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Evolution of Iberia during the Cenozoic with special emphasis on the formation of the Betic Cordillera and its relation with the western Mediterranean

C. Sanz de Galdeano

Instituto Andaluz de Ciencias de la Tierra, 18071 Granada (Spain); tel. (34) 958 246267, fax (34) 958 243384; csanz@goliat.ugr.es

ABSTRACT

Key-words: Iberia; Betic Cordillera; Cenozoic; western Mediterranean.

The extensional process affecting Iberia during the Triassic and Jurassic times change from the end of the Cretaceous and, throughout the Palaeocene, the displacement between the African and European plates was clearly convergent and part of the future Internal Zone of the Betic Cordillera was affected. To the west, the Atlantic continued to open as a passive margin and, to the north, no significant deformation occurred. During the Eocene, the entire Iberian plate was subjected to compression, which caused major deformations in the Pyrenees and also in the Alpujarride and Nevado-Filabride, Internal Betic, complexes. In the Oligocene continued this situation, but in addition, the new extensional process occurring in the western Mediterranean area, together with the constant eastward drift of Iberia due to Atlantic opening, compressed the eastern sector of Iberia, giving rise to the structuring of the Iberian Cordillera. The Neogene was the time when the Betic Cordillera reached its fundamental features with the westward displacement of the Betic-Rif Internal Zone, expelled by the progressive opening of the Algerian Basin, opening prolonged till the Alboran Sea. From the Late Miocene onwards, all Iberia was affected by a N-S to NNW-SSE compression, combined in many points by a near perpendicular extension. Specially in eastern and southern Iberia a radial extension superposed these compression and extension.

RESUMO

Palavras-chave: Ibéria; Cordilheira bética; Cenozóico; Mediterrâneo ocidental.

O processo de extensão que afectou a Ibéria durante o Triásico e Jurássico alterou-se a partir do final do Cretácico. Ao longo do Paleocénico, o deslocamento entre as placas africana e europeia foi claramente convergente, tendo sido afectada parte da futura zona interna da Cordilheira bética. A Oeste, o Atlântico continuou a abrir como uma margem passiva e, para Norte, não houve deformação significativa. No Eocénico, a placa ibérica foi submetida a compressão que originou deformações nos Pirinéus e nas zonas béticas internas das Alpujarridas e Nevado-Filabridas. Esta situação manteve-se no Oligocénico; todavia, no Mediterrâneo ocidental houve novos processos distensivos que, juntamente com a deriva para Este da Ibéria devido à abertura do Atlântico, originou compressões no sector Este conduzindo à estruturação da Cordilheira ibérica. No Neogénico, a Cordilheira bética adquiriu as características essenciais, com deslocamento para Oeste da zona interna bético-rifenha, progressivamente segregada pela abertura da Bacia argelina que se estendeu até o mar de Alboran. A partir do Miocénico superior, a Ibéria foi submetida a compressão N-S a NNW-SSE, com extensão quase perpendicular; no Este e Sul, além desta compressão, houve distensão radial.

INTRODUCTION

Iberia is a lithospheric (sub) plate located between the NW of Africa and the SW European plate (Fig. 1). From the beginning of the Mesozoic until late in the Early Cretaceous the movements of Iberia coincided generally with those of Europe, whereas, from that time to the Oligocene, Iberia moved together with Africa. Since the Oligocene or early Miocene, the Iberian Peninsula has been joined to Europe (Malod, 1989).

The nucleus of the Iberian Peninsula is the Iberian (or Hesperian) Massif (Fig. 2), which was deformed during Hercynian orogeny; this massif is surrounded by several domains. To the north lies the Bay of Biscay, the oceanic crust of which formed during the Cretaceous. To the northeast is the Pyrenean Cordillera, comprised by a Palaeozoic nucleus and a Mesozoic and Tertiary cover. The Iberian Cordillera is situated to the east and the Catalan Coastal Range to the southeast of the Pyrenees, while the Betic Cordillera occupies the south and southeast border. To the west, the peninsula is bounded by the Atlantic Ocean, forming a passive margin.

Within the Iberian Massif, there are two large Tertiary basins (Duero and Tagus), separated by the Spanish Central System. The Guadalquivir Basin is located south of the massif and north of the Betic Cordillera, while the Ebro Basin lies between the Iberian Cordillera and the Pyrenees. Numerous smaller Tertiary basins exist in all the domains mentioned above.

REGIONAL SITUATION OF THE IBERIA PENINSULA AND THE MAIN FEATURES OF THE BETIC CORDILLERA

The geologic evolution of Iberia during the Mesozoic and the Tertiary has been greatly controlled by the interaction between the African and European plates,

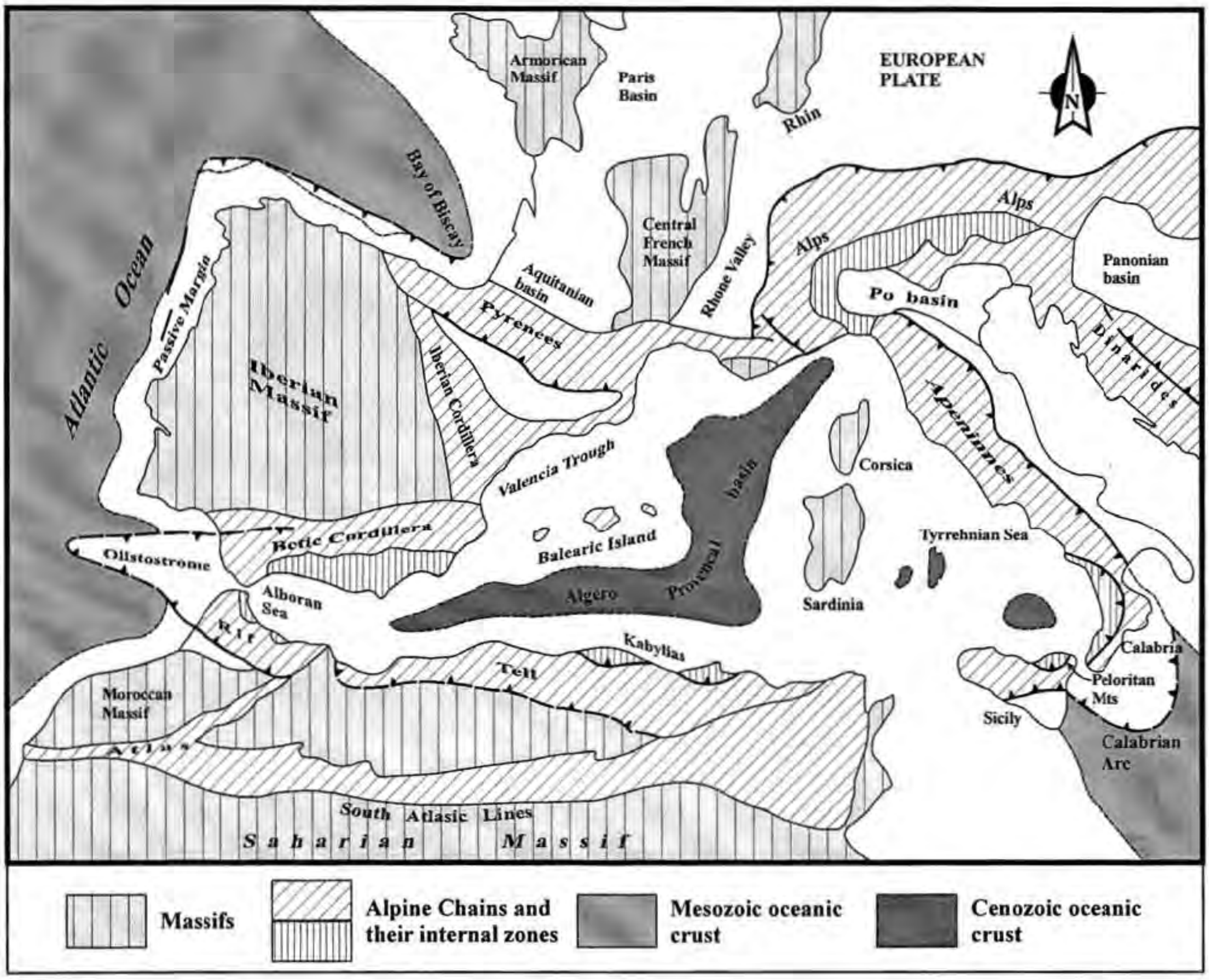

Fig. 1 - Geological situation of Iberia.

which in turn were related to processes of oceanic growth, especially to the opening of the Atlantic and also by the evolution of the western end of the Tethys.

