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Discussion on the differentiation of tectonic units in the Alpujarride Complex (Betic Cordillera)

Discusión sobre la diferenciación de unidades tectónicas en el Complejo Alpujárride (Cordillera Bética)

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ABSTRACT

The Alpujarride Complex, situated in middle position in the tectonic complexes of the Betic-Rif Internal Zone, is divided into many units distributed in three superposed groups. Nevertheless, the significance and even the existence of some of these units, is still under discussion. In this sense, the present article attempts to clarify some of these aspects, which are essential for an understanding of this Internal Zone. Among others, the following points are examined: a) the existence of transitional units between the Malaguide and Alpujarride complexes; b) the position of the Ronda peridotites under the Alpujarride and not thrusting it; c) the large shears and bevels that many tectonic units present, to the point of disappearing in some cases; d) the progressive lower metamorphic grade of its units towards the NE; and e) the overlap between the different groups of Alpujarride units, a process that is probably not complete.

The discussion of these and other aspects provides a more complete vision of the structure and meaning of the complex.

Keywords: Alpujarride Complex; Betic Cordillera; Betic Internal Zone; Nappes.

RESUMEN

El Complejo Alpujárride, situado en una posición media en los complejos tectónicos de la Zona Interna Bético-Rifeña, se divide en muchas unidades distribuidas en tres grupos superpuestos. Sin embargo, el significado e, incluso, la existencia de algunas de estas unidades es discutido. Este es el tema del presente artículo, en un intento de aclarar aspectos que son importantes para el conocimiento de la Zona Interna. Destacan entre otros: a) la existencia de unidades de carácter transicional entre los complejos Maláguide y Alpujárride, b) la posición de las peridotitas de Ronda bajo el Alpujárride y no cabalgándolo, c) las grandes cizallas y biselamientos que presentan muchas unidades tectónicas, hasta el punto de desaparecer en algunos casos, d) el progresivo menor grado metamórfico de sus unidades hacia el NE, y e) que probablemente la superposición entre de los diferentes grupos de unidades alpujárrides no sea completa. La discusión de estos y otros aspectos permite mostrar una visión más completa de la estructura y significado del complejo.

Palabras clave: Complejo Alpujárride; Cordillera Bética; Mantos de corrimiento; Zona Interna Bética.

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Introduction

The Alpujarride Complex at present occupies the largest area of the complexes forming the Betic (and Rif) Internal Zone. Situated in an intermediate tectonic position in the Internal Zone, it is divided into numerous units. Nevertheless, no general agreement has been reached concerning either the differentiation of these units or their structure and relationships, hampering a complete understanding of the Betic Cordillera. In fact, the attribution of some tectonic units remains controversial, and, moreover, lacks a general overview of their structure, distribution, and geological meaning.

The determination of the tectonic units that really exist is a critical issue in itself, but even more so when several recent studies—especially those dealing with general aspects of the Alpujarride Complex—use divisions of units which were made previously and which need to be reviewed before developing the new data compiled. Three examples of this are the following: the article by Williams & Platt (2017) dealing with superposed directions of shear and refolded metamorphic isogrades, using a division of units (particularly in the southern sector of Granada) that clearly should be reviewed, indicating as stratigraphic contacts some thrust contacts later affected by normal faults (in addition to numerous folds that are introduced but that either do not exist or are not as indicated). This means that many of the results they offer may not be of value. Another such work is that of Bessière *et al*. (2021), which deals with the exhumation of the Ronda peridotites, whose attributed position is debatable. Finally, the article by Aerden *et al*. (2022), with excellent microtectonic data, suffers, in my opinion, from using a division of Alpujarride units that, although proposed by other previous authors, could bias their results.

In short, failing to use an adequate differentiation of units can add confusion to the understanding of the Alpujarride Complex and in turn of the Internal Zone of the Betic Cordillera.

