

# Triassic-Miocene paleogeography and basin evolution of the Subbetic Zone between Ronda and Málaga, Spain

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## Abstract

During the Triassic, continental and supratidal environments prevailed in the north of the Ronda-Málaga region whereas intertidal and shallow marine environments characterize the south. From the Jurassic up to the Miocene, the Ronda-Málaga region was the scene of shallow marine environments in the north and open or deeper marine environments in the south. The Miocene reveals rapidly changing paleo-environments. During the Aquitanian a submarine fan system developed with clastic supply from an emerged area in the north. In the Burdigalian, deformation started to the south of the study area and depositional patterns completely reversed, now showing detritus supply from an emerged area in the south. The entire area emerged during Langhian and Serravallian times and several local extension basins developed in the Tortonian. Backstripping analysis reveals four phases of accelerated subsidence related to extension in the Mesozoic: Anisian-Ladinian (241–235Ma), Norian-Hettangian (223–203Ma), Callovian-Tithonian (161–146Ma), and Cenomanian-Turonian (97–89Ma). These phases can be correlated with tectonic events in the Central Atlantic Ocean. The Tertiary subsidence record shows a change from slow to rapid subsidence in the Late Oligocene and Early Miocene related to a change from extensional to compressional tectonics. Throughout the Middle and Late Miocene and the Pliocene, strike-slip tectonics resulted in local extension and compression giving rise to renewed basin development. The paleogeographic reconstructions together with subsidence analysis allow to discuss the tectonostratigraphic evolution of the Ronda-Málaga region within the framework of western Mediterranean plate tectonics.

## 1. Introduction

In the study of the geology of the Betic Cordilleras of southern Spain much emphasis has been placed on the eastern part and only relatively few recent studies have been undertaken in the western part of the orogen. In this paper, the results of detailed stratigraphic mapping and facies analysis are presented for the Ronda-Málaga region in this western part (Fig. 1). This region is of interest because it is located near the border between the External and Internal Zones of the Betic Cordilleras. Structurally, sedimentation patterns reflect the change from the so-called Betic to the so-called Gibraltar trend. Stratigraphic mapping and facies analysis allow to reconstruct paleo-environments for the Triassic up to and including the Miocene period. To

gain a better understanding of basin development and lithospheric dynamics in relation to plate-tectonic kinematics, a quantitative subsidence analysis has been carried out. The results of this backstripping analysis are presented and discussed with reference to the framework of western Mediterranean plate tectonics.

After outlining the general geology of the Betic Cordillera fold belt, the stratigraphy of the area surrounding Ronda (Fig. 2) is discussed with emphasis on depositional facies. Paleogeographic reconstructions are presented, based on stratigraphic data from 29 locations in the Ronda-Málaga region and on literature. The last part of the paper is devoted to a subsidence analysis in relation to Atlantic and Mediterranean plate kinematics.

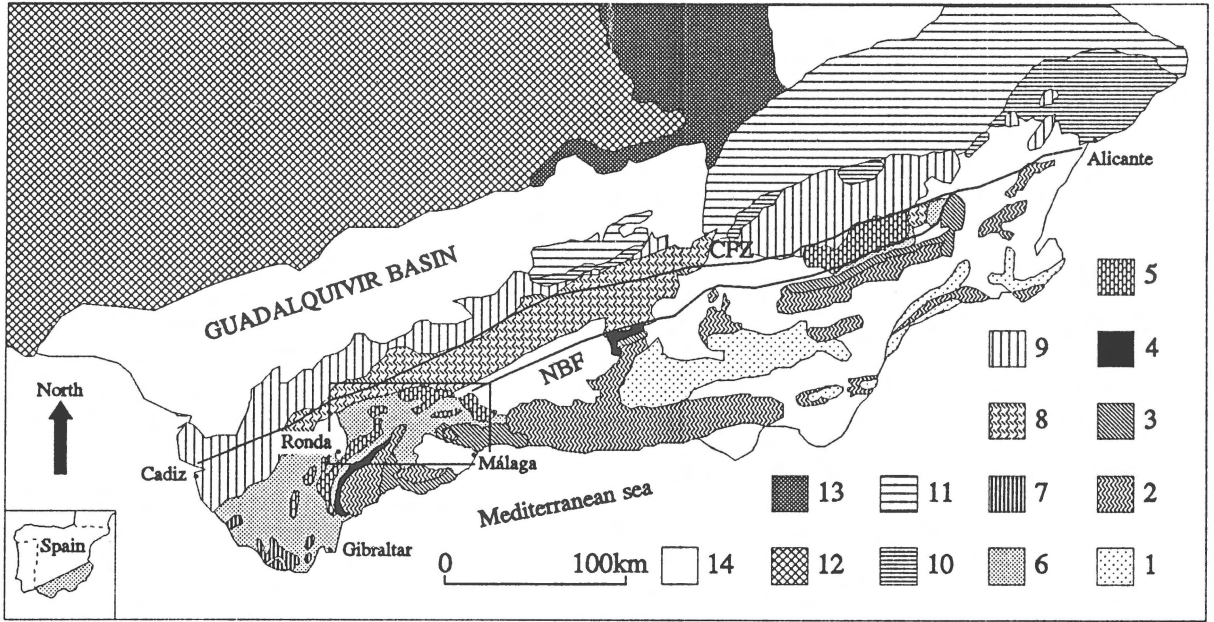


Fig. 1. Tectonic sketch map of the Betic Cordilleras (modified after Bakker et al. 1989, Geel et al. 1992). The area of investigation is outlined by the black box. Legend: 1–4 = Internal or Betic Zone; 1 = Veleta and Mulhacen Complexes (Nevado-Filabride Complex), 2 = Alpujarride and Almagrde Complexes, 3 = Malaguide Complex, 4 = Dorsale Unit, 6–11 and part of unit 5 = External Zone; 5 = Penibetic and southern Subbetic Zone, 6 = ‘flysch’ units, 7 = parautochthonous External units, 8 = median Subbetic Zone, 9 = northern Subbetic Zone, 10 = Intermediate Units, 11 = Prebetic Zone, 12 = Hercynian Meseta (undifferentiated), 13 = Mesozoic cover of the Hercynian Meseta, 14 = Late Tertiary and Quarternary basins, NBF = North Betic Fault, CFZ = Crevillente Fault Zone.

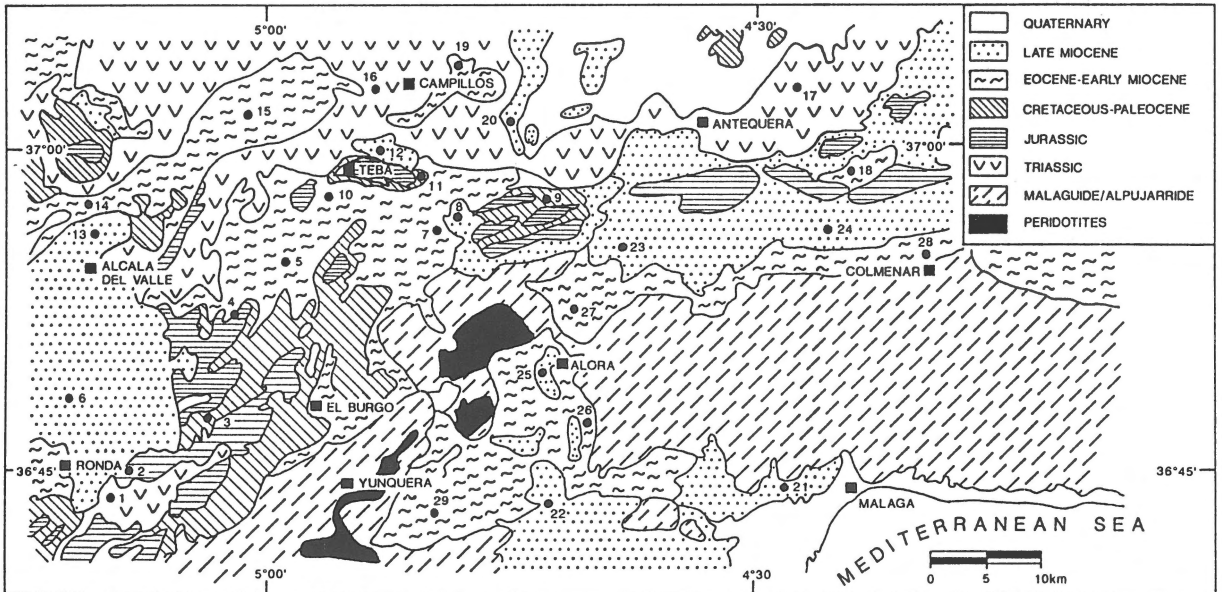


Fig. 2. General geologic map of the investigated area. Numbers indicate sections used for the paleogeographic reconstructions.

## 2. Geology of the Betic Cordilleras

The Betic Cordilleras of southern Spain form the northern part of the Betic-Rif orogenic belt and constitute the westernmost part of the Alpine-Mediterranean chain. Classically, the Betic Cordilleras are subdivided into a northern External Zone and a southern Internal or Betic Zone (Egeler & Simon 1969, Torres-Roldán 1979; Fig. 1). These zones are separated by flysch sediments of Early Cretaceous to Early Miocene age (Fontboté 1984, Bouillin et al. 1986).

The External Zone, in most tectonic models for the orogen, is regarded as the passive continental margin of the Iberian continent (Hermes 1978, García-Hernandez et al. 1980, De Smet 1984, De Ruig 1992). On the basis of paleogeographic criteria the External Zone is further subdivided into a Prebetic Zone in the north and a Subbetic Zone in the south, separated by Intermediate Units. The Prebetic Zone represents the former shelf environment where shallow marine deposition prevails, whereas the deposits of the Subbetic Zone are characterized by a pelagic facies reflecting deeper marine environments (Fallot 1948, De Smet 1984). The Subbetic Zone may be subdivided into a northern and a southern Subbetic Zone mainly formed by non-argillaceous Jurassic limestones, and a median Subbetic Zone formed by marly Jurassic limestones.

The Internal Zone consists of a stack of four nappe complexes composed of essentially metamorphic rocks of Triassic and older ages. These complexes are in descending order: (1) the Malaguide Complex, (2) the Alpujarride Complex, (3) the Mulhacen Complex, and (4) the Veleta Complex (Bakker et al. 1989). The Mulhacen and Veleta Complexes formerly constituted the Nevado-Filabride Complex, but have been separated because they show a marked difference in metamorphic characteristics (De Jong 1991). The Veleta Complex is characterized by conditions of metamorphism of relatively low pressure and temperature (Díaz de Federico et al. 1979, De Jong 1993), whereas the Mulhacen Complex shows an early phase of high-pressure - low-temperature metamorphism (Vissers 1981, Bakker et al. 1989). The Alpujarride Complex is characterized by high-pressure - low-temperature metamorphism, however, with generally lower maximum pressures than found in the Mulhacen Complex (Goffé et al. 1989, Bakker et al. 1989). The Malaguide Complex is nearly non-metamorphic and contains also post-Triassic rocks (Egeler & Simon 1969). The Dorsale Unit is regarded as the margin of the Malaguide Complex (Bouillin et al. 1986). A fifth tectonic unit can be found in tectonic

windows below the Alpujarride and Malaguide nappe complexes: the Almagride Complex (Simon 1987, De Jong 1991). The Almagride Complex consists of low-grade metamorphic red-beds, evaporites, and carbonates. Because of the similarity of the Triassic sediments found in the Almagride Complex and the External Zone, the Almagride Complex is presently regarded as the southernmost part of the External Zone (Simon 1987).

The Internal Zone as a whole is often regarded as an allochthonous tectonic element (referred to as the Alboran Microplate; Andrieux et al. 1971, Dercourt et al. 1986), which finds its origin far to the northeast of its present position (LeBlanc & Olivier 1984). Geel et al. (1992) argue that the Betic Zone and the Internal Zones of the African-Rif orogen formed part of an eo-Alpine orogenic belt which was the continuation of the Calabrian-Kabylian belt (Dercourt et al. 1986). The Internal Zone was juxtaposed against the Iberian margin during a complex Miocene orogeny, causing the External Zone to develop into a fold-and-thrust belt (De Ruig 1992, Geel et al. 1992). In the western part of the Betic Cordilleras, the Subbetic thrust sheets border the Miocene Guadalquivir Basin, which is regarded as the foreland basin of the Betic Cordilleras (Vegas & Banda 1982). In the eastern Betic Cordilleras, Miocene foreland-basin sediments are incorporated in the thrust sheets (De Ruig 1992).

## 3. Outline of the stratigraphy of the Ronda-Málaga region

A total of 29 stratigraphic sections have been investigated (Hamzah 1992, Agbor 1992, Yan 1992, Shendy 1992). Their locations are shown on Fig. 2.

