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The Triassic palaeogeographic transition between the Alpujarride and Malaguide complexes. Betic–Rif Internal Zone (S Spain, N Morocco)

C. Sanz de Galdeano[a,*], B. Andreo[b], F.J. García-Tortosa[a], A.C. López-Garrido[a]

[a]Instituto Andaluz de Ciencias de la Tierra (CSIC-Univ. de Granada), Facultad de Ciencias, 18071 Granada, Spain
[b]Departamento de Geología, Facultad de Ciencias (Polígono de Teatinos), Univ. de Málaga, 209071 Málaga, Spain

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Abstract

Various tectonic units situated between the Malaguide and Alpujarride complexes (in the Betic–Rif Internal Zone, S Spain and N Morocco) present Triassic successions sharing features of both complexes the presence of which indicates a transitional domain. These units (which we term Intermediate units) are situated preferentially near the external limit of the Betic–Rif Internal Zone, generally adapted to the shape of the Arc of Gibraltar. The palaeogeography of this area is reconstructed on the basis of the general geometric position of these units and their relationships with equivalent domains in the western Mediterranean, the scarce existing palaeomagnetic data and the directions of tectonic displacement. The most problematic reconstructions concern those units on the N border of the Betic–Rif Zone, as they have significant clockwise rotations (up to 200°), S and SE tectonic displacements, and a different geometric distribution from the rest of the units. We conclude that in general the transition between the Malaguide and Alpujarride complexes was gradual, the Malaguide domain located S of the Alpujarride, with the intermediate units lying, evidently, between the two complexes. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Betic cordillera; Rif; Gibraltar arc; Malaguide complex; Alpujarride complex; Triassic palaeogeography

1. Introduction

Geological setting. The Betic–Rif Internal Zone (S Spain and N Morocco, Fig. 1) are comprised of four tectonic complexes, which from bottom to top are the Nevado–Filabride, the Alpujarride (called Sebtide in the Rif), the Malaguide (Gomaride in the Rif) and the Calcareous Dorsal. The Nevado–Filabride does not concern this study.

The Alpujarride complex has undergone metamorphism, although in some units the degree of metamorphism is low. This complex is formed by a sedimentary succession starting in the Palaeozoic (and probably older in some units) and usually well-exposed Triassic metasediments; the vast majority of the units lack a stratigraphic record beyond the upper Triassic. Its Triassic successions are generally formed, from bottom to top, by schists, phyllites with quartzitic intercalations and a carbonate sequence generally comprising the middle and upper Triassic. These carbonates can show metapelitic intercalations. Overall, three large groups of units make up the Alpujarride, the lower, middle and upper, with increasing metamorphism towards the top. In the

* Corresponding author. Fax: +34-9-58-243384.
E-mail addresses: csanz@ugr.es (C. Sanz de Galdeano), andreo@ccuma.sci.uma.es (B. Andreo).

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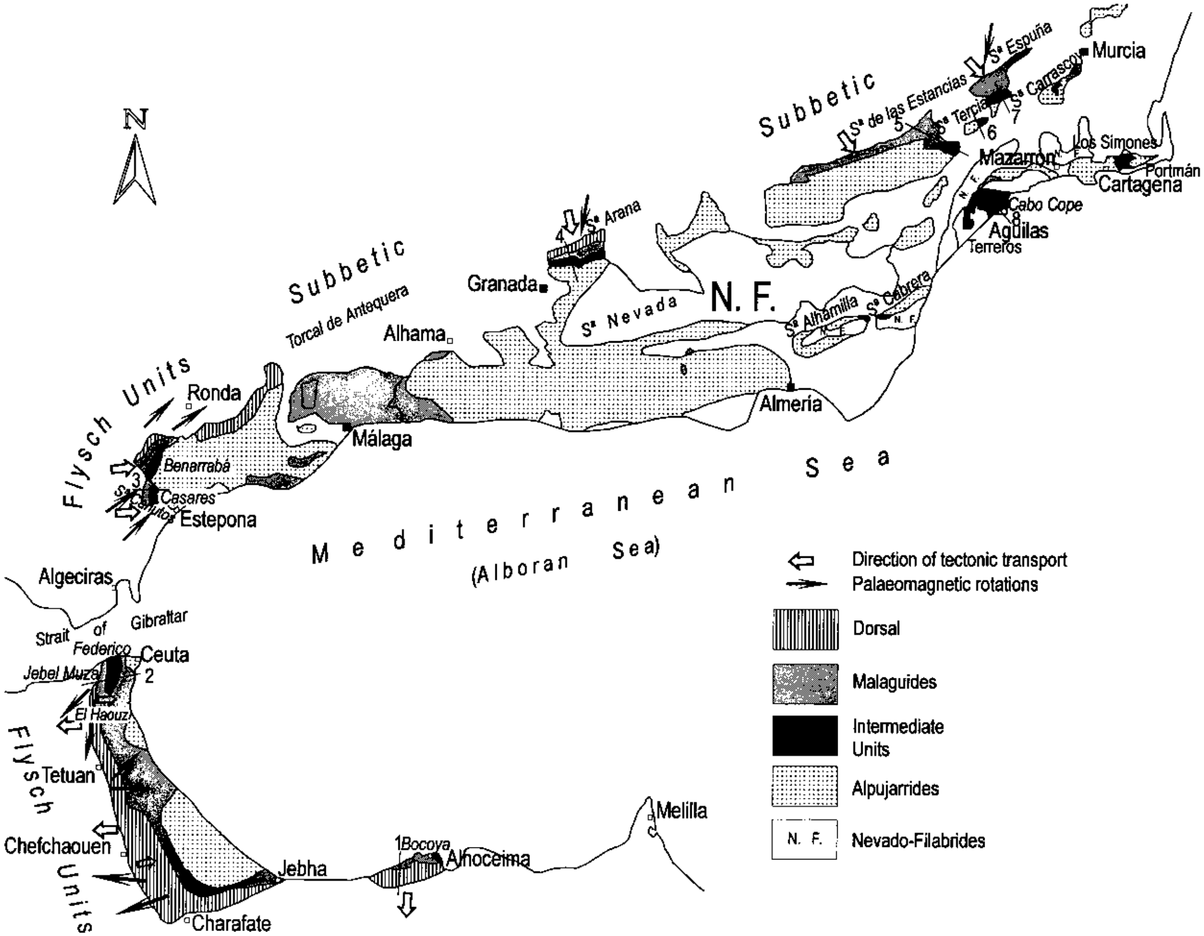


Fig. 1. Simplified map of the Betic–Rif Internal Zone, indicating the position of the intermediate units between the Alpujarride and Malaguide complexes. The numbers and the lines show the position of the cross-sections in Figs. 4 and 5.

western sector the upper units have peridotites emplaced at their base.

The Malaguide, except for its lowest formations (early Palaeozoic or even older), is scarcely or not at all metamorphosed. In many sectors the stratigraphic sequence, apart from the Triassic, includes Jurassic, Cretaceous and Tertiary sediments, although there are numerous stratigraphic gaps among these sediments. Its Triassic successions are formed by conglomerates, especially at the bottom, sandstones and red lutites. In the middle Triassic carbonate intercalations can occur, that are generally but not always, rather thin. There are also carbonates of the end of the Triassic, passing to the Jurassic.

The geometric relationship between the Malaguide and the Alpujarride is practically constant in the Betic Cordillera and the Rif. The Malaguide complex tectonically overlies the Alpujarride complex, save some exceptions accounted for by local, later thrusts. In wide areas of the Betic–Rif zone, both complexes could be easily distinguished by their different lithostratigraphic characteristics, although, in some sectors where the upper formations of the Alpujarride units are missing, it has been suggested (Tubía et al., 1993) that the Malaguide is simply the top of the Alpujarride stratigraphic sequence. However, this assumption can be discounted by the occurrence in these areas of upper Triassic formations of the Alpujarride preserved below the Malaguide.

