 km near the coast and dips gently seaward beneath the continental shelf, reaching 22 km depth beneath the shelf break. The seismic structure of the crust shows a very significant thickening beneath the Cantabrian Mountains and an abrupt transition toward the continental margin. This crustal structure is characterized by a detachment and delamination of the upper crust related with the northward underthrusting of the southern lower crust below the northern one.

The morphology of the continental shelf and slope is markedly different in the IAM-12 and ESCIN-4 profiles. The continental shelf in the IAM-12 profile is mostly a planar surface that dips gently (2º) seaward reaching the continental break located at a depth of ~450 km. On land seismic refraction data locate the continental Moho at about a depth of 23 km near the coast.

The general features of the North Iberian Margin, such as sedimentary basins on the shelf and an accretionary prism with associated marginal trench sediments buried by post

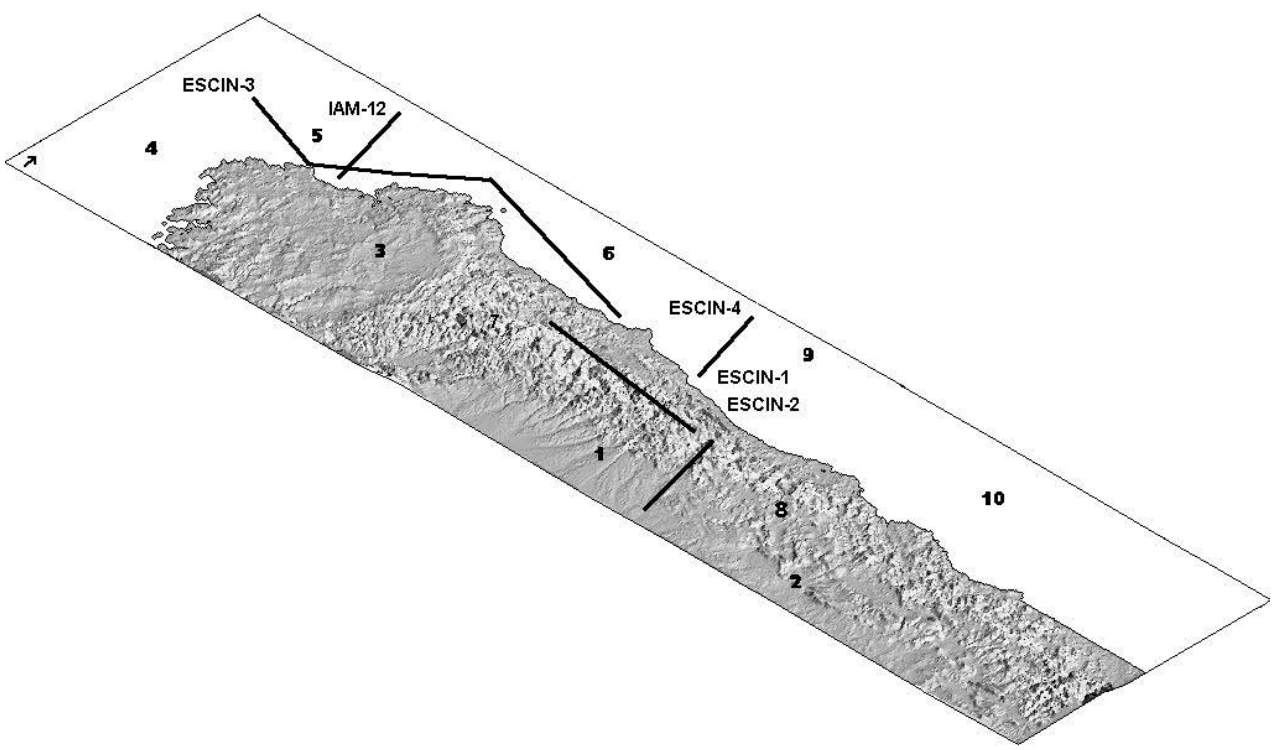

Fig. 7. Seismic profiles. [Heavy black lines = seismic profiles; 1: Duero basin, 2: Ebro basin, 3: Miño basin, 4: Atlantic Ocean, 5: Ortegal Spur, 6: Bay of Biscay, 7: Cantabrian Uplift, 8: Basque-Cantabrian basin, 9: Danois Bank, 10: Landes Plateau].

Table 3

Data Asturian mesoblocks

Mesoblock	Denomination	Localities	Strike	Fractures (%)	Hmax (m)	Maximum Altitudinal Difference or DV (m/km²)	Basins	Blocks	Fluvial' Knots
9.1	Oviedo	Avilés, Gijón, Miranda del Ebro, Mieres, Oviedo	E W	7	2.648	190	7	117	90
9.2	Bilbao	Bilbao, Casteiz, Pamplona, Santander, Santurtzi, San Sebastián	E W	5	1.421	200	7	65	45
9.3	Huesca	Barbastro, Foix, Huesca, Lleida, Lourdes	E W	8	3.555	60	8	120	600
9.4	Perpignan	Lavelane, Perpignan	E-W	3	2.913	620	5	12	100

Table 4

Data on the morpholineaments of the Septentrional macroblock

Lineament	Denomination	Order	Strike	L (km)	Ks	Number of Knots
A2	Almería	2	NE-SW	800	0,89	9
A7	Santa Tecla	2	NE-SW	270	0,93	3
A8	Navia	2	E-W to SE	650	0,98	6
A9	Rentería	2	E-W	370	0,96	3
L17	Miranda del Ebro	3	SW to N-S	180	0,78	1
L18	Pamplona	3	N-S	130	0,98	2

Table 5

Data on the morphotectonic knots of the Septentrional macroblock

Knot	Order	Denomination	Developed in the Lineament
33	3	Ourense	A7
34	2	Nogueira de Ramuín	
35	3	Becerreá	A7
31	2	Embalse de Meaumenza	
34	2	Nogueira de Ramuín	
36	3	Bembibre	
37	3	Pancorbo	
38	3	Haro	
39	3	Alfaro	A8
38	3	Haro	L7

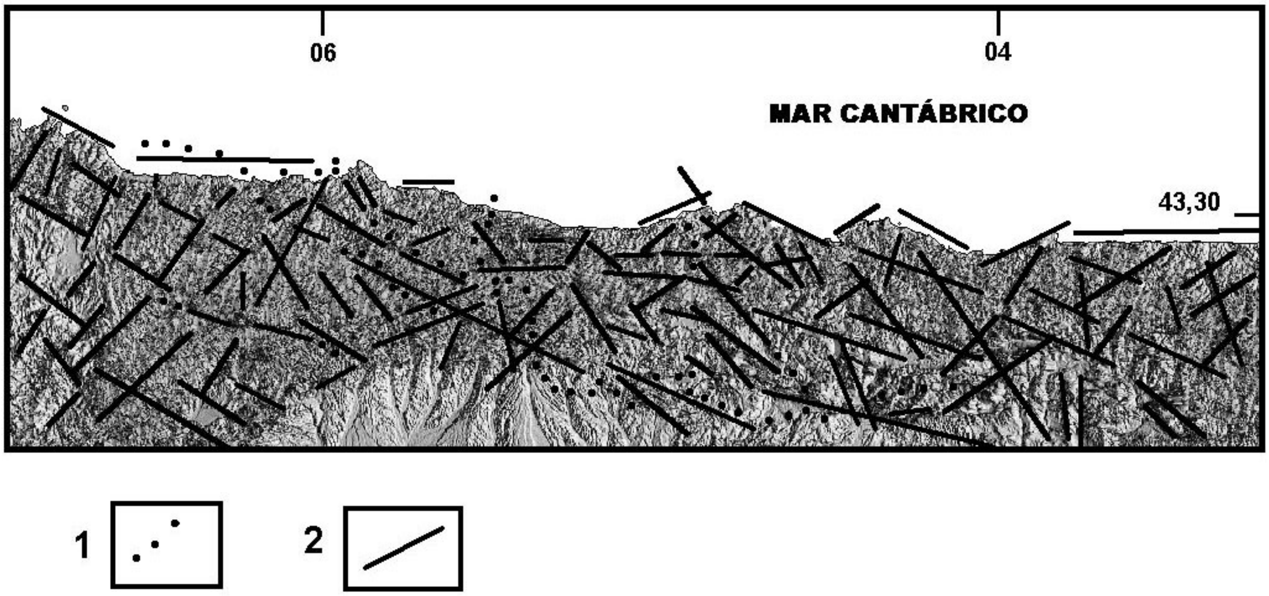

Fig. 8. Lineaments in Asturias. [Interpreted from: 1- the gravimetric data; 2- the relief].

convergence sediments overlying the oceanic basement. The oceanic crust of the Bay of Biscay underlies a very thick undisturbed sedimentary package about 3 km thick.

Compression in the Cantabrian Uplift (western prolongation of the southern Pyrenean orogenic front) and in the Le Danois basin was probably coeval with subduction. However, Neogene to Recent compressional structures in the Cantabrian Uplift and Le Danois basin indicate that deformation in the continental plate continued after subduction stopped. Recent tectonic activity is evidenced in the upper plate by minor seismicity, active uplift of the shelf, and the presence of recent slump deposits along sharp topographic breaks in the lower continental slope.

Iberian and Eurasian plate convergence activated the continental margin, and a marginal trench developed in the Tertiary. The trench is defined in the gravimetric map by a succession of negative anomalies in the E-W trend. The activation of the North Iberian Margin implicated the inversion of the extensional basins both in the continental shelf and on land and reactivated extensional faults as reverse ones. Also, it is possible to hold that the complete reworking of the Variscan crust that characterizes the Duero basin is evidenced beneath the Cantabrian Mountains and should be attributed to Alpine tectonics.