At the beginning of the Mesozoic, the Iberian Massif was located near Tunisia and Algeria (Fig. 3A). Throughout this period the Western Mediterranean (western end of the Tethys Ocean) underwent a major process of extension and formation of oceanic crust, which probably extended from the original areas of sedimentation of the Betic-Rif cordilleras to beyond the basin of the Internal Zone of the Alps (Ligurian Basin). At the same time, the progressive opening of the South Atlantic gradually displaced Africa to the east, so that Iberia moved relatively over 1200 km westwards. During the Cretaceous, the opening of the Central and North Atlantic caused the anti-clockwise rotation of the Iberian Massif (some 30 degrees in all, Fig. 3B), thereby inducing the opening of the Bay of Biscay. This may have occurred together with some displacement of Iberia towards the south, southwest or southeast, simultaneously with the first convergent movement between Africa and Europe and with the first compressive deformations in the Internal Zone of the Alps.

All these movements, firstly extensional and afterwards compressive, were responsible for the future differentiation of the diverse complexes of the Betic Cordillera. This cordillera is composed of the Internal and External zones, as well as the Flysch units (Campo de Gibraltar units, formed from the former Flysch Basin) and many Neogene basins (Fig. 4). The Internal Zone is made up of three complexes, which are from bottom to top: the Nevado-Filabride, the Alpujarride and the Malaguide. The Nevado-Filabride and the Alpujarride, strongly affected by the Alpine metamorphism, present a series ranging from the Palaeozoic to the Mesozoic, specially the Triassic. The Malaguide generally was not affected by this metamorphism. It presents a Palaeozoic series and its Jurassic to Tertiary series are much better developed than in the other two complexes, but with abundant hiatuses. Another complex, the Dorsal, which corresponds partially to the stratigraphic cover of the Malaguide (the Internal

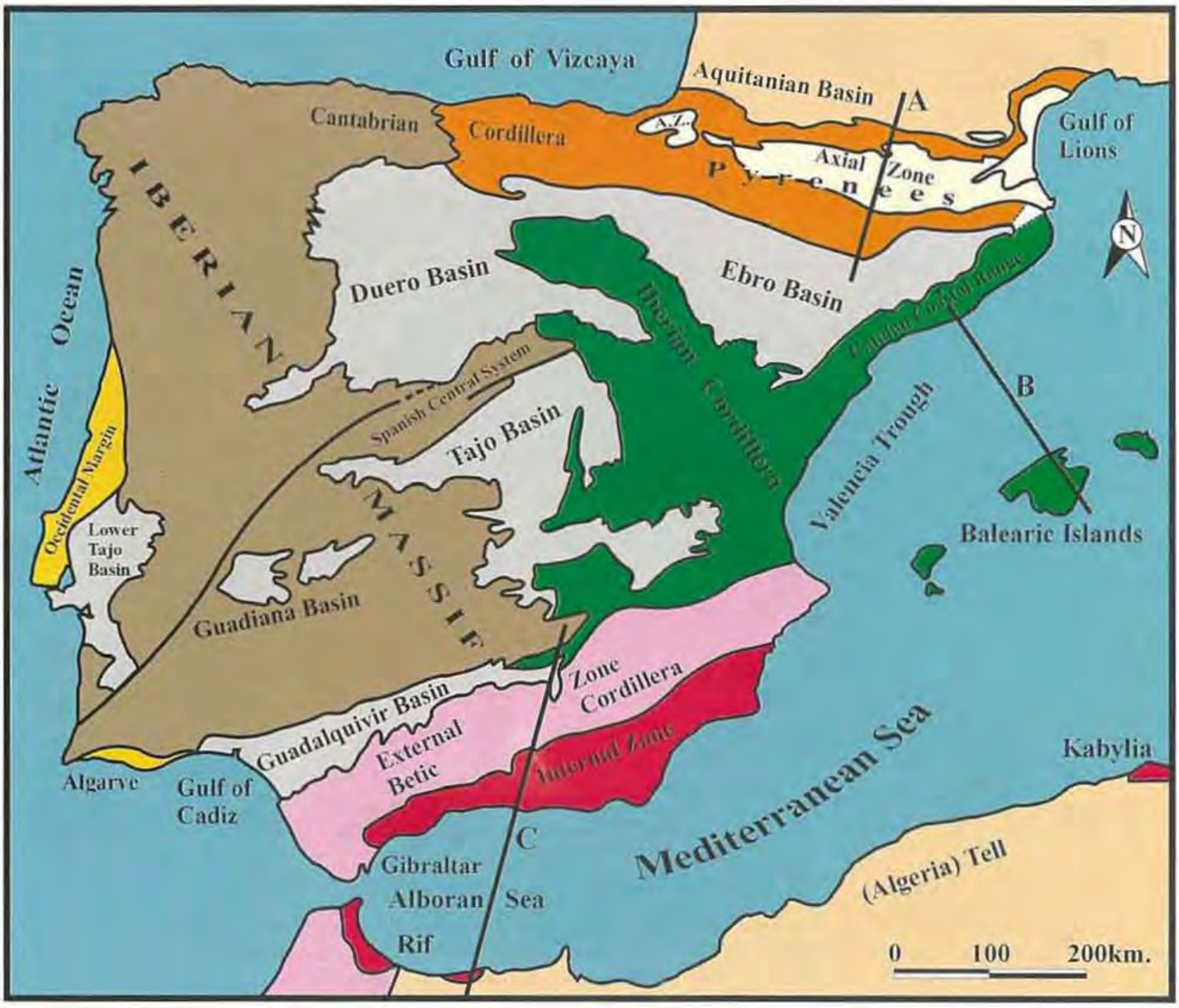

Fig. 2 - Highly simplified geological scheme of the principal domains in the Iberian Peninsula (simplified and modified from Julivert *et al.*, 1972). The position of cross-sections of figures 5 and 7 is marked.