The Dorsal complex is divided into two main domains, the Internal and the External. The Internal Dorsal is directly related to the Malaguide, forming part of its Mesozoic cover, while the External Dorsal extend till the Predorsal, and it till the Flysch basin situated to the north of the Rif External Zone and the Tell (in Algeria).

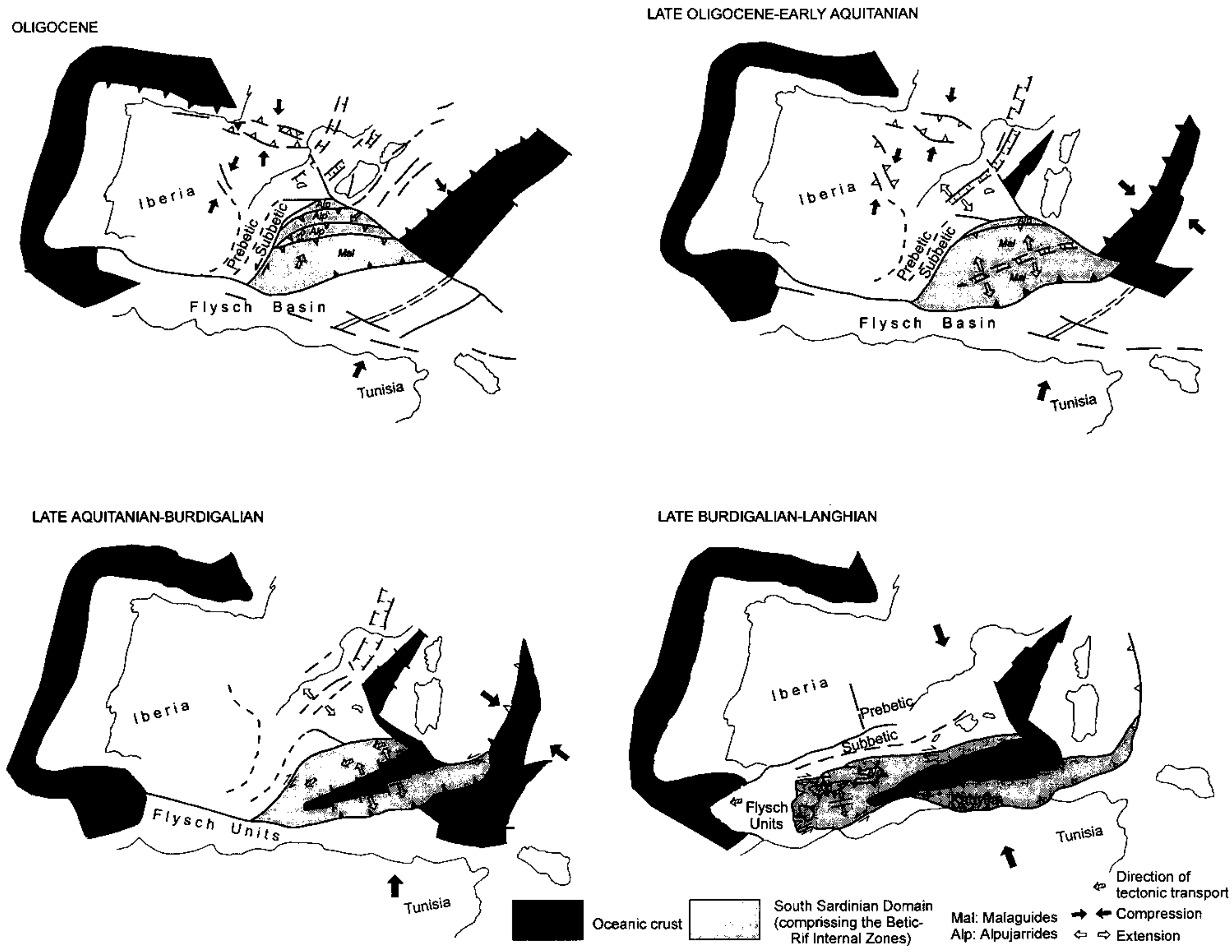
To approach the final reconstruction of the original relationships between the Malaguide and Alpujarride complexes, we should first examine prior hypotheses on the palaeogeography of the Betic–Rif Internal Zone as well as on its Cenozoic tectonic evolution, from the time when the Malaguide complex overthrusted the Alpujarride complex. We accept that the Malaguide complex was originally situated S and SE of the Alpujarride, while the Nevado–Filabride was situated generally N of the Alpujarride (Durand-Delga and Fontboté, 1980; Martín-Algarra, 1987; Sanz de Galdeano, 1997, among others). In accordance with these reconstructions, the Malaguide Complex thrust northwards or, rather, towards the NE over the Alpujarride Complex after the latter was largely already structured.

This thrusting must have begun in the Oligocene, while upper? Aquitanian–lower Burdigalian formations lie unconformably over both the Malaguide and the Alpujarride (Bourgois et al., 1972; Boulin et al., 1973) clearly indicating that the Malaguide complex overthrust the Alpujarride complex before the Burdigalian.

During and after the superposition of the Malaguide over the Alpujarride, the Betic–Rif Internal Zone was displaced westwards, contemporary with the opening of the Algerian basin (Fig. 2). This opening extended to the Alboran Sea, where there was significant spreading and crust thinning, although there was no formation of new oceanic crust, in contrast with the Algerian basin. The Betic–Rif Internal Zone was also affected by this spreading, particularly in the parts closest to the extension of the Alboran Sea itself (Fig. 2, last map). Nonetheless, the outer part of the Internal Zone sectors collided with the Rif and Betic External Zones and underwent compression (Balanyá and García-Dueñas, 1986).

Moreover, the westward displacement of the Betic–Rif Internal Zone caused changes in most of its westernmost units, rotating and shaping the Arc of Gibraltar. Likewise, the Betic–Rif External Zones and Flyschs basin were significantly deformed, shaping the arc. Furthermore, the displacement of the Betic–Rif Internal Zone affected the Betic External Zone, specially the Subbetic, that were partially dragged and divided in many units that were clockwise rotated (Sanz de Galdeano, 1997).

The existence of the Intermediate units between the Alpujarride and Malaguide complexes. Between the Malaguide and Alpujarride complexes are different units characterised by: (a) being tectonically situated between the two; (b) presenting a lower degree of metamorphism than in the Alpujarride unit situated at their bottom as well as greater (or slightly greater) metamorphism than the (non-metamorphic) Malaguide complex situated at the top; (c) their stratigraphic Triassic successions having intermediate characteristics (according to the existence or not of levels of conglomerates, the development of the pelites, or metapelites, and


OLIGOCENE
Iberia
Prebetic
Subbetic
Alp
Mal
Flysch Basin
Tunisia
LATE OLIGOCENE-EARLY AQUITANIAN
Iberia
Prebetic
Subbetic
Mal
Flysch Basin
Tunisia
LATE AQUITANIAN-BURDIGALIAN
Iberia
Flysch Units
Tunisia
LATE BURDIGALIAN-LANGHIAN
Iberia
Prebetic
Subbetic
Flysch Units
Tunisia
Oceanic crust
South Sardinian Domain (comprissing the Betic-Rif Internal Zones)
Mal: Malaguides
Alp: Alpujarrides
Direction of tectonic transport
Compression
Extension

especially the development of the carbonates) in relation to the Triassic successions of the Alpujarride and Malaguide units. In the areas where several thrusting units of this type outcrop, the same trend of intermediate characteristics appears. We shall refer to these units as Intermediate units.