The aim of the present study is to provide a critical discussion of the division of the Alpujarride tectonic units, showing their most controversial aspects and analyzing them. For this, a general differentiation of the Alpujarride tectonic units is presented, together with their geometry and relationships. Other aspects, such as microtectonics, are not addressed (these are examined in the previous studies cited), nor are details of the development of metamorphism or the stratigraphy because there are excellent previous works (e.g. Jabaloy *et al*., 2019).

Geological setting

The main division of the Betic Cordillera corresponds to the Internal and External zones; moreover are differentiated into the Flysch (or Campo de Gibraltar) units and the Neogene basins (Vera, 2004).

The External Zone refers to the Mesozoic and Cenozoic sedimentary cover of the S and SE region of the Paleozoic Iberian Massif submerged from the end of the Permian. This cover is divided into the Prebetic and Subbetic, according to the original shorter or longer distance to the ancient coast, respectively. For this reason, the Subbetic presents sedimentary facies generally related to deeper marine environments while the Prebetic in some cases even has continental facies.

The Internal Zone is partially common to the Betic Cordillera and to the Rif Mountains, the former in southern Spain and the latter in northern Morocco. The zone is formed by three superimposed tectonic complexes that, from bottom to top, are: the Nevado-Filabride, the Alpujarride, and the Malaguide (Durand-Delga & Fontboté, 1980; Jabaloy *et al*. 2019). Or four complexes may be discerned, if the Frontal units (or “Dorsal”) are considered a separate complex.

The Nevado-Filabride Complex, not present in the Rif, is formed by Paleozoic and Mesozoic, mainly Triassic, sedimentary formations, at present metamorphosed. These contain intercalated igneous rocks, particularly basic and ultrabasic rocks, situated mainly within the late Carboniferous and Permian formations.

The lithological formations of the Alpujarride Complex, called Sebtide in the Rif, are generally metamorphosed, having ages ranging from the Paleozoic to the Triassic, or even younger in some units. It also contains igneous rocks, notably peridotites. In terms of the metamorphism, the Alpujarride Complex was initially submitted to a high-pressure (and low-temperature) phase, even on the order of

12 kbar (Alonso-Chaves *et al*., 2004b) or equivalent compressional push, this being compatible with a subduction, though this phenomenon could also be explained by continental collision without clearly defined subduction. This was followed by a major episode of low pressure and high temperature. However, as indicated, these last aspects lie beyond the scope of the present study. Nor do they concern the division in units of other complexes, and thus offer no clues regarding the division or not of the Nevado-Filábride Complex.

The Malaguide Complex, called Gomaride in the Rif, has Paleozoic to Cenozoic rocks, generally not metamorphosed. Only in the lower parts of its lithological sequences does it show a low grade of metamorphism.

Clearly linked to the Malaguide Complex is the "Dorsal" Complex (Durand-Delga & Foucault, 1967) or Frontal units (Serrano, 1998). This complex is formed by Mesozoic and Cenozoic sedimentary sequences and corresponds in part to the cover of the Malaguide Complex, but also forms independent units (Wildi *et al*, 1977), some of them with Alpujarride affinities in the Triassic partion of their succession.

A short overview of the Alpujarride Complex, concerning the topic of the present discussion, can be summarized as follows. The term "Alpujarride" was used for the first time by Van Bemmelen (1927). Later, Egeler & Simon (1969) synthesized the articles published up to that year. Aldaya *et al*. (1979) offered a nearly complete correlation of the main Alpujarride units. Sanz de Galdeano (1997, 2022) and Alonso-Chaves *et al.* (2004a) made a general revision of the Betic-Rif Internal Zone. Also, Jabaloy *et al*. (2019) described the Internal Zone in detail, accepting the previous division of the tectonic units. Other more specific studies are mentioned below, when describing the features of the Alpujarride Complex in different areas.

Different sectors into which the Alpujarride can be divided

The Alpujarride Complex extends from the NE to the SW ends of the Betic Internal Zone (Fig. 1). Due to the different locations of the units and their diverse geological settings, the Alpujarride units are described in several sectors as beginning with the western part and moving progressively to the east.