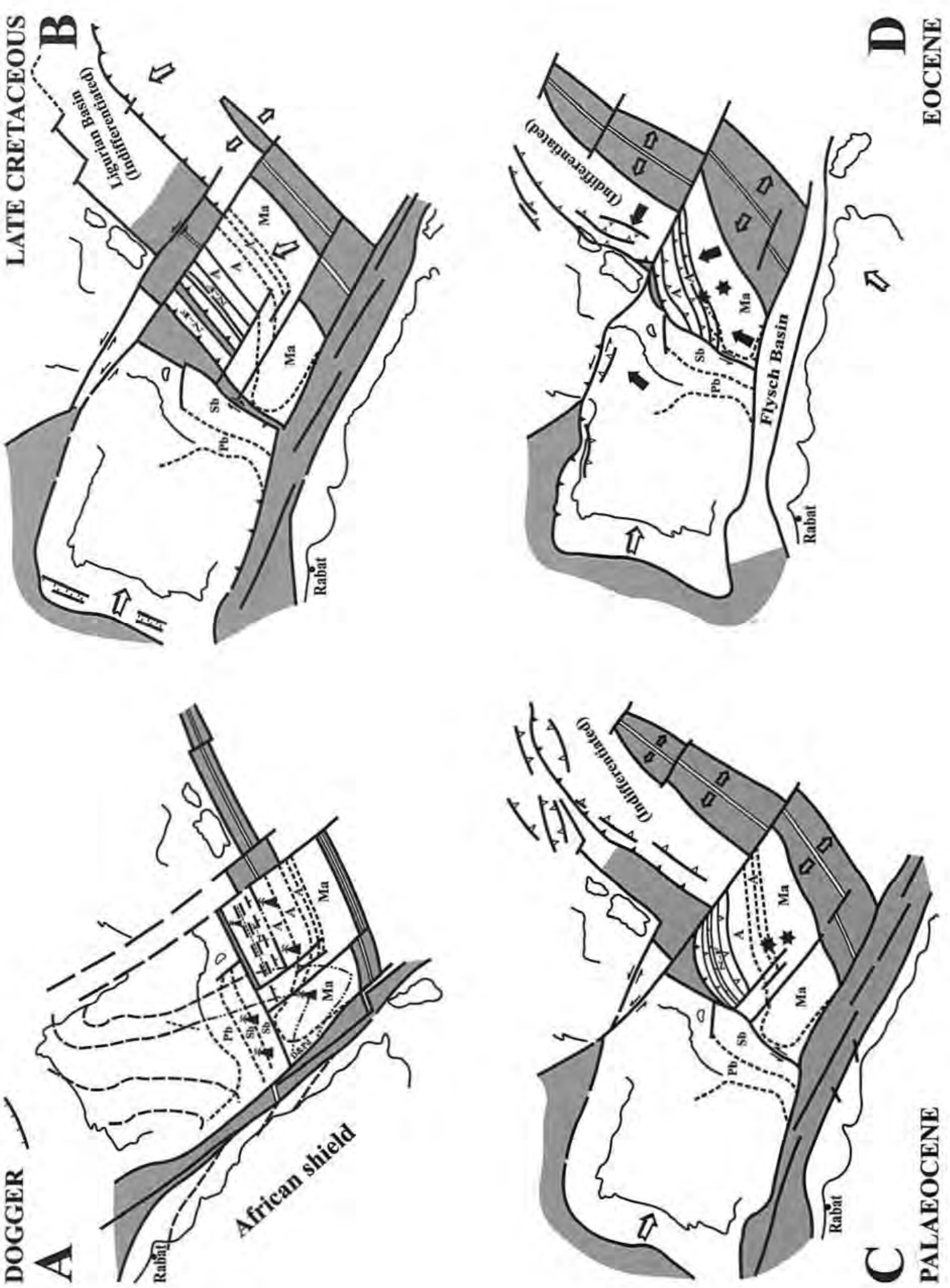

Fig. 3 - Interpretative schemes of the evolution of Iberia. A: Situation of Iberia at the beginning of the Dogger, when the western Mediterranean area was affected by extension. B: During the Late Cretaceous, the western Mediterranean, after the rotation of Iberia, underwent the first compressions. C: During the Palaeocene, the process of subduction of the western Mediterranean affected strongly the Betic Internal Zone. D: During the Eocene, the Pyrenees, Cantabrian area and the Betic Internal Zone underwent important compressions. Key of the abbreviations: A: Alpujarride, D & Pd: Dorsal and Predorsal, Ma: Malaguide, N-F: Nevado-Filabride, Pb: Prebetic, Sb: Subbetic. Taken from Sanz de Galdeano (1997). The arrows indicate the direction of tectonic transport. Opposed arrows: extension. Stars: peridotite intrusions. Grey colours: oceanic crust.

Dorsal), formed the passage to the south (the External Dorsal) to the Flysch Basin. The Internal Zone of the Rif, in the north of Morocco is the same Betic Internal Zone (although there, in the Rif, the Nevado-Filabride Complex is absent), and thus we will refer to the Betic-Rif Internal Zone.

The External Zone of the Betic Cordillera is formed by the Subbetic (to the south) and the Prebetic (outcropping to the NE). Both domains have Mesozoic and Tertiary sediments, those of the Prebetic corresponding to a more shallow marine basin or even to continental environment. The External Zone in the Rif is also formed by Mesozoic and Tertiary sediments but differs from the Betic External Zone. In fact, this last zone formed the cover of the south and southeast border of the Iberian Massif, while the Rif External Zone made a progressive passage towards the north of the Mesozoic and Tertiary cover of the Atlas.

The infilling of the Neogene basins began with the Early Miocene, but most of the basins, apart from the Guadalquivir Basin, developed from the Tortonian onwards, covering areas of the Internal and External zones (Sanz de Galdeano & Vera, 1992).

EVOLUTION DURING THE PALEOCENE AND THE EOCENE

The displacement between the African and European plates was clearly convergent from the end of the Cretaceous throughout the Palaeocene (Tapponier, 1977). In the western Mediterranean the Ligurian Basin, which formed during the Mesozoic, began in the Cretaceous to undergo a subduction (Fig. 3 C), probably dipping to the south. That is, the oceanic crust of the Ligurian Basin sank

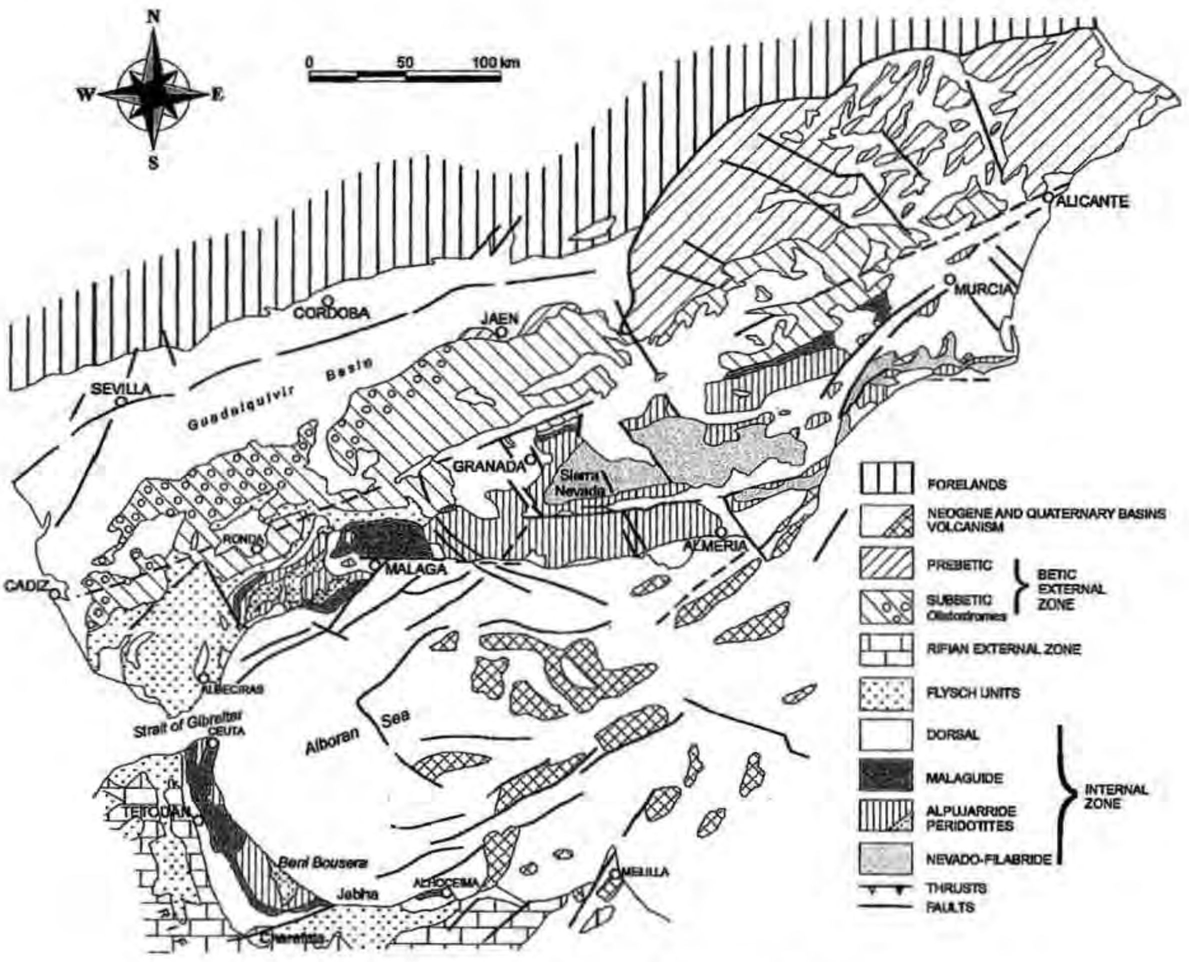

Fig. 4 - General geologic map of the Betic Cordillera.