The presence of Intermediate units between the Malaguide and Alpujarride has been pointed out at several places: in the Rif, the Federico units were considered intermediate between the Alpujarride and the Malaguide by Durand-Delga and Kornprobst (1963). Likewise, in the Casares sector, in the extreme W of the Internal Zone, S Spain (Fig. 1) several units show the same intermediate characteristics (Didon et al., 1973; Sanz de Galdeano et al., 1999). Such units have also been cited in the area NE of Granada (Sanz de Galdeano et al., 1995a,b,c) and in the sierras de las Estancias (Fernex, 1964; Kampschuur et al., 1981) and Espuña (Paquet, 1969). Finally, García-Tortosa et al. (2000) point out, apart from a Malaguide unit E of Cartagena, an Intermediate unit. Several years ago, in this sector, Durand-Delga (in Ovejero et al., 1976) indicated Alpujarride units very similar to the Malaguide.

Objective. The aim of this study is to propose, through the study of the present situation of these Intermediate units and, considering the Cenozoic evolution of the contact of the Malaguide and Alpujarride complexes, a reconstruction, during the Triassic, of the palaeogeographic relationships between the Alpujarride and Malaguide complexes. Considering that most of the data presented in this article are already known, we discuss the different Intermediate units between the Alpujarride and Malaguide complexes only briefly, simply to indicate the units in each sector and some of their characteristics. However, these units have neither been presented jointly nor has their overall significance been discussed, with the exception of Sanz de Galdeano (1997), but in this case not as the main objective.

2. Intermediate units between the Alpujarride and Malaguide complexes

Overall, the outcrops of these units form an arc (Fig. 1), in agreement with the general distribution of the Rif and the Betic Cordillera. The sectors where these units crop out, described first for the Rif and then for the Betic Cordillera are as follows: (a) the Bocoya region (Al Hoceima); (b) the area between Jebha and Ceuta, particularly in the area of the Federico guard towers; (c) the area of Casares and Benarraba, in S Spain; (d) NE of Granada, in Sierra Arana; (e) in the sierras de las Estancias, Tercia and Espuña; (f) in the sierras of Alhamilla and Cabrera; (g) in the areas of Aguilas and Carrascoy; and (h) in the area of Mazarron–Cartagena. All the above areas, up to the Sierra Espuña ((a)–(d)), are peripheral, near the outer border of the Betic–Rif Internal Zone, whereas the areas (f)–(h) lie in more internal positions of the Betic Cordillera.

2.1. Bocoya area

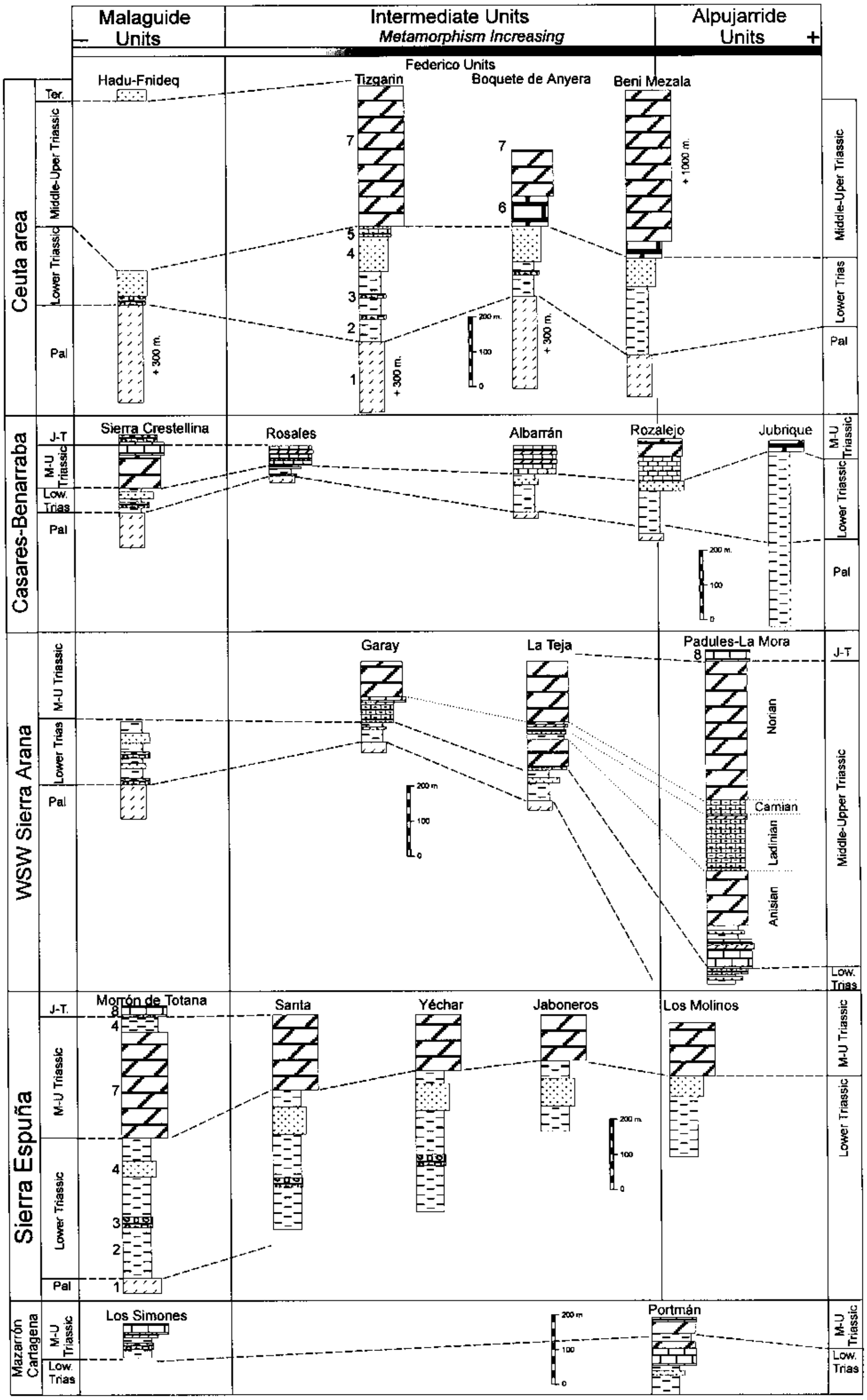
Near Al Hoseima (Figs. 1 and 4, cross-section 1) there is the Ain el Hajar unit, considered Alpujarride by Andrieux and Mégard (1973), forming several small outcrops. It is very similar to the Federico units described below.

2.2. From Jebha to Ceuta. Federico units

In this area (Figs. 1, 3 and 4, cross-section 2), below the Malaguide complex there are three intermediate units (the Federico units, after Kornprobst, 1974).

The upper intermediate unit, the Tizgarin (Fig. 3),

Fig. 2. Geological evolution of the Betic–Rif Cordilleras from the Oligocene. (In this time the Alpujarride complex is tectonically superposed to the Nevado–Filabride complex and for this reason the last complex is not visible. The Dorsal is situated south of the Malaguide and the intermediate units in the area of the contact between the Malaguide and Alpujarride complexes, but, owing the scale of the figures, are not differentiated). The westward displacement of the Betic–Rif Internal Zone, contemporary with the formation of the Alboran Sea, is shown. During this displacement to the west, the Arc of Gibraltar was formed, as can be seen better in Fig. 6. During the Oligocene–early Aquitanian, the Alpujarride complex underthrust the Malaguide Complex (the Nevado–Filabride had been previously overthrust by the Alpujarride). Immediately, the present Argelian–Provençal basin of the western Mediterranean began to open in a process that probably continued up until the Middle Miocene. During the late Aquitanian–Burdigalian, several tectonic units of the Alpujarride appear under the Malaguide, as seen in the last map of the figure (slightly modified from Sanz de Galdeano, 1990, 1997).