Using Bouguer's map of gravimetric anomalies of the IP, a narrow band appears that is latitudinally oriented with 0-50 mGal values from the western part of the IP to the east of Bilbao. Towards the continental interior there is another band approaching -50 mGal. The map also reveals surface gravimetric anomalies including a latitudinal band, but with small positive maximums and negative relatives, to the west of the longitude of Cabo Peñas and Oviedo. To the east of this line of longitude, the maximums are much fewer in quantity. To the south and east of Oviedo, a section of negative values of up to -18 mGal is found. To the northeast, in the locality of Muros and in the surroundings of the Narcea River, there is a chain of positive maximums. These structures not only could describe blocks of different dispositions and size like those commented upon in previous outlines, but also indicate the dimensions and directions of the most important fractures in the terrain. In this sense a framework is presented with alignments that are drawn using the transformations of the gravimetric field (Figure 8). To this end a computerized system was used (Córdoba, 1998) in order to: 1) delimit edges and alignments; 2) estimate ascending and descending analytical transformations.

Geophysics: seismicity

The reference works used in the outline are: Herraiz *et al*. (1998), Instituto Geográfico Nacional (1962-1966, 1967-1978, 1979-1980, 1981, 1982, 1992, 1996, 1997, 1998, 1999, 2000, 2003), Jiménez *et al*. (1999), Martín Martín (1984), Mezcua (1982), Mezcua and Martínez Solares (1983), Mezcua *et al*. (1980, 1991), Udías *et al*. (1989) and Udías and Buforn (1991).

Moderate seismicity is associated with convergence between Eurasian and African plates and is distributed over a wide area of deformation (Figure 1). This deformation can be explained by continent-continent collision. Seismic activity in Spain is considered moderate compared to other countries in the Mediterranean, a group which has the highest level in Europe. The seismicity of the Ibero - Mogrebí region can be divided into three large sectors (-30ºW/-25ºW, -25ºW/-13ºW, -13ºW/-10ºW), the central region being the most active. The seismicity of the central region as an interplate area shows the greatest frequency and energy produced. Meanwhile the seismicity of the interior of the IP is a different type and has attracted less attention. Nevertheless, we believe that it is no less important than the situation in the central region and is even more complicated to study. By studying 14 focal mechanisms, the interpretation given for this region is that the pattern of regional tectonic force is of maximum horizontal compression in a NW-SE direction.

In the context of regional tectonics, the present-day dynamic of the IP is a natural continuation of the historical – geological development experienced over time. This dynamic is found in the seismicity studied (historically and instrumentally) and by the observed neotectonic characteristics. In Table 6, we see that of the 12 most important earthquakes in Spain, none occurred in Asturias. Figure 9 lists the IP earthquakes according to a selection of data from the Instituto Geográfico Nacional (National Geographical Institute). The catalogue of the Instituto Geográfico Nacional (for years 0718-1995) lists 32 earthquakes in Asturias (Figure 10, Table 7), including 16 with a magnitude (Mmax=4,6), 8 with a determination of depth (Hmax=16 km), 8 with determinations of depth and magnitude, and two were situated in the maritime zone. Also, there are 14 seismic events in the preliminary catalogue of the Instituto Geográfico Nacional (1999-2003) (Table 8) with a Mmax=3,7. Of this group, Nos. 1, 2, 4 and 8 are in the maritime region. To the east of Asturias, in the same period, 158 events were identified with a Mmax=4,9. This result points to a significant difference in seismic activity. All of the earthquakes in Asturias are shallow (< 20 km).

Seismic zones can be delineated using maps of epicentral density (ED) and of seismic activity (SA) (Riznichenko, 1992). The former are cartographic entities that characterize the quantity of epicenters per unit area, but without differentiating on the basis of magnitude. They were applied here. Also, the isoseismal maps can support a research in order to identify a seismic source (Riznichenko, 1992). In Mezcua's catalogue (1982), there are three isoseisms in the Asturias region (Figure 11, Table 9). The zones where the isoseisms occur indicate the existence of at least two seismogenetic zones, both parallel and in an E-W direction, one in the marine area and another in the continental zone.

In Asturias and Cantabria there is no permanently working seismic station (Figure 12). Since the seismicity in the region is low, the level of detection of the closest stations cannot in any way register weak or very weak events there. Figure 9 shows the seismicity of the IP. The lack of information about Asturias compared to the adjacent areas is evident.

With a N-S profile from Cabo Busto passing through Cangas de Narcea and continuing to Dagaña it is possible to demonstrate that seismicity is located only in the eastern part. In general, seismicity is found around the Ría de Pravia, Oviedo and Colunga, which is on the coast. Also, the three seismic events found in the maritime sector are north of Cabo Peñas, in particular to the northwest and northeast. In the

Table 6

The strongest historic earthquakes of the Iberian Peninsula (Mezcua and Martínez Solares, 1983)

Date dd.mm.aa	Time hh mm ss	Coordinates Lat N; Lon W (-) E (+)	Depth (km)	Maximal Intensity (MSK)	Locality
18.12.1396	12 00	39 10.0; -00 15.0		IX	Tabernes-Valencia
02.02.1428	08 00	42 18.0; +02 23.0		IX	Camprodon-Gerona
05.04.1504	09 00	37 24.0; -05 36.0		X	Carmona-Sevilla
09.11.1518		37 13.0; -01 52.0		IX	Vera-Almería
22.09.1522		36 55.0; -02 30.0		IX	Almería
--.--.1645		38 42.0; -00 27.0		IX	Alcoy-Alicante
09.10.1680	07 00	36 30.0; -04 24.0		IX	Málaga
23.03.1748	06 15 00	39 00.0; -00 39.0		IX	Enguera-Valencia
01.11.1755	09 50 00	37 00.0; -10 00.0		X	SO del Cabo San Vicente
25.08.1804	08 30 00	36 50.0; -02 50.0		IX	Dalias-Almería
21.03.1829	18 30 00	38 06.0; -00 42.0		X	Torrevieja-Alicante
25.12.1884	21 08 09.0	36 57.0; -03 59.0	15	X	Arenas del Rey-Granada

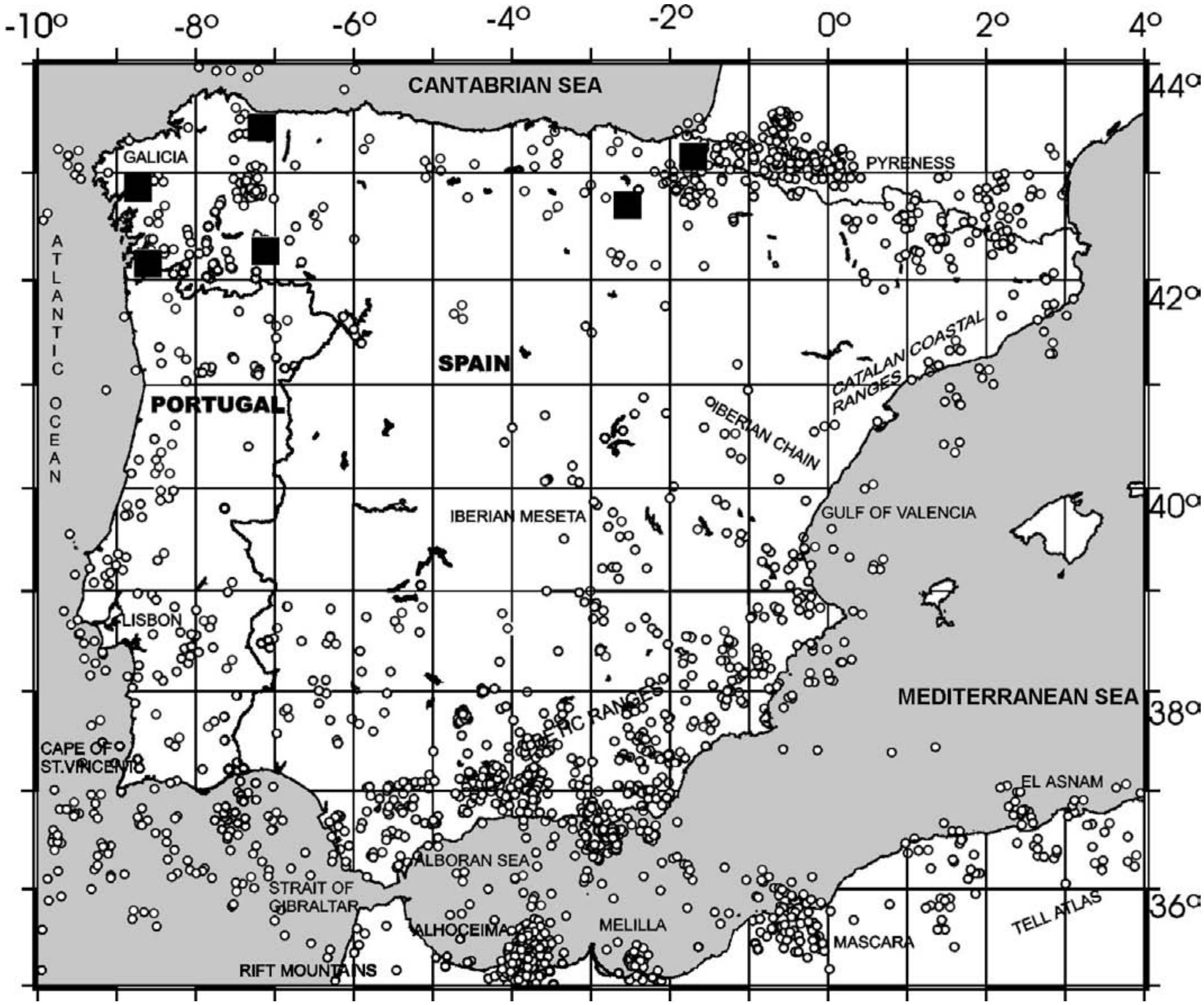

Fig. 9. Seismicity of the Iberian Peninsula (1979-1996). [Data provided by Instituto Geográfico Nacional. Circles = epicenters; black squares = permanent seismic station in the northern.]

sector north and west of Oviedo there is activity. Cotilla and Córdoba (2003) state that the alignment of Navia, around the towns of Sarria and Becerreá (in Galicia), is seismoactive.

