Part G

General

G1 Tertiary stages and ages, and some distinctive stratigraphic approaches

P.F. FRIEND

Abstract

A standard scheme of stages for the Tertiary is presented, and their ages discussed. Sequence stratigraphy was becoming established as an approach to the analysis of the Spanish Tertiary before it became widely used internationally. Geomagnetic polarity reversal stratigraphy has been shown to be an important approach to the dating of some non-marine successions.

Introduction

Basin stratigraphy generally provides the best key to the geometry and timing of development of the basin. Because much of this book reports recent work on the stratigraphic analysis of the various local Tertiary successions, this chapter has been written to introduce Tertiary stratigraphic terminology for those unfamiliar with it, and to draw attention to some of the special techniques used on the Spanish material.

The Tertiary stages

A geologic time scale 1989 or *GTS 89* (Harland *et al.*, 1990) is the starting point of this introduction. It has been widely used because of its broad and balanced coverage.

Fig. 1 presents the scheme of eras, sub-eras, periods and stages proposed for standard use in *GTS 89*. The stages are, to a great extent, the basic units for indicating the ages of rocks in the Tertiary successions, and are now based on global correlations using planktonic oceanic faunas and floras. Fig. 1 also shows correlations between the various standard stages and certain stages and divisions used more locally in Spain. These local schemes have been developed where correlations with the standard stages are particularly uncertain. For example, the stages of column (5) (Fig. 1) have been developed using faunas of benthonic foraminifera, and are therefore applied where deposits include these fossils and lack planktonic forms (e.g. Luterbacher *et al.*, 1991). The stages and Mammal Neogene zones (Mein, 1975, 1990) of columns (6) to (8) have been developed where marine faunas are completely lacking and the biostratigraphy depends on land faunas (consisting mainly of mammals) (see Chapters C3 and C5).

Ages of the Tertiary stages

Fig. 2 presents some recent time-scale age estimates for the boundaries between the standard Tertiary stages. These time scales are those of Harland *et al.* (1990), Cande and Kent (1992), and Odin and Odin (1990). The greatest difference in the three estimates for any particular stage boundary is 4.0 Ma in the middle Eocene, but is only 1.5 Ma in the Neogene, and the differences are less for stage boundaries before and after these two maxima.

Sequence stratigraphy

A *depositional sequence* has been defined (Mitchum *et al.*, 1977) as:

> a stratigraphic unit of a relatively conformable succession of genetically related strata and bounded at its top and base by unconformities or their correlative conformities

Fig. 3 illustrates some typical sequence relationships.

Sequences matching the above definition form the major subdivisions in most of the Tertiary basins of Spain, and the recognition and study of depositional sequences have contributed greatly to recent advances. Indeed, it was in the continental (non-marine) basin fills of Spain that A.G. Megias developed his pioneering use of 'Tectosedimentary units' or 'TSUs' (1973, doctoral thesis, University of Granada, and subsequent publications), which appear to be identical to the depositional sequences defined above. His TSUs are bounded by 'rupturas sedimentarias' (Castillian), sometimes translated as 'ruptures' (English) but better translated as breaks or boundaries.

The belief that many depositional sequences are a response to global sea-level change (Vail *et al.*, 1977) has such exciting implications in terms of dating events and correlating changes, that it has had a major impact on stratigraphic work over the last 15 years. But it is now clear (Galloway, 1989; Miall, 1986, 1991) that careful analysis must be carried out before a particular depositional sequence can be interpreted as caused by global sea-level change. In fact, most non-marine, inland sequences, particularly, seem likely to have been formed primarily by tectonic or climatic factors.