The stratigraphic record of the southernmost Subbetic Zone in the Ronda-Málaga region consists of sediments ranging in age from Triassic up to Pliocene. In the following text, which also incorporates observations from the literature, these are discussed focusing on the exposed sequences north and east of Ronda and on Neogene deposits north of El Burgo (Fig. 2).

### 3.1 Triassic

Triassic units exposed east of Ronda (Fig. 2, section 1) range in age from Spathian to Rhaetian (Fig. 4). The earliest Triassic (Tr1) consists of a sequence of very thick to thin beds of red-coloured conglomerates and sandstones (with components up to 5 cm in

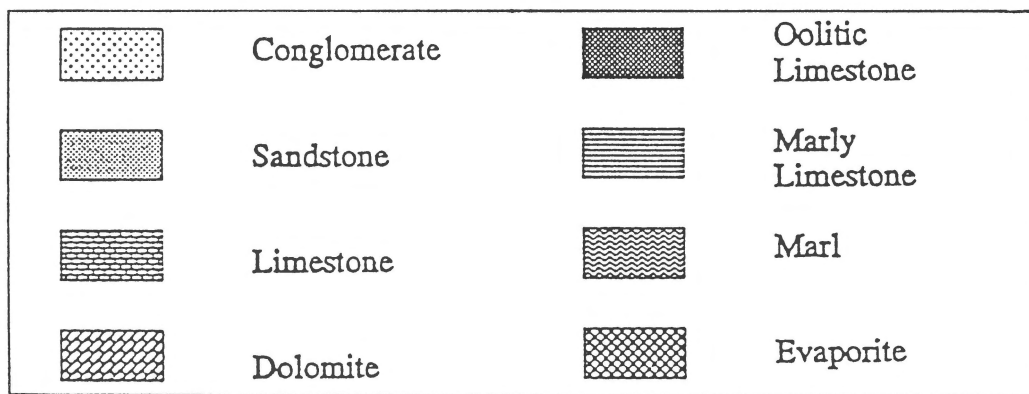


Fig. 3. Legend to the lithology in the stratigraphic columns of Figs 4–7 and the composite stratigraphic column of Fig. 12. Sedimentary structures: CC = caliche crusts, CL = convolute lamination, CR = current ripples, DC = desiccation cracks, FU = fining upward, GB = graded bedding, HB = herringbone cross-bedding, HCS = hummocky cross stratification, OL = olistostromes, PL = parallel lamination, WR = wave ripples.

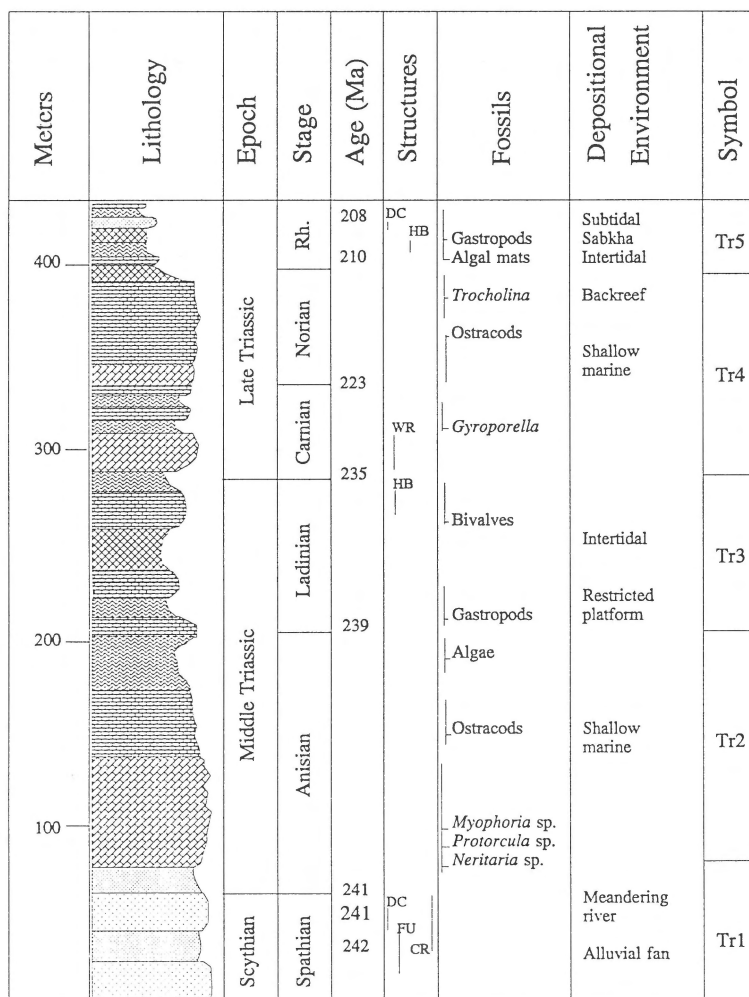


Fig. 4. Stratigraphic column of the Triassic deposits outcropping in the Subbetic Zone east of Ronda (location 1 on Fig. 2). Legend: see Fig. 3.

size) which are fining upward to medium grained sandstones. Red beds of the same age and composition are found throughout the Betic Cordilleras (Simon 1987). Trough-shaped and wedge-shaped cross-stratification in the order of centimetres is common in the coarser sandstones. The base of a set of cross strata may be coated with a red pelitic film. Mud cracks have been observed locally, as well as small-scale fining upward sequences. The red conglomeratic sandstones are thought to represent the lower part of a coarse-grained alluvial fan whereas small-scale fining upward sequences suggest deposition by a 'meandering' type of river. This interpretation is consistent with the observations made by Roep (1972) in the Vélez-Rubio area, 200 km to the northeast. Fossils have not been found in the clastic sequence, but from geologic relations an Early-Middle Triassic (Spathian-Early Anisian) age is inferred.

The lower part of the sequence Tr2 consists of dolomites containing *Myophoria*, *Protorcula*, and *Neritaria* together with other species yielding an Anisian age (Dürr 1967). Overlying these dolomites is a series of limestones containing fragments of ostracods. Remains of algae were found in marls at the top of Tr2.

The bottom of Tr3 is formed by a resistant limestone bed containing abundant gastropods. Dürr (1967) recognized a Ladinian fauna and described local intervals of evaporites in the Tr3 sequence, although this observation is disputed by Bourgois (1978). The carbonate sequence represented by units Tr2 and Tr3 was deposited in a shallow marine, restricted platform environment.

The lower part of the Late Triassic consists of approximately 110 m of limestones and dolomites with interbedded marls. This sequence (Tr4) was dated by Martín-Algarra (1980) on the basis of Dasycladacea (e.g. *Gyroporella* sp. aff. *verticillata*) as Carnian-Norian. A backreef environment of deposition is interpreted on the basis of the occurrence of *Trocholina* at the top of Tr4.

This sequence is overlain by 40 m of multicoloured marls alternating with sandstones and evaporites (Tr5). These marls were dated as Rhaetian by Blumenthal (1933) which is consistent with dating by Besems & Simon (1982) of similar Triassic rocks in the Murcia Province in the eastern part of the External Betic Cordilleras. Our observations agree with the general opinion that the Late Triassic facies originated in a continental or shallow marine evaporitic environment.

The Triassic north of Campillos and Antequera (see Fig. 2 for location) consists of 150–200 m of evaporites (mainly anhydrite, gypsum and halite) alternating with coarse alluvial fan deposits. Thin intervals of well-bedded algal stromatolites record short-term marine influences.

### 3.2 Jurassic

Jurassic rocks exposed near Ronda (Fig. 2, section 2) consist of approximately 400 m of limestones, dolomites, marls, and marly limestones (Fig. 5; Azémar et al. 1979). The earliest Jurassic and possibly the latest Triassic (Rhaetian?) consists of a 40–70 m-thick unit of light-grey, sugary dolomites interbedded with oolitic limestones (J1). This unit has been dated on the basis of the stratigraphic relationship with the overlying unit, a relatively thin (less than 50 m) sequence of well-bedded, grey-brown lime-mudstones and marls. These micrites are frequently laminated and contain abundant gastropods, bivalves and crinoids (J2). On the basis of the gastropod fauna, the sequence was dated Sinemurian-Bathonian by Dürr (1967). The presence of *Haurania* indicates a lagoonal environment of deposition and a Pliensbachian to Bathonian age. Therefore the age of the underlying unit J1 is inferred as earliest Jurassic.

The lower part of the Middle and Late Jurassic unit J3 consists of a 200 m-thick series of well-bedded, monotonous limestones and marls with occasional dolomites (J3). In the middle and upper part of this sequence, abundant crinoids and bivalves were found. Dürr (1967) dated the series as Callovian-Oxfordian on the basis of corals and hydrozoans. The carbonates were deposited in a lagoonal environment as evidenced by the presence of *Alveosepta*. *Alveosepta* occurs only in the middle part of the sequence and indicates an Oxfordian to Kimmeridgian age. Towards the top of the sequence, the occurrences of oolitic limestones indicate wave action in a shallow marine environment.

The latest Jurassic rocks (J4) consist of a series of 120 m of well-bedded oolitic limestones developing into marly limestones containing abundant belemnites and ammonites at the top of the sequence, suggesting an abrupt deepening of the depositional environment. The age of unit J4 is inferred as Kimmeridgian-Tithonian (Durand-Delga et al. 1959). The base of the sequence was dated as the boundary between the Oxfordian and Kimmeridgian from the presence of *Cladocoropsis mirabilis* and *Acrosmilia* aff. *fromenteli*. The occurrence of *Saccocoma* indicates a

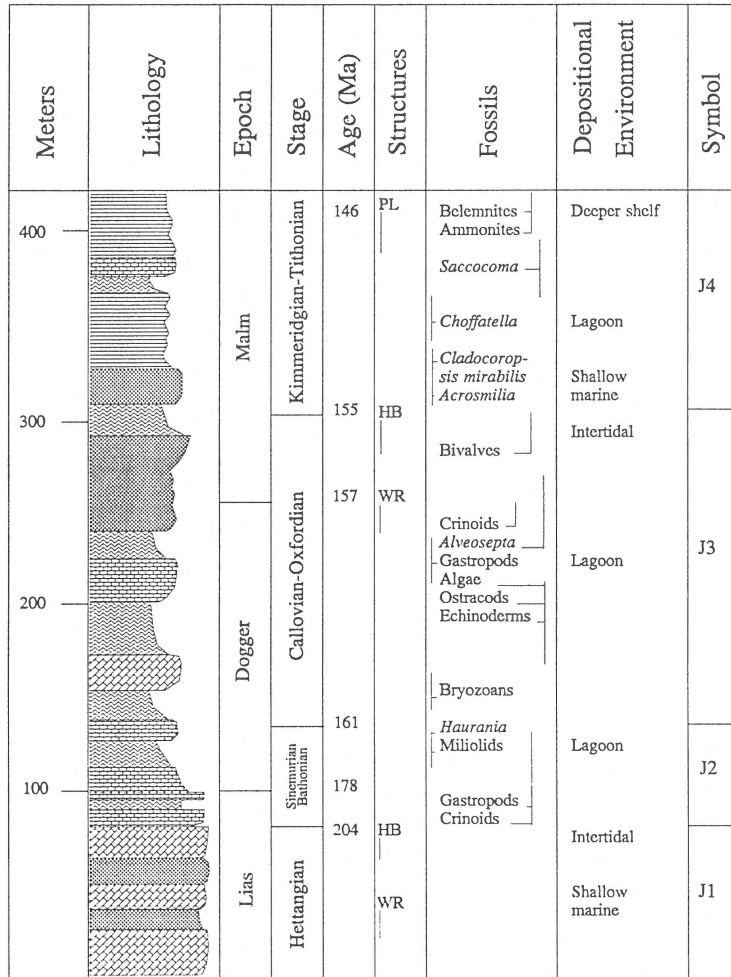


Fig. 5. Stratigraphic column of the Jurassic deposits outcropping in the Subbetic Zone east of Ronda (location 2 on Fig. 2). Legend: see Fig. 3.

pelagic facies and a Kimmeridgian and Tithonian age.

In the north, near Archidona (15 km east of Antequera, Fig. 2), the thickness of the Jurassic is approximately 750 m. The Hettangian-Sinemurian comprises a basal part of dolomites and algal stromatolites which are locally brecciated due to wave action or desiccation. The upper part of the Hettangian-Sinemurian contains 200 m of oolitic grainstones and algal wackestones. A deepening of the depositional environment is inferred from a series of 300 m of marly limestones containing radiolarians and planktonic foraminifera. These marly limestones were dated as Pliensbachian to Kimmeridgian by Delgado & Sanz de Galdeano (1981). The latest Jurassic exposed near Archidona consists of turbidites and marly units containing abundant ammonites and *Aptychus* (Delgado & Sanz de Galdeano 1981).