Malaguide Units
Intermediate Units
Metamorphism Increasing
Alpujarride Units
Federico Units
Ceuta area
Hadu-Fnideq
Tizgarin
Boquete de Anyera
Beni Mezala
Ter.
Middle-Uper Triassic
Lower Triassic
Lower Trias
Pal
+ 300 m.
+ 1000 m.
200 m.
100
0
Casares-Benarraba
Sierra Crestellina
Rosales
Albarrán
Rozalejo
Jubrique
J-T
M-U Triassic
Low. Trias
WSW Sierra Arana
Garay
La Teja
Padules-La Mora
Norian
Carnian
Ladinian
Anisian
Middle-Upper Triassic
Sierra Espuña
Morrón de Totana
Santa
Yéchar
Jaboneros
Los Molinos
Mazarrón Cartagena
Los Simones
Portmán

is comprised of a basement of upper Palaeozoic schistose shales and greywackes, with remains of plants. This basement is overlain by wine-coloured phyllites with intercalated conglomerates and pink and green quartzites. This succession is similar to the Malaguide lower Triassic series. Above are bluish limestones, multi-coloured limestones, and calc-schists, capped by grey dolomites of middle–upper Triassic.

The middle unit, Boquete de Anyera, is very similar to the Tizgarin unit, but with a slightly higher degree of metamorphism. The middle–upper Triassic carbonates appear as bluish-grey marbled limestones and massive dolomites.

The bottommost intermediate unit, the Beni Mezala, shows an increasing degree of metamorphism, but its stratigraphic succession is very similar to the last two units (Fig. 3).

Farther east, two Alpujarride units crop out, the Hacho de Ceuta (Fig. 4, cross-section 2) and the Beni-Boussera, with a higher degree of metamorphism.

2.3. Casares–Benarraba area

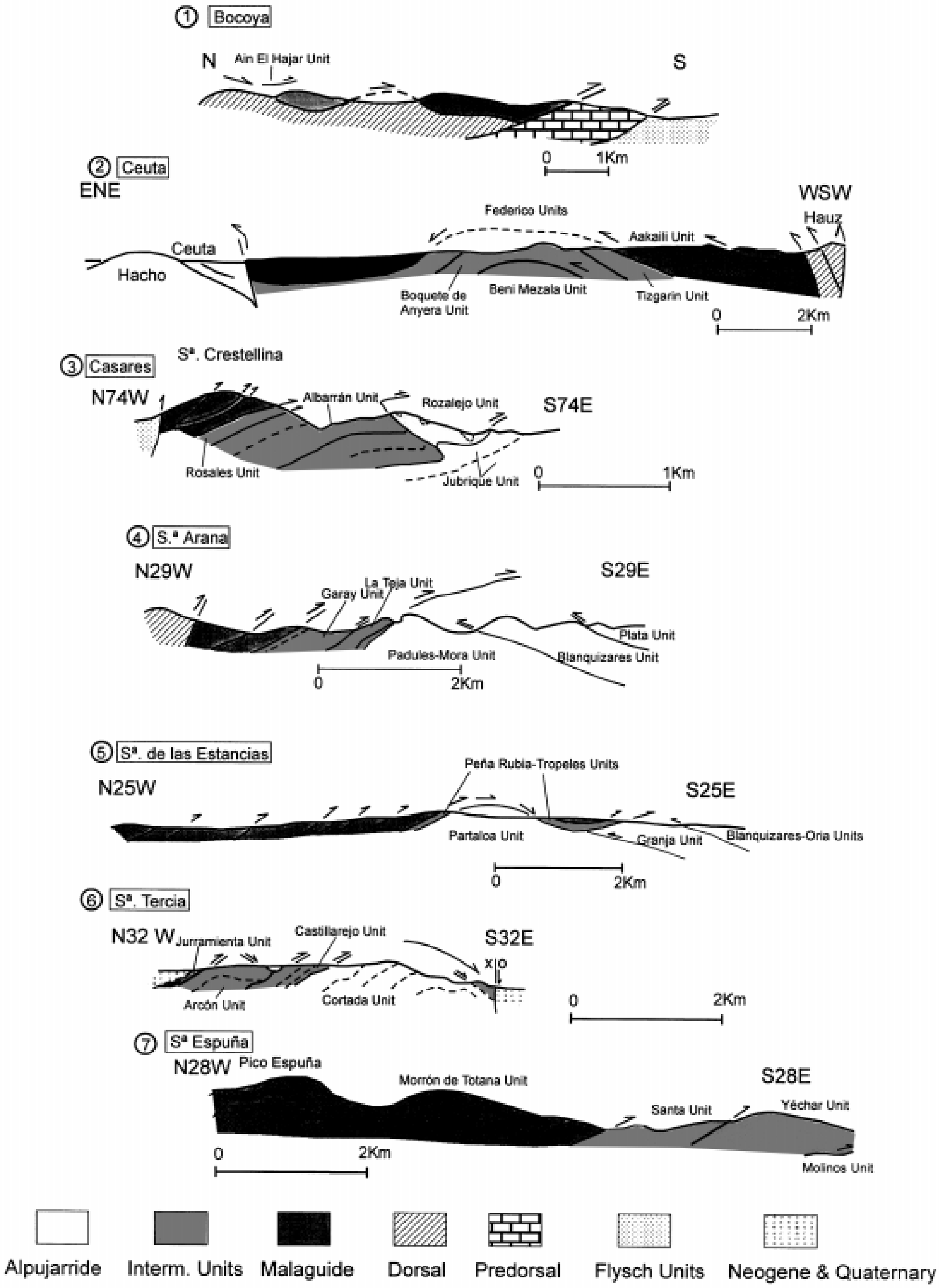
This area lies in the westernmost part of the Internal Zone in S Spain (Fig. 1) where the thrust slices of Benarrabá (Balanyá, 1991) and, further south, of the Casares (Didon et al., 1973; Kornprobst, 1974) are Intermediate units (Sanz de Galdeano et al., 1999). According to the latter authors, these units show a progressive decrease in metamorphism from E to W and a gradual change of lithology (Figs. 3 and 4, cross-section 3). Possible Palaeozoic rocks appear in all the units: gneisses and schists in the Jubrique unit, dark phyllites in the Rozalejo unit, similar to the Malaguide Palaeozoic lutites although transformed into phyllites in the Albarran unit, slightly schistose in the Rosales unit and unmetamorphosed in the Malaguide Crestellina unit. The lower Triassic succession is composed of bluish-grey schists and dark quartzites in the Jubrique unit, greyish phyllites and quartzites with small pebbles in the Rozalejo unit, purple phyllites and white quartzites with centimetric pebbles in the Albarran unit, anchimetamorphic sediments (lutites, sandstones and conglomerates) in the Rosales unit and unmetamorphosed sediments in the Crestellina unit. The middle–upper Triassic succession of the first four units are: foliated marbles in the Jubrique unit, marbly thin-bedded limestones and dolomites in the Rozalejo unit, somewhat recrystallised thin-bedded limestones and dolomites in the Albarran unit, and practically unmetamorphosed thin-bedded limestones and dolomites in the Rosales unit. In the Crestellina unit (Malaguide) the carbonates are unmetamorphosed and their deposition does not correspond to the middle Triassic but to the late Triassic and Jurassic. Therefore, this group of units situated between the Jubrique unit (Alpujarride) and the Crestellina unit (Malaguide) shows tectonic, metamorphic and stratigraphic characteristics intermediate between the two complexes.

2.4. Sierra Arana area

In this sector (Fig. 1) the Dorsal crops out in the north, the Malaguide directly south of it, and, farther south, there is a series of small thrust slices making up units with intermediate character, the lower units showing more metamorphism and with an increasing development of the carbonates.

In the ENE of this sector, there are several tectonic slices. The most northerly and upper ones correspond to the Malaguide Complex, showing the Palaeozoic basement (Fig. 3) and the red lower Triassic sediments unconformably overlying the basement. As the thrust slices are located in a lower position, and therefore more southerly, they begin to show a slight degree of metamorphism and increasing fissility. At the same time, the red colour of the lutites and sandstones of the Malaguide Triassic grade to wine colour, then to purple with grey tones dominating in the lowest thrust slices, where the rocks are metamorphic phyllites and quartzites. The Palaeozoic basement displays a similar transition: the lower the tectonic position of the thrust slices, the more schistose and metamorphic it becomes.