under Africa or under the domain situated between Europe and Africa, called the South-Sardinian domain (Sanz de Galdeano, 1990, 1997) o Alkapeca (Alboran, Kabylia, Peloritani Mountains and Calabria) (Bouillin *et al.*, 1986). (The name of Alboran in this case refers to the Betic-Rif Internal Zone). At the end of the Cretaceous and the beginning of the Palaeocene an approximately N-S compression weakly affected Iberia. To the west, the Atlantic continued to open as a passive margin and, to the north, no significant deformation occurred and sedimentation continued in most of the Pyrenees.

The process of subduction affecting the Ligurian Basin moved progressively to collision towards the end of the Palaeocene or in the Early Eocene. Then, during the Eocene, the entire Iberian plate was subjected to compression (Fig. 3 D), which caused major deformations, most significantly in the Pyrenees (Pyrenean Eocene phase), forming large nappes (Megías, 1988). Deep seismic profiles show that the Iberian plate is subducted beneath the European plate (Roure *et al.*, 1989; Suriñach *et al.*, 1993) (Fig. 5 A), even though there may not previously have been a large volume of oceanic crust.

During these deformations of the Pyrenees, the foreland basin (Ebro Basin) (Anadón *et al.*, 1985) migrated southwards, while the northern margin of the basin was partially incorporated into the younger thrust sheets (Muñoz *et al.*, 1988).

The compressive movements were transmitted further to the west during this Eocene phase, so that the northwestern margin of Iberia tended to become superposed over the Bay of Biscay; i.e., part of the oceanic crust in the Bay of Biscay was subducted beneath Iberian (Boillot *et al.*, 1984). Part of the Cantabrian coast (N and NW Iberia) was also deformed.

Some deformation also occurred in the Catalan Coastal Range, with approximately N-S compression (continuing into part of the Oligocene) (Guimerà, 1983), together with strong development of NE-SW sinistral strike-slip faults (Anadón *et al.*, 1985). The crust that was to become the Iberian Cordillera from the Oligocene onwards (Viallard, 1989) was also affected.

These compressional episodes also had an effect on the Spanish Central System during the Eocene, causing crustal thickening (Vegas *et al.*, 1990) and reactivation of late Hercynian faults.

With regard to the present-day Betic Cordillera, the Betic-Rif Internal Zone were located some 500 km east of their present position (Fig. 3) and underwent a major stage of tectonic structuring and metamorphism. The first process of formation of nappes in the Nevado-Filabride

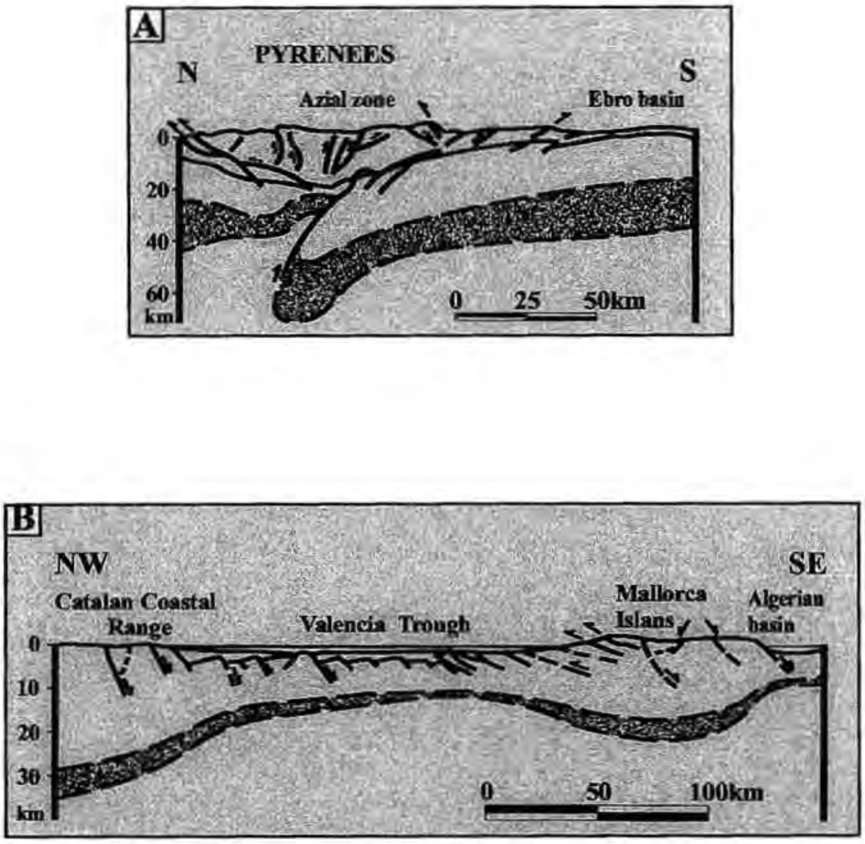

Fig. 5 - Schematic geological cross-sections. A: Interpretation of the geological structure of the Pyrenees. Simplified from Muñoz (1992) and modifications inspired in Velasque *et al.*, (1989). B: Structure of the Valencia trough. Simplified from Martí *et al.* (1992) and Fontboté *et al.* (1990). Lower crust in points. Their position is marked in Fig. 2.

Complex probably occurred from the Late Cretaceous and continued throughout part of the Palaeocene with tectonic transport towards the NW. The total shortening of the Nevado-Filabride Complex was at least 200 km and, at the same time, the oceanic crust practically disappeared from the SW end of the Ligurian Basin. The Alpujarride and the Malaguide, originally situated more to the south and southeast, remained in a position of back-arc and did not undergo important deformations. In the Malaguide Complex, the Upper Cretaceous and the Palaeocene are both partially or completely absent, perhaps due to a possible emersion of this area. According to Garrido (1995), at this time and in this position of the Alpujarride and Malaguide complexes, there could have been the intrusion of the peridotites existing at the bottom of some upper units of the Alpujarride as well as in the Kabylias (which can be considered equivalent to the Malaguide Complex in the N of Algeria).

The length of time of these processes of subduction and collision that especially affected the Nevado-Filabride as well as perhaps some of the most internal units of the Alpujarride remains unclear. It even remains debatable whether one or more intercalate periods of relaxation and extension occurred. De Jong (1991) considered the Palaeocene to be an epoch of cooling, relaxation and exhumation. Probably this relaxation occurred at the end of the Palaeocene, exhuming part of the units which formely were deeply sunken during the subduction and subsequent collision. Monié *et al.* (1991) place this exhumation 48 m.y. a., during the Early Eocene. In this sense, the conglomerate marbles described by Puga *et al.*, (1996) in the top of several units of the Nevado-Filabride could have formed during this stage of exhumation.

Meanwhile, the Betic External Zone underwent no major deformations, although in some places, especially in the Prebetic, there are well-developed unconformities.