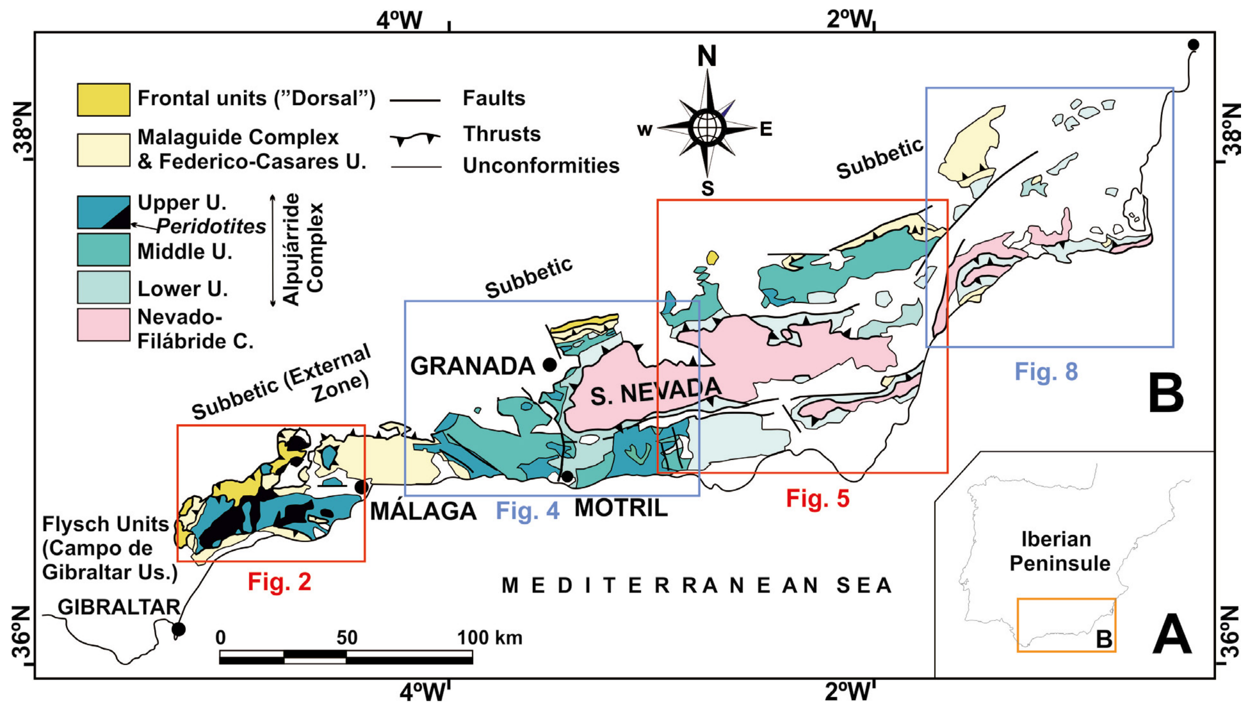

Fig. 1. A: position of the Betic Cordillera in the Iberian Peninsula. B: general distribution of the Alpujarride tectonic units. The quadrates mark the position of figures 2, 4, 5 and 8.

In the presentation of these sectors, when discussing whether previously proposed tectonic units exist, articles that initially differentiated them are cited with preference. Therefore, others who have followed these divisions may not be indicated, unless they introduced some noteworthy novelty. Thus, for example, for the proposal to differentiate the Ballabona-Cucharón Complex, the article given preference here is that of Simon (1964). Subsequently, various authors have used this differentiation, but without the novelty of the initial proposal.

In many sectors, lower, middle, and upper Alpujarride tectonic units are indicated, according to their geometric position (Aldaya *et al*., 1979). This division is followed whenever possible.