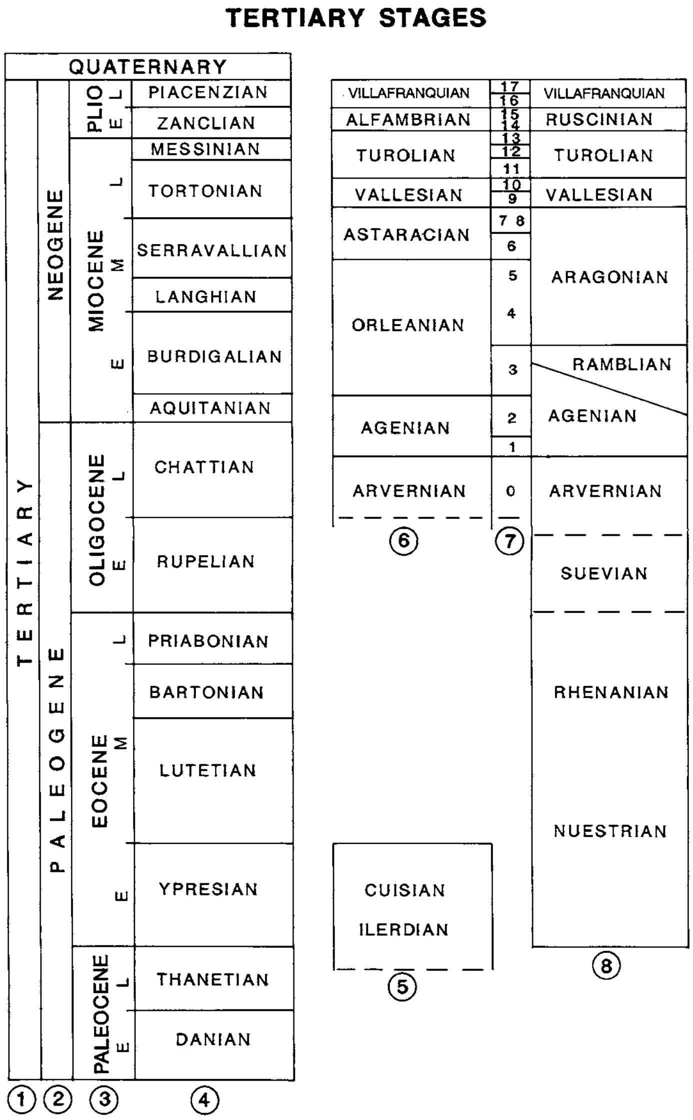

Fig. 1. Tertiary stratigraphic names used in this book. Columns (1) to (4) show the eras (1), sub-eras (2), periods (3) and stages (4), according to the *GTS 89* time scale (Harland *et al.*, 1990). Conventional divisions of the periods into early (E), middle (M) and late (L) are shown. The boundaries between the units in columns (1) to (4) are spaced vertically according to the ages assigned in the *GTS 89* (see Fig. 2). Column (5) shows stages based on benthonic foraminifera (Luterbacher *et al.*, 1991). Columns (6) to (8) are Neogene mammal ages (6), the MN zones (7) of European mammal biostratigraphy and European continental stages (8) from charts by Calvo *et al.* (this volume) and Gomez *et al.* (this volume).

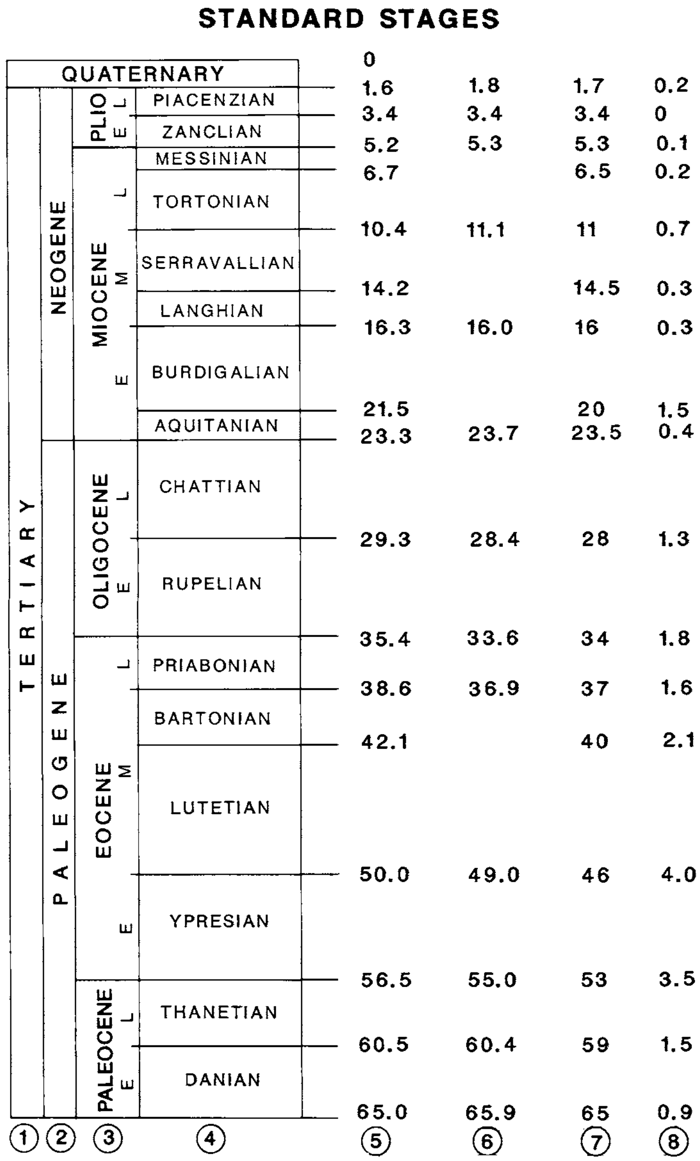

Fig. 2. Recently quoted ages (in Ma) for the standard Tertiary stages. Columns (1) to (4) as explained in the caption for Fig. 1. Column (5) contains the ages quoted in *GTS 89* (Harland *et al.*, 1990). Column (6) contains ages indicated by Cande and Kent (1992). Column (7) contains ages quoted by Odin and Odin (1990). Column (8) shows the maximum difference in the ages quoted in columns (5) to (7).

Geomagnetic polarity reversal stratigraphy

One significant approach to the dating of long successions in the largely unfossiliferous continental basins of northern Spain has been the work on paleomagnetic reversal stratigraphy by Burbank and his group (see Chapters E11, E13 and E14). Whereas the first of these chapters uses the *GTS 89* reversal time scale, the second and third have used the polarity reversal scale developed by Cande and Kent (1992). Fig. 4 compares the ages attributed by Cande and Kent for the top of the highest normal polarity interval for each of the standard ocean-floor anomaly intervals, with the equivalent ages quoted in *GTS 89* (Harland *et al.*, 1990). The Cande and Kent ages are generally younger than the *GTS 89* ages, by a maximum of 1.5 Ma at ages of about 40 Ma, and the discrepancies are less for both older and younger Tertiary anomalies.