With respect to the seismogenetic zones, Martín Martín (1984) presented a map of IP in which Asturias does not even have a source zone. On the other hand Jiménez *et al*. (1999), without commenting on Martín's map, considered Asturias-Cantabria to be a seismogenetic source with the parameter, b=1,02 (Mmáx=5,8) and an earthquake/year/km^2 estimation of (M> 4)= 6,4.10^{-6} with a Peak Ground Acceleration (m/s^2)= 0,4-0,8 value with 90% probability not exceeding 50 years. In an attempt to make a comparison, it is noted that Galicia has a value range of 0,8-1,6. And in Cotilla and Córdoba (2004) it is argued that Asturias belongs to zone C (from Figure 13), the region with the lowest level of seismoactivity of the IP.

4. RESULTS AND DISCUSSION

According to the framework of the morphoisohypsis of the IP (Figure 12) (Cotilla and Córdoba, 2004) the Cantabrian edge is defined as having a large rectangular block (macroblock) with an E-W direction (isoline of 400 m), a symmetry that manifests itself in blocks of smaller areas and maximum altitudes above 1500 m. The largest block is divided in a NW direction, along the continuation of the Ebro River. The area of the Ebro is made up of two blocks at alti-

Table 7

Data on Asturian earthquakes (0718-1995) (Instituto Geográfico Nacional)

Nº	Year	Month	Day	Hour	Min	Sec	Lat N	Lon W	H (km)	M_b	I (MSK)	Locality
1	0718						43,30	05,10				Asturias
2	1522	06					43,37	05,83				Oviedo
3	1755	10	31				42,70	06,00			V	León
4	1843	11	12				43,50	05,67				Gijón
5	1861	10	10				43,55	06,13				Cudillero, Oviedo
6	1877	09	10				43,60	06,10				Cudillero, Oviedo
7	1897	03	08				43,55	05,67				Gijón
8	1909	05	03	00	30		43,33	06,42			V	Gijón
9	1915	01	02	19	06		43,20	06,30			IV	Tineo, Oviedo
10	1930	08	18				43,33	06,42			VI	Sta.Mª Genestraza, Oviedo
11	1930	08	21	01	00		43,30	02,60			III	Cangas de Tureo, Oviedo
12	1932	04	27	23	20		43,30	04,40			IV	Cabezón de la Sal, Santander
13	1932	04	28	02	53		43,30	04,40			III	Cabezón de la Sal, Santander
14	1932	05	03	11	32	42	43,30	04,40			III	Cabezón de la Sal, Santander
15	1932	05	04	16	30		43,30	04,40			IV	Cabezón de la Sal, Santander
16	1932	05	06				43,30	04,08				Caldas de Besaya
17	1950	04	04	03	06	22	43,30	06,00		4,6	VI	Teverga, Oviedo
18	1965	01	07	13	30	27	43,20	04,10		4,1	VII	Reocín
19	1965	05	09	12	57	29	43,14	-04,04		3,6		NE of Reinosa, Sant.
20	1975	08	01	02	49	46,20	43,20	-05,21	5,0	3,5		SE of Pola de Laviana, Oviedo
21	1976	11	26	09	16	53,70	43,33	05,24	1,3	3,4		Cangas de Onís, Oviedo
22	1982	11	29	07	15	19,60	43,80	-05,50	0,9	3,5		Mar Cantábrico
23	1983	04	20	19	13	50,70	43,51	05,29	16,0	3,9		Oviedo
24	1987	02	19	02	17	52,30	43,05	05,03	5,0	3,1		León
25	1989	02	20	20	52	28,80	43,11	05,10	9,0	3,7		Oviedo
26	1989	10	26	03	14	53,20	43,77	-06,12		3,4		Mar Cantábrico
27	1990	03	23	04	17	43,60	42,77	04,56	5,0	3,2		León
28	1990	03	27	00	02	43,90	43,08	04,47	5,0	3,1		Santander
29	1991	03	09	14	02	37,00	43,01	06,18	10,0	2,9		León
30	1993	06	28	03	25	41,90	43,02	04,90	15,0	3,2		León
31	1993	11	16	20	13	26,30	43,21	05,39		2,8		Oviedo
32	1995	03	11	08	02	50,40	43,22	05,87		3,2		Oviedo

tudes higher than 1000 m: 1) West (approximately coinciding with the Cantabrian Range), 2) East (including the Pyrenees). By looking at another map with a different detail scale, in Asturias (Figure 13) it is possible to underline a group of specific characteristics that allow us to assume that many other diverse blocks exist there.

The Ks applied to the Cantabrian coastline show the tectonic conditioning, and in particular the coast is a decidedly straight line along the length of the Asturian coast. Accordingly, the sector from the Eo river (Ribadeo estuary), in the west, to the Deva river, in the east, has a Ks=0,81. This could be explained by a system of parallel faults, active in a normal way, which at the present time are below the sea.

The uplift, seen at a scale of 1:50.000, of the drainage network of Asturias has permitted us to draw more than thousand rivers of different orders (Figure 5D). Their average density is 0,69 km/km^2, which is relatively low. This network has a dendritic shape and in general there are few meanders (< 4%). Their fundamental characteristic is narrowness (52% of the rivers have a "V" shape), and they fall quite steeply. The total length of the network is approximately 6000 km. A significant variation in the number of rivers occurs

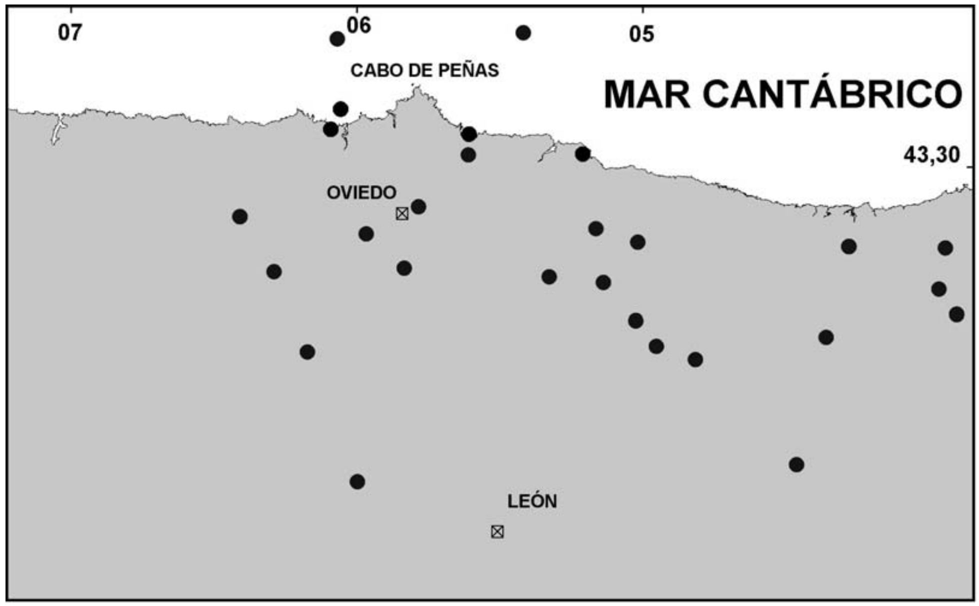

Fig. 10. Seismicity of Asturias. [Data provided by Instituto Geográfico Nacional. Black circles = epicenters.]

Table 8

Selection of Asturian earthquakes (1999-2003)

Nº	Year	Month	Day	HH	MM	Lat N	Lon W	Mb
1	1999	05	28	08	51	44,13	-07,66	3,1
2	1999	09	23	09	07	44,17	-07,91	3,7
3	2000	02	03	22	15	43,36	-06,32	2,1
4	2000	10	03	20	41	43,73	-03,45	2,2
5	2001	02	19	02	10	43,21	-05,91	2,6
6	2001	08	05	19	32	43,74	-04,91	2,6
7	2002	02	08	01	32	43,05	-05,09	2,6
8	2002	02	18	11	17	43,95	-07,03	2,0
9	2002	03	09	01	19	42,61	-06,38	2,3
10	2002	05	05	14	15	43,11	-05,51	2,4
11	2002	06	01	04	44	43,01	-07,22	1,6
12	2002	07	01	02	35	42,90	-05,09	1,7
13	2003	01	14	22	08	43,36	-06,49	2,0
14	2003	01	29	00	21	43,02	-06,65	2,3

based on elevation. Accordingly, 70% of rivers are situated at elevations of <400 m, between 400 m - 1000 m we find 26%, and >1000 m only 4% exist.

Using the data from the IPEF method as a starting point, five principal zones are found in Asturias (Figure 5C). The values of this parameter rise, in general, from west to east, with maximum values occurring in the eastern basin of the Nalón river. Minimum values appear near the coast and from Avilés in the west to Ribadesella in the east. Although the listing of average slope points out the heterogeneity of Asturias, it also allows us to visualize the zone from Avilés to Ribadesella as one of lower values and more regularity. Consequently this sector could be considered a block.