### 3.3 Cretaceous

The Cretaceous sequence exposed in the Ronda area (Fig. 2, section 3) is relatively thin (generally less than 300 m, Fig. 6). The lowermost unit (K1) is composed of marls alternating with marly limestones and contains radiolarians, bryozoans, and several foraminifer species. The base of the sequence is formed by a 10 m-thick layer of nodular bituminous marly limestone. Occurrences of *Praealveolina* in the lower part of the K1 unit indicate a Late Albian to Turonian age. ITGE (1990) dated the unit K1 as Cenomanian-Turonian. This suggests a non-depositional or erosional hiatus during the Early Cretaceous. Miliolids and *Praealveolina* in the basal and middle part of unit K1 record a lagoonal environment and radiolarians at the top of K1 a deeper shelf environment. The Senonian is mainly represented by a series of

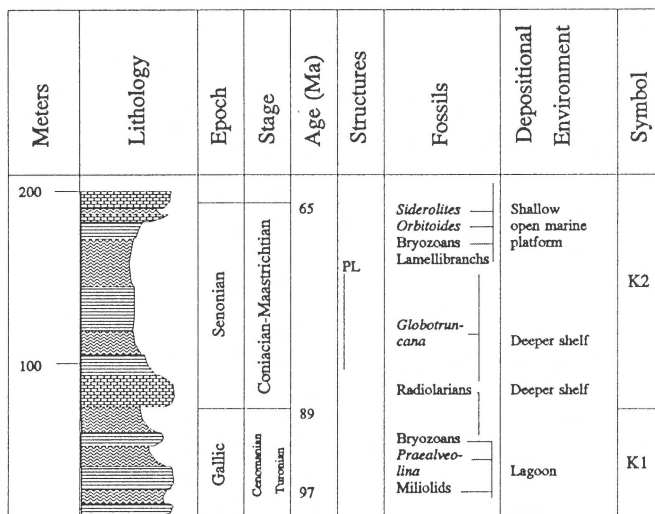


Fig. 6. Stratigraphic column of the Cretaceous deposits outcropping in the Subbetic Zone east of Ronda (location 3 on Fig. 2). Legend: see Fig. 3.

well-bedded, red-coloured marly limestones and marls of the 'Couches Rouges' facies (in Spanish 'Capas Rojas', K2). The base of unit K2 is formed by a series of thick-bedded limestones. The marls and marly limestones contain abundant planktonic foraminifera (e.g. *Globotruncana*) which indicate a Coniacian to Maastrichtian age (Azéma 1961) and a deeper facies. The top of the K2 sequence contains *Siderolites* and *Orbitoides* which yields a Maastrichtian age and a shallow open marine platform environment of deposition. However, Kockel (1960) mentioned *Globorotalia* species indicating a Paleocene or younger age for what is here taken as the top of unit K2. The thickness of this unit diminishes from 250 m south, to less than 50 m north of the study area.

Some 5 km north of Antequera a more complete Cretaceous sequence occurs. The Neocomian is represented as a thin (15 m) unit composed of marls and marly limestones containing abundant *Nannoconus* species indicating pelagic conditions. A series of 60 m thickness of bituminous marls with radiolarians of Cenomanian-Turonian age and with *Globotruncana* and *Rotalipora* overlies this unit. The Couches Rouges facies overlying the Cenomanian-Turonian marls is represented by 200 m of red-coloured marls and thin-bedded limestones containing abundant *Globotruncana* and *Rugoglobigerina* species. The sequence passes upward into Paleocene (*Globigerina daubjergensis* zone, Dürr 1967).

### 3.4 Paleocene-Miocene

The Tertiary stratigraphy described below (Fig. 7) is exposed at three representative groups of locations in the western part of the study area: El Burgo (Fig. 2, sections 3, 5, 6), Ardales (sections 7, 9), and Teba (sections 10–12).

The distribution of Paleocene deposits over the area is very irregular. In places they are lacking and Eocene deposits rest directly on top of the 'Capas Rojas' unit, in other places a thick Paleocene sequence ( $\pm 150$  m) is found. The Paleocene in El Burgo shows *in-situ Microcodium* in detrital limestones. The occurrence of *in-situ Microcodium* is generally accepted to indicate a non-marine origin (Esteban 1974) and it is restricted to coastal zones with predominantly non-saline water. According to Smith (1979), *in-situ Microcodium* only occurs in Paleocene-Early Eocene series although Klappa (1978) claims occurrences of *Microcodium* in the Eocene and Pleistocene. The Paleocene deposits of Ardales and Teba, on the contrary, were deposited in deeper marine environments. Occurrences of *Dictyoconus* in the Teba section indicate deposition at the platform margin. A deeper shelf environment is deduced from the occurrence of *Globigerina* and *Globorotalia* in the Ardales section.

Late Paleocene-Eocene deposits reach a maximum thickness of 300 m and consist of bioclastic limestones with terrigenous clasts, marly limestones and marls. In the El Burgo area, these deposits often show

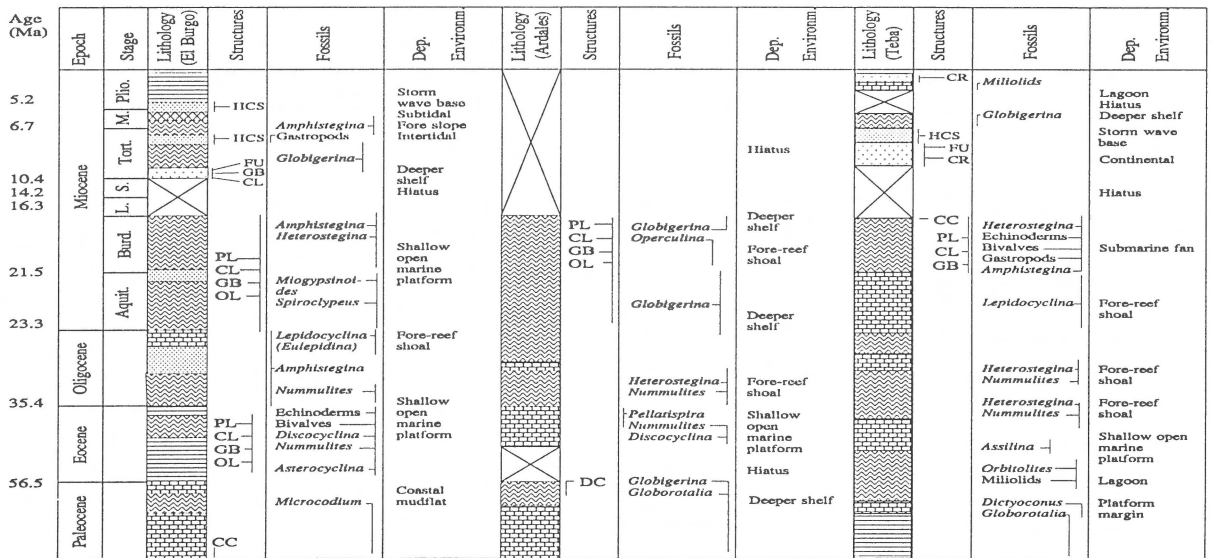


Fig. 7. Tertiary stratigraphy in the El Burgo section (Paleocene is number 3, Eocene-Burdigalian number 5, and Tortonian-Pliocene number 6 in Fig. 2), the Ardales section (Paleocene is number 9, Eocene-Burdigalian number 7), and the Teba section (Paleocene is number 11, Eocene-Burdigalian number 10, and Tortonian-Pliocene number 12). Note that the time scale changes after Oligocene. Legend: see Fig. 3.

convolute bedding, graded bedding and other characteristics of turbiditic sequences. On the basis of the occurrence of *Nummulites*, *Asterocyclina* and *Discocyclina*, the Late Paleocene to Eocene age was established for the El Burgo section (Dürr 1967). Local occurrences in the Late Paleocene-Eocene deposits of the El Burgo section of chaotic masses of blocks of limestones from Jurassic units cemented by marls containing abundant foraminifera have been interpreted as olistostromes deposited in deeper water environments. The Eocene deposits of the El Burgo and Ardales sections record a shallow open marine platform environment of deposition with the presence of *Nummulites* and *Discocyclina*. The occurrence of abundant *Miliolids* in the lower part of the Eocene deposits of the Teba section indicates a lagoonal environment which deepens to a shallow open marine platform environment as deduced from the presence of *Heterostegina* near the top of the Eocene section.

The Late Paleocene-Eocene deposits in the El Burgo section are overlain by a 100 m thick Oligocene sequence consisting of red marls and intercalated bioclastic limestones and sandstones. The limestones contain *Amphistegina*. Near the top of the El Burgo

section, *Lepidocyclina* (*Eulepidina*) indicates a fore-reef shoal environment. *Nummulites* is present at the base of the sequence. *Heterostegina* and *Nummulites* present in the lower part of the Oligocene sections of both Ardales and Teba, which consists mainly of marls, indicate a fore-reef shoal environment of deposition. The Oligocene in both the Ardales and Teba sections reaches a maximum thickness of 150 m.

The Early Miocene and possibly Late Oligocene sediments in the El Burgo and Ardales sections consist of grey-green marls and micaceous sandstones showing convolute bedding, graded bedding, parallel lamination and other characteristics of turbiditic sequences. Occurrences of *Miogyopsis* (or *Miogyopsisinoides*, Peyre 1974) and *Spiroclypeus* in the El Burgo section indicate a Late Oligocene to Early Miocene age. Peyre (1974) dated the sequence as Aquitanian. The Ardales section records deeper shelf environments with the presence of *Globigerina*. A fore-reef shoal environment of deposition for the Aquitanian of the Teba section is deduced from the occurrence of *Lepidocyclina* in bioclastic limestones. The thickness of this unit is highly variable and ranges from 200 to 500 m in the studied area. Similar sediments of the same age have been esti-

mated to reach a thickness of 1000 m near Gibraltar (Didon 1960, 1969).

Turbidites of Burdigalian age in all three sections are represented by a thick sequence of marls with intercalated sandstones and conglomeratic lenses showing graded and convolute bedding. These marls contain fragments of *Microcodium* and often also reworked fossil fragments from Jurassic and Early Tertiary sediments which are present in a chaotic mass interpreted as an olistostrome. The thickness of this unit varies from 800 m to locally more than 1500 m (Dubois & Magre 1972). In the El Burgo and Teba sections, the fauna in these sediments contains *Amphistegina*, *Heterostegina*, planktonic foraminifera, and reworked fragments of bryozoans and corals. It was dated by Serrano-Lozano (1979) as Burdigalian. The Aquitanian-Burdigalian boundary in the sediments of the El Burgo and Teba sections is marked by the last observance datum of *Catapsydrax dissimilis* (top of zone N5, planktonic foraminiferal zonation of Blow 1969), whereas the Burdigalian-Langhian boundary in these sections is marked by the first appearance datum of *Praeorbulina glomerosa* (within zone N8). *Operculina* occurs in the middle and lower parts of the Burdigalian in the Ardales area, whereas *Globigerina* is abundant near the top of the Ardales section.

No Langhian and Serravallian deposits were found.

The Tortonian and Messinian sediments exposed north of Ronda (shown in Fig. 7 as the top of the El Burgo section) have been studied by Serrano-Lozano (1980). In these sediments, a basal series of 50 m of conglomerates and arenites with an overall fining upward trend shows characteristics of a turbidite sequence, e.g. convolute bedding and graded bedding. Overlying these conglomerates is a series of 600 m of marls containing abundant *Globigerina* which are overlain by a 60 m-thick sequence of sandstones which contain hummocky cross stratification indicating storm-induced wave action below the fairweather wave base. An assemblage of *Globigerina bulloides*, *Globigerina decoraperta*, *Globigerinoides obliquus*, *Globorotalia continuosa*, and *Sphaeroidinellopsis seminulina*, found in the marls, was interpreted as Early Tortonian (Serrano-Lozano 1980). Overlying the Early Tortonian north of Ronda is a sequence of marls (200 to 300 m thick) with an upward increase of sandstone intervals containing minor halite intercalations recording a shallowing upward trend from a deeper marine to a continental and/or shallow marine environment. Dating by Serrano-Lozano (1980) on the basis of

*Globorotalia* subzones yielded an estimate of Late Tortonian and Messinian (*Globorotalia mediterranea* subzone to *Globorotalia humerosa* subzone). Locally, the Late Tortonian and Messinian unit is topped by a relatively thin (approximately 5–150 m) marly limestone unit dated as Pliocene (Serrano-Lozano 1980). In the Ardales section, sediments younger than Burdigalian are absent. Middle Tortonian continental deposits (alluvial fan and braided river deposits) in the Teba area are overlain by Late Tortonian and Messinian deep-water marls containing *Globigerina*. Unconformably overlying these *Globigerina* marls are lagoonal sediments containing Miliolids which in turn are unconformably overlain by coarse alluvial fan deposits. The Tortonian-Pliocene sediments of the Teba section have a thickness ranging from 200 to 500 m.