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0521021987 - Tertiary Basins of Spain: The Stratigraphic Record of Crustal Kinematics
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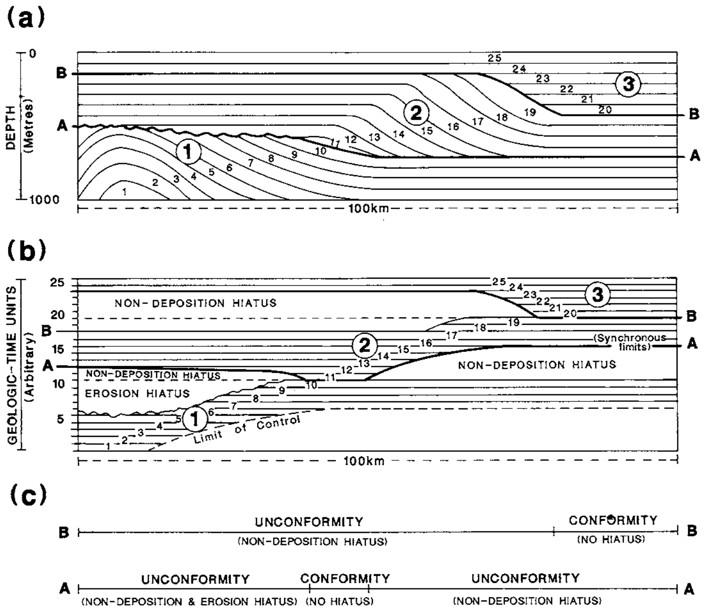

Fig. 3. Possible scale and relationships between three depositional sequences. (a) Depth–location relationships along a profile, with time-units (1) to (25), and (b), time–location relationships along the same profile, to illustrate the pattern of deposition, non-deposition hiatus and erosion hiatus, and (c) the changes in the sequence boundaries (A) and (B) across the profile. (Redrawn from Mitchum *et al.*, 1977.)

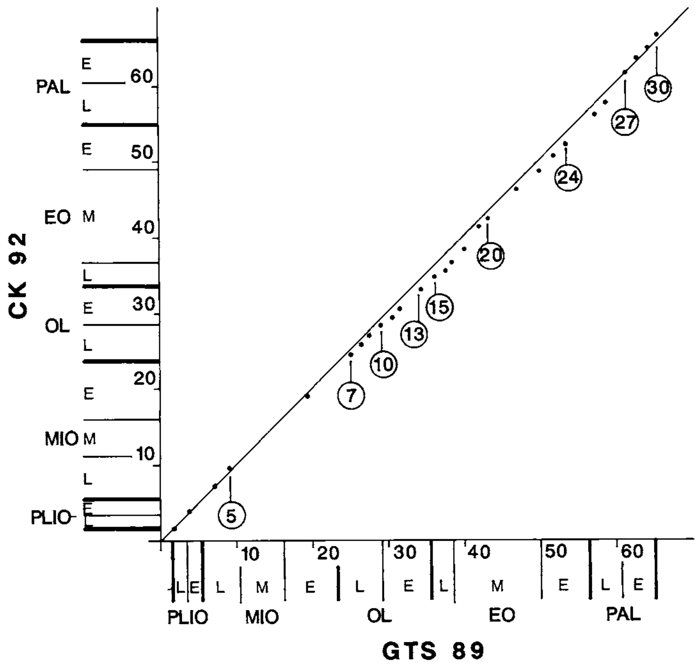

Fig. 4. The relationship between ages estimated in the *GTS 89* time scale (Harland *et al.*, 1990) and the *CK 92* time scale (Cande and Kent, 1992). Each point on the graph represents the ages quoted for the top of the youngest normal polarity interval in each of the major numbered magnetic anomalies conventionally recognised in ocean-floor anomaly mapping. The straight line on the graph will coincide with points of identical age on the two scales.

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G2 Cenozoic latitudes, positions and topography of the Iberian Peninsula

A.G. SMITH

Abstract

Four maps of the Iberian peninsula at 65, 35, 16 and 0 Ma show the positions of Iberia relative to Europe and Africa as estimated from ocean-floor spreading data. The maps themselves are in a global paleomagnetic reference frame. The Cenozoic changes in latitude of Seville, Madrid and Barcelona are also shown. In early Paleocene time the latitude of Seville was as low as 30°. The origins of the present high topography of the Spanish meseta are unclear.

Introduction

The chapters in this volume discuss the Tertiary basins in Spain. The nature of their sedimentary fill is controlled partly by tectonics, paleoclimate and paleotopography. This short chapter comments on all of these features from a broader viewpoint than that which has necessarily been adopted by most of the accompanying chapters and also raises some general questions. In particular, this chapter highlights three topics: 1. Cenozoic positions of the Iberian peninsula relative to Eurasia and Africa as estimated from published Atlantic ocean-floor spreading data; 2. Cenozoic paleolatitudinal changes of the peninsula; and 3. the peninsula's anomalously high topography.