EVOLUTION DURING THE OLIGOCENE (AND PART OF EARLY AQUITANIAN)

Some of the processes active in the Eocene continued in the Oligocene, and consequently Iberia began to move together with Europe. Basically, N-S or NW-SE compressions continued in the Pyrenees (Megías, 1988) (Oligocene phase) (Fig. 6 A), causing more displacements of nappes and southward migration of the foreland basin (Ebro Basin).

The deformation occurring in the Cantabrian zone (NW Iberia) and the Bay of Biscay was much weaker during the Oligocene (and later in the Neogene) than in the Eocene (Boillot *et al.*, 1984).

However, a new phenomenon developed during the Oligocene, adding to the convergence of Africa and Europe. This was the approximately E-W extension affecting Central Europe since the Eocene, and reaching the Western Mediterranean (in the Oligocene) through the Rhône Valley (Boillot *et al.*, 1984). The present Gulf of Lyon opened in NE Iberia and the eastward displacement and gradual anti-clockwise rotation of Corsica and Sardinia began. Further southwards, the Valencia Trough opened (Fig. 6 B), which in turn caused eastward displacement and gradual rotation of the Balearic Isles.

This extensional process occurring in the western Mediterranean (with the initial opening of the Valencia Trough, Fontboté *et al.* 1990; Maillard *et al.* 1992), together with the constant eastward drift of Iberia due to Atlantic opening, compressed the eastern sector of Iberia (in an approximately E-W direction). Particularly during the Late Oligocene (Viallard, 1985; Simón, 1990) and until the earliest Miocene, this gave rise to the structuring of the Iberian Cordillera (Fig. 6 A & B), which is a clearly intracontinental cordillera and presents a generally moderate degree of deformation.

Within the Iberian Massif the reactivation of originally late Hercynian faults determined most of the Alpine structure of the Spanish Central System, and to a large extent also controlled the formation of the Duero and Tagus Basins, as well as many other smaller ones (Vegas, 1975). The age of these structures is not accurately known. Although, in general terms, we can accept that some deformation began at the end of the Cretaceous (Vegas *et al.*, 1986), the first well-developed episode occurred during the Oligocene-Early Miocene (Capote *et al.*, 1990), coinciding with the deformation of the Iberian Cordillera.

With respect to the present-day Betic Cordillera, during the Late Eocene and the Early Oligocene renewed compressions affected strongly the Nevado-Filabride Complex and, especially in this case, the Alpujarride Complex, forming a great part of their present nappe structure and overthrusted the Nevado-Filabride (Fig. 6 A). The probable direction of compression was NNW-SSE to N-S. Meanwhile, the Malaguide Complex and the Dorsal underwent great tectonic instability, forming large deposits of breccias and unconformities (Serrano *et al.*, 1995).

The overthrusting of the Malaguide on the Alpujarride Complex, could have begun during the Oligocene and part of this process ocurred at the end of the Oligocene (Fig. 6 B), perhaps till the beginnings of the Aquitanian.

At this time, during the Oligocene and the Early Aquitanian, tectonic instability in the Betic External Zone caused some deformations and unconformities, but on the whole this area continued receiving sedimentation.

EVOLUTION FROM THE AQUITANIAN TO MIDDLE MIOCENE

Some approximately N-S compression also occurred in the Iberian Cordillera during part of the Miocene (Simón Gómez and Paricio Cardona, 1988). The compression also affected the Pyrenees and some overthrusts formed. NW-SE to NNW-SSE compression occurred throughout the Early and Middle Miocene in the Spanish Central System.

Undoubtedly the most important phenomena occurred in the western Mediterranean and, closely linked to these, in the Betic and Rif cordilleras. This was the time when the Betic Cordillera reached its fundamental features. The precise way in which this Neogene structuring occurred

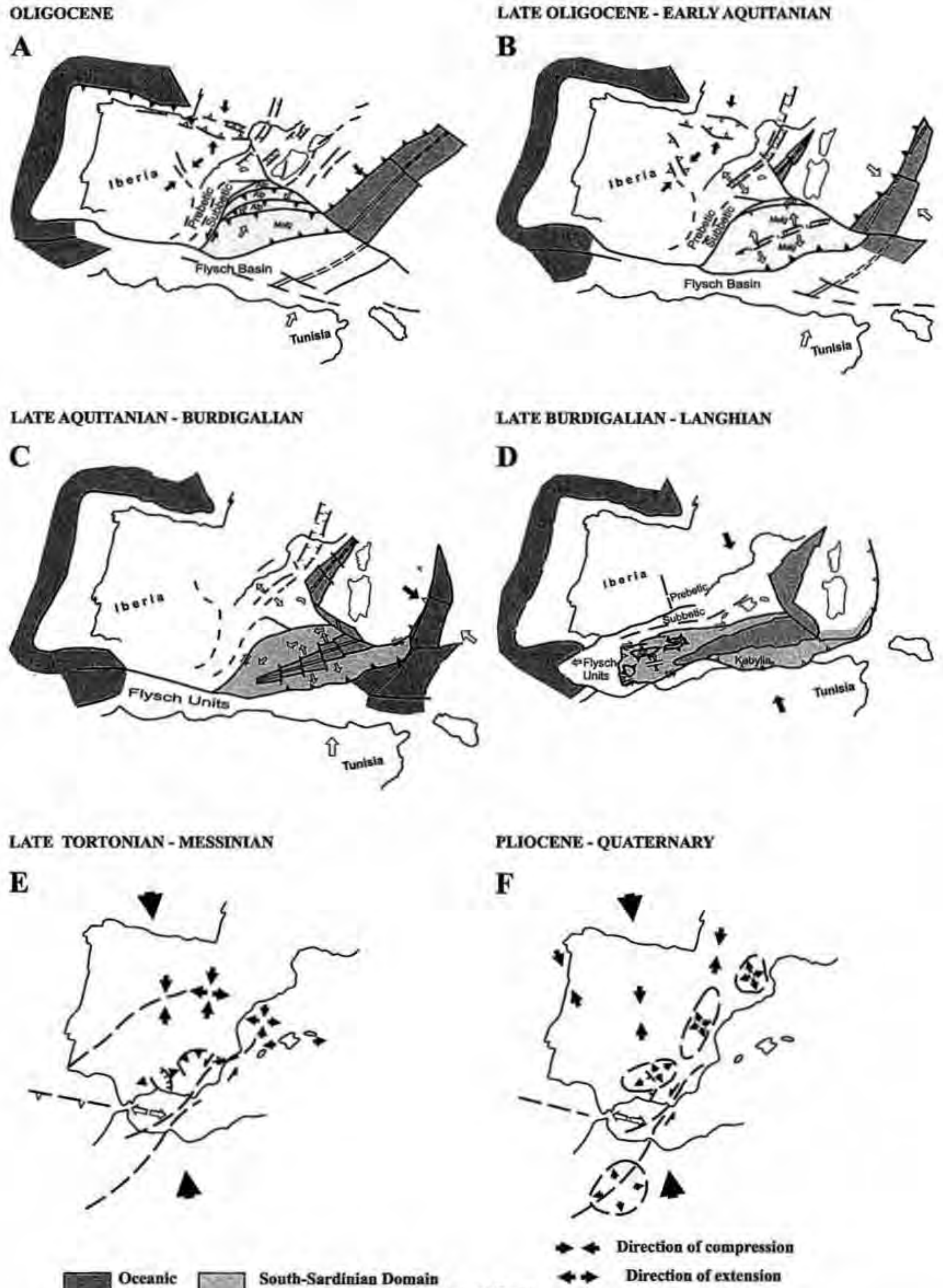

Fig. 6 - Interpretative schemes of the evolution of SE Iberia. A: During the Oligocene, continued the deformations in the Pyrenees and in the Betic-Internal Zone and began the structuration of the Iberian Cordillera. B: During the Late Oligocene- Early Miocene, the opening of the Algero-Provençal basin accelerated. Then began the overthrusting of the Malaguide Complex over the Alpujarride and, immediately, the extension of the Algerian Basin prolonged to the Alboran area. C: During the Early Miocene continued the opening of the Algerian Basin and, especially, during the Burdigalian the Betic-Rif Internal Zone was westwards expelled. D: This westwards expulsion continued during the Late Burdigalian till the Middle Miocene. The Flysch Basin and the Subbetic were strongly deformed. E: During the Late Miocene, N-S to NNW-SSE compressions affected the entire Iberia, combined in many points with a near E-W extension. F: Continued the same geodynamic situation, but some eastern areas of Iberia underwent radial extension. Alp: Alpujarride; Malg: Malaguide. A to D taken from Sanz de Galdeano (1997).