Also in many cases, towards the E and NE, the metamorphic grade of the tectonic units is less than that of their more western equivalents. This generally refers to both detrital metasediments and carbonates, as has been pointed out by several authors, as indicated below.

The western sector

In this sector (Fig. 2), extending from the western end of the Betic Internal Zone to the proximities of the city of Málaga, two main problems arise: the differentiation of the units (many tectonic units have been described) and the position and meaning of the Ronda Peridotites.

Background

In this sector Hoeppener *et al*. (1964), Dürr (1963), and Didon (1969) considered a unit, the Blanca unit (Fig. 2 A), as lying under the Ronda Peridotites, these being in turn overlaid by the Casares unit. However, Mollat (1968) and Buntfuss

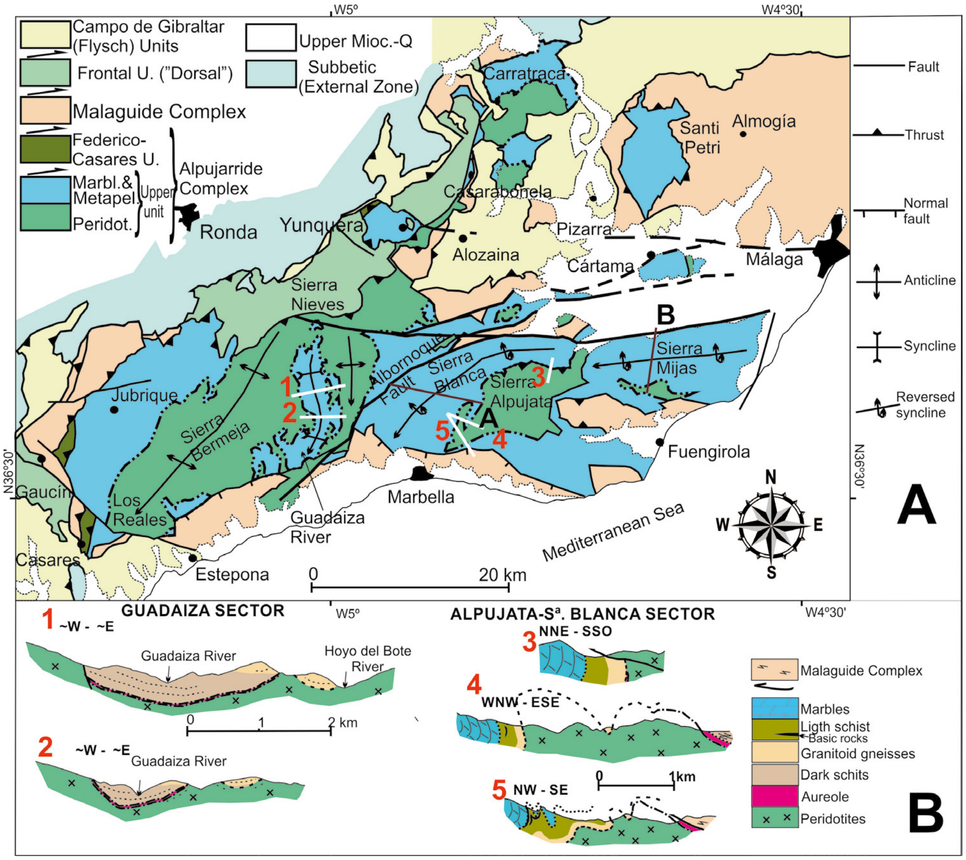

Fig. 2: A: geologic map of the western part of the Betic Internal Zone. White lines and red numbers indicate the positions of the cross-sections of B. B: geologic cross-sections of the sectors of Guadaiza River and Sierra Alpujata-Sierra Blanca areas showing the position of the Ronda Peridotites. The position of the cross-sections A and B of the Fig. 3 is indicated.