Cenozoic position and orientation

In Cenozoic time the Iberian peninsula has behaved as part of a microplate directly linked to Africa and Eurasia by orogenic belts. In principle, the position of the peninsula relative to the stable parts of the Eurasian and African plates can be determined by fixing Iberia and restoring the orogenic belts to their late Cretaceous shapes and then adjusting the positions of Eurasia and Africa accordingly. However, the uncertainties in this approach are considerable because it involves palinspastically restoring fold and thrust belts, unstraining the more deformed zones as well as recognizing and evaluating all major strike–slip deformation.

A more general approach is to use the Atlantic ocean-floor spreading data to reposition Iberia, Eurasia and Africa. Africa may be repositioned relative to Europe by using the spreading history of

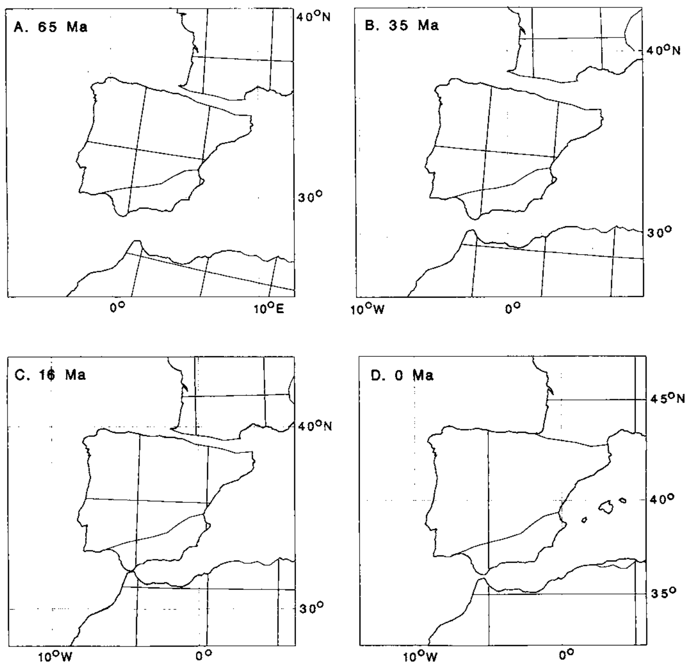

Fig. 1. Maps of Iberia, Europe and Africa in a paleomagnetic latitude frame of reference. Present-day latitude and longitude grids are shown for convenience. Iberia has been repositioned relative to Europe using data from the Bay of Biscay. Europe and Africa have been repositioned relative to one another from ocean-floor spreading data. A. 65 Ma (Cretaceous–Tertiary); B. 35 Ma (Eocene–Oligocene); C. 16 Ma (Early–Middle Miocene) and D. 0 Ma (present-day).

the central Atlantic between Africa and North America (Klitgord & Schouten, 1990), and of the North Atlantic between North America and Europe (Srivastava & Tapscott, 1986). Iberia can be repositioned relative to Europe from the data of Olivet *et al.* (1984) and Sibuet *et al.* (1980). The magnetic anomaly scale and numerical time scale is that of Harland *et al.* (1990). Fig. 1 shows four maps: for 65 Ma (the Cretaceous–Tertiary boundary); 35 Ma (approximately the Eocene–Oligocene boundary); 16 Ma (approximately the Early–Middle Miocene boundary); and 0 Ma (present-day) based on these data. All four maps show an arbitrary northern boundary to Iberia in the Pyrenees; the Betics have been retained in their present-day position relative to Iberia as a whole; fragments of a formerly continuous continental area to the E of Iberia (the Balearic Islands, the Grande and Petit Khabylie of N Africa, Corsica, Sardinia and small fragments now forming part of southern Italy and northern Sicily) have been omitted. The *relative positions* of Eurasia, Africa and Iberia are those implied by the spreading data, but the reassembly has been rotated into a global paleomagnetic reference frame (see below).

Because of the uncertainties in the spreading data these maps should not be used as evidence of movements on a scale of 100–200 km. However, the maps are reliable on a smaller scale, i.e. for larger effects. The following effects are probably real: 1. there is very little rotation of Spain with respect to Africa during the Cenozoic; 2. there is a small rotation relative to Europe in the same period; 3. Iberia was separated both from southern Europe and the Betics and/or Africa in early Cenozoic time; 4. the removal of these spaces presumably by compression to give rise to orogenic belts; and 5. there have been no large (> 200 km) strike–slip motions between Iberia and either Africa or Europe in Cenozoic time. Strike–slip motion of < 200 km may have occurred, but is not resolvable from these data. The constraints provided by the ocean-floor data must be satisfied by all Cenozoic tectonic syntheses.