#### 4. Triassic-Late Miocene paleogeographic reconstructions

In the following text sections, paleogeographic reconstructions are presented. These are based on a total of 29 stratigraphic sections measured in the Ronda-Málaga region (Fig. 2) in conjunction with previous work by Dürr (1967), Serrano-Lozano (1979, 1980), Peyre (1974), González-Donoso & Serrano-Lozano (1977), Kockel (1960), and others.

From the stratigraphic sections, time-facies profiles have been constructed which were used to reconstruct the paleogeography as presented below. An example of a time-facies profile for the Neogene through the northern part of the studied region from Periana to Alcalá del Valle is shown in Fig. 8.

##### 4.1 Pre-Miocene

During the Triassic the Ronda-Málaga region has been the scene of continental conditions and supratidal environments in the north and intertidal and shallow marine environments to the south. Southeast of Ronda and east of Alcalá del Valle, Triassic limestones and marls record a shallow-marine intertidal environment sometimes subjected to subaerial exposure. North of Antequera and Campillos, thick evaporite sequences indicate continental sabkha settings dominated by the interplay of fluvial and lacustrine processes. Coarse-grained, cross-bedded clastic limestones east of Antequera were formed by alluvial fans and associated braided rivers.

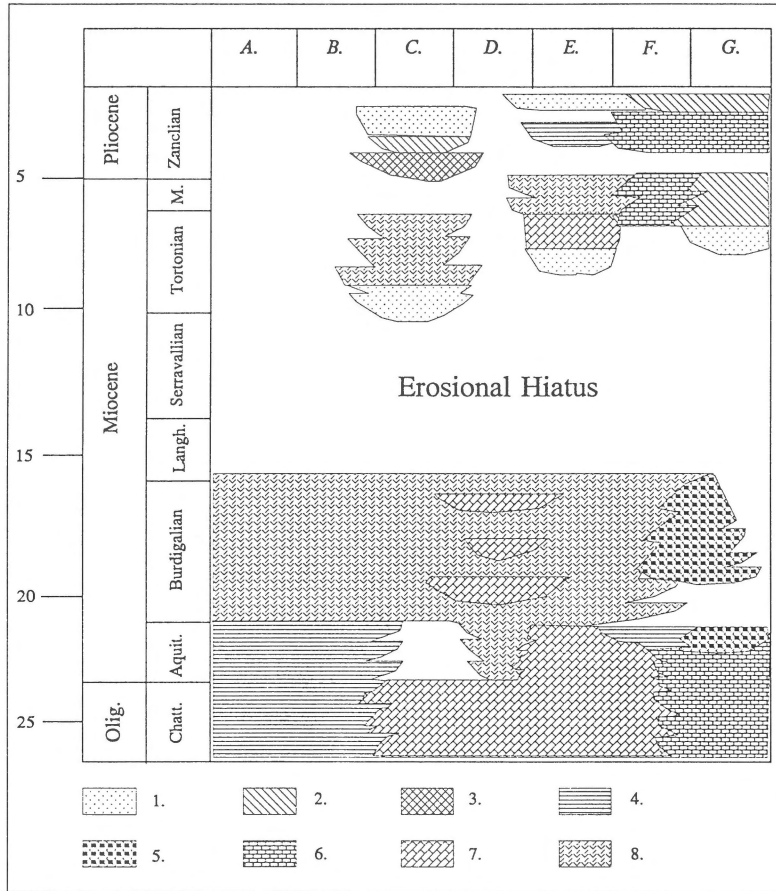


Fig. 8. Time-facies profile for the Neogene of the northern part of the Ronda-Málaga region. Legend: 1. Alluvial fan and fluvial environment, 2. Supratidal and continental sabkha, 3. Intertidal, 4. Lagoon, 5. Backreef, 6. Shallow open marine platform, 7. Fore-reef shoal, 8. Deeper shelf, A. Periana, B. Colmenar, C. Antequera, D. Ardales, E. Teba, F. Cañete la Real, G. Alcalá del Valle.

In the northern part of the area, Early Jurassic bioclastic limestones near Teba and north of Archidona (15 km east of Antequera) were formed in a very shallow-marine high-energy environment. During the Sinemurian-Bajocian this environment deepened to a marine pelagic environment in which marls with abundant radiolarians and ammonites were deposited showing occasional turbiditic influences. Further to the south, northeast of Ronda, a shallow-marine restricted environment existed throughout the Early and Middle Jurassic deepening to a marine pelagic environment in the Late Jurassic.

The Early Cretaceous marks a period of non-deposition in large parts of the studied region. During the Late Cretaceous, marine pelagic sedimentation

prevailed with environments generally deepening to the southeast. Detritus supply was from the northwest to the southeast (e.g. Baena-Perez & Jerez-Mir 1982).

A regional differentiation of sedimentary facies can be observed during the Paleocene. Marine deposition continued in various locations, whereas *in-situ* occurrences of *Microcodium* are evidence for subaerial exposure of the Triassic-Cretaceous limestones near El Burgo and between Antequera and Campillos.

Eocene conglomerates and bioclastic limestones directly overlie Cretaceous limestones and a Paleocene hardground west of Archidona. The conglomerates possibly have a continental origin, whereas the limestones were deposited in a shallow-marine high-energy environment. Waterdepth increased southward

with decreasing detritus supply. Near Colmenar and Teba, marls containing abundant *Nummulites* record a shallow-marine open-shoal environment which existed throughout Eocene and Oligocene times. Near Teba, Late Eocene and Oligocene marls and limestones deposited in a fore-reef shoal environment overlie Early Eocene lagoonal sediments. West of Ardales, the stratigraphic record shows a non-depositional hiatus during the Early Eocene. Late Eocene, shallow marine carbonates rest on Paleocene deep-marine marls near Ardales. Further south, near El Burgo and south of Alora, a submarine fan system developed, characterized by mass flows and turbidites.

#### 4.2 Late Oligocene and Miocene

During the Late Oligocene and Miocene, the Ronda-Málaga region is the scene of rapidly changing environments related to tectonic episodes. Four different periods can be recognized, each controlled by a different tectonic regime: (1) Late Oligocene-Aquitania, (2) Burdigalian, (3) Langhian and Serravallian, and (4) Tortonian and Messinian.

##### 4.2.1 Late Oligocene-Aquitania (Fig. 9)

During the Late Oligocene and Aquitania a submarine fan system developed, characterized by mass flows and turbidites south of the line Casabermeja-Ardales-Teba. These turbidites are the lateral equivalents of the so-called Aozaina Formation (western Betic Cordilleras, Hermes 1985) and the Ciudad Granada Formation (eastern Betic Cordilleras, Geel et al. 1992). The Jurassic-Cretaceous limestone areas east of Ronda, north of Ardales and west of Cuevas del Becerro emerged, shedding clastics into the newly formed basins. Simultaneously, detritus was supplied from the Triassic high which stretched from Campillos to Antequera. Although the main direction of detritus supply was from north to south, some east-west oriented paleo-current directions indicate influx of clastics from local high areas. Limestones formed in a fore-reef shoal environment evidence a shallow-marine platform situated west of the line Ronda-Teba. Lagoonal conditions prevailed in the area surrounding the emerged Jurassic limestone block of Cañete la Real. Marls and limestones containing abundant lepidocyclinids and bryozoan debris, found north-east of Ardales and south of Campillos, indicate open shoal conditions; however, the occurrence of reef-building organisms may point to the existence of patch reefs or fringing reefs bordering

the Triassic high (see also Peyre 1974). North of Colmenar open marine limestones of Oligocene age containing abundant diatoms (dated by Hermes & Smith 1975) are concordantly overlain by Aquitania sandstones showing eolian influences (see also Durand-Delga 1980), thus pointing to a very rapid uplift in Late Oligocene-Aquitania time.

##### 4.2.2 Burdigalian (Fig. 10)

The paleogeography in the Burdigalian is completely different from that of foregoing periods. Near Pizarra, Tortonian bioclastic limestones rest unconformably upon Aquitania turbidite fan deposits, indicating an emerged landmass which stretched south of the line Colmenar-Alora-Cuevas del Becerro. Detritus supply was mainly from south to north although olistostromes south of Teba record southward supply directions from a local Jurassic limestone block north of Teba. Besides clastics derived from Triassic-Cretaceous limestone units, also marble blocks can be found in submarine fans. These marbles may have originated from Alpujarride nappe complexes to the south. Large quantities of clastics were shed into a narrow sea-arm parallel to the line Colmenar-Alora. A north-south emerged area separated this arm from a marine basin north of Teba that deepened northward. Deposition and simultaneous folding or tilting of strata is indicated by interangular unconformities found in Burdigalian sediments northwest of Cañete la Real. Toward the close of the Burdigalian, depositional environments became more shallow as the Subbetic Zone was gradually being uplifted and incorporated in the thrust load (see also Hermes 1977).

##### 4.2.3 Langhian and Serravallian

Throughout the investigated area Langhian and Serravallian sediments are missing. North of Teba and northeast of Ardales, Tortonian sediments unconformably overlie Burdigalian fan deposits. Apparently large areas emerged during the Langhian and Serravallian. Simultaneously, marine sedimentation continued in the Guadalquivir Basin north of the investigated area (Lanaja et al. 1987, Santos-García et al. 1991, Tjalsma 1971; see Fig. 1 for location).

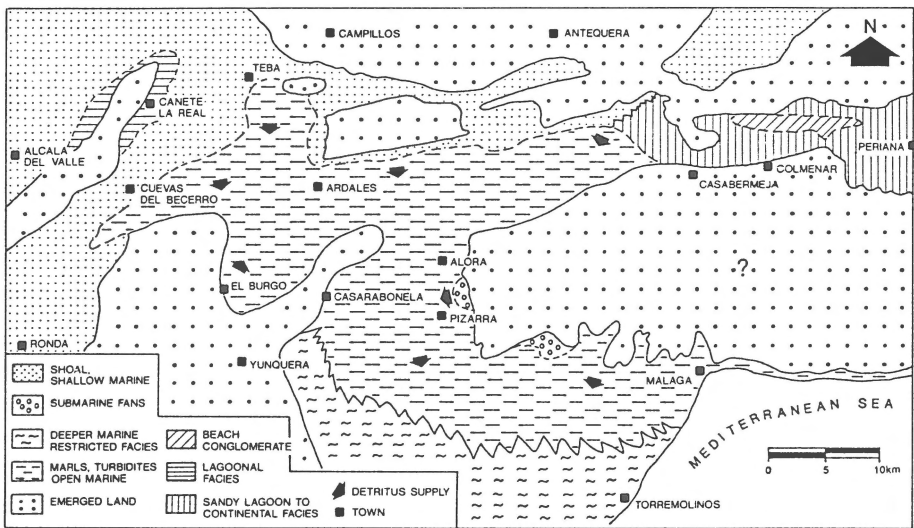


Fig. 9. Interpreted facies distribution for Late Oligocene-Aquitian times in the Ronda-Málaga area (see text 'Paleogeographic reconstructions').

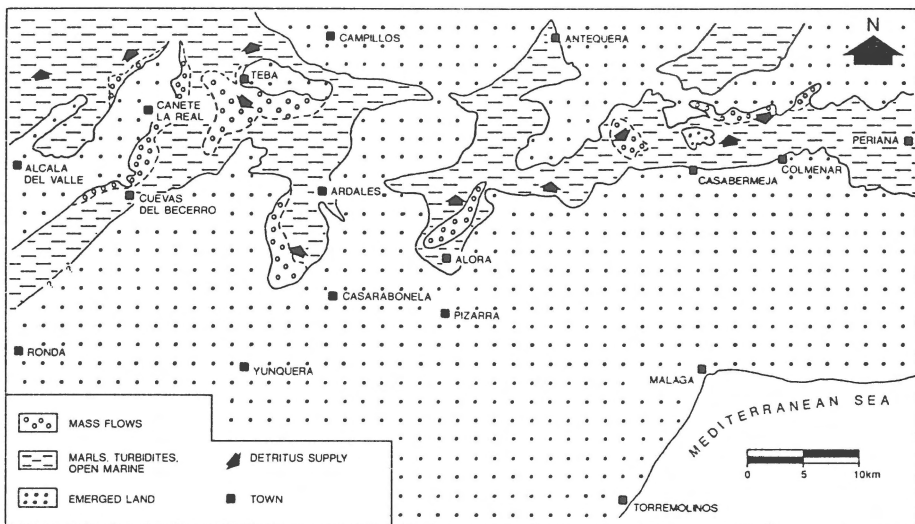


Fig. 10. Interpreted facies distribution for Burdigalian times in the Ronda-Málaga area (see text 'Paleogeographic reconstructions').