(1970) held that the Blanca unit in some places overlies the peridotites. Didon *et al*. (1973) defined the Federico-Casares units, situated above the Los Reales unit. This latter name, Los Reales, was used by Bourgois (1978) to indicate the Ronda Peridotites as well as the overlying metasediments (the Casares unit and other upper units).

Later, Navarro-Vila & Tubía (1983) and Tubía (1988) differentiated the unit of Ojén (encompassing the unit of Sierra Blanca) situated at the bottom, above the Guadaiza unit, and, over this unit, the Los Reales unit (with the Ronda Peridotites). Martín-Algarra (1987) followed this division with the peridotites situated above the Blanca unit. Balanyá and García-Dueñas (1991) joined the Ojén and Guadaiza units in the Guaro nappe, above which they situated the Bermeja unit (only the Ronda Peridotites); over this unit (over the peridotites) they placed the Jubrique unit, and at the top the Benarrabá Tectonic Imbrications (another name of the Federico-Casares units). Bessière *et al*. (2021) did not consider the previously cited position of the Ronda Peridotites in the Guadaiza area, considering the contact of the peridotites with the tectonic units of this sector to correspond to a large-scale extensional detachment (joining in this detachment contacts formed in two notably different times, the Carboniferous and early Miocene).

Sanz de Galdeano (2017, 2019, 2021, 2022) considered the Guaro nappe to have no real independent existence, but rather to form part of the Jubrique unit (or Los Reales unit, when the peridotites situated at its bottom are also considered).

Lithological sequences

Despite the great number of tectonic units cited, only two types of units are considered here, the Jubrique (or Los Reales) unit and the Federico-Casares units. This drastic reduction is explained in the Discussion.

The Jubrique unit: Its lower visible metasedimentary sequences are Paleozoic dark schists and quartzites (Carboniferous and probably even older), with a thickness reaching more than 2000 m at some points. Above lie phyllites of several hundred meters thick, also containing quartzites. These latter rocks date to the Triassic and perhaps also to the Permian. At a higher position appear Triassic marble formations more than 1000 m thick (not in the area of Jubrique), which have interleaved calc schists, quartzites, and other rocks.

Furthermore, igneous rocks are abundant, particularly peridotites (the Ronda Peridotites) situated under the Jubrique unit, whose meaning is described later. Their emplacement provoked the formation of a migmatitic aureole, partially corresponding to gneisses (Tubía *et al.*, 2013), which in opinion of Ruiz-Cruz & Sanz de Galdeano (2014) occurred during the Carboniferous. But this age is debated.

Moreover, in the area of the Guadaiza River (Fig. 2 B, cross-sections 1 and 2), appear orthogneisses whose age and meaning are also discussed below. The proposed ages are early Miocene (Esteban *et al*. 2011) or Carboniferous-Permian (Acosta-Vigil *et al*., 2014; Sanz de Galdeano & Ruiz-Cruz, 2016).

The Federico-Casares units: This name, given by Didon *et al*. (1973), corresponds to units situated in the Rif (Federico) and in the Betics (Casares). They have also been named Imbrications of Benarrabá (Balanyá & García Dueñas, 1991) and Intermediate units (Sanz de Galdeano *et al*., 2001). These units have a low metamorphic grade which progressively diminishes in the higher units. They present Paleozoic and Triassic rocks.

Structure

The understanding of the structure of the Alpujarride in this sector depends on the position attributed to the Ronda Peridotites and also by the age of their emplacement. This is discussed in the next section. Here, other aspects of the structure are indicated:

A general overview of the structure of the sierras Blanca and Mijas is indicated, respectively, in the cross-sections A and B of the Fig. 3. Notably, they bear substantial reversed folds with opposed vergences, also implying the peridotites.

Clearly related to the Jubrique unit is the "subunit" of Yunquera. This corresponds to a tectonic slice situated under the Jubrique unit (Sanz de Galdeano, 2021) in the contact with the Federico-Casares units and very near the Subbetic (External Zone). This Yunquera unit has lithological sequences equivalent to the Jubrique unit.