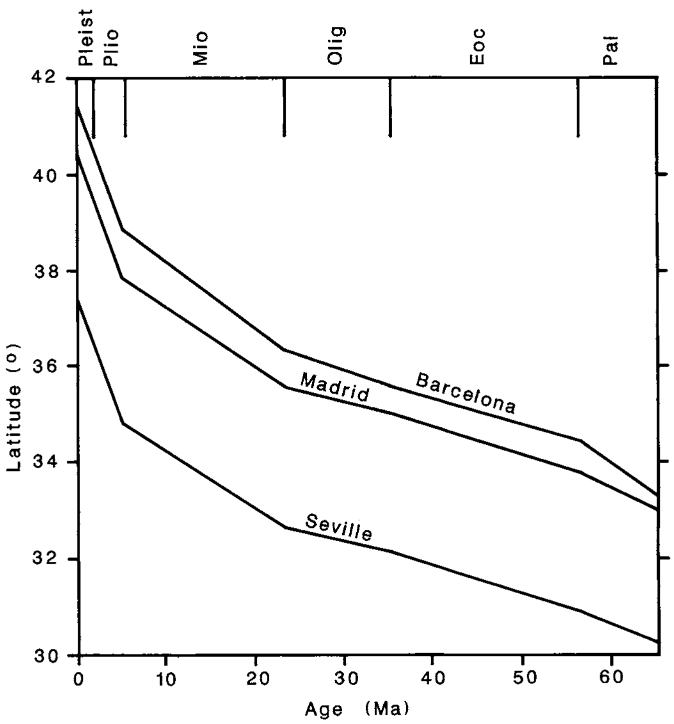

Fig. 2. The Cenozoic changes in latitude of Seville, Madrid and Barcelona, estimated from reconstructions placed in a global paleomagnetic frame of reference.

Paleolatitudes

Paleomagnetic pole positions give directly the former latitude of a point on the Earth's surface. Though there are some reliable Cenozoic pole positions from the Iberian peninsula, they are relatively few in number and not well distributed in time. The most reliable method for determining the paleolatitude of a point in the Iberian peninsula is to link the peninsula to a larger reference continent, such as Eurasia, by using ocean-floor speading data. The global paleomagnetic pole can be determined relative to this reference continent (e.g. Besse & Courtillot, 1991) and hence the paleolatitude of any point on Eurasia and any continental fragments that can be linked to it can be found. The poles used are those in the ORACLE database version 1 of Lock & McElhinny (1991). Fig. 2 shows the estimated changes in latitude of the sites of three Spanish cities – Barcelona, Madrid and Seville – throughout the Cenozoic Era. The numerical ages are taken from Harland *et al.* (1990). The uncertainties are difficult to estimate but are probably less than 2°.

The overall changes are relatively small (8°). However, the southern part of the Iberian peninsula was close to 30° in the Paleocene – at the same latitude as parts of the northern Sahara today. Other things being equal, one might therefore expect the climate to have been more arid in such areas than it was in later Cenozoic time.

Paleotopography

The peninsula is remarkable for its high topography, averaging several hundred metres. If isostatically balanced, an increase in thickness over that of a normal crust at sea level would be in the range 3–6 km. High topography is often associated with orogenic belts due to crustal thickening by collision and underplating. Though the peninsula is bordered by the Pyrenees to the N and the Betics to the S, the lateral extent of the high topography in the Iberian peninsula is much greater than is found adjacent to other orogenic belts of a similar age, such as the Alps and the Carpathians. Seismic studies (see Chapter G6) show that the crust under the Spanish meseta has an average seismic structure, though it is not clear whether the anticipated increase in thickness would be detectable. The high topography appears unlikely to be an orogenic effect.

High topography in non-orogenic areas is often associated with 'hot-spots', but large-scale Cenozoic hot-spot activity is absent. Even central Spain seems to have been near sea level during Late Cretaceous time (C.J. Dabrio, pers. commun.), but there is no obvious Cenozoic cause for the high topography. Thus, the ultimate origin of the topography and what sustains its present height is a key problem in regional Iberian studies.

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G3 Tertiary tectonic framework of the Iberian Peninsula

C.M. SANZ DE GALDEANO

Abstract

During the Tertiary, Iberia was strongly deformed. It was located between the large EuroAsiatic and African plates, and was displaced east relative to the opening Atlantic, along with N–S convergence. During the Eocene, major compressional deformation occurred in the Pyrenees and Bay of Biscay, and this continued in the Oligocene. The opening of new basins in the Mediterranean led to the compression and formation of the Iberian Cordillera. The Betic–Riffian Internal zones, strongly deformed in the Palaeocene, were expelled westwards towards the end of the Oligocene and in the Neogene. In the Betic and Iberian Cordilleras, regional uplift with radial extension coexisted with N–S compression, starting in the Late Miocene. The interior of the Iberian massif, particularly the Spanish Central System, was also deformed under these regimes, and the inner basins were formed. The Ebro and Guadalquivir Basins were clearly foreland basins.

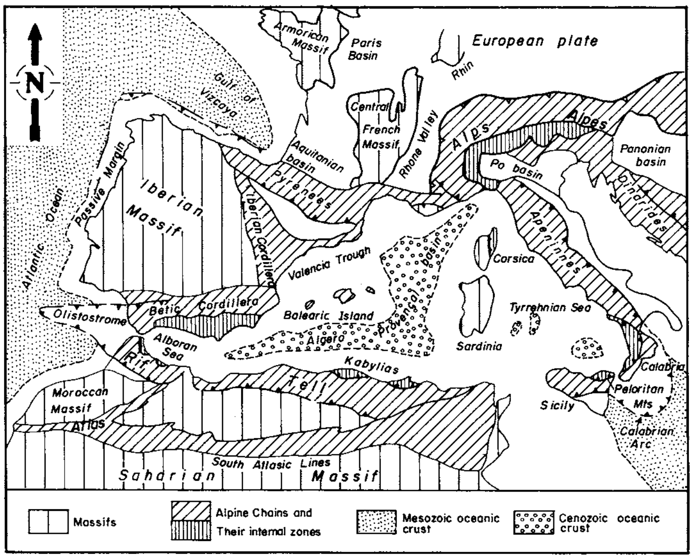

Fig. 1. General situation of Iberia.