Fig. 3. Lithological successions in the main sectors where intermediate units appear between the Malaguide and Alpujarride complexes. The metamorphism increase towards the Alpujarride Units; 1, Palaeozoic basement; 2, Lutites, phyllites, micaschists; 3, Conglomerates; 4, Sandstones, quartzites; 5, Calcschists, 6, Marbly dolomites and limestones; 7, Dolomites and limestones, Marbles; 8, Jurassic–Tertiary succession.



① Bocoya
N
Ain El Hajar Unit
S
0 1Km
② Ceuta
ENE
WSW
Federico Units
Hauz
Aakaili Unit
Ceuta
Hacho
Boquete de Anyera Unit
Beni Mezala Unit
Tizgarin Unit
0 2Km
③ Casares
Sª. Crestellina
N74W
Albarrán Unit
Rozalejo Unit
S74E
Rosales Unit
Jubrique Unit
0 1Km
④ S.ª Arana
N29W
S29E
La Teja Unit
Garay Unit
Plata Unit
Padules-Mora Unit
Blanquizares Unit
0 2Km
⑤ Sª. de las Estancias
Peña Rubia-Tropeles Units
N25W
S25E
Partaloa Unit
Granja Unit
Blanquizares-Oria Units
0 2Km
⑥ Sª. Tercia
N32 W
Jurramienta Unit
Castillarejo Unit
S32E
Arcón Unit
Cortada Unit
0 2Km
⑦ Sª Espuña
N28W
Pico Espuña
Morrón de Totana Unit
S28E
Santa Unit
Yéchar Unit
0 2Km
Molinos Unit
Alpujarride
Interm. Units
Malaguide
Dorsal
Predorsal
Flysch Units
Neogene & Quaternary

To the WSW (Fig. 4, cross-section 4) there are only two Intermediate units (Garay and Teja units), forming major outcrops. In the Garay unit, which is under the Malaguide complex, the upper Palaeozoic succession is very similar to the basement of the Malaguide complex, although, for instance, the pebbles of the conglomerates are markedly stretched. Its Triassic stratigraphic sequences (Fig. 3) are formed by purple phyllites and quartzites, showing deformed pebbles of conglomerates. At the top, there are calc-schists, thin-bedded limestones and dolomites, these latter being attributable to the Norian.

The Teja unit, cropping out below the Garay unit, overthrusts the Padules-Mora Alpujarride unit (Sanz de Galdeano, 1995a,b,c), and it has a Palaeozoic basement composed of slates, greywackes, and conglomerates slightly metamorphosed to phyllites and quartzites. The Triassic sequences are highly similar to those of the Garay unit, although the phyllites are predominantly grey and the carbonates are thicker.

The Padules-La Mora shows lower Triassic members comprised predominantly of grey phyllites and quartzites overlain by calc-schists, followed by a more developped carbonate sequences from the Ladinian to the Rhaetian.

2.5. The sierras de las Estancias, Tercia and Espuña

Sierra de las Estancias. On its northern and eastern border, there are several Malaguide units and various intermediate units between the Malaguide and Alpujarride (Figs. 1 and 4, cross-section 5).

Mac Gillavry et al. (1963), Egeler et al. (1971) and Geel (1973) described numerous Malaguide units on the northern border of the Sierra de las Estancias and, to the SE, two units having intermediate characteristics between the Malaguide and Alpujarride. These units on the eastern border of this sierra, are the Peña Rubia unit, at the base, overthrusting the Alpujarride units, and the Tropeles unit, at the top (Fernex, 1965; Kampschuur et al., 1981).

Sierra Tercia. This small sierra (Figs. 1 and 4, cross-section 6) contains a Malaguide unit, the Jurramienta unit, underlain by the intermediate Arcon and Castillarejo units. The Arcon unit, overlying the Castillarejo, is roughly 150 m thick and consists of Triassic lutites and multi-coloured quartzites, as well as occasional gypsum, capped by dark carbonates. The Castillarejo unit is formed of slates and multi-coloured quartzites up to 150 m thick that are overlain by dark carbonates, with sporadic chert, up to 200 m thick. Beneath lies an Alpujarride unit, the Cortada unit.

Sierra Espuña. This sierra (Figs. 1, 3 and 4, cross-section 7) was studied in detail by Paquet (1969), Lonergan (1991) and Martín-Martín (1996). Below and south of the Malaguide Morrón de Totana unit lie three Intermediate units with increasing Alpujarride characteristics towards the bottom: the Santa, the Yechar and the Jaboneros units (this last unit appearing only very locally). Below the two first units lies an Alpujarride unit, the Molinos, with a low degree of metamorphism. The bottom of the Jaboneros unit is not visible.

The Santa unit, practically non-metamorphic, is composed of red and green lutites, thick quartzites with red conglomerates. At the top, grey and yellow carbonates, with some gypsum, are intercalated, these being overlain by dark carbonates, sometimes chert-bearing. The series is considered to be Triassic.

The Yechar unit, tectonically under the Santa unit, present a Triassic stratigraphic succession very similar to that of the Santa unit, but the red colour of the lutites turns to brown and the conglomerates are red at the base and grey higher up.

The Jaboneros unit, in the lower position of these Intermediate units, is formed of purple to bluish phyllites and quartzites, capped by dark carbonates.

The Alpujarride Molinos unit (Fig. 3) consists of lower Triassic grey phyllites, that towards the top are locally purple and green, while of multi-coloured quartzites, with lighter tones dominating towards the top, are overlain by middle–upper Triassic dolomites.

All the above areas are located on the outer border of the Betic–Rif Internal Zones, forming an arc. In addition, there are also several intermediate units more distant from the outer arc, described below.

Fig. 4. General geological cross-sections in some of the areas with Intermediate units. Their locations are marked in Fig. 1 (cross-section 1: simplified from Platzman et al., 1993; cross-section 2: modified from Didon et al., 1973; cross-section 3: simplified from Sanz de Galdeano et al., 1999, cross-sections 4–7: simplified and modified from Sanz de Galdeano, 1997).

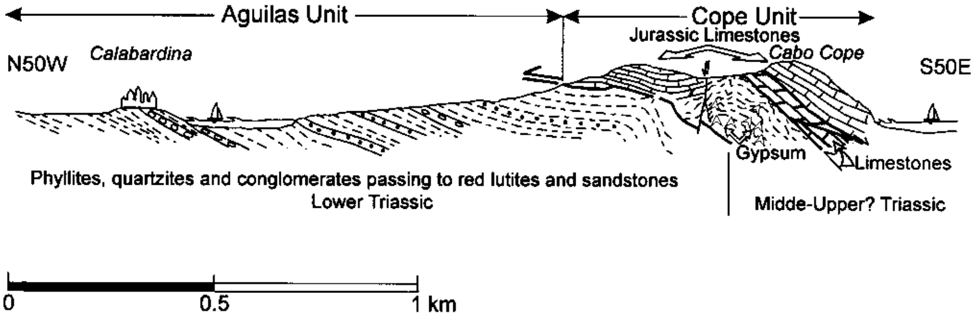


Fig. 5. Geologic cross-section in the Aguilas–Cope sector. Position marked in Fig. 1 (cross-section 8).

2.6. The area of the Sierras Alhamilla and Cabrera

The northern and western borders of the Sierra Cabrera (Fig. 1) have several outcrops considered to belong to the Malaguide complex (Rondeel, 1965), with dark Palaeozoic lutites and Jurassic and Tertiary sediments. Nevertheless, its Triassic sequences are formed by phyllites reminiscent of the equivalent Alpujarride rocks. These types of small outcrops are also found in the Sierra Alhamilla, particularly on the northern border, some in the south and a few in the east, where this sierra joins the Sierra Cabrera.