All of the rivers of 5th order of the Narcea of the Nalón have a clear N-S direction. The Nalón and one of its tributaries, the Aller, border, on opposite sides, the Picos Pollo (1051 m) and Culladiella (1105 m) and the Sierra de San Mamés (which constitute a block) and later meet in Ferreros, to the south of Oviedo where the Nalón reaches order 7. A bit farther downstream, specifically in Pravia, the Nalón bends north

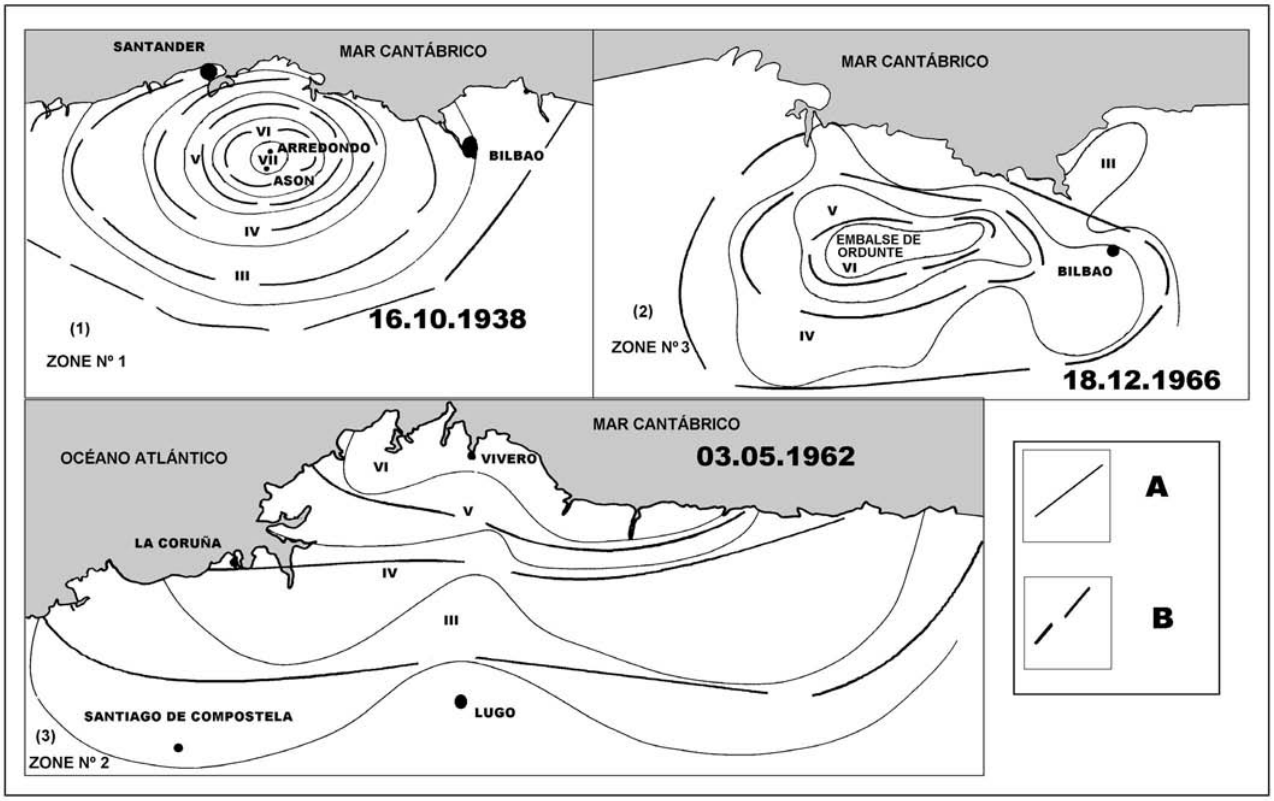

Fig. 11. Zones of isosists in the north of Iberian Peninsula. [See Table 9. {A: model, B: eliptical adjustment (according to Cotilla and Córdoba (2004))}. Belonging to: mesoblock 9.2- (1) and (2); Galicia macroblock- (3).]

Table 9

Data on the isosists (Mezcua, 1982)

Nº	Date	Time (hh:mm:ss)	Lat N	Lon W	H (km)	M_b	I (MSK)	Locality
1	16.10.1938	02:19:45,0	43,15º	-03,37º		4,9	7	Arredondo
2	03.05.1962	23:27:22,8	43,53º	-07,09º	5	4,3	6	Cantábrico
3	18.12.1966	13:51:36,0	43,15º	-03,18º		3,8	6	Embalse de Ordunte

to flow into the Pravia fjord. The Narcea does not make the Nalón rise in order. The morphoisohypsis at 1000 m marks the end of the 5º order rivers south of Oviedo.

In general, the principal rivers in Asturias initially run in a NE or NW direction and later change to a S-N course. The bearing of the Nalón river changes many times and its watershed has a rectangular shape aligned in an E-W direction. This watershed is very asymmetric. The aforementioned E-W alignment manifests itself in Pravia - Oviedo - Pola de Siero - Infiesto - Cangas de Onis - Buria de Onis. In this region, the headwaters of the Nora (a tributary of the Nalón) and Sella are involved, but in different directions. The Sella river, in the northeast part of Asturias, changes direction, from E-W and N-S to NE when it meets the Ribadesella. Other rivers: 1) Noreña (tributary of the eastern branch of the Nalón river); 2) a) Piloña (tributary of the western branch of the Sella) and b) Gueña (eastern tributary of the Sella); 3) Cares (western tributary of the Dera) are markedly aligned E-W, and in the Nausa the asymmetry is to the west and the E-W inflection disappears. The watershed of the eastern part of the Deva is also asymmetric. This asymmetry is manifested to the east in a rectangular watershed approximately parallel (Sierra de Cuera) to the coastline. The watersheds of the Eo and Navia rivers, situated in the western part of Asturias, are approximately rectangular in a N-S direction and have Ks of

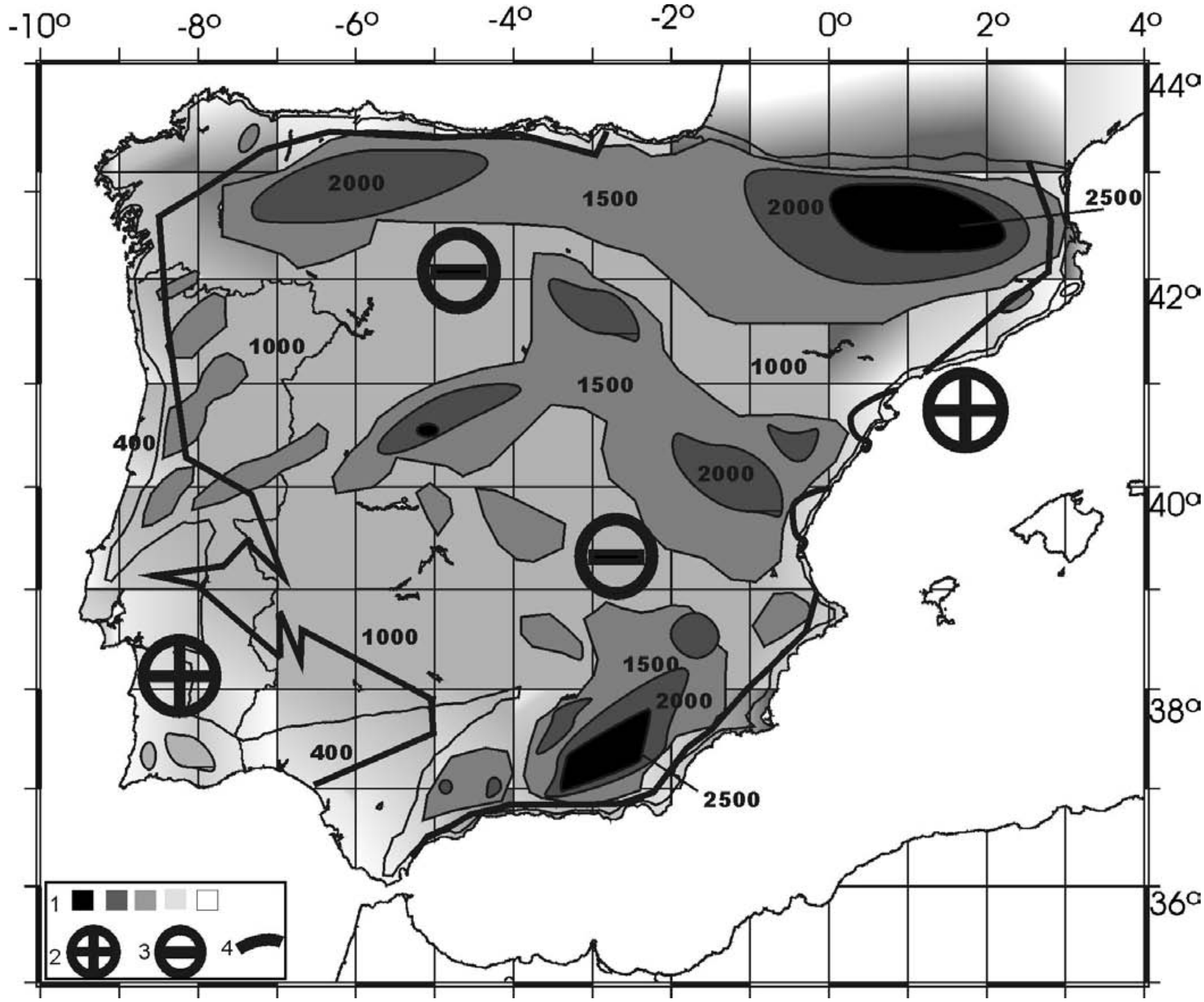

Fig. 12. Simplified morphoisohypses map of Iberian Peninsula. [Original scale 1:500.000. 1: Selection of isobases in five grey colour intervals (in meters); 2 / 3: represent signs of values of Bouguer Anomalies (Mezcua and Benarroch, 1996); 4: zero value of Bouguer Anomaly (Mezcua and Benarroch, 1996).]

0,80 and 0,86, respectively. The Navia river reaches order 6 near the town of Becerreá (Galicia) and maintains this order practically throughout the length of its course. This is the river whose headwaters are farthest from the coastline. The Navia river collects water fundamentally between two PPSO, parallel to each other, 25 km apart, and does not have tributaries that increase its order in Asturias. From the point where it reaches this order, it maintains a straight NE course. The Narcea river also reaches order 6, but in the town of Cangas del Narcea, and keeps a NE course until approximately the town of San Bartolomé (to the east of Grado) and later heads north for 15 km to join the Nalón.

As was stated before, the arrangement of the principal mountain alignments in Asturias is related to the installation of reverse faults in the Tertiary, just as it is in the rest of the Cantabrian Range. Over this alpine relief the river network flows down steep slopes. Among the existing fluvial formations existing in the region there are basins, flood fans, alluvial plains, valleys and terraces. The flood formations are located in detritic lithologies although their development is favoured by sharp inclines (> 40º). "V" –shaped transverse sections of river valleys are characterized by the presence of breaks in the slopes on the sides, linked to the presence of resistant rocks. Occasionally the valleys are flat-bottomed ("U"-shaped).

There is a significant contrast between the source and the inferior course of Asturian rivers. This is noticeable in the valleys they pass through and their longitudinal profile.