Introduction

The Iberian Peninsula has existed as a lithospheric plate located between the African and European plates (Fig. 1) throughout the Mesozoic and Tertiary. From the beginning of the Mesozoic until late in the Early Cretaceous its movements mainly coincided with those of Europe, whereas from that time to the Oligocene it moved together with Africa. Since the Oligocene or Early Miocene, the Iberian Peninsula has been joined to Europe (Malod, 1989).

Uchupi (1988) and to a lesser extent Boillot *et al.* (1984) provide syntheses of the general tectonic situation of the Iberian Peninsula throughout the Mesozoic and Cenozoic. This chapter will concentrate on its evolution during the Cenozoic.

The nucleus of the Iberian Peninsula is the Iberian (or Hesperian) Massif (Fig. 2), which was deformed in the Hercynian. Several Alpine domains and cordilleras are located around this mainly Palaeozoic massif. Thus, to the north is the Bay of Biscay, with oceanic crust formed during the Cretaceous. To the northeast we find the Pyrenean Cordillera, consisting of a Palaeozoic nucleus and a cover of Mesozoic and Tertiary sediments. The Iberian Cordillera is located to the east of the Iberian Massif, and the Catalan Coastal Range to the southeast of the Pyrenees. The Betic Cordillera is situated to the south and southeast. To the west, the peninsula is bounded by, and forms a passive margin to, the Atlantic Ocean.

Two large Tertiary basins (Duero and Tagus) are found in the Iberian Massif, separated from each other by the Spanish Central System (a cordillera mainly controlled by the Alpine movement of late Hercynian faults). The Guadalquivir Basin is located south of the Massif, while the Ebro Basin is somewhat further away between the Iberian Cordillera and the Pyrenees. Numerous smaller Tertiary basins are found in all the domains mentioned above.

Principal evolutionary features of the Iberian Peninsula during the Mesozoic

In order to understand the evolution of the Iberian Peninsula during the Tertiary, we must place it in its geological context, particularly with regard to the processes occurring in the Western Mediterranean. Many of these processes were caused by

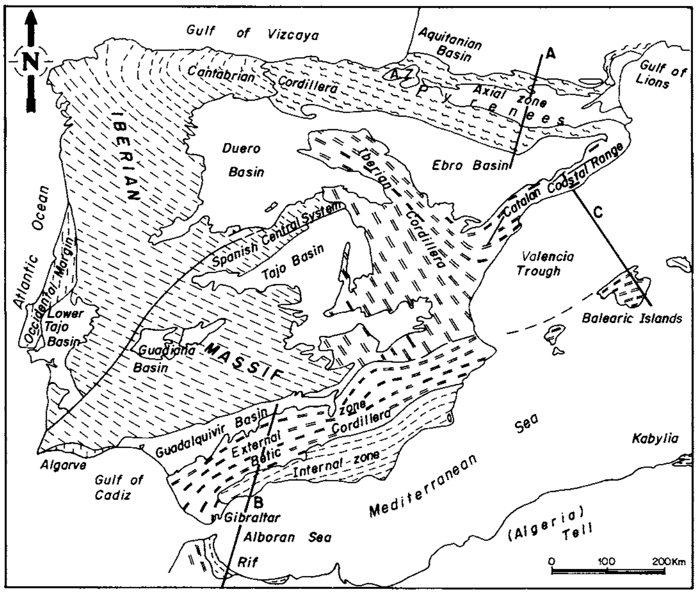

Fig. 2. Highly simplified geological scheme of the principal domains in the Iberian Peninsula. Lines, A, B and C mark locations of sections shown in Fig. 5. (Simplified and modified from Julivert *et al.*, 1972).