2.7. The Aguilas and Carrascoy areas

Aguilas area. In the northern part of this sector appears the Alcaibar unit, considered by Álvarez and Aldaya (1985) and Álvarez (1987a,b) to belong to the Malaguide complex, but its Triassic pelites are practically transformed into phyllites and its carbonates are similar to others of the Alpujarride complex. However, as in Sierra Cabrera, this unit has some Jurassic and Tertiary sedimentary remnants that are not at all metamorphic (Durand-Delga et al., 1962).

To the south, the Aguilas unit (Figs. 1 and 5) belongs to the Alpujarride (Bon et al., 1989). Its Triassic succession is formed by bluish phyllites and quartzites. Topwards, these rocks grade into purple and green phyllites and red and white sandstones, capped by red lutites and red and white sandstones. There are sporadic intercalations of fine-grained (centimetre-sized) quartzitic conglomerates (at Calabardina, within the phyllites there are several metre-thick layers of conglomerates with well-rounded quartzites, including some pebbles up to 20 cm in diametre) and some levels of carbonated clasts, both features uncommon in the Alpujarride complex, but similar in appearance to the Malaguide Triassic series. There, the Cabo Cope Malaguide unit overthrusts the Aguilas unit.

Considering its metamorphic and lithostratigraphic characteristics as well as its tectonic position, we include the Aguilas unit in the Intermediate units.

Sierra Carrascoy (Fig. 1). A highly tectonised Malaguide unit (the Navela unit) crops out in this sierra. Kampschuur (1972) reported the presence of the Pestillos unit underneath it, with Triassic formations very similar to the Malaguide, although slightly metamorphosed. The red lutites and conglomerates are partially transformed into phyllites and quartzites. Farther downwards lies the Carrascoy unit, which is an Alpujarride unit.

2.8. Mazarrón–Cartagena area

The highest Alpujarride unit in this sector is the Portman unit (Figs. 1 and 3), which has red and purple phyllites and quartzites at the base, similar to the Intermediate units described above. At the top, the Triassic limestones and dolomites are continued by possibly Jurassic limestones. East of Cartagena, over the Portman unit, the Simones unit belonging to the Malaguide complex locally outcrops (García-Tortosa et al., 2000).

3. Palaeomagnetic data and directions of emplacement of units

Although no palaeomagnetic data are available for the Bocoya sector, the data of Mégard (1969), Azzouz (1992) and Platzman et al. (1993) indicate that the tectonic displacement of the Malaguide complex was towards the south, overthrusting the Dorsal. Remarkably, the Ain El Hajar intermediate unit overthrusts the Malaguide in this sector, whereas in the other zones the Malaguide always overlies these units or lies directly over the Alpujarride.

Palaeomagnetic data are available for some Dorsal units in the western area between Jebha and Ceuta (Fig. 2). Platzman (1992) and Platzman et al. (1993) have reported declinations that after tectonic tilt correction "appears to have been rotated in an anticlockwise direction… They range from 128° in Jebel Mousa to 41° at Bab Taza" although "sites located in the Tetuan area show significant clockwise rotations". These data are obtained in External Dorsal and Predorsal units. In the Alpujarride complex, Saddiqui et al. (1995) interpret the peridotites of Beni Bousera to have an anticlockwise horizontal rotation of 76 ± 13°. This rotation appears to have occurred during the Aquitanian–Burdigalian, supporting the previously cited data for the Dorsal. The general directions of tectonic emplacement for the units between Jebha and Ceuta (Platzman et al., 1993) are outwards from the Internal Zone (that is, towards the W or SW and S, depending on the points), in addition to some backthrusts, but the first overthrusts probably were to the N or NE.

The only palaeomagnetic data known for the Internal Zone units in the Casares sector (north of Gaucín) are from a sample apparently taken in the Dorsal (site 29 of the Fig. 2 of Platzman and Lowrie, 1992), indicating a clockwise rotation of approximately 67°. In contrast, there are considerable data for the Betic External Zone rocks close to the Betic Internal Zone. Platzman (1992) and Platzman and Lowrie (1992), for instance, report clockwise rotations in the Penibetic (Internal Subbetic, belonging to the Betic External Zone) from the vicinity of Estepona (S^{a} Canutos), through sectors near Ronda, up to the Torcal de Antequera (Fig. 2). The values range from a few degrees up to nearly 90°, with an approximate average of 50°. These authors distinguish between rotations in upper Jurassic rocks (38 ± 8°) and those in upper Cretaceous rocks (61 ± 11°). This lesser extent of rotation in the Jurassic rocks is due to the anticlockwise rotation of some 23° of Iberia during the Cretaceous.

Villalaín et al. (1992, 1994) reported quite similar data in this sector, although some units, such as the Canutos, registered rotations of up to 140°. Generally, however, the rotations are much smaller, even in that same unit.

The present overthrust displacement of the units in this sector of Casares are predominantly eastwards within the Intermediate units, although the whole Internal Zone moves westwards. Kirker and Platt (1998), studying this area and its prolongation to the NE, indicate kinematic data showing that the direction of displacement is towards the WNW. These last data refer to the contact between the Betic Internal and External Zone as well as to the External Zone.

Parés et al. (1992) used palaeomagnetic data to determine a clockwise rotation of 194° in the External Dorsal of Sierra Arana, NE of Granada. The thrust slices in the Malaguide and the intermediate units show clear southward and southeastward thrust displacements (Figs. 2 and 3).

Throughout the entire eastern sector, palaeomagnetic data are available only for Sierra Espuña. Mäkel et al. (1984) sampled probable Anisian rocks, reporting an anticlockwise rotation of about 45°. However, Allerton et al. (1992 and 1993) disagree with these results, obtaining instead a clockwise rotation of some 200° for Sierra Espuña, of which around 140° most probably would have occurred during the Oligocene–early Miocene.

In Sierra de las Estancias, Aldaya et al. (1991) conclude that the Malaguide was displaced ENE in relation to the Alpujarride. The Malaguide units, on the northern border of that sierra, overthrust the Intermediate units of Tropeles and Peña Rubia (Fig. 3, cross-section 5). All of these units move southwards and overthrust Alpujarride units located farther to the south.

Paquet (1969) reported that in Sierra Espuña the units were probably emplaced southwards, whereas Lonergan (1991) holds that the units moved northwards, but without providing convincing data.

No palaeomagnetic data are available for sectors situated in the interior of the Internal Zone. The direction of movements that can be deduced are N or NW, although many of the thrust contacts between units were subsequently affected by later extensional tectonics or by diverse types of faults.

4. Palaeogeographic reconstruction of the intermediate domain between the Malaguide and Alpujarride during the Triassic

In the Bocoya area, the External Dorsal is situated south of the Malaguide and the Internal Dorsal, while the small outcrops of the Ain el Hajar unit appear to the north of the Malaguide. If the distribution of these domains in the Rif and of equivalent domains in the Kabylia (Algeria) is considered, this would be approximately the original distribution of the units. On other hand if the extension of the Alboran sea is discounted, the Bocoya area, in the Rif, would have to be placed farther to the north, that is, closer to the Betic outcrops.