#### 4.2.4 Tortonian and Messinian (Fig. 11)

During the Tortonian and Messinian, new basins came into existence: north of Teba, around Ronda, and south of Pizarra.

Northeast of Teba, Tortonian conglomerates progressively overlie Jurassic limestones. These conglomerates contain both Triassic components shed southward into the basin from the Campillos-Antequera high, as well as Cretaceous-Jurassic limestone pebbles.

Detritus supply was mainly from the south. In northern direction, outside the area studied, this basin deepened as indicated by shallow marine limestones containing lamellibranchs and debris of bryozoans. Southeast of Campillos, coarse clastic sediments of Tortonian age were deposited in a very shallow marine environment, whereas in a narrow area northeast of Antequera (outside the area of Fig. 11) such sediments grade-up into yellowish white siltstones with plant debris and gastropods interpreted as lacustrine deposits.

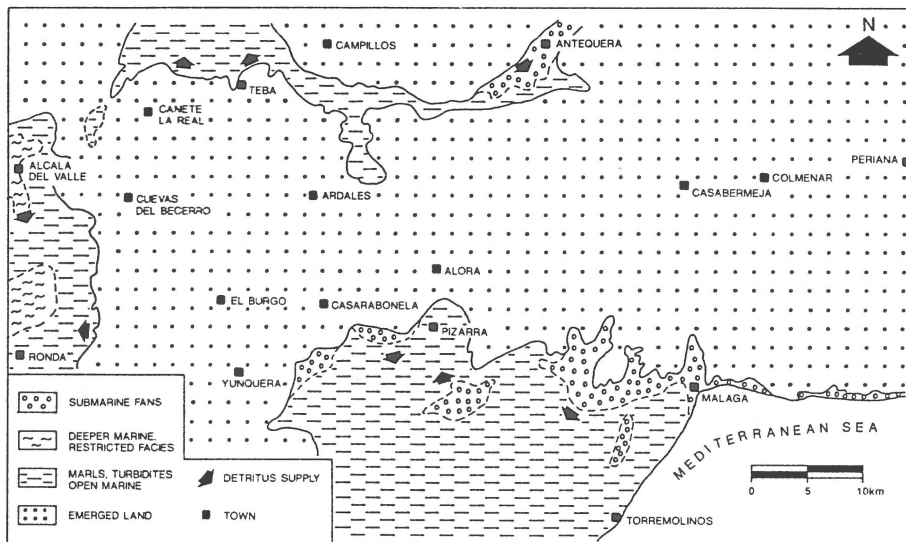


Fig. 11. Interpreted facies distribution for Tortonian times in the Ronda-Málaga area (see text 'Paleogeographic reconstructions').

North of Ronda, a basin was formed in the Early Tortonian which existed throughout the Tortonian and Messinian. The infill of this basin is asymmetric and its thickness increases in northwestern direction (Serrano-Lozano 1980). Early Tortonian continental conglomerates, interpreted as fluvial or alluvial fan deposits, are restricted to a small area north and east of Ronda, whereas coeval shallow marine conditions prevail on the northern margin of the basin (Serrano-Lozano 1980). Throughout the Tortonian and Early Messinian this basin continued to subside. East of Ronda, hummocky cross stratification indicates storm-induced wave action below the fairweather wave base with NNE-SSW to W-E current directions. To the north and west, deeper marine marls were deposited which show occasional turbiditic influences. Toward the close of the Messinian the basin north of Ronda emerged and sedimentation continued only along the northern edge where algal limestones are found (Gonzalez-Donoso & Serrano-Lozano 1977).

A third basin developed south of Alora in which marls and submarine turbidite fans were deposited during the Tortonian.

## 5. Quantitative subsidence analysis and its implications for geodynamics

The aim of backstripping analysis is to produce a graphical representation of the vertical movement of a stratigraphic horizon in a sedimentary basin as an indicator of the subsidence and uplift history in the basin since the horizon was deposited (Van Hinte 1978). Stratigraphic data needed for a backstripping analysis include a stratigraphic column showing present-day thicknesses, rock types, ages, and estimated paleo-water depths. To obtain a subsidence curve, first the paleo-sediment and paleo-water columns are reconstructed. Sediment thicknesses are corrected for compaction. Corrections for possible changes in sea-level relative to present-day sea level yield the basement subsidence. Then the total load of sediments on the basement is removed to give the tectonic subsidence; the undistorted basin subsidence that would occur in the absence of sedimentation.

In this study, a water-loaded tectonic subsidence curve corrected for the effects of sediment loading and paleo-bathymetry was calculated for an area with pronounced Neogene subsidence. The Subbetic composite stratigraphic record (Fig. 12) was derived from sections 1-6 located north and northeast of Ronda (Fig. 2). Backstripping techniques discussed by Steckler & Watts (1978), Sclater & Christie (1980), and Bond & Kominz (1984) were used. The time scale of Harland

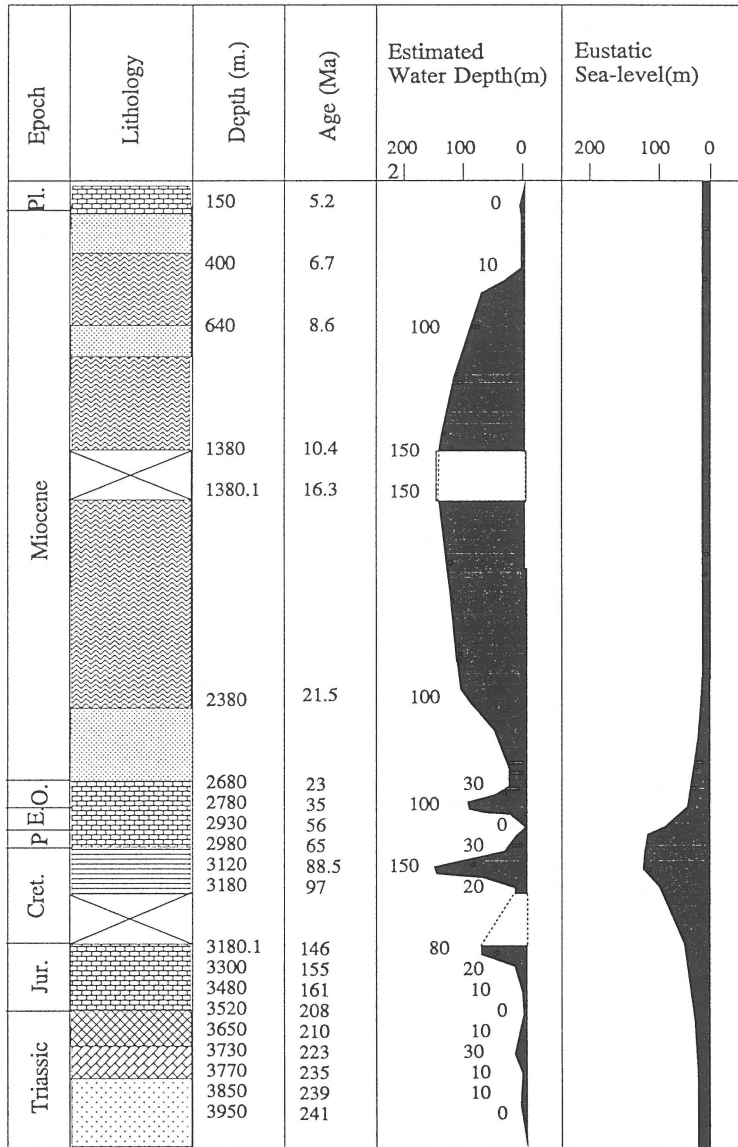


Fig. 12. Composite stratigraphic section for the Subbetic Zone of the Ronda-Málaga region used for backstripping analysis. The column is based on sections 1-6 of Fig. 2. Legend: see Fig. 3.

et al. (1990) was adopted. Lithological effects, in particular compaction and densities of evaporites, have been corrected for, using an exponential decrease of porosity with depth (Bond et al. 1983). Each stratigraphic unit between two chronostratigraphic horizons has been assigned a sand, silt, shale, carbonate, and anhydrite percentage, with each lithology responding according to its own compaction scheme. Porosity-depth relations were defined over two intervals (a deeper and a shallow relation), therefore two exponential expressions were necessary to describe the delithifica-

tion procedure and a depth at which the deeper relation takes over from the shallow relation (see Bond & Kominz 1984). Minimum and maximum compaction effects have been tested using the parameters listed in Table 1. Other parameters used in the backstripping analysis are listed in Table 2. These represent the range of values commonly observed in quantitative subsidence analysis (Bond & Kominz 1984). The results of incorporating compaction effects showed that the uncertainties in basement and tectonic subsidence related to the range

Table 1. Maximum (upper part) and minimum (lower part) compaction parameters used for different lithologies in the backstripping analysis

Lithology	$\phi_1$	$C_1$	$\phi_0$	$C_0$	$z_p$	$\rho_{gr}$
Sand	0.29	0.216	0.40	0.51	1.0	2.65
Silt	0.42	0.375	0.60	1.00	0.5	2.68
Shale	0.50	0.475	0.70	1.10	0.5	2.72
Carbonate	0.52	0.442	0.78	1.33	0.5	2.71
Halite	0.00	0.100	0.00	0.10	0.0	2.03
Anhydrite	0.00	0.100	0.00	0.10	0.0	2.95
Sand	0.20	0.480	0.20	0.480	0.0	2.65
Silt	0.25	0.325	0.25	0.325	0.0	2.68
Shale	0.37	0.470	0.53	1.050	0.5	2.72
Carbonate	0.20	0.580	0.20	0.580	0.0	2.71
Halite	0.00	0.100	0.00	0.100	0.0	2.03
Anhydrite	0.00	0.100	0.00	0.100	0.0	2.95

- $\phi_1$  = surface porosities (given as fraction) for the deep porosity-depth relation  
 $C_1$  = characteristic depth constants (in  $\text{km}^{-1}$ ) for the deep porosity-depth relation  
 $\phi_0$  = surface porosities (given as fraction) for the shallow porosity-depth relation  
 $C_0$  = characteristic depth constants (in  $\text{km}^{-1}$ ) for the shallow porosity-depth relation  
 $z_p$  = depth (in km) at which the deeper porosity-depth relation takes over from the shallow one  
 $\rho_{gr}$  = grain density (in  $\text{g/cm}^3$ ) of the corresponding lithology

in compaction parameters are in the order of several tens of metres.

Depositional depths were estimated from the sedimentary facies and faunal content, and quantified using the paleo-bathymetric scale of Ingle (1980). According to this scale, the accuracy of the paleo-waterdepth estimates obtained is within 50 m for shallow-water deposits, but increases to 100–500 m for deeper-water deposits.

Effects of long-term eustatic sea level changes (after Kominz 1984) on the inferred tectonic subsidence were incorporated. Airy isostasy was assumed, thus ignoring the effect of a finite strength of the lithosphere on its response to sediment loading. This assumption, however, does not significantly affect the shape of the subsidence curve (Watts et al. 1982), particularly during rift stages, when the lithosphere is mechanically weak (e.g. Hegarty et al. 1988). Similarly, the reduced basement cooling resulting from the

Table 2. Parameters other than compaction used in the backstripping analysis

Parameter	Symbol	Value
Initial lithospheric thickness	$L$	125 km
Initial crustal thickness	$C$	31.3 km
Coefficient of thermal expansion	$\alpha$	$3.4 \times 10^{-5} \text{ } ^\circ\text{C}^{-1}$
Asthenospheric temperature	$T_m$	1333 $^\circ\text{C}$
Thermal diffusivity	$\kappa$	$0.008 \text{ cm}^2 \text{ s}^{-1}$
Mantle density	$\rho_m$	$3.33 \text{ g cm}^{-3}$
Crustal density	$\rho_c$	$2.8 \text{ g cm}^{-3}$
Isotherm describing the ETT*	$T_e$	333 $^\circ\text{C}$
Water density	$\rho_w$	$1.03 \text{ g cm}^{-3}$
Surface porosity of sediment infill	$\phi(o)$	0.55
Characteristic depth constant	$c$	$0.55 \text{ km}^{-1}$

EET = Effective Elastic Thickness

blanketing effect of sediments was ignored (Turcotte & Ahern 1977, Lucazeau & Le Douaran 1985). Detailed knowledge of the thermal structure of the lithosphere throughout the evolution of the basin would be required to incorporate this effect into our analysis. However, because of the long time scale on which lithospheric cooling operates, a correction of the blanketing effect will not significantly alter the shape of the subsidence curves (Lucazeau & Le Douaran 1985).