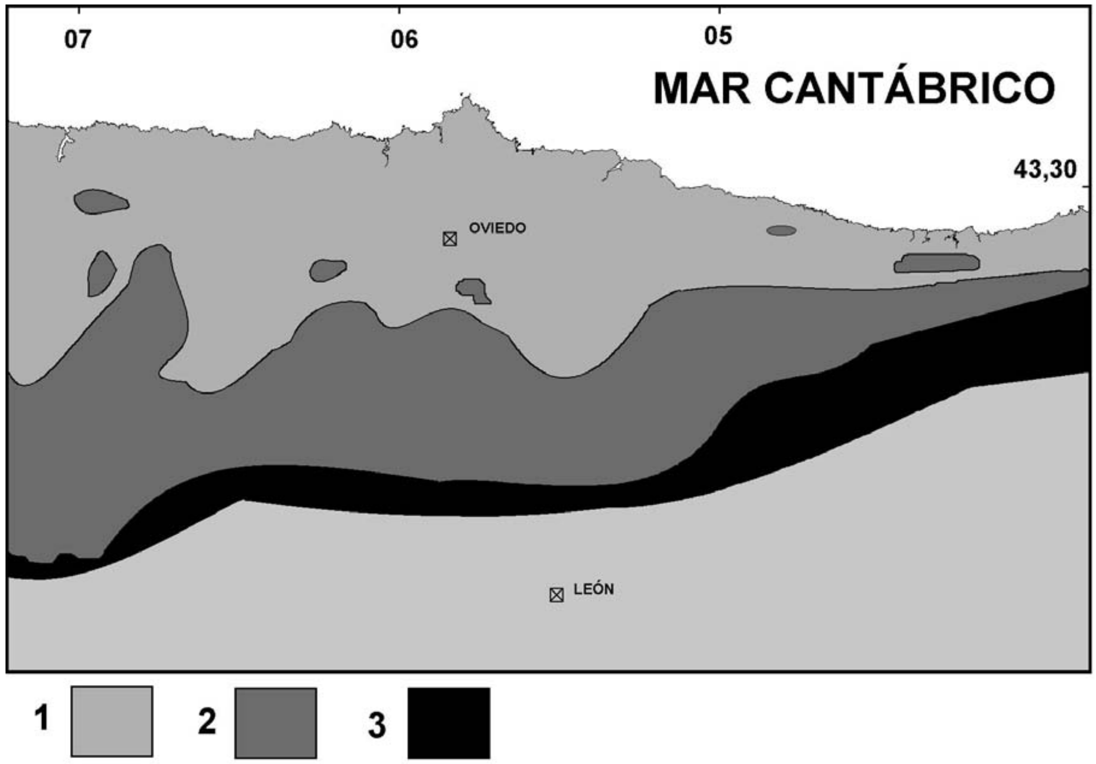

Fig. 13. Morphoisohypses sketch of Asturias. [1: 0-1.000, 2: 1.000-1.500, 3: 1.500-2.000 (m)].

Two distinct stretches appear: 1) the superior one (h> 600 m), which is quite irregular, given its sharp slopes and the broken-relief structures; 2) the inferior one, with smoother and generally uniform slopes (< 2,5º). From this evidence it is possible to state that the higher part of the profile is not in equilibrium. On the other hand, the lower valleys display a certain maturity and even senility. The river sources, in contrast, rise suddenly up over these lower courses and have young characteristics. This phenomenon generally occurs above 300 m, where valleys cut into the mountains and appear devoid of sediments, whereas below this elevation there are only wide valleys, in fluvial troughs, with well-developed alluvial deposits. The fill in the last kilometres before the river mouths is especially important due to the width and depth of the deposits.

In the Cantabrian river network in general, and in the Asturian network in particular, two types of rivers are identified based on their structural conditioning: 1) those that flow through natural structures formed by fractures and which later are channelled by basins and Tertiary depressions. Usually their direction is E-W, changing later to S-N, following the dominant structural directions (i.e. the Nalón, the Norta and the Piloña); 2) those that cut into the underlying structures, channelled by fractures and tectonic alignments. Their courses are almost straight S-N, perpendicular to the coast and are the steepest and shortest (i.e. the Sella, the Pas, the Mier and the Nervión).

Tables 10 and 11 list eight flow parameters for the Eo, Navia, Narcea, Nalón and Sella rivers. The lists record that the Sella and Navia rivers are the steepest and gentlest gradients, respectively. Nevertheless, their sources are not the highest in the region. A fluvial tributary (Murmillos) of the Narcea has the steepest gradient in Asturias and the province also has other sectors with very steep drops. The San Isidro river (tributary of the Nalón) is an example. Three areas of anomalous gradients in tributaries are identified: 1) Cubia, Riosa, San Isidro, Teverga and Trubia, tributaries of the Nalón; 2) Pigüeña and Saliencia, tributaries of the Narcea; 3) Dobra and Ponga, of the Sella. These sectors correspond to important fractures in the terrain.

The terraces and associated alluvial flats of the main river valleys have areas with different types of deposits (poorly preserved, discontinuous and affected by the tectonics). The terraces have incomplete sequences, they are asymmetric and not well developed. The flood plains are only found in wider sectors of the fluvial valleys, generally belonging to the lower third of the profile. Meanwhile, in the higher sectors of the principal rivers there is important evidence of movements of earth on the sides of the hills. The

Table 10

Data on the Asturian rivers

River	Order	Ac (km^2)	L (km)	Maximum Slope (%)	Mean Slope (%)	Slope (m/km)	Tributaries	Location	Strike	Ks
Eo	5	819	78,50	16,09	4,03	9,11	Bidueiso, Cabreira, Suarón	W Oviedo	NE	0,80
Navia	6	2.572	178,45	13,33	5,15	6,95	Agüeira, Ibias	W Oviedo	NE	0,86
Narcea	6	2.468	123,11	7,70	3,84	12,18	Cibea, Muniellos, Naviego, Pigüeña, Saliencia, Somiedo	W Oviedo	NW	0,79
Nalón	7	4.827	144,85	19,75	6,60	9,94	Aller, Caudal, Cubia, Nora, Riosa, San Isidro, Teverga, Trubia	SW Oviedo	E-W/NE	0,42
Sella	7	1.246	72,94	27,70	9,58	21,94	Dobra, Piloña, Ponga	E Oviedo		0,81

Table 11

Data on the Asturian rivers and their tributaries

NALÓN

Tributary	L (km)	Order	Ks	Slope (%)	Mean Slope (%)	Slope (m/km)	Abnormal Slopes
Aller	42,29	6	0,72	27,00	10,15	35,47	
Caudal	61,38	6	0,80	23,50	8,73	22,48	
Cubia	41,00	4	0,88	17,17	7,08	28,78	1
Nora	88,65	5	0,73	20,00	7,52	3,84	
Riosa	16,14	4	0,87	23,00	8,61	61,96	
San Isidro	20,90	5	0,91	35,08; 25,00	11,21	80,38	2
Teverga	31,70	5	0,89	5,92; 17,33	6,54	50,47	2
Trubia	46,34	6	0,82	19,10; 12,50	7,61	33,66	2

NARCEA

Tributary	L (km)	Order	Ks	Slope (%)	Mean Slope (%)	Slope (m/km)	Abnormal Slopes
Cibea	21,30	4	0,83	23,33	9,99	74,18	
Muniellos	13,00	4	0,82	36,36	16,22	104,62	
Naviego	32,70	3	0,77	21,74	9,15	52,60	
Pigüeña	49,28	5	0,85	63,63; 6,15	13,04	29,22	2
Saliencia	16,42	4	0,92	7,82; 6,03; 5,91	3,59	84,04	3
Somiedo	29,12	4	0,92	41,17	13,17	63,19	

NAVIA

Tributary	L (km)	Order	Ks	Slope (%)	Mean Slope (%)	Slope (m/km)
Agüeira	44,66	5	0,90	4,15	2,03	18,81
Ibias	60,56	5	0,89	6,10	2,83	20,81

SELLA

Tributary	L (km)	Order	Ks	Slope (%)	Mean Slope (%)	Slope (m/km)	Abnormal Slopes
Dobra	24,44	4	0,88	17,50; 13,20	8,76	63,83	2
Piloña	57,88	5	0,89	30,30	10,73	13,81	
Ponga	28,67	5	0,91	20,00; 15,60	9,74	51,62	2

severity of the movements are related to the following factors: 1) structure and lithology, 2) altitude and slope, 3) moisture and vegetation cover.

Jiménez Sánchez (2000) results coincide with ours for the sector belonging to the northeastern source of the Nalón river. On this basis, and given the dimension and shape of the Nalón river basin, it is possible, for the purposes of neotectonic analysis, to consider that it covers two different regions: 1) the eastern one (the Nalón basin); 2) the western (the Narcea basin). The eastern region is located mostly in the middle of the central Carboniferous basin, and its sculpting has been done almost completely in slates, arsenics and conglomerates, in mountain limestones, and in Devonian only, on the edges of the basin. On the other hand the Narcea region developed principally over slates and Cambrian quartzites and Silurians, and in its lower portion in the Devonian. Noticeably, the Sil river (the most important tributary of the Miño river) begins on the opposite slope, but in the same sector as the Narcea river. The Nalón basin structure is a result of the meeting of two superimposed styles: 1) initially Hercynian tectonics of the Jurassic style; 2) alpine tectonics of blocks bordered by vertical faults. Both styles have had a marked influence on the morphogenesis.

Table 12 records the number of Principal Divides (from orders 1 to 5) in Asturias. Using the framework of the fluvial network of the IP (Figure 5A) (Cotilla and Córdoba, 2004) it is possible to appreciate that: 1) the PPPO is approximately parallel to the coastline and that to the south of the Navia river basin it has a marked inflexion that could be associated with earthquakes in Sarria - Becerreá); 2) the northern basins of the PPPO are considerably smaller than the southern ones. This is much more evident when looking at the outline of the PPSO. In particular, in the area of Asturias there are three different fluvial limits with: 1) the Duero to the southwest (the largest); 2) the Ebro basin to the southeast; 3) the Miño basin to the west and the southwest (the smallest). The PPPO is located exactly on the southern edge of Asturias, from approximately the Cienfuegos mountain pass (in the Sierra de Ancares) to the Ventaniella pass, and later continues to the east towards Cantabria. A little farther north the parallelism with the morphoisohypsis at 1500 m is clear.