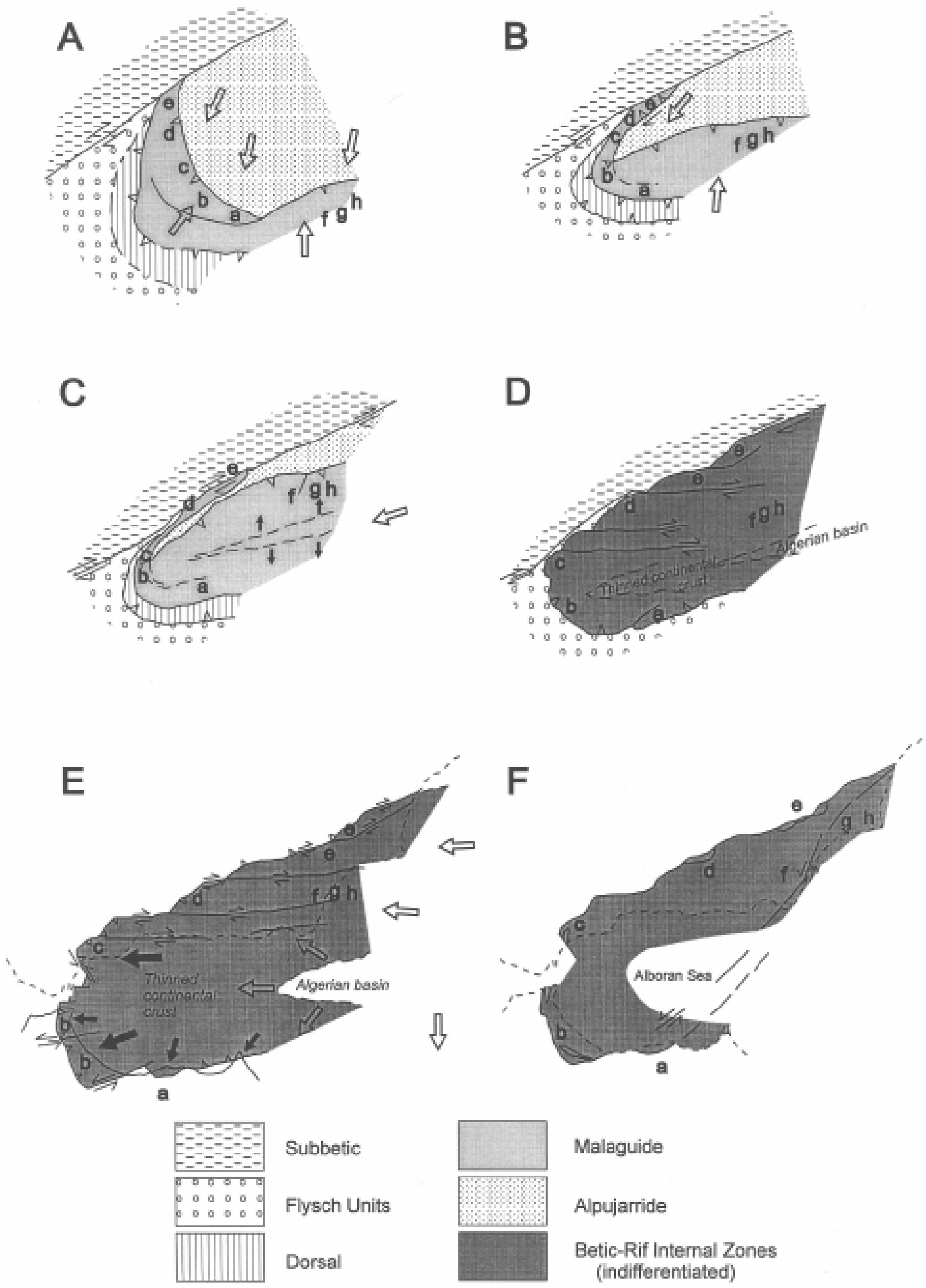
The units in the Jebha–Ceuta area are aligned NNW–SSE to N–S, in accordance with their adaptation to the arc which the Betic–Rif Internal Zone forms in the Strait of Gibraltar (Fig. 1). Also, the palaeomagnetic data (Platzman, 1992; Platzman et al., 1993) of this area agree with the nearly N–S present orientation of the units. To reconstruct the palaeogeography of these units, we must consider their original orientation to be approximately E–W. This Jebha–Ceuta sector was originally WSW of Bocoya, probably somewhat closer than at present, since the Jebha–Charafate fault limiting it to the S (Figs. 1 and 2) has displaced it farther WSW (Olivier, 1982). The general situation would have been similar to that of the Bocoya, with the Alpujarride towards the north, the Intermediate units (the Federico units) and the Malaguide farther south, and the Dorsal more to the south.

In the Casares–Benarraba area, the units are orientated almost N–S to NNE–SSW, also conforming to the bending form of the Arc of Gibraltar. The abovementioned palaeomagnetic data (Platzman, 1992; Platzman and Lowrie, 1992; Villalaín et al., 1992, 1994), show notable clockwise rotations, especially in the Penibetic. The orientation of the Penibetic itself is also evidence of its adaptation to the Arc of Gibraltar. The reconstruction of the original position of the units in the Casares sector is similar to that of the Bocoya and Jebha–Ceuta areas. The Casares units would have been situated directly west of the latter.

The original position of the units comprising the Sierra Arana, Estancias and Espuña area is more difficult to determine. Currently, the Dorsal in Sierra Arana is situated to the N of the Malaguide to which overthrusts to the S and SE. It overlies the Intermediate units in the same direction, and which in turn overlie the Alpujarride. That is, the situation is the opposite of that in the Bocoya area. In the Estancias and Espuña sectors, the Dorsal is lacking, but the rest of the units are distributed as in the Sierra Arana.

To explain the emplacement of these units in the Sierra Arana to Sierra Espuña areas, various hypotheses might be considered. The simplest suggests that these units have been displaced to the north or northwest, overthrusting the Alpujarride, but this hypothesis has the following drawbacks: (a) it does not explain how there, after such great movement, the Intermediate units have been best preserved than in the sectors situated directly to the south, within the Internal Zone; (b) nor does it account for the S and SE direction of displacement of the units in the Sierra Arana and Estancias (and, in our opinion, also in Sierra Espuña); and (c) still less does it explain the data of Parés et al. (1992) and Allerton et al. (1992 and 1993) indicating that the Dorsal in Sierra Arana and the Malaguide in Sierra Espuña have rotated clockwise some 200°.

Fig. 6. Hypothetical reconstruction of the formation of the Arc the Gibraltar, also showing the highly pronounced dragging of the Intermediate units of Arana, Estancias, Tercia and Espuña sierras and their rotations. The small letters indicate the succesive positions of the different sectors in which the intermediate units appear. a, Bocoya; b, Jebha–Ceuta; c, Casares; d, Sierra Arana; e, Estancias, Tercia and Espuña sierras; f, Alhamilla–Cabrera; g, Aguilas–Cabo Cope; h, Cartagena. A: the overthrusting of the Malaguide complex has begun and the area between Jebha and Sierra Espuña is partially rotated clockwise (approximately late Oligocene). B and C: the process of the overthrusting of the Malaguide complex has ended and the Intermediate units of Sierra Arana to Sierra Espuña continue to undergo dragging and rotation. In the interior of the Betic–Rif Internal Zone the process of opening of the Alboran Sea begins (Aquitanian to early Burdigalian). D and E: the opening of the Alboran Sea ends in this period and the Betic–Rif Internal Zone splits into several crust segments, the displacement of which contributes to increasing the distance and displacement of the Sierra Arana to Sierra Espuña units. The faults contributing to these last displacements coincide with the present E–W tectonic corridors now present in the Betic Cordillera (late Burdigalian to middle Miocene). F: from the late Miocene onwards, the NE–SW fault situated in the SE of the Betic Cordillera displaces northwards the Aguilas–Cope and Cartagena–Portman Intermediate units.



A second hypothesis posits that the unit emplacement occurred from N to S signifying that the Malaguide and Intermediate units were originally farther north of the Alpujarride. However, this seems unlikely if we consider, as a whole, the Malaguide and equivalent domains in Algeria (Kabylias), in Sicily (Monti Peloritani) and in Calabria, as Bouillin (1984) did (the South-Sardinian Domain of Sanz de Galdeano, 1990).