in the Betic-Rif region is debatable, with oppossing hypotheses on several aspects. One group of hypotheses considers the present structure to have formed due to the existence of a dome of the upper mantle, located approximately in the Alboran Sea, moving as an intumescence and forming a radial displacement of the different complexes. Another group explains the present position of the Internal Zone by its strong westward displacement. A third group considers the existence of a subduction in which the Alboran Sea opened as a back-arc. A common feature to those hypotheses is the great crust mobility necessary in each case.

We will take into account the second group of hypotheses, although combined with possible subduction. In this sense we must consider a double process:

a) The extension that began in the Oligocene in the western Mediterranean continued to develop throughout the Neogene. This process continued throughout the Early Miocene, forming the (Algero-)Provençal basin.

b) Around the Oligocene a new subduction began, sinking the oceanic crust of the NW Africa. This subduction dipped to the N and therefore differed from to the previous ones. At this point, it was the African plate which was sinking, beginning with the oceanic crust formed during the Mesozoic and part of the Tertiary south of the Alkapeca domain, that is, directely north of the African plate (this area corresponding to the Flysch Basin). At present, the rest of this subduction is to be found in southern Italy, in the Calabrian arc.

During the process of formation of the Provençal Basin the different domains that previously occupied the western Mediterranean began to be expelled. Corsica and Sardinia moved eastwards and rotated anti-clockwise, while to the west formed the oceanic crust of the Provençal Basin (Rehault *et al.*, 1984). However, the opening of the Valencia Trough did not significantly continue beyond the Early Miocene. The Provençal Basin extended southwards, developing a new basin in an approximately E-W direction (the Algerian Basin) also with new oceanic crust (Algero-Provençal basin when considered in a whole) (Fig. 6 B). The westward continuation of the Algerian Basin opened the Alboran Sea or Basin (Sanz de Galdeano, 1990, 1996, 1997), in which oceanic crust was not clearly formed, although the continental crust noticeably thinned (Figs. 6 C & D and 7). Boillot *et al.* (1984) considered the Algerian Basin to be a back-basin related to a possible subduction of Africa.

This extensional process caused major compressions on its margins. Towards the south, in this case combined with the African subduction, these compressions caused the formation of the Kabylias nappes in the Tell Cordillera in Algeria; this happened approximately at the beginning of the Late Burdigalian. Then, the eastern part of the Flysch Basin was completely disorganized.

The Betic-Rif Internal Zone was expelled to the WSW, originally lying some 500 km east of its present position, according to the interpretations of Andrieux *et al.* (1971), Durand Delga (1980), Durand Delga & Fontboté (1980), Sanz de Galdeano (1990, 1997), Martín Algarra (1987), etc. In this process, this internal zone destroyed the western part of the Flysch Basin and dragged it in its front, forming the present Flysch units of the north of the Rif and of the Campo de Gibraltar.

The process of expulsion to the WSW of the Betic-Rif Internal Zone lasted for a relatively long time. It must have begun during the Late Oligocene, when the collision made the Alpujarride Complex overthrust the Nevado-Filabride. In this moment, the process of extension in the western Mediterranean and the African subduction began to accelerate, and both complexes began to be expelled at the same time. This provoked the thrust of the Malaguide Complex over the Alpujarride complex, thereby initialy absorbing in this area the effects of the expanding Algero-Provençal Basin. Afterwards, these three complexes, now the whole Betic-Rif Internal Zone, were jointly expelled WSWward, reaching and disorganizing the most internal sectors of the Flysch Basin during the end of the Aquitanian, although the more external part (to the south) continued receiving deposits. This basin was destroyed completely at the beginning of the Late Burdigalian.

During this process of westward displacement, the Betic-Rif Internal Zone was affected in a double way: extension in its areas next to the progressively opening Algerian Basin, while its front underwent compression. This extension advanced as far as the present Alboran Sea, which in fact is the western end of the Algerian Basin, where its continental crust greatly thinned.

At the beginning of its expulsion, the Betic-Rif Internal Zone was greatly thickened and many of its units, currently outcropping, were situated several tens of kilometres deep. At the same time as the westward displacement of the Internal Zone, many of its units were uplifting and undergoing a rapid exhumation. In this way, there was a combination of westward movements (approximately 500 km in total) and exhumations on the order of 40-60 km in several units. This occurred in approximately 10 m.a. and the principal movement was from the end of the Early Burdigalian to the Langhian.

The external zones of both the Betic Cordillera and the Rif were deformed by the advance of the Betic-Rif Internal Zone beginning towards the end of the Early Burdigalian. The Subbetic Basin was entirely destroyed (Fig. 6 D) and divided into many different units, usually having clockwise rotations. Then formed the Betic foreland basin (Guadalquivir Basin, formerly the North Betic Strait). Also, the Gibraltar arc formed, not being palaeogeographic in origin, but clearly tectonic.

To the north, the Prebetic and the Balearic Isles underwent strong compressions in a NNW-SSE direction, and, therefore, the Prebetic presents a large area with a clear superposition of folds. The folds formed during the Oligocene correspond to the structuring of the Iberian Chain and, those formed during from the Miocene, correspond to the structuring of the Betic Cordillera. Further eastwards, compression also took place during part of the Burdigalian and Langhian in the Balearic Isles. This was transmitted to the Valencia Trough, where some

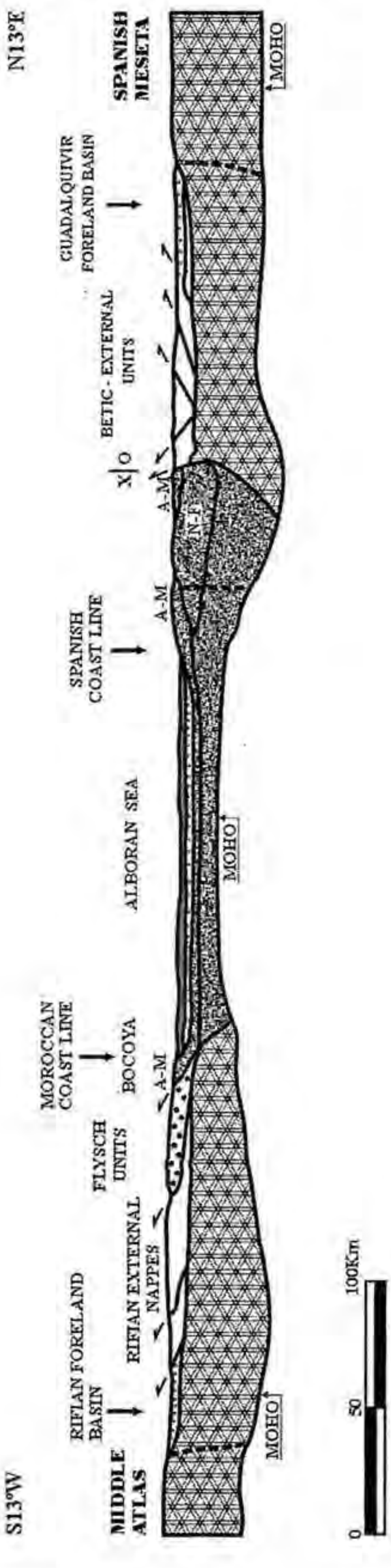

Fig. 7 - Cross-section from the Betic Cordillera to the Rif. Note the assimetry of the distribution of the Betic-Rif Internal Zone in both sides of the Alboran Sea. This feature was caused by the openning and thinnig of the continental crust of the Alboran Sea. Its position is marked in Fig. 2.

tectonic inversion occurred and overthrusts formed (Fontboté et al., 1990; Banda & Santanach, 1992).