Based on the evolution of the Principal Watershed in Asturias, we believe that it is very significant that: 1) all of the “large” basins are bordered on the south (their headwaters) by the PPPO; 2) the slopes of the fluvial basins from the PPPO to the coast are longer in the west, and diminish to the east. Also, it is noteworthy that the PPSO in the Nalón and Sella river basins is parallel to the coast. To the north of the Nalón river's PPSO (the surroundings of Áviles – Gijón, Villaviciosa and Collenga) the system is clearly oriented E-W although there is a definite N-S alignment at the headwaters of the basins of the tributaries. The PPSO of the eastern part of the Nalón river basin keeps a NW direction just like the PPPO of the IP in the Asturias - Cantabria sector. The Nalón basin is bordered on the east by a PPSO oriented approximately N-S. From the Pravia river mouth, which has an approximately N-S direction from the Narcea river and toward which the Nalón river bends, it is obvious that there is tilting to the west as far as the mouth of the Ribadeo. To the east of the PPSO of the Navia river, the fluvial network is manifestly irregular and heterogeneous. It is the high basin of the Navia river that reflects the bending of the PPPO of the IP in the northwest sector. The estuary at Áviles (Villaviciosa) is characterized by the presence of small rivers, which are located to the north of the PPSO. A similar situation is the mouth of the Santusto, to the west of the Tina Menor estuary.

It is clear that in Asturias there has been a significant rise in the number of PPTO, PPCO and PPQO. This can be detected, as was previously seen, in the rivers (i.e. the Sella river basin). There is also dissymmetry in fluvial slopes separated by these divides and it is very pronounced in the south and southeast. From the mouth of the Pravia river to the Ribadesella there is no fluvial course greater than order 3, and there are only a series of short divides with orders 3, 4 and 5. Spatially this zone corresponds to a coastal block not typical of the Asturias style.

Also, it is possible to hold that the fluvial morphology of Asturias is conditioned by four factors: 1) the lithological variety of the Palaeozoic substrata; 2) the influence of Hercynian and alpine tectonics; 3) the Quaternary evolution of the zone; 4) the structure. In this way it is possible to confirm that the course of the principal rivers is, in general, a result of the tectonic gradients shaped during the Tertiary deformation, which created the relief of the Cantabrian Range.

The sectors of neotectonic uplifting on the 2nd – 3rd order (the youngest ones) are located approximately to the north of the morphoisohypsis at 1500 m. There is a spatial coincidence of the highest altitudes and the maximum values of the DV parameter. The area where they coincide is small. The highest value is found in the immediate area of Somiedo - Cordal de la Mesa - Monte Raneiro (which corresponds to the headwaters of the Narcea and its tributaries, Somiedo and Saliencia, and the tributary of the Nalón the Trubia). Also there are some sectors a little more to the east, in the Cordal de Carrocedo - Serranía de las Fuentes de Invierno Range (at the headwaters of the Nalón). At the same time the sectors of 4th –5th order, the oldest found here, are discovered fundamentally at a lower altitude (~800-1000 m) than those of 2nd-3rd order. Their areas are also larger. There is a spatial coincidence of uplifted sectors of the 2nd-3rd order with those of 4th-5th order in Somiedo, Cordal de los Llanos and the Serranía de las Fuentes de Invierno. This means that these zones have always had a tendency toward uplift in the neotectonic stage. Uplifted sectors have not been found to the north of the latitude of Oviedo. The area of sectors of 2nd-6th order (the greatest time interval) covers practically all of the territory of Asturias. Figures 14A, 14B and 14C show zones of the IP and Asturias with a tendency for tectonic movement, always in agreement with the methods applied here.

The study of fractures in Asturias establishes a territorial division (Figure 15) into four approximately rectangular shaped zones: 1) from Punta de Foz Escairo (in Galicia) to the mouth of the Navia, on the north coast, and from Triacastela (in Galicia) to the Sierra de Ancares, in the south, predominantly N-S in direction; 2) from the mouth of the Navia to the Pravia estuary and from the Sierra de Ancares to the Sierra de Sobia, to the south of Oviedo, predominantly NE in direction; 3) from the mouth of the Pravia to Ribadesella and from Oviedo to Cangas de Onís, predominantly N-S; 4) to the south of Oviedo - Cangas de Onís predominantly in N-S and NW-SE directions. In general there is increasing fracturing from north to south. The density of the fractures in these zones differs greatly. The greatest density is in zone 2, in the surroundings of the Sierra de Degaña, Conón, Pico Albos - Somiedo. The lowest density is in zone 4. The density is also low in Oviedo – El Entrego - Pola de Siero. We interpret the shape of the Nalón river basin and its tributaries, in the context of a specific type of fracturing, as the result of the deformations produced by tectonic activity and later reactivation related to this network of fractures.

By taking advantage of the results of all the previous

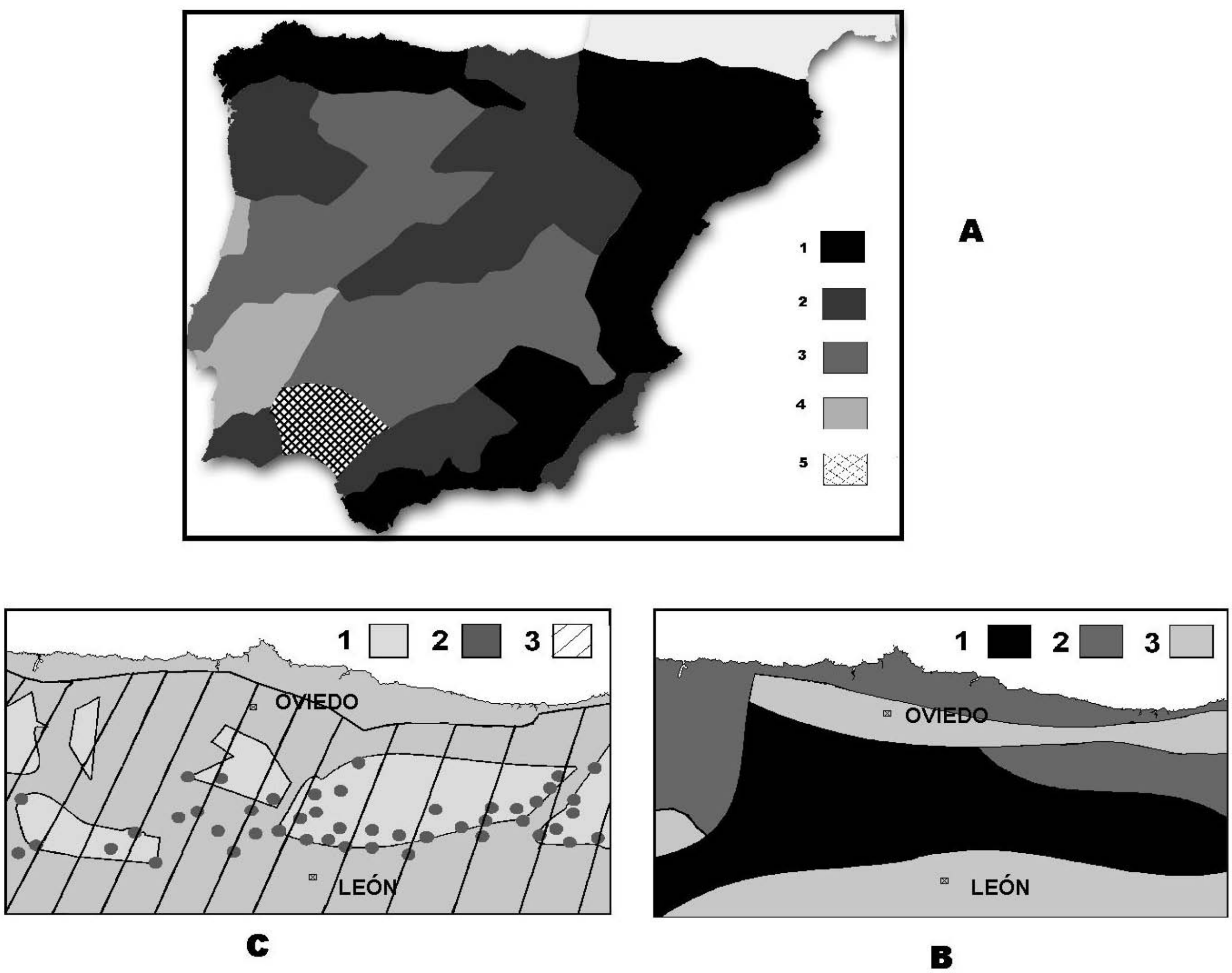

Fig. 14. Neotectonic zones determined by morphometric methods. [{All methods: A) Iberian Peninsula (Uplifting: 1- intense, 2- moderate, 3- weak; Downthrow: 4- intense, 5- weak); B) Asturias (Uplifting: 1- intense, 2- moderate, 3- weak)}; {Isobase differences in Asturias: C) 1: 2nd–3rd order, 2: 3rd-4th order, 3: 4th-5th order.].

research methods, it has been possible to set up a suitable framework which establishes the morphotectonic regionalization of Asturias (Figure 16). The greatest neotectonic complication is found to the west of Pravia. The greatest quantity of blocks, morphoalignments and knots occurs in this zone. The largest amount of neotectonic uplift is also found in the eastern part of the region. Also, geomorphologic data tells us that there are three areas of neotectonic interest in the central part of Asturias. They are situated to the south of the Pravia estuary and to the east of Oviedo. They are: 1) the immediate surroundings of the Las Traviesas, Begega and Sellera Sierras, where the Narcea and its tributary, the Pigüeña, meet; 2) the area around the Pravia where the Sandamías, Sellera and Fontebona Sierras appear and where the Nalón and Narcea rivers join; 3) the meeting point of the Nalón and its tributary the Nora in the west of Oviedo.