A third hypothesis proposes that the units forming

Sierra Arana to Sierra Espuña came from the W or WSW, as suggested by Durand-Delga (1980) and Sanz de Galdeano (1997). To understand this direction of displacement, we must consider the thrusting of the Malaguide complex over the Alpujarride complex. This overthrusting has northward direction, probably to the NNE and even NNW, depending on the place. Contemporaneously was the westward displacement of the entire Betic–Rif Internal Zone. In this process, some of the Alpujarride, Intermediate, Malaguide and Dorsal units situated in the western part of the Internal Betic–Rif Zone rotated, adapting to and forming the future Arc of Gibraltar (Fig. 6). This was especially significant to the units situated in a NW position: the units from Sierra Arana to Sierra Espuña (see their successive positions in Fig. 6A–C). This hypothesis accounts for and, indeed, requires the clockwise rotations that Parés et al. (1992) and Allerton et al. (1992 and 1993) deduced independently.

The Casares sector is currently separated from the Sierra Arana by some 160 km and the Sierra Arana from the Sierra de las Estancias by about 75 km. Nevertheless, the original distance existing between their equivalent units may have been shorter, given that the Betic–Rif Internal Zone was later divided into various crust segments (Fig. 6D and E) with different displacement values, as suggested by Sanz de Galdeano (1996). According to this author, the Dorsal was displaced around 80 km between the

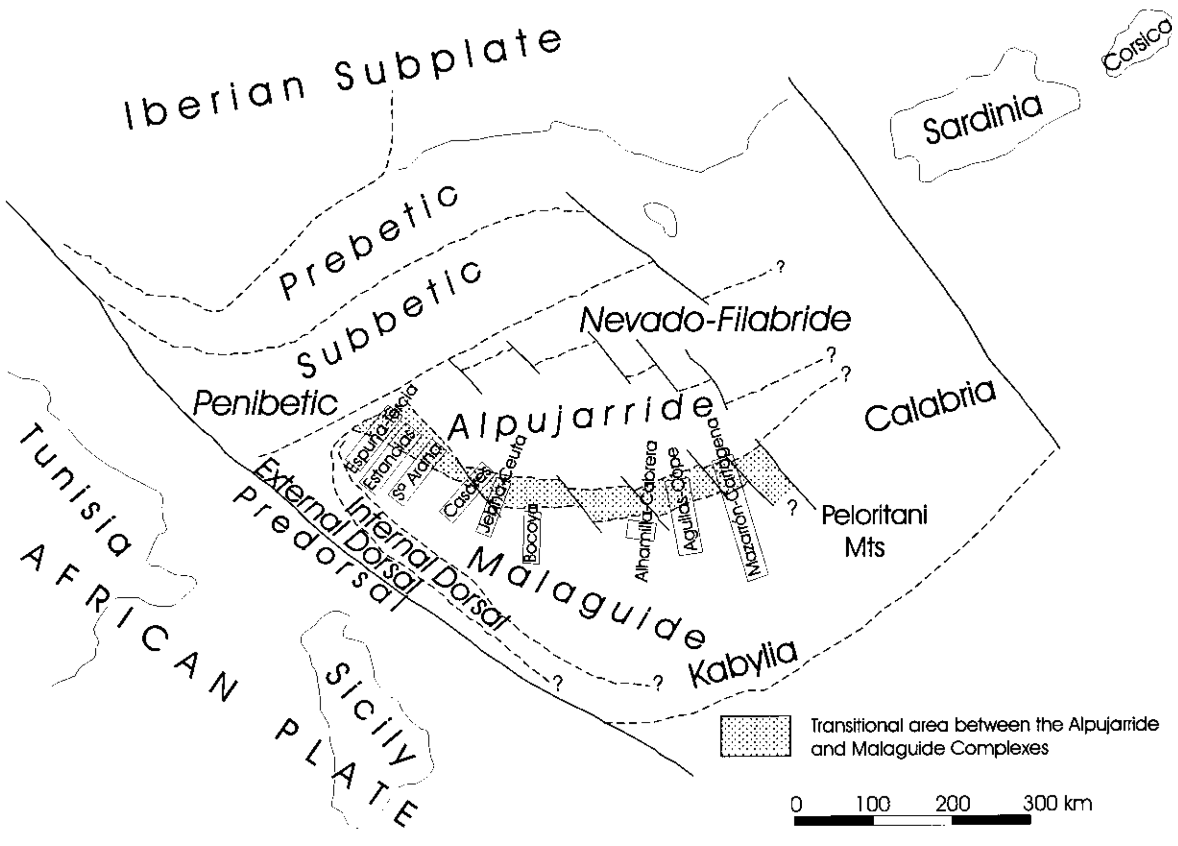


Fig. 7. Schematic reconstruction of the palaeogeography of the (future) Betic Cordillera and part of the Rif during the Triassic, showing the possible original position of the Intermediate units. Note the location of the (future) Betic–Rif Internal Zone, much farther east than its current position. Likewise, the Iberian Block is also much farther east, as the opening of the south Atlantic, which subsequently displaced Africa eastwards with respect to Iberia and Europe, was not yet significant. The rectangles correspond to the estimated areas where the Intermediate units were located. Modified from Sanz de Galdeano (1997).

sector SE of Ronda and SW of the Granada basin. If all these displacements are taken into account, the distances between Casares and Sierra Arana are at least halved, practically eliminating the distance between Sierra Arana and Sierra de las Estancias. By contrast, the present distance between the Intermediate units in the sector of the sierras Estancias–Espuña with respect to the Aguilas and Cartagena sectors has decreased due to the sinistral faults in the SE Betic Cordillera (Fig. 6F), active primarily since the late Miocene, which move northwards the Aguilas–Cartagena sectors (Larouzière et al., 1988).

Furthermore, the distinct positions of the Intermediate units over the Alpujarride Complex must also be taken into account (Fig. 3). In the Rif, Casares, and the sectors of Alhamilla–Cabrera, Aguilas–Cope and Mazarron–Cartagena, the Intermediate units invariably lie on the highest Alpujarride unit of each sector. Notwithstanding, in Sierra Arana the Intermediate units basically overlie the Padules–La Mora unit, lower Alpujarride unit for us, which they overthrust southwards. The Padules unit in turn is overlain in the S by middle and upper units of the Alpujarride tectonic stack. In the Sierra Estancias the Intermediate units overlie the middle Alpujarride units, whereas in the Tercia and Espuña sierras (and in Carrascoy) they are superimposed over the lower Alpujarride units.

In summary, the northern sectors present in the Malaguide complex north of the Alpujarride complex, show clockwise rotations of about 200°, the thrust displacement is southwards or southeastwards and the intermediate units overthrust lower (or middle in one case) Alpujarride units. Overall, this can be explained by the major eastward drag of units, as advanced in our hypothesis. Assuming the validity of this third hypothesis, the resulting palaeogeographic reconstruction (Fig. 7) reveals that the Sierra Arana unit would have originally been W or NW of the Casares–Benarraba sector, followed by the entire sector of Sierras Estancias to Espuña.

The positions of the Sierra Alhamilla–Cabrera, Aguilas–Cope and Mazarron–Cartagena sectors, situated far from the outer border of the Betic–Rif Internal Zone, present no apparent difficulties. That is, these were probably situated east of Bocoya, although not directly, but somewhat farther away.

5. Conclusions

The presence of the Intermediate units indicates that the change from the Alpujarride to the Malaguide complexes was not abrupt, but rather there was a wide transitional domain between them. This is clear for the Triassic, the lithologic successions of which are generally less varied in Malaguide on comparing with Alpujarride, specially when referred to the development of the carbonates.

In the proposed palaeogeographic interpretation, the Malaguide domain was located south of Alpujarride, with the Intermediate units obviously lying between the two complexes. The current arc-like distribution of the Intermediate units thus resulted from the Tertiary tectonic evolution of the region, due to the structuring of the Malaguide complex over the Alpujarride complex, combined with the westward displacement of the entire Betic–Rif Internal Zone. This process gave rise to the tectonic Arc of Gibraltar and in the northern sector, the units of the Sierra Arana, Sierra de las Estancias, Espuña and Carrascoy were dragged, at the same time causing their important rotations.

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