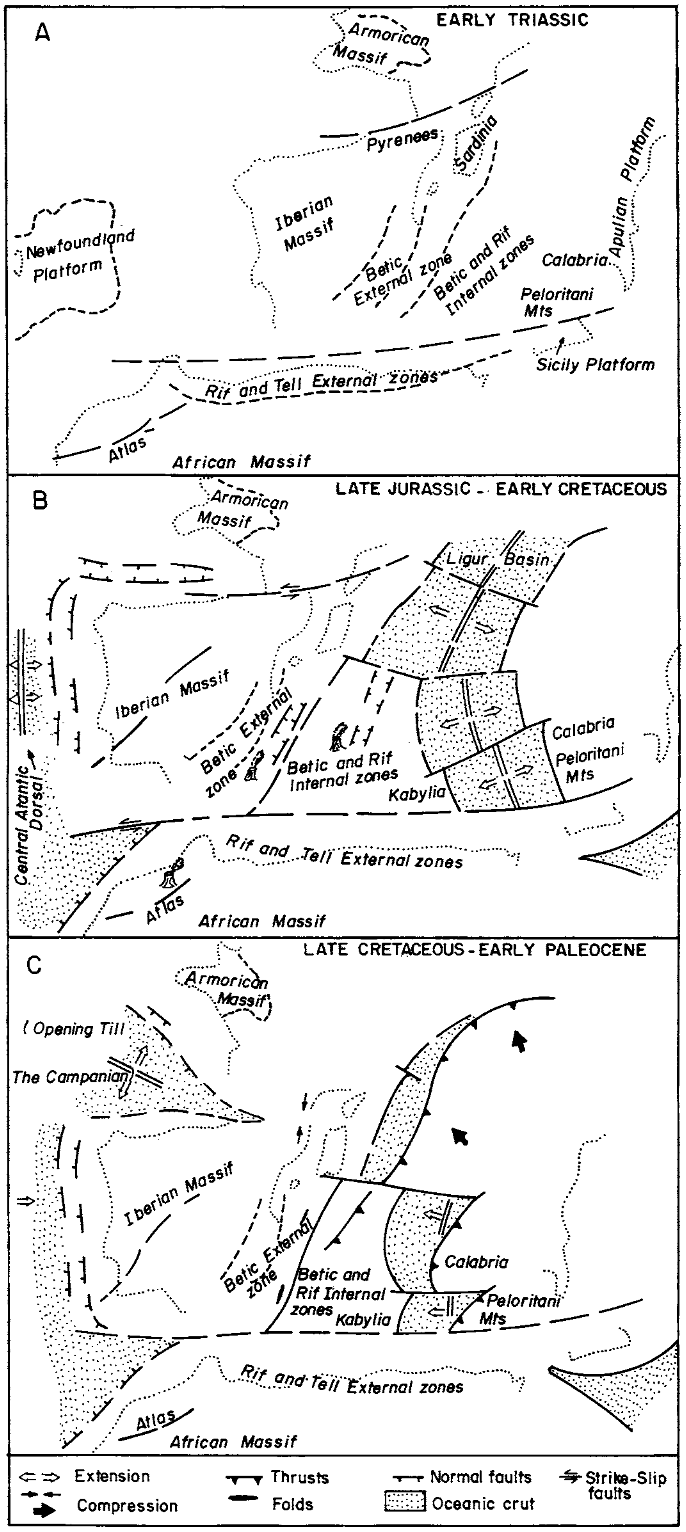

Fig. 3. Highly simplified interpretative schemes of the evolution of Iberia. A: Early Triassic. B: Late Jurassic–Early Cretaceous. C: Late Cretaceous–Early Palaeocene.

interactions between the African and European plates, which in turn were related to processes of oceanic growth, especially to the opening of the Atlantic. We must therefore give an albeit schematic outline of the evolution of Iberia during the Mesozoic.

Most palaeogeographic reconstructions locate the Iberian Massif opposite the coasts of Tunisia and Algeria during the Triassic (Fig. 3A). Throughout this period, the Jurassic and part of the Cretaceous (Fig. 3B), the Western Mediterranean underwent an important process of extension, crustal thinning and even creation of oceanic crust. The latter occurred in the possibly highly complex Ligurian Basin (Biju-Duval *et al.*, 1977; Dercourt *et al.*, 1986), which probably extended from the Betic–Riffian Internal Zone to beyond the basin of the Internal Zone of the Alps. During this process the opening of the South Atlantic gradually displaced Africa to the east, so that Iberia moved relatively over 1200 km westwards.

The Central and North Atlantic began to open during the Late Jurassic. Later, during the Aptian–Albian, this gradual opening caused the Iberian Massif to rotate counter-clockwise (some 30 degrees in all), thus inducing the opening of the Bay of Biscay that separated western France from northwest Spain. This process continued at least until the Campanian (Olivet *et al.*, 1982; Boillot *et al.*, 1984) and may have occurred together with some displacement of Iberia towards the south, southwest or southeast, although this question is still the subject of debate. At the same time the first convergent movement took place between Africa and Europe and the first compressive deformations occurred in the internal zones of the Alps.

During the rest of the Late Cretaceous, Iberia did not as a rule undergo important deformation. To the west the Atlantic contin-