Table 13 shows the quantity of morphoalignments and knots, from order 2 to 6, found in Asturias. A description of these morphoalignments and knots appears on tables 14 and 15, respectively. It is evident, from the morphotectonic classification carried out, that there is a transversal differentiation in the Asturian territorial units (Figure 16). Therefore blocks 9.1.1 and 9.1.4 make up the main NE axis and blocks 9.1.2, 9.1.3, 9.1.6 and 9.1.7 are practically latitudinally oriented. Block 9.1.5 is a structure that serves as an inflexion zone between the two groups comprised by the aforementioned blocks, since it has a N-S direction. It can also be stated that to the west of the Pravia knot (5) there are morphotectonic blocks with a NE direction, to the south the direction is clearly N-S and later it changes to NW. Bordering this knot there are two latitudinal blocks parallel to the coast (Nos. 9.1.2 and 9.1.3). In general, there is a predominance of E-W and N-S directions in the outlined blocks.

Three order 4 morphotectonic knots are located in the surroundings of Oviedo (Nos. 4, 5 and 6) (Figure 16). Previously it was mentioned that there are important geomorphologic contrasts near Oviedo. The lineament L9 is also linked, in Asturias, with four knots of the 4th order (Nos. 5, 6, 7 and 12) and this undoubtedly gives it the highest level of importance (Figure 16). This morphoalignment approximately coincides with the Ventaniella fault in its southern and central parts.

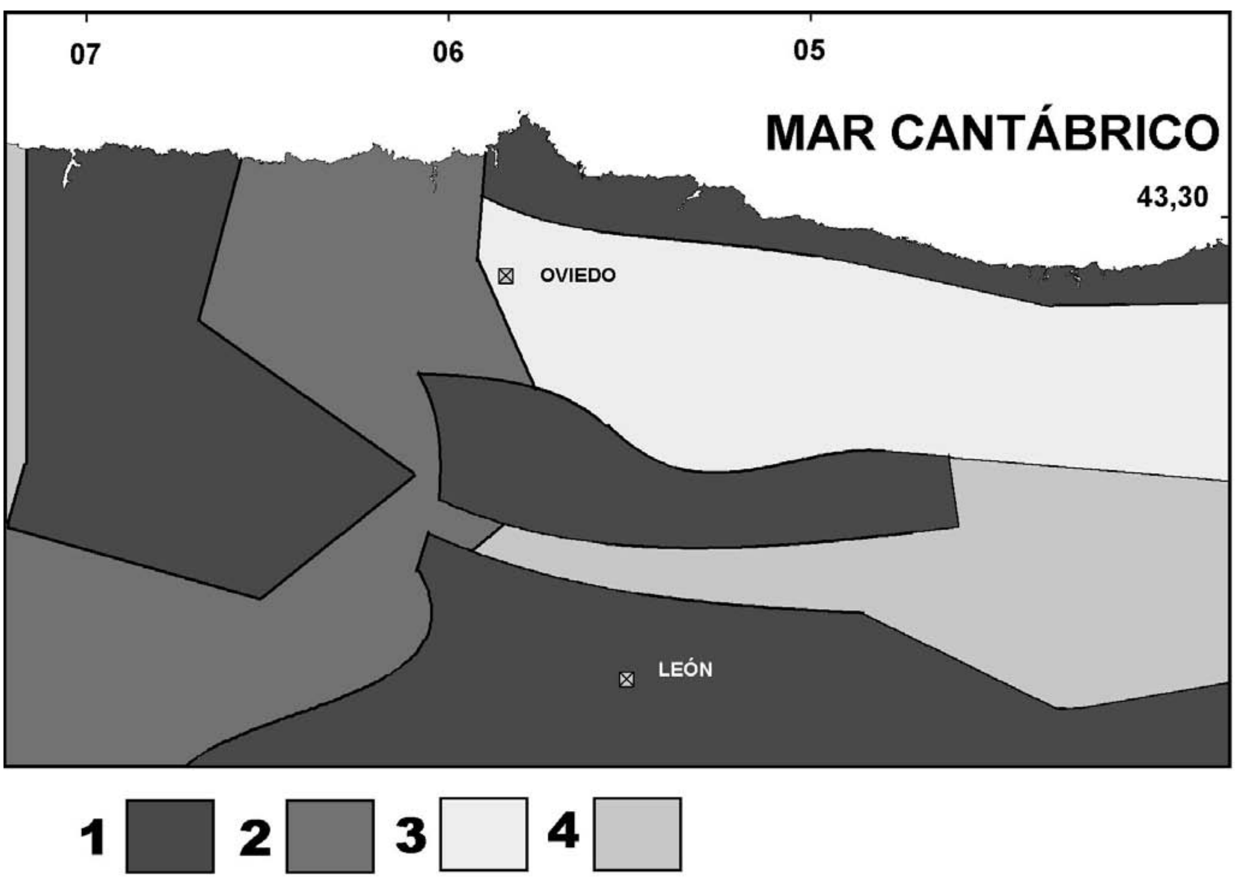

Fig. 15. Representation of the fracture zones in Asturias. [Direction: 1- N-S, 2- NE, 3- NW, 4- E W.]

Table 12

Data on the Asturian Main Watersheds

Main Watershed (PP)	Number
First Orden (PO)	1
Second Orden (SO)	6
Third Orden (TO)	12
Fourth Orden (CO)	12
Fifth Orden (QO)	3

Table 13

Number of the morphotectonic elements (lineals and their intersections = knots) in Asturias

	Order				
	2º	3º	4º	5º	6º
Lineaments	1	1	10	35	77
Knots	-	2	11	31	86

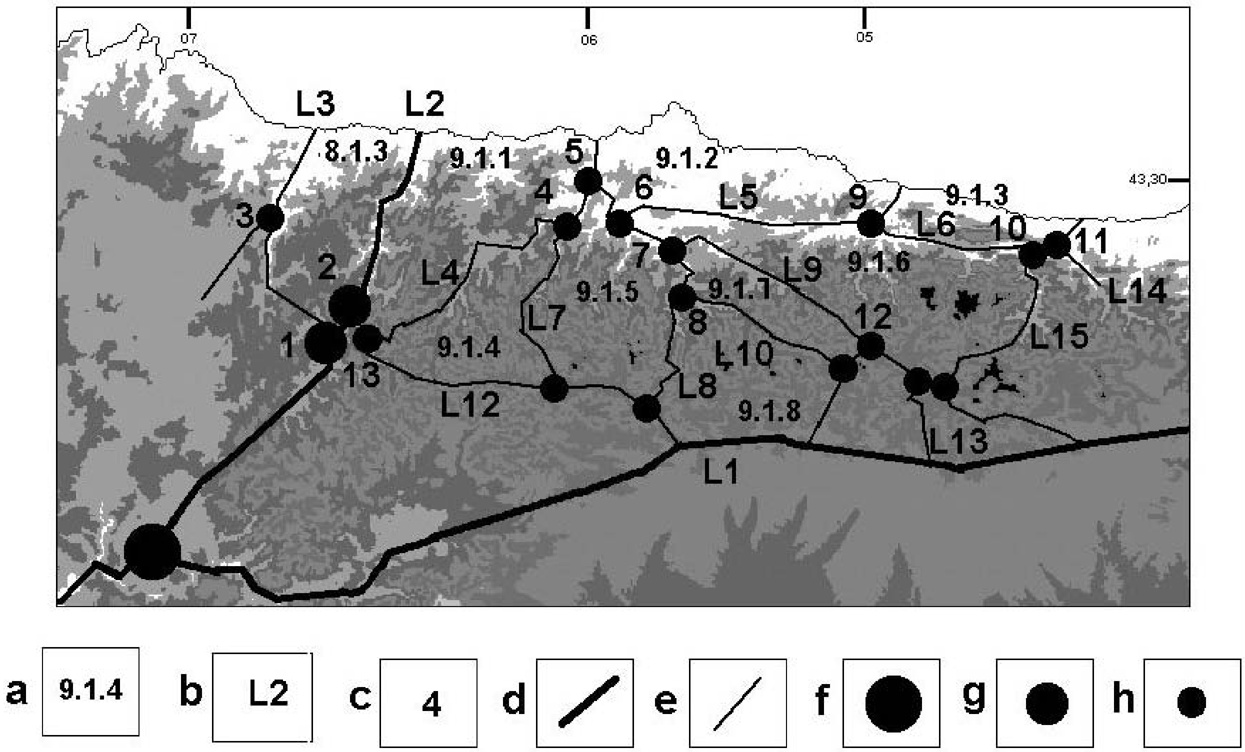

Fig. 16. Morphotectonic sketch of Asturias. [Identification of: {a- block, b- morpholineament, c- knot}; Order of morpholineament (see table 14): {d- 2nd, e- 3th}; Order of knot (see table 15): {f- 2nd, g- 3th, h- 4th}.]

It should be pointed out that: 1) in blocks 9.1.4, 9.1.5, 9.1.6, 9.1.7 and 9.1.8 there exist sectors of neotectonic uplifts; 2) these sectors correspond to blocks 9.1.5, 9.1.7, and 9.1.8, precisely where these sectors are most active; 3) there is a direct relationship between the Asturias mesoblock and A) the Galicia marcoblock; B) the Cantabria mesoblock. For this reason, although the surface area of Asturias is smaller, a comparison is made in Table 16 with the mentioned structures (Cantabria and Galicia).

We consider Asturias to be, from a morphotectonic point of view, a transition zone between the Pyrenees and Galicia. In the former there is a predominance of E-W oriented morphostructures and in the latter NE. This morphotectonic regionalization corresponds reasonably with transversal and longitudinal differentiation of the crust found in seismic profiles. Therefore, on the basis of the depth of the seismoactive layer, we find that the seismogenic potential of the eastern part of the Asturias is greater than the western part.