### 5.1 Interpretation of the subsidence record

From the Mesozoic tectonic subsidence curve (Fig. 13) for the southern Subbetic Zone, four distinct periods of relatively rapid subsidence are apparent: (1) a Middle Triassic period (Anisian-Ladinian; 241–235Ma), (2) a Late Triassic-Early Jurassic period (Norian-Hettangian; 223–203Ma), (3) a Middle-Late Jurassic period (Callovian-Tithonian; 161–146Ma), and (4) a Middle Cretaceous period (Cenomanian-Turonian; 97–89Ma). These periods represent rifting episodes along the southeastern Betic margin that can be correlated with the stepwise opening of the Central Atlantic and Ligurian oceans which induced transtensional movements between Africa and Iberia (Vegas & Banda 1982, Lemoine & Trümpy 1987). The subsidence patterns observed for each of these phases show an initial phase of rapid subsidence and a subsequent phase of decelerating subsidence which is typical for rifted margins, where the rapid subsidence is caused by the isostatic response of the lithosphere to crustal thinning and the slower subsidence is driven by thermal re-equilibration

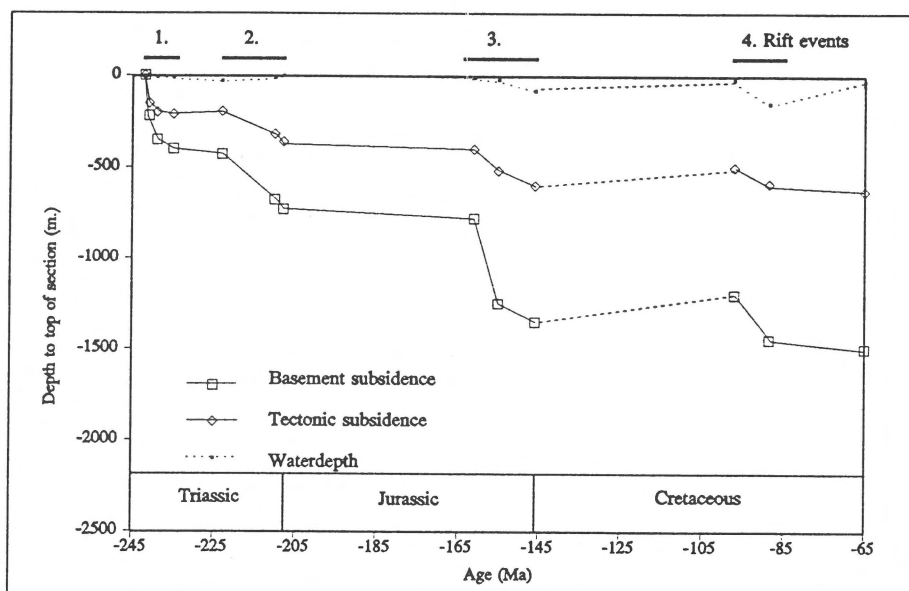


Fig. 13. Mesozoic subsidence curves for the southern Subbetic Zone near Ronda. Tectonic and basement subsidence derived from quantitative subsidence analysis incorporating paleowaterdepth and eustatic sealevel fluctuations.

(McKenzie 1978). The duration of these rifting events is in the order of 10 to 20Ma. The first and third rifting events resulted in an average tectonic subsidence rate of 3.5 cm/1000 years whereas the second and fourth rifting events show tectonic subsidence rates in the order of 2 cm/1000 years. These subsidence rates are relatively low compared to those of rift basins and other rifted margins, but not abnormal. For comparison, the Sirte Basin of Libya shows tectonic subsidence rates exceeding 10 cm/1000 years during active rifting (Van der Meer & Cloetingh 1993), and Kooi et al. (1989) found tectonic subsidence rates of 5 cm/1000 years for the Central Graben of the North-Sea Basin. Comparable tectonic subsidence rates have been calculated for rifted margins (e.g. the U.S. Atlantic continental margin, 5 cm/1000 years, Heller et al. 1982, the eastern margin of Canada, 4 cm/1000 years, Cloetingh et al. 1990, and the Levant margin, 5 cm/1000 years, Tibor et al. 1992) although subsidence at the Gulf of Lions margin clearly exceeds these values (18 cm/1000 years during an Oligocene to Early Miocene rifting event, Burrus et al. 1987).

The Middle Triassic and the Late Triassic-Early Jurassic rifting phases (Fig. 13, rift events 1 and 2) coincide with a period of distensive wrench tectonics throughout the Atlantic realm (Ziegler 1988, 1990). Volcanic detritus of Middle Triassic age in the Malaguide Complex (Roep 1972, Mäkel 1985)

and metatuffaceous rocks in the Mulhacen Complex demonstrate rifting (De Jong & Bakker 1991).

Dercourt et al. (1986), Savostin et al. (1986), and Srivastava et al. (1990) showed that a sinistral transtensional zone developed after the Late Triassic-Early Jurassic rifting, which separated Iberia from North Africa. This strike-slip zone connected the Jurassic Central Atlantic basin with the Ligurian basin east of Iberia (Dercourt et al. 1986). Movement on this strike-slip system and simultaneous initiation of the Central and South Atlantic rifts (Savostin et al. 1986) coincides with Middle-Late Jurassic rifting (Fig. 13, rift event 3). North Atlantic rift propagation between Iberia and Newfoundland commenced after the Bathonian-Callovian, contemporaneously with crustal separation in the South Atlantic and Ligurian oceans (Dercourt et al. 1986, Lemoine & Trümpy 1987, Srivastava et al. 1990). At the same time, the Subbetic Zone experienced strong subsidence and mafic volcanism related to rifting (Puga et al. 1989a); in the Mulhacen Complex the widespread occurrence of olivine-bearing gabbros (De Jong & Bakker 1991) and pillow lavas (Puga et al. 1989b) evidences crustal extension.

The Middle Cretaceous extension period of Fig. 13 (rift event 4) is not commonly recognized in basin studies of the Betic Cordilleras. Peper & Cloetingh (1992) recognized a Middle Triassic, an Early Jurassic, and a Late Jurassic-Early Cretaceous rifting phase.

However, Cenomanian extensional fault activity is well known from the Prebetic Zone (De Ruig 1992) and olistostromes of Middle and Late Cretaceous age have been reported by various authors (e.g. Paquet 1967, Vera et al. 1982). There are no clear indications to relate this extensional phase to plate-tectonic movements. Sea floor spreading patterns in the Central Atlantic Ocean suggest that Iberia moved independently from Africa and Eurasia (Srivastava et al. 1990) and rotated clockwise triggering transtensional movements in the Bay of Biscay (Puigdefàbregas & Souquet 1986, De Jong 1991). De Jong (1991) argues that these transtensional movements were compensated by subduction and continental thrusting in the Internal Betics, east of Iberia. This interpretation, however, is not consistent with the observed extension in both the Prebetic and Subbetic Zones.

The Coniacian-Late Oligocene subsidence history of the southern Subbetic Zone (Figs 12, 13) shows relatively low and decelerating subsidence rates indicating that rifting activity ceased and stable conditions prevailed. However, both the Internal and External Zones of the Betic Cordilleras record tectonic phases which can be correlated with collision in the Pyrenean domain (De Ruig et al. 1991). Maastrichtian-Danian and Middle Eocene uplift was found by Kenter et al. (1990) in the External Zone. De Ruig (1992) pointed out that a regression 60Ma ago accompanied by slope faulting and associated olistostromes marked a phase of Middle Paleocene compression. He suggested that uplift of basin flanks and subsidence of the basin centre indicate a continental margin under compression causing a magnification of the peripheral bulge and subsequent seaward migration of the shoreline (see Cloetingh et al. 1985). The Paleocene sediment record of the southern Subbetic Zone of the Ronda-Málaga region that has been investigated here shows widespread occurrence of *in-situ Microcodium* which indicates subaerial exposure (Klappa 1978) reflecting a shallowing rather than a deepening of this part of the basin.

The Eocene sedimentary record of the southern Subbetic Zone shows an initial influx of non-calcareous detritus in the Early Eocene, associated with sandy turbidites. This seems to correspond to the Eocene compression interpreted by Geel (1973). In the subsidence record, the Eocene tectonic events are not resolved, possibly because the magnitude of these events is too small to trigger a significant uplift in the central part of the basin. Eocene compression can be directly related to the collision in the Pyrenees which began 59Ma ago and culminated in the Middle Eocene as a result of

northward movement of Africa and Iberia (Srivastava et al. 1990). This movement gradually ceased in the Late Oligocene as Iberia became part of the Eurasian plate. Simultaneously, compressive deformation concentrated on the Iberian continental margin.

A phase of Late Oligocene-Aquitainian extension is well known throughout the western Mediterranean (Rehault et al. 1984, De Ruig 1992, De Jong 1991). Renewed subsidence during the Aquitainian (Fig. 14, tectonic phase 1) indicates this extension in our subsidence record. Extension in the Betic Cordilleras was immediately followed by thrust emplacement of the Internal Betic Zone onto the southern Iberian margin. De Jong (1991) argued that thrust emplacement occurred between 21.5 and 19Ma. This corresponds to a Burdigalian peak of subsidence in Fig. 14 (tectonic phase 2).

Following the thrusting of the Internal Zone onto the Iberian margin, a period of strike-slip related tectonics (Bon et al. 1989) affected the Betic Cordilleras during the Late Langhian and Serravallian (Fig. 14, Tectonic phase 3). Recent investigations showed that strike-slip related tectonics continued until the Pliocene (e.g. Kleverlaan 1989, Van der Straaten 1993). Dextral wrench movement resulted in the formation of N70°E and N100°E strike-slip faults and associated intramontane pull-apart basins in the eastern Betic Cordilleras (Montenat et al. 1987), as for example the Abáran basin described by Van der Straaten (1990, 1993). Simultaneously, basins developed in the western Betic Cordilleras, like the Neogene basin north of Ronda. The subsidence curve shows that the southern Subbetic Zone emerged contemporaneously with this wrenching. Many authors have suggested that the westward movement of the Alboran microplate relative to the Iberian margin along the Crevillente and North Betic fault zones (Fig. 1) was the principal cause of this strike-slip related deformation (Le Blanc & Olivier 1984, Andrieux et al. 1977). More recently, these wrench fault zones were interpreted as major tear faults accommodating westward overthrusting of the Internal or Betic nappe pile over the External Zone (e.g. Frizon de Lamotte et al. 1991).

Renewed extension during the Tortonian and Messinian (Fig. 14, tectonic phase 4) is indicated by coarse terrigenous influx of detritus and rapid subsidence of the basin. Post-dating this event is a compressional phase in the Pliocene (Fig. 14, tectonic phase 5) causing the observed N-S trending folds in the Tortonian and Messinian sediments. The Tortonian-Pliocene sedimentary and tectonic history of the Ronda-Málaga

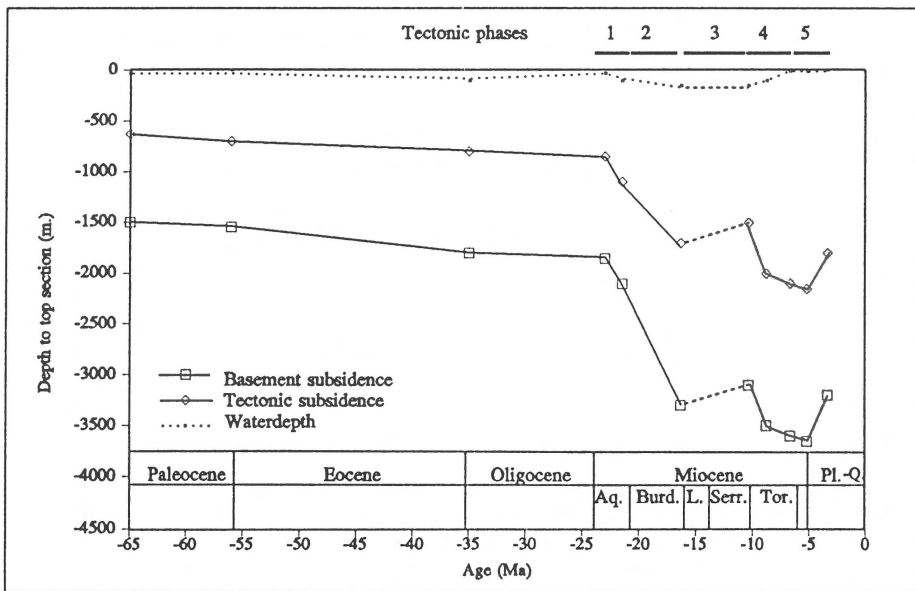


Fig. 14. Tertiary subsidence curves for the southern Subbetic Zone near Ronda. Tectonic and basement subsidence derived from quantitative subsidence analysis incorporating paleowaterdepth and eustatic sealevel fluctuations.

region is interpreted as resulting from strike-slip related deformation. The Neogene basins opening during the Late Miocene are considered pull-apart basins related to NE-SW trending strike-slip faults.