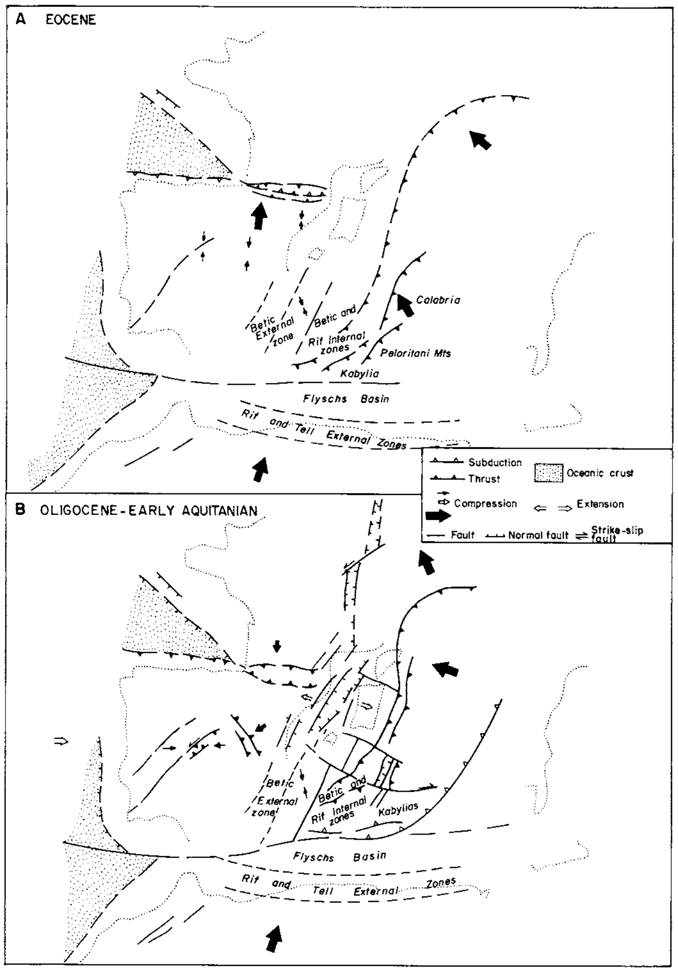

Fig. 4. Interpretative schemes of the evolution of Iberia. A: Eocene. B: Oligocene–Early Aquitanian.

ued to open, while, to the east, the Betic–Riffian Internal Zone seems to have been affected by important tectonic instability and even subduction (De Jong, 1991). The first compressive movements and nappe formation took place in the Eastern Pyrenees (Muñoz *et al.*, 1988), while extension continued in the rest of this cordillera (Ducasse *et al.*, 1986). (Fig. 3C).

Tectonic evolution during the Palaeocene and Eocene (Fig. 4A)

Displacement of the African plate relative to the European plate was clearly convergent at the beginning of the Tertiary and throughout the Palaeocene (Tapponier, 1977). In the Western Mediterranean this brought about subduction of the oceanic crust previously formed in the Ligurian Basin, which clearly affected the internal zones of the Alps and Betic Cordilleras, which, in the case of the latter, were located some 500 km east of their present position. Although weak, approximately N–S, compressive movements affected Iberia, and there was no very important deformation, not even in the Betic external zones. To the west the Atlantic

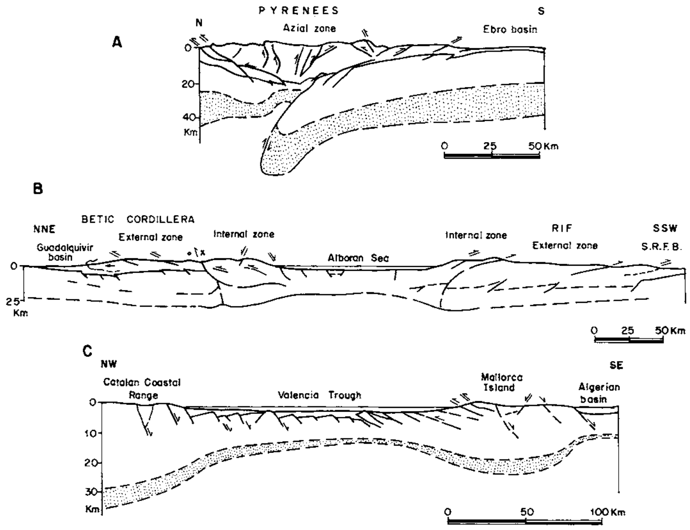

Fig. 5. Schematic geological cross-sections; their positions are marked in Fig. 2. A: Interpretation of the geological structure of the Pyrenees. Simplified from Muñoz (1992) and modifications suggested by Velasque *et al.* (1989). B: Interpretation of the cross-section from the Betic Cordillera to the Rif. C: Structure of the Valencia trough. Simplified from Martí *et al.* (1992) and Fontboté *et al.* (1990). Lower crust stippled.

continued to open as a passive margin and, to the north, there was no significant deformation, and deposition continued in most of the Pyrenees.

A new stage began towards the end of the Palaeocene or in the Early Eocene, in which collision took place after subduction. The Betic–Riffian internal zones, which did not as yet form part of Iberia, underwent an important stage of tectonic structuring and metamorphism.

This Eocene compression was transmitted to the entire Iberian plate with multiple consequences. The most significant of these occurred in the Pyrenees, which were heavily deformed forming important nappes (Megías, 1988) (Pyrenean Eocene phase). Modern deep seismic profiles show that the Iberian plate is subducted beneath the European plate (Roure *et al.*, 1989; Suriñach *et al.*, 1993) (Fig. 5A), even though there may not previously have been a large volume of oceanic crust.

The foreland basin (Ebro Basin) in the Southern Pyrenees (Anadón *et al.*, 1985) migrated southward (simultaneously) with the progressive deformation of the cordillera, while the northern margin was partially incorporated into the younger thrust sheets (Muñoz *et al.*, 1988).

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

There was some deformation in the Catalan Coastal Range, with approximately N–S compression (continuing into part of the Oligocene) (Guimerà, 1983, 1988) and important development of