It is well-known that seismicity indicates the activity of structures (Riznichenko, 1992). Accordingly, since seismic events exist in: 1) the marine structure of the Cantabrian Sea; 2) blocks 8.1.3, 9.1.2, 9.1.5 and 9.1.6; and 3) the linea-

Table 14

Short description of the morphotectonic lineaments (ALIN) (from orders 2 to 4) in Asturias

Nº	Order	Denomination	Main Strike
L1	Macroblock	Septentrional	E-W
L2	Mesoblock	9.1	E-W
L3	Block	8.1.3	NE
L4	Block	9.1.1	NE
L5	Block	9.1.2	NE
L6	Block	9.1.3	E-W
L7	Block	9.1.4	N-S
L8	Block	9.1.5	N-S
L9	Block	9.1.6	E-W
L10	Block	9.1.7	E-W
L11	Block	9.1.8	N-S
L12	Block	Galicia	E-W
L13	Block	Cantabria	NE
L14	Block	Cantabria	NW
L15	Block	Castilla-León	NE

Table 15

Short description of the knots of lineaments (from orders 2 to 6) in Asturias

Knot	Order	Denomination	Formed by the Lineaments
1	3	Charitón (Coca)	A8-11
2	3	Marentes (Maqueira de Muñiz)	A8-12
3	4	Puente Nuevo	3-11
4	4	Lodón-Alava	4-7
5	4	Pravia	4-9
6	4	Embalse de Furacón	5-9
7	4	Soto de Ribera	8-9
8	4	Ujo	8-10
9	4	Parres	5-6
10	4	Peñamellera Baja	6-15
11	4	Buelles	6-14
12	4	Puerto de Tana	9-10
13	4	San Antolín (Ibia)	4-12

Table 16

Quantitative comparation of the morphostructures

	Knots					Microblocks	Lineaments		
	2º	3º	4º	5º	6º		2º	3º	4º
Asturias Mesoblock	-	2	11	31	86	208	1	1	10
Cantabrian Mesoblock	-	-	11	29	76	305	1	1	10
Galicia Macroblock	1	2	17	46	107	328	2	2	9

ment of Navia near Sarria – Becerreá, it can be said that there is a good fit between the morphotectonic proposal ventured here and the level of seismicity detected in Asturias. It is stressed that the data on morphotectonics and seismicity have been obtained and presented independently. All these data detail, for the first time, a seismic regionalization (Figure 17, Table 17) that improves the results of Cotilla and Córdoba (2004). To confirm this result we show the recent seismic data according to the Instituto Geográfico Nacional (Table 18).

Figure 13 from Herraiz *et al*. (2000) allows us to interpret, using Shmax trajectories, that the greatest seismic activity in Asturias is in the east-central area. These trajectories indicate that the Asturias region is undergoing a N-S to NE-SW compression. They are perpendicular to the morphoalignments (Nos. 4, 5, 8 and 9) and, most definitely, to the 9.1.6, 9.1.7 and 9.1.8 territorial units. Furthermore, it can be said that the northern part of the peninsula, as an active Territorial Unit of the Iberia megablock, is effectively subject to a tensor of compressive forces in the NE-SW direction, but it receives an important influence from the seafloor spreading of the Atlantic. This result comes from interpreting the organization of the morphostructures of a lower order (from the meso to the nanoblock being the scale used in this research).

Finally, we believe that in order to find out the true seismic potential of Asturias it is necessary to install three permanent seismic stations. Two of these stations should be placed in the east-central part (blocks 9.1.5 and 9.1.6) and the third one in the environs of Becerreá.

5. CONCLUSIONS

These earthquake processes, as we understand them today, vary not only on the basis of the different geodynamic conditions where they occur but also on the basis of other

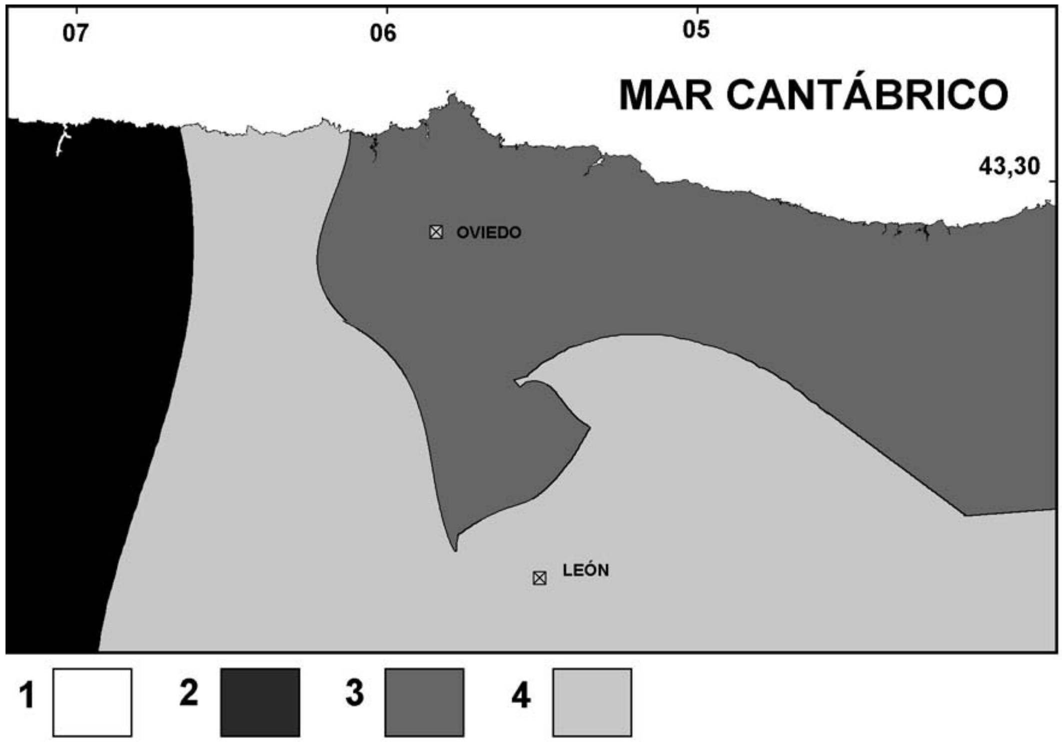

Fig. 17. Seismic zones of Asturias. [Mmax: 1- 5,5, 2- 5,3, 3- 5,0, 4- <5,0. See table 17.]

Table 17

Seismogenic zones of Asturias

Zone	Localities	Mmax / hmax (km)	Characteristics
1	Mar Cantábrico	5,5 / 20	System of structures oriented E-W and linked to Atlantic Ocean structures. It is the largest sized structure.
2	Sarria-Becerreá (Galicia), Castropol, Navia, Ribadeo, San Tirsdo de Oscos, Vegadeo	5,3 / 20	Structures with a NE direction. There have been a series of earthquakes.
3	Avilés, Gijón, Llanes, Muros de Nalón, Ribadesella	5,0 / 10-20	Structures oriented E-W and related to Cantabrian structures.
4	León (Castilla – León), Cangas de Narcea, Luarca	5,0 / 10-40	Structures related with the Castilla León zone. It has the least activity.

characteristics of the tectonic framework and its environment. For this reason, here we analised the problem with a multidisciplinary group. Following the guidelines suggested by Alekseevskaya *et al.* (1977), we looked for geophysical characteristics to give coherent explanations. These results show how to continue studies of seismic danger in interior plate zones, like the IP, and in fact this path was used recently by Cotilla *et al.* (1997) and Goshkov *et al.* (2000) among others.

The morphotectonic analysis of Asturias, seen from the systematic perspective of Rantsman (1979), provides a first framework for a regionalization on the more active units. In general terms, Asturias is defined as an active mesoblock

Table 18

Recent seismic data (Instituto Geográfico Nacional)

Period	Number of Events	Mmax	Mmin	Localities	Asociated to
28.05.99-18.02.04	13	3,7	1,3	Mar Cantábrico	Northern fault system
16.12.02-01.07.03	19	3,1	1,0	Sarria-Becerreá-Triacastela	L2, block 8.1.2
29.01.03-15.02.04	4	2,3	1,6	Cangas de Narcea	L4, block 8.1.3
29.01.03-15.02.04	4	2,3	1,6	Pola de Allande-Tineo-Salas-Grandas	Block 8.1.3
07.03.04	1	1,8		Cudillero-Pravia-Muros-Salas	Block 8.1.3
08.02.04	1	1,1		Pedrafita do Cebereiro-Fabreo-Candín	Block 8.1.3
03.03.04	1	0,9		Riano-Puebla de Ullo-Reyero-Acebedo-Maraña-Prioro	Knot 6

with a tendency toward uplift. The Asturias mesoblock falls into the western part of the Northern macroblock, also known as macroblock 9, relatively dependent on the Iberia megablock. This mountainous continental mesoblock interacts differently with other bordering lithospheric units, of oceanic type (not studied here) and continental type (macroblocks: 7= Arqueado and 8= Galicia). In this way, localized seismicity in the region can be explained with coherence. This seismicity could belong to Asturias or it could not, but it must be associated with the tectonic lines (including their intersections) that transport the forces / deformations of the system.

Territorial units are distinguished in the cartography of Asturias (1 mountain mesoblock, 8 blocks, 208 microblocks and 668 nanoblocks), morphoalignments (quantity/order: 1/2, 1/3, 10/4, 35/5 and 77/6) and morphotectonic knots (quantity/order: 2/3, 11/4, 31/5 and 86/6). At the block order level there is a transverse differentiation of the territorial units and of the morphoalignments. The number of morphostructures increases significantly from west to east. There is a clear relationship between the morphostructures and the seismicity, underlining the greater activity of the blocks neighbouring Oviedo and of the northern and eastern parts. The marine sector is manifestly seismoactive.

The north of the peninsula, as an active Territorial Unit of the Iberia megablock, is effectively subject to a tensor compressive forces in a NE-SW direction but is strongly influenced by sea floor spreading of the Atlantic Ocean. This finding leads us to interpret the organization of the morphostructures as lower order (from the meso to the nanoblock, this being the scale applied in this research).

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