## 6. Conclusions

The Ronda-Málaga region, forming part of the southern Subbetic Zone of the Betic Cordilleras, has been the site of polyphase tectonism resulting in rapidly changing sedimentary environments throughout the Tertiary.

Throughout the Triassic the Ronda-Málaga region was the scene of continental conditions and supratidal environments in the north and intertidal and shallow marine environments to the south. During the Jurassic and Cretaceous the area formed part of the slope of the Iberian continent as shallow marine shelf conditions prevailed with environments deepening southward. The onset of the Tertiary marked a period of increased tectonic activity resulting in the development of a submarine fan complex fed by large quantities of clastics shed in from the north. A reversal of facies patterns is observed in the Burdigalian during which detritus supply was dominantly from the south. The entire area emerged during the Serravallian and Langhian.

After this, deposition resumed and continued throughout the Late Miocene in a number of narrow basins.

Quantitative subsidence analysis of stratigraphic data from the southern Subbetic Zone exposed near Ronda revealed a number of phases of accelerated subsidence which can be correlated with tectonic events in the Central Atlantic Ocean and with the deformation history of the western Mediterranean and the Betic Cordilleras. The Mesozoic subsidence history is characterized by four periods of rifting: (1) a Middle Triassic period (Anisian-Ladinian; 241-235Ma), (2) a Late Triassic-Early Jurassic period (Norian-Hettangian; 223-203Ma), (3) a Middle-Late Jurassic period (Callovia-Tithonian; 161-146Ma), and (4) a Middle Cretaceous period (Cenomanian-Turonian; 97-89Ma). The stress regime changed from extensional to mainly compressional in the Paleocene, related to the onset of the Pyrenean collision. The end of this collision in the Late Oligocene marks the beginning of accelerated but localized subsidence related to a period of NNE-SSW extension during the Aquitanian. The rapid local subsidence during the Burdigalian is related to NW-SE thrusting of the Internal Zone over the External Zone and subsequent emplacement of the Subbetic Zone over the Prebetic Zone. During the Late Langhian and Serravallian, the area emerged; northward directed movement was blocked and a system of wrench faults developed of which the North

Betic fault zone and the Crevillente fault zone were the most important. During the Tortonian, local extension basins developed as pull-apart corridors within a period of wrench-related deformation which continued throughout the Late Miocene and Pliocene. Late-stage compression during the Pliocene is evidenced by N-S to NNE-SSW trending folds in Tortonian and Messinian sediments.

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## References

- Agbor, B. 1992 Some aspects of the emplacement of the Ronda peridotite (Sierra Bermeja), Málaga Province, Spain – Unpublished M.Sc. thesis, ITC, Enschede: 71 pp
- Andrieux, J., J.M. Fontboté & M. Mattauer 1991 Sur un Modèle explicatif de l'Arc de Gibraltar – *Earth Planet. Sci. Lett.* 12: 191–198
- Azéma, J. 1961 Étude géologique des abords de Málaga (Espagne) – *Estudios Geol.* 27(2): 131–160
- Azéma, J., A. Fourcault, E. Fourcade, M. García-Hernández, J.M. Gonzalez-Donoso, A. Linares, A.C. López-Garrido, P. Rivas & J.A. Vera 1979 Las Microfacies del Jurásico y Cretácico de las Zonas Externas de las Cordilleras Béticas – *Univ. Granada*: 83 pp
- Baena Perez, J. & L. Jerez Mir 1982 Síntesis para un ensayo Paleogeográfico entre la Meseta y la zona Bética (s.str.) – IGME (Instituto Geológico y Minero de España), Madrid: 256 pp
- Bakker, H.E., K. De Jong, H. Helmers & C. Biermann 1989 The geodynamic evolution of the Internal Zone of the Betic Cordilleras (south-east Spain): a model based on structural analysis and geothermobarometry – *J. Metamorph. Geol.* 7: 359–381
- Besems, R.E. & O.J. Simon 1982 Aspects of Middle and Late Triassic Palynology 5. On the Triassic of the Subbetic Zone in the province of Murcia (Betic Cordilleras, southeastern Spain) – *Proc. Kon. Ned. Akad. Wetensch.*, Ser. B. 85: 29–51
- Blow, W. 1969 Late middle Eocene to Recent planktonic foraminiferal biostratigraphy. In: P. Brönnimann & H.H. Renz (eds), *Proceedings First Internat. Conf. Planktonic Microfossils*, Geneva, 1967 – Brill, Leiden: 119–142
- Blumenthal, M. 1933 Geologie der Bergen um Ronda – *Ecl. Geol. Helv.* 26: 44–92
- Bon, A., C. Biermann, D.B. Koenen & O.J. Simon 1989 Middle Miocene strike-slip tectonics in the Aguilas-Mazarrón region, SE Spain – *Proc. Kon. Ned. Akad. Wetensch.* 92(2): 143–157
- Bond, G.C. & M.A. Kominz 1984 Construction of tectonic subsidence curves for the early Paleozoic miogeocline, southern Canadian Rocky mountains: Implications for subsidence mechanisms, age of breakup, and crustal thinning – *Geol. Soc. Am. Bull.* 95: 155–173
- Bond, G.C., M.A. Kominz & W.J. Deulin 1983 Thermal subsidence and eustasy in the lower Paleozoic miogeocline of western North America – *Nature* 306: 775–779
- Bouillin, J.P., M. Durand-Delga & Ph. Olivier 1986 Betic-Rifian and Tyrrhenian Arcs: distinctive features, genesis and development stages. In: F.C. Wezel (ed.) *The Origin of Arcs*. Elsevier, Amsterdam: 281–304
- Bourgeois, J. 1978 La transversale de Ronda, Cordillères Bétiques, Espagne, Données géologiques pour un modèle d'évolution de l'Arc du Gibraltar – Ph.D. thesis, Université de Besançon: 445 pp
- Burrus, J., F. Bessis & B. Doligez 1987 Heat flow, subsidence and crustal structure of the Gulf of Lions (NW Mediterranean): a quantitative discussion of the classic passive margin model – *Mem. Can. Soc. Petrol. Geol.* 12: 1–15
- Cloetingh, S., F. Gradstein, H. Kooi, A.C. Grant & M. Kaminski 1990 Did plate reorganization cause rapid late Neogene subsidence around the Atlantic? – *J. Geol. Soc. London* 147: 495–506
- Cloetingh, S., H. McQueen & K. Lambeck 1985 On a tectonic mechanism for regional sealevel variations – *Earth Planet. Sci. Lett.* 75: 157–166
- De Jong, K. 1991 Tectono-metamorphic studies and radiometric dating in the Betic Cordilleras (SE Spain) – with implications for the dynamics of extension and compression in the western Mediterranean area – Ph.D. thesis, Vrije Universiteit, Amsterdam: 204 pp
- De Jong, K. 1993 The tectono-metamorphic evolution of the Veleta Complex and the development of the contact with the Mulhacén Complex (Betic Zone, SE Spain) – *Geol. Mijnbouw* 71: 227–237
- De Jong, K. & H.E. Bakker 1991 The Mulhacén and Alpujarride Complex in the Sierra de los Filabres, SE Spain: Lithostratigraphy – *Geol. Mijnbouw* 70: 93–103
- Delgado, F. & C. Sanz de Galdeano 1981 Estudio geológico de la Sierra de Gibalto y sectores próximos (provincias de Granada y Málaga) – *Estudios Geol.* 37: 69–75
- Dercourt, J., L.P. Zonenshain, L.E. Ricou, V.G. Kazmin, X. Le Pichon, A.L. Knipper, C. Grandjacquet, I.M. Shortshikov, J. Geyssant, C. Lepvrier, D.H. Pechersky, J. Boulin, J.C. Sibuet, L.A. Savostin, O. Sorokhtin, M. Westphal, M.L. Bazhenov, J.P. Lauer & B. Biju-Duval 1986 Geological evolution of the Tethys belt from the Atlantic to the Pamirs since the Lias. In: J. Aubouin, X. Le Pichon & A.S. Monin (eds), *Evolution of the Tethys – Tectonophysics* 123: 241–315
- De Ruig, M.J. 1992 Tectono-sedimentary evolution of the Prebetic Fold Belt of Alicante (SE Spain) – a study of stress fluctuations and foreland deformation – Ph.D. thesis, Vrije Universiteit, Amsterdam: 207 pp
- De Ruig, M.J., J. Smith, T. Geel & H. Kooi 1991 Effects of the Pyrenean collision on the Paleocene stratigraphic evolution of the southern Iberian margin (southeast Spain) – *Geol. Soc. Am. Bull.* 103: 1504–1512
- De Smet, M.E.M. 1984 Wrenching in the External Zone of the Betic Cordilleras, Southern Spain – *Tectonophysics* 107: 57–79
- Diaz de Federico, A., M.T. Gomez-Pugnaire, E. Puga & F.P. Sassi 1979 New problems in the Sierra Nevada Complex (Betic Cordilleras, Spain) – *N. Jb. Geol. Pal. Mh.* 10: 577–585