In the Betic Cordillera, major extensional processes have been cited during the Early and Middle Miocene, linked to the progressive exhumation of the Internal Zone. At the same time, occurred a transcurrent tectonics by E-W to N70E faults which also contributed to the westward displacement. García-Dueñas *et al.* (1992) describe ductile-fragile shear zones with low-angle faults, moving the hanging blocks to the WNW, W and SW. These same structures appear to have contributed to the thinning of the Alboran crust.

EVOLUTION DURING THE LATE MIOCENE TO THE PRESENT (THE NEOTECTONIC PERIOD, *sensu lato*)

Some areas present notable deformations (Fig. 6 E). In the Spanish Central System the NW-SE to NNW-SSE compression continued throughout the Early and Middle Miocene, but changed the direction to N-S from the Late Miocene to the Quaternary (Capote *et al.*, 1990). These compressions caused reverse faults with imbricate thrusts (de Vicente *et al.*, 1992) and strike-slip faults, which contributed to the uplift of the system and clearer separation of the Duero and Tagus Basins, as well as the formation of many small basins. More northernly, in the Iberian Chain, the Sierra de Cameros was also deformed (Pérez Lorente, 1987).

From the Middle Miocene onwards, NE-SW sinistral strike-slip faults (Cabrera *et al.*, 1988) led to the formation of basins such as the Cerdaña Basin, cutting the Pyrenean structural trend. Compressions of NW-SE to almost N-S direction are also detected in Portugal, at least from the Tortonian on.

Moreover, at the same time, especially in the eastern part of Iberia from the Middle-Late Miocene onwards, a WNW-ESE extension (Moissenet, 1989) occurred, followed by a radial extension particularly from the Pliocene onwards, as Simón Gómez (1990) cited in the Iberian Chain (Fig. 6 F).

In the Betic Cordillera, after the period of the displacement of the Betic-Rif Internal Zone and of structuring in both cordilleras, that is, from the end of the Middle Miocene (end of the Serravallian) and especially from the Tortonian onwards, NNW-SSW compression also occurred. At this point, most of its neogene basins began to be formed (Sanz de Galdeano & Vera, 1992). The evolution of these basins was specially controlled largelly by new sets of faults. Among these, the most important line of faults is that of the Alhama-Lorca-Palomares and Carboneras faults, which control many of the eastern neogene basins. These faults are mainly left-lateral strike-slip faults, though also having strong vertical displacements, generally sinking the west block. These allowed the extrusion of substantial volcanics effussions, and cut and affected the crust in such a way that the eastern block is much thinner (Montenat *et al.*, 1987). Faults of this system continue to the SSW in the Alboran Sea, passing the area of Alboran Isle and reaching the Rif (Fig. 4).

More westerly, other fault systems affect the Betic Cordillera. For instance, the faults N of Granada that form the W border of Sierra Nevada and more to the S pass to the low valley of the Guadalfeo river. These faults mark the western limit of the Nevado-Filabride Complex and, to the S, the western limit of the lower Alpujarride units. The general displacements indicate a tectonic transport to the SW and a sinking of the west block of these faults, while the east block progressively uplifts. This mechanism is repeated in other sets of faults, although to a lesser degree. The general result is that the Betic-Rif Internal Zone is more sunken to the west. This fact is consistent in general with the progressive opening of the Alboran Sea in the same direction. The focal mechanism in the Alboran Sea shows a roughly E-W extension, combined with a N-S to NNW-SSE compression (Buforn *et al.*, 1995).

The continental crust in Alboran is very thin, with a minimum of about 15 km (Hatzfeld & Boloix, 1976) (Fig. 7) and there are important volcanic effussions. However, perhaps, the more striking fact is the existence of many earthquakes with focus located at intermediate depth, which roughly form a westerly convex arc. These

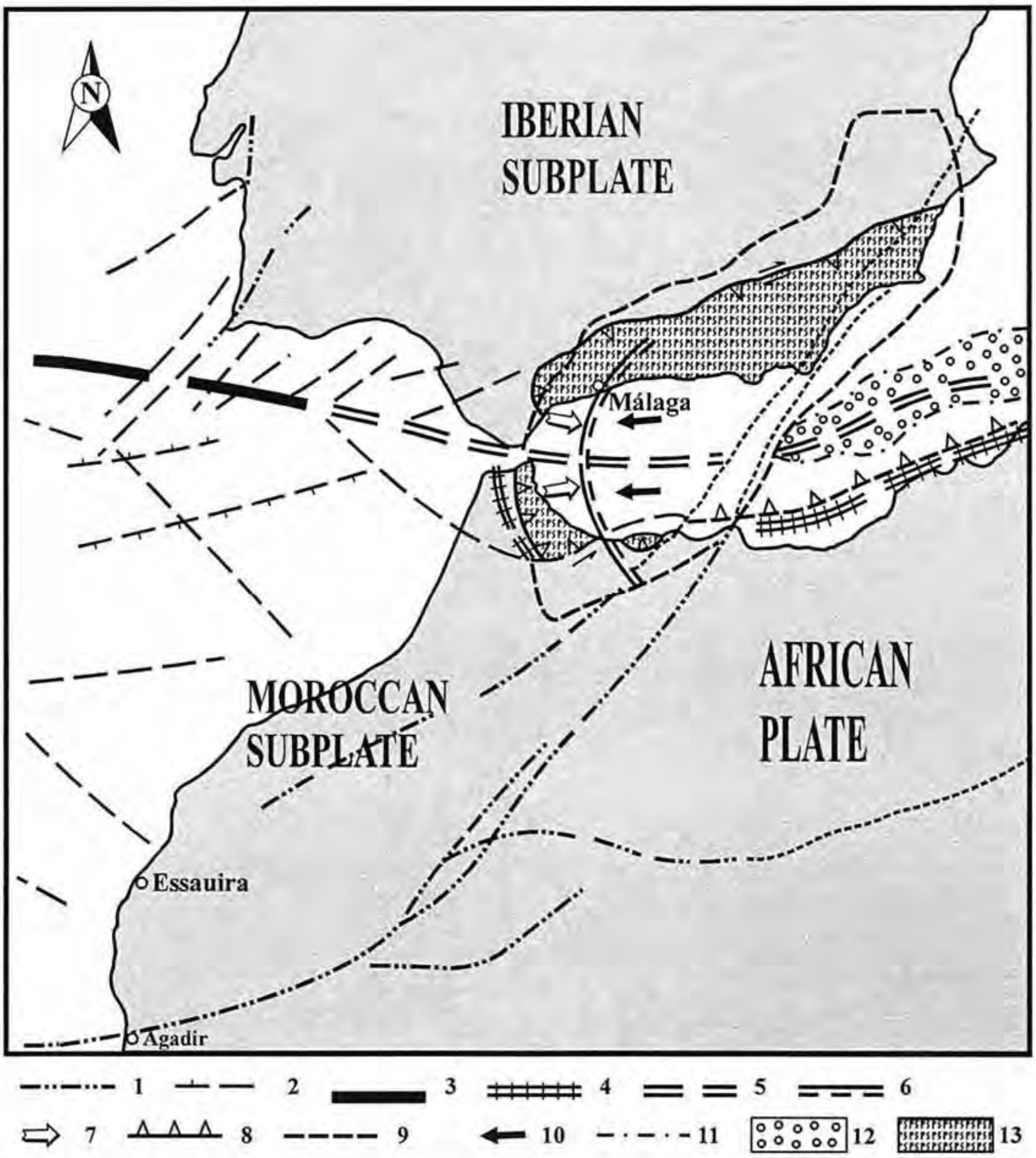

Fig. 8 - Interpretation of the present tectonic situation of the Iberian-Moroccan area. 1: Faults. 2: Probable faults. 3: Approximate contact between the Iberian and African plates. 4: Former contact between the African plate ant the South-Sardinian domain. 5: Possible prolongation to the east of the contact between the African and Iberian plates. 6: Position of the arc produced by the sinking of the Iberian and African lithospheres in the W Alboran Sea. 7: Arrows indicating direction of crustal sinking in the W Alboran Sea. 8: Present boundary of the Betic-Rif Internal Zone. 9: Position, according Blanco & Spackman (1993) of the sunken lithospheric sheet in the Betic-Rif area. 10: General direction of displacement of the Betic-Rif Internal Zone. 11: Approximate limit of the oceanic crust. 12: Oceanic crust in the Algerine Basin. 13: Betic-Rifain internal zone.

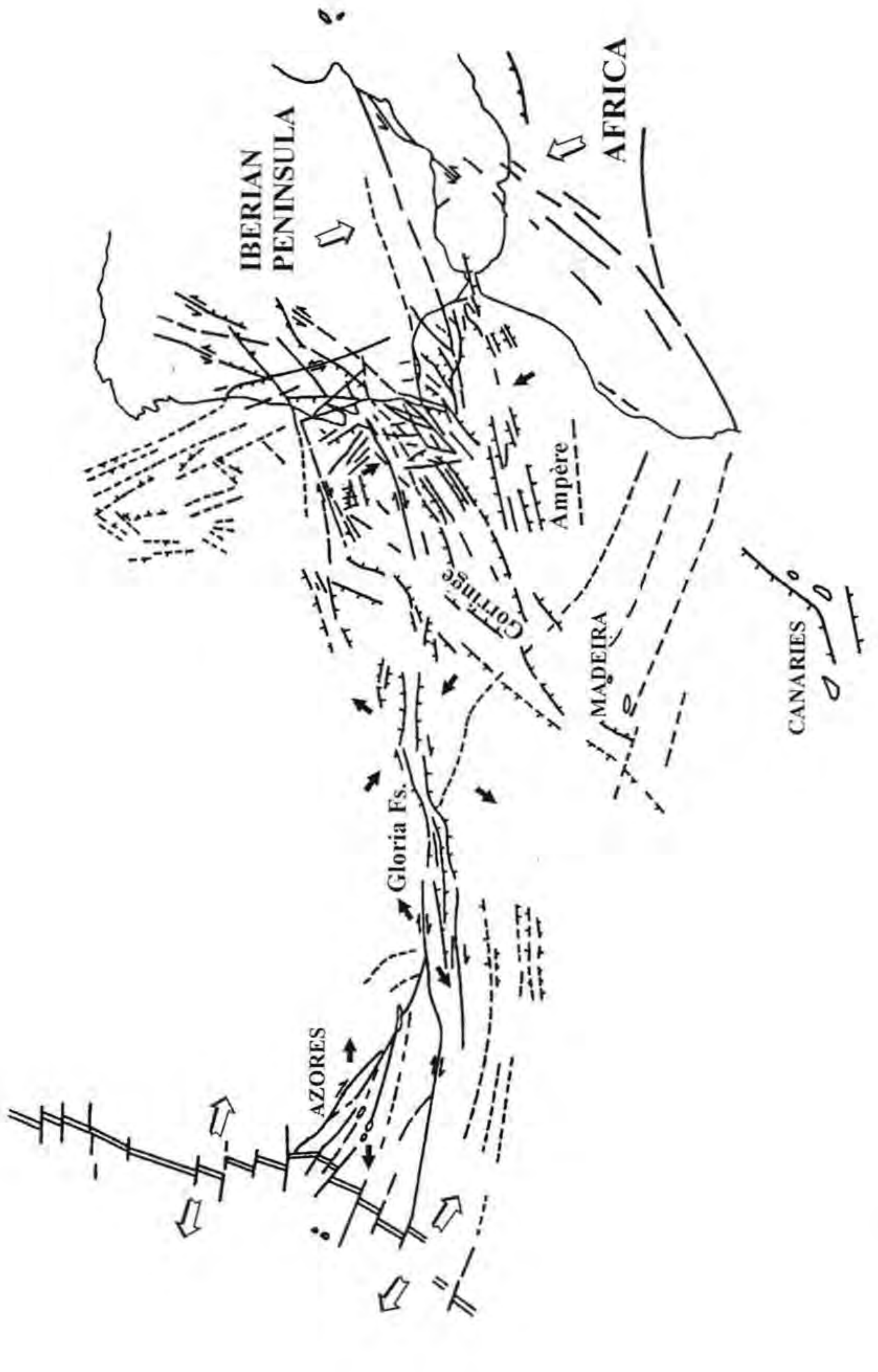

Fig. 9 - Outline of the main faults affecting the contact between the African and Iberian plates between the Azores Islands and the Gibraltar arc. Drawn from data of Auzende *et al.* (1979), Baldy *et al.* (1977), Buforn *et al.* (1988), Emery & Uchupi (1984), Madeira & Ribeiro (1990), Mauffret *et al.* (1988), Moreira (1985) and Udías *et al.* (1986).

earthquakes have been interpreted as posible evidence of subduction (Buforn *et al.*, 1995, Morales *et al.*, 1999), although possibly it is only the result of the collision of the lithosphere of the Alboran Domain against the lithosphere of the European (Iberian in this area) and African plates, which could bend and sink, but without real subduction (or perhaps with only incipient subduction) (Fig. 8).

In this sense, it is worth mentioning the record of four very deep earthquakes, more than 600 km in a vertical approximately situated S of Granada. Blanco & Spackman (1993) described a sunken lithospheric body in the area of the Betic Cordillera, and perhaps with the present data, the most accurate interpretation would be to consider these deep earthquakes as being linked to this lithospheric body and the origin of this sunken body to the process of the westward displacement of the Betic-Rif Internal Zone, the lithospheric root of which could have begun sinking from the Early Miocene.

A final problem is to determine the present limit between the African and the European plates in this area of the Alboran. Probably, at the end of the Palaeozoic the limit was quite clear. Afterwards, with the formation of the Ligurian Basin a part of the European plate was separated, forming the Alkapeca or South Sardinian domain, but to the south, the Flysch basin continued marking the main limit between the two plates. Nevertheless, with the formation of the Algero-Provençal basin and the destruction of the South Sardinian domain, the limit between these plates is not clear. In fact, the old limit has been destroyed with the displacement of the Kabylias to the south and of the Betic-Rif Internal Zone to the west.

If we consider all the limit from the Azores to the Alboran Sea, the contact between both plates is relatively clear till the area of Gorringe (Fig. 9), from where the great number of faults makes it difficult to ascertain the real position of the limit. Probably this limit continues towards the Gibraltar area, but its position it is not clear. From Gibraltar to the east the same occurs, but this limit probably tends to be re-situated in the axis of Alboran Sea and the Algerian Basin.

Finally, mention should be made of the process of regional uplift with radial extension described by Simón Gómez (1990) in the Iberian Cordillera (and which may also have affected the Valencia Trough). This process also affected most of the Betic Cordillera from the Tortonian and more especially the Pliocene onwards (Sanz de Galdeano & López Garrido, 1991). As this phenomenon affects a wide area (Fig. 6 F), it is difficult to determine the reason for its formation. Isostatic explanations can be considered over a great part of the Betic and even Atlasic areas, but, on the whole, it is probably connected with movements originating in the mantle.

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