- Didon, J. 1960 Le flysch gaditan au Nord et au Nord-est d'Algésiras (Province de Cadix, Espagne) – *Bull. Soc. Géol. France* (7)2: 352–361
- Didon, J. 1969 Étude géologique du Campo de Gibraltar (Espagne Méridionale) – Ph.D. thesis, Université de Paris: 539 pp
- Dubois, M. & J. Magre 1972 Présence de Burdigalien dans la région d'Ubrique (Province de Cadix, Espagne Méridionale) – *Ann. Sc. Univ. Besançon, 3ème série, fasc. 17*: 113–116
- Durand-Delga, M. 1980 La Méditerranée occidentale: étapes de sa genèse et problèmes structuraux liés à celle-ci – *Mèm. hors. sér. Soc. Géol. France* 10: 203–224
- Durand-Delga, M., J. Magne & Y. Peyne 1959 Découverte du Crétacé moyen dans le Bétique de Málaga et le Pénibétique d'Antequera (Andalousie) – *C.R. Se. Ac. Sc. Paris* 249: 2796–2798
- Dürr, S.H. 1967 Geologie der Serrania de Ronda und ihrer Südwestlichen ausläufer (Andalusien) – *Geol. Romana* 6: 1–73
- Egeler, C.G. & O.J. Simon 1969 Sur la tectonique de la Zone Bétique (Cordillères bétiques, Espagne) – *Verh. Kon. Ned. Akad. Wetensch. XXV*(3): 90 pp
- Esteban, M. 1974 Caliche Textures and 'Microcodium' – *Bull. Soc. Geol. Ital.* 92: 105–125
- Fallot, P. 1948 Les Cordillères Bétiques – *Estudios Geol.* 8: 83–172
- Fontboté, J.M. 1984 La Cordillera Bética. In: *Libro Jubilar J.M. Ríos, Geología de España, II, IGME (Instituto Geológico y Minero de España), Madrid*: 251–343
- Frizon de Lamotte, D., J. Andrieux & J.C. Geuzou 1991 Cinématique des chevauchements néogènes dans l'Arc bético-rifain: discussion sur les modèles géodynamiques – *Bull. Soc. Géol. France* 162: 611–626
- García-Hernández, M., A.C. Lopez-Garrido, P. Rivas, C. Sanz de Galdeano & J.A. Vera 1980 Mesozoic paleogeographic evolution of the External Zone of the Betic Cordilleras – *Geol. Mijnbouw* 59: 155–168
- Geel, T. 1973 The geology of the Betic of Málaga, the Subbetic, and the zone between these two units in the Vélez Rubio area (southern Spain) – Ph.D. thesis, Universiteit van Amsterdam, GUA Papers of Geology, Ser. 1, 5: 179 pp
- Geel, T., Th.B. Roep, W. ten Kate & J. Smith 1992 Early-Middle Miocene stratigraphic turning points in the Alicante region (SE Spain): reflections of Western Mediterranean plate-tectonic reorganizations – *Sed. Geol.* 75: 223–239
- Goffé, B., A. Michard, V. García-Dueñas, F. González-Lodeiro, P. Monié, J. Campos, J. Galindo-Zaldivar, A. Jabaloy, J.M. Martínez-Martínez & J.F. Simancas 1989 First evidence of high-pressure, low-temperature metamorphism in the Alpujarride nappes, Betic Cordilleras (S.E. Spain) – *Eur. J. Mineral* 1: 139–142
- González-Donoso, J.M. & F. Serrano-Lozano 1977 Sobre la presencia de materiales de edad Messiniense en la región de Ronda (Málaga) – *Studia Geol.* 13: 163–183
- Hamzah, A. 1992 Structural Geology of the External Zone of the Betic Cordilleras of the Ronda area, Málaga Province, Spain – Unpublished M.Sc. thesis, ITC, Enschede: 60 pp
- Harland, W.B., R.L. Armstrong, A.V. Cox, L.E. Craig, A.G. Smith & D.G. Smith 1990 A geologic time scale 1989. Cambridge Univ. Press, Cambridge, 263 pp
- Hegarty, K.A., J.K. Weissel & J.C. Mutter 1988 Subsidence history of Australia's southern margin: constraints on basin models – *Am. Assoc. Petrol. Geol. Bull.* 72: 615–633
- Heller, P.L., C.M. Wentworth & C.W. Poag 1982 Episodic post-rift subsidence of the United States Atlantic continental margin – *Bull. Geol. Soc. Am.* 93: 379–390
- Hermes, J.J. 1977 Late Burdigalian folding in the Subbetic north of Vélez Blanco, Province of Almería, Southeastern Spain – *Proc. Kon. Ned. Akad. Wetensch. Ser. B.* 80(2): 89–99
- Hermes, J.J. 1978 The Stratigraphy of the Subbetic and southern Prebetic of the Vélez Rubio-Caravaca area and its bearing on the transcurrent faulting in the Betic Cordilleras in southern Spain – *Proc. Kon. Ned. Akad. Wetensch. Ser. B.* 81: 1–54
- Hermes, J.J. 1985 Algunos aspectos de la estructura de la zona Subbética (Cordilleras Béticas, España Meridional) – *Estudios Geol.* 41: 157–176
- Hermes, J.J. & J. Smith 1975 New data on 'silexites' of the west Mediterranean area – *Proc. Kon. Ned. Akad. Wet., Ser. B.* 79(2): 115–122
- Ingle, J.C. 1980 Cenozoic paleobathymetry and depositional history of selected sequences within the southern California continental borderland. Cushman Foundation Spec. Publ. 19: 163–195
- ITGE (Instituto Tecnológico GeoMinero de España) 1990 Mapa Geológico de España, Escala 1:50.000, Hoja 1051 (15–44) Ronda, Segunda Serie, Madrid
- Kenter, J.A.M., J.J.G. Reymer, H.C. Van der Straaten & T. Peper 1990 Facies patterns and subsidence history of the Jumilla-Cieza region (southeastern Spain) – *Sed. Geol.* 67: 263–280
- Klappa, C.F. 1978 Biolithogenesis of Microcodium: elucidation – *Sedimentology* 25: 105–125
- Kleverlaan, K. 1989 Neogene history of the Tabernas Basin (SE Spain) and its Tortonian submarine fan development – *Geol. Mijnbouw* 68: 421–432
- Kockel, F. 1960 Die Geologie des gebietes zwischen Rio Guadalhorce und dem Plateau von Ronda (Südspanien) – Ph.D. thesis, Universität Bonn: 341 pp
- Kominz, M.A. 1984 Oceanic ridge volumes and sealevel change and error analysis – *Am. Assoc. Petrol. Geol. Mem.* 36: 109–127
- Kooi, H., S. Cloetingh & G. Remmelts 1989 Intraplate stresses and the stratigraphic evolution of the North Sea Central Graben – *Geol. Mijnbouw* 68: 49–72
- Lanaja, J.M., R. Querol & A. Navarro 1987 Contribución de la exploración petrolífera al conocimiento de la geología de España. IGME (Instituto Geológico y Minero de España), Madrid: 465 pp
- LeBlanc, D. & Ph. Olivier 1984 The role of strike-slip in the Betic-Rifian orogeny – *Tectonophysics* 101: 345–355
- Lemoine, M. & R. Trümpy 1987 Pre-oceanic rifting in the Alps. In: C. Froidevaux & Tan Tjong Kie (eds), *Deep Internal Processes and Continental Rifting* – *Tectonophysics* 133: 305–320
- Lucazeau, F. & S. Le Douaran 1985 The blanketing effects of sediments in basins formed by extension: a numerical model. Applications to the Gulf of Lyon and Viking Graben – *Earth Planet. Sci. Lett.* 40: 92–102
- Mäkel, G.H. 1985 The geology of the Malaguide Complex and its bearing on the geodynamic evolution of the Betic-Rif orogen (southern Spain and northern Morocco) – Ph.D. thesis, Universiteit van Amsterdam, GUA papers of Geology, Ser. 1, 22: 263 pp
- Martín-Algarra, A. 1980 Rasgos de la sedimentación y su evolución a lo largo del Mesozoico en el dominio de la Unidad de las Nieves (Cordillera Bética, Andalucía). IX. Congreso Nac. de Sedimentología, Resúmenes y Comunicaciones. Salamanca, p. 88
- McKenzie, D. 1978 Some remarks on the development of sedimentary basins – *Earth Planet. Sci. Lett.* 40: 25–32
- Montenat, C., P. Ott d'Estevou & P. Masse 1987 Tectono-sedimentary characters of the Betic Neogene basins evolving in a crustal transcurrent shear zone (SE Spain) – *Bull. Centres Rech. Explor. Prod. Elf-Aquit.* 11(1): 1–22

- Paquet, J. 1967 Étude géologique de l'Ouest de la Province de Murcie (Espagne) – Ph.D. thesis, Université de Lille: 593 pp
- Peper, T. & S. Cloetingh 1992 Lithospheric dynamics and tectono-stratigraphic evolution of the Mesozoic Betic rifted margin (southeastern Spain). In: E. Banda & P. Santanach (eds), *Geology and Geophysics of the Valencia Trough, Western Mediterranean – Tectonophysics* 203: 345–361
- Peyre, Y. 1974 Géologie d'Antequera et de sa région (Cordillères Bétiques), Espagne – Ph.D. thesis, Université de Paris: 538 pp
- Puga, E., M. Portugal, A. Diaz de Federico, G.M. Bargossi & L. Morten 1989a The evolution of the magmatism in the External Zones of the Betic Cordilleras during the Mesozoic – *Geodyn. Acta (Paris)* 3: 253–266
- Puga, E., A. Diaz de Federico, G.M. Bargossi & L. Morten 1989b The Nevado-Filabride metaophiolite association in the Cobdar region (Betic Cordillera, SE Spain) preservation of pillow structures and development of coronitic eclogites – *Geodyn. Acta (Paris)* 3: 17–36
- Puigdefàbregas, C. & P. Souquet 1986 Tectono-sedimentary cycles and depositional sequences of the Mesozoic and Tertiary from the Pyrenees. In: E. Banda & S.M. Wickman (eds), *The geological evolution of the Pyrenees – Tectonophysics* 129: 173–203
- Rehault, J.P., G. Boillot & A. Mauffret 1984 The Western Mediterranean Basin geological evolution – *Mar. Geol.* 55: 447–477
- Roep, Th.B. 1972 Stratigraphy of the 'Permo-Triassic' Saladilla formation and its tectonic setting in the Betic of Málaga (Vélez Rubio region, SE Spain) – *Proc. Kon. Ned. Akad. Wetensch., Ser. B.* 75: 223–247
- Santos-García, J.A., F. Jerez-Miró & J.L. Muñoz del Real 1991 Los depósitos Miocenos en los alrededores de Andujar (depresión del Guadalquivir, Provincia de Jaen) – *Estudios Geol.* 47: 33–42
- Savostin, L.A., J.C. Sibuet, L.P. Zonenshain, X. Le Pichon & M.J. Roulet 1986 Kinematic evolution of Tethys belt from the Atlantic Ocean to the Pamirs since the Triassic – *Tectonophysics* 123: 1–35
- Slater, J.C. & P.A.F. Christie 1980 Continental stretching: an explanation of the post-mid Cretaceous subsidence of the central North Sea basin – *J. Geophys. Res.* 85: 3711–3739
- Serrano-Lozano, F. 1979 Los Foraminíferos planctónicos del Mioceno superior de la cuenca de Ronda y su comparación con los de otras áreas de las Cordilleras Béticas – Ph.D. thesis, Universidad de Málaga: 272 pp
- Serrano-Lozano, F. 1980 Los materiales del Mioceno Superior de la Cuenca de Ronda (Málaga) – *Estudios Geol.* 36: 231–236
- Shendy, M.M. 1992 The application of Remote Sensing and soil survey in the establishment of a Geographical Information System for a part of the Guadalhorce Catchment – Unpublished M.Sc. thesis, ITC, Enschede: 94 pp
- Simon, O.J. 1987 On the Triassic of the Betic Cordilleras (Southern Spain) – *Cuad. Geol. Ibérica* 11: 385–402
- Smit, J. 1979 Microcodium: its earliest occurrence and other considerations – *Revue de Micropaleontologie* 22(1): 44–50
- Srivastava, S.P., W.R. Roest, L.C. Kovacs, G. Oakley, S. Lévesque, J. Verhoef & R. Macnab 1990 Motion of Iberia since the Late Jurassic: Results from detailed aeromagnetic measurements in the Newfoundland basin. In: G. Boillot & J.M. Fontboté (eds), *Alpine evolution of Iberia and its continental margins – Tectonophysics* 184: 229–260
- Steckler M.S. & A.B. Watts 1978 Subsidence of the Atlantic type continental margin off New York – *Earth Planet. Sci. Lett.* 41: 1–13
- Tibor, G., Z. Ben-Avraham, M.S. Steckler & H. Fligelman 1992 Late Tertiary subsidence history of the southern Levant margin and its implications for the Messinian event – *J. Geophys. Res.* 97: 17593–17605
- Tjalsma, R.C. 1971 Stratigraphy and foraminifera of the Neogene of the Eastern Guadalquivir Basin (Southern Spain) – *Utrecht Micropal. Bull.* 4: 161 pp
- Torres-Roldán, R.L. 1979 The tectonic subdivision of the Betic Zone (Betic Cordilleras, southern Spain): its significance and one possible geotectonic scenario for the westernmost Alpine belt – *Am. J. Sci.* 279: 19–51
- Turcotte, D.L. & J.L. Ahern 1977 On the thermal and subsidence history of sedimentary basins – *J. Geophys. Res.* 82: 3762–3766
- Van der Meer, F. & S. Cloetingh 1993 Intraplate stresses and the subsidence history of the Sirte Basin (Libya). In: S. Cloetingh, W. Sassi & F. Horváth (eds), *The origin of sedimentary basins: Inferences from quantitative modelling and basin analysis – Tectonophysics* 226: 37–58
- Van der Straaten, H.C. 1990 The Abarán Basin – a Neogene pull-apart basin in SE Spain – Ph.D. thesis, Vrije Universiteit, Amsterdam: 193 pp
- Van der Straaten, H.C. 1993 Neogene strike-slip faulting in southeastern Spain: the deformation of the pull-apart basin of Abarán – *Geol. Mijnbouw* 71: 205–225
- Van Hinte, J.E. 1978 Geohistory analysis – Application of micropaleontology in exploration geology – *Am. Assoc. Petrol. Geol. Bull.* 62: 201–222
- Vegas, R. & E. Banda 1982 Tectonic framework and Alpine evolution of the Iberian Peninsula – *Earth Evolution Sciences* 4: 320–342
- Vera, J.A., M. García-Hernández, A.C. López-Garrido, M.C. Comas, P.A. Ruiz-Ortiz & A. Martín-Algarra 1982 La Cordillera Bética. In: *El Cretácico de España*. Univ. Complutense, Madrid: 515–632
- Visser, R.L.M. 1981 A structural study of the central Sierra de los Filabres (Betic Zone, SE Spain), with emphasis on deformational processes and their relation to the Alpine metamorphism – Ph.D. thesis, Universiteit van Amsterdam, GUA Papers of Geology, Ser. 1, 15: 154 pp
- Watts, A.B., G.D. Karner & M.S. Steckler 1982 Lithospheric flexure and the evolution of sedimentary basins – *Phil. Trans. Roy. Soc. Lond. Ser. A* 305: 249–281
- Yan, L. 1992 TMU based versus SMU based data modelling for the design of an Environmental Management Data base – Unpublished M.Sc. thesis, ITC, Enschede: 69 pp
- Ziegler, P.A. 1988 Evolution of the Arctic-North Atlantic and Western Tethys – *Am. Assoc. Petr. Geol. Mem.* 43: 198 pp
- Ziegler, P.A. 1990 Geological Atlas of Western and Central Europe. Shell Internationale Petroleum Maatschappij, The Hague: 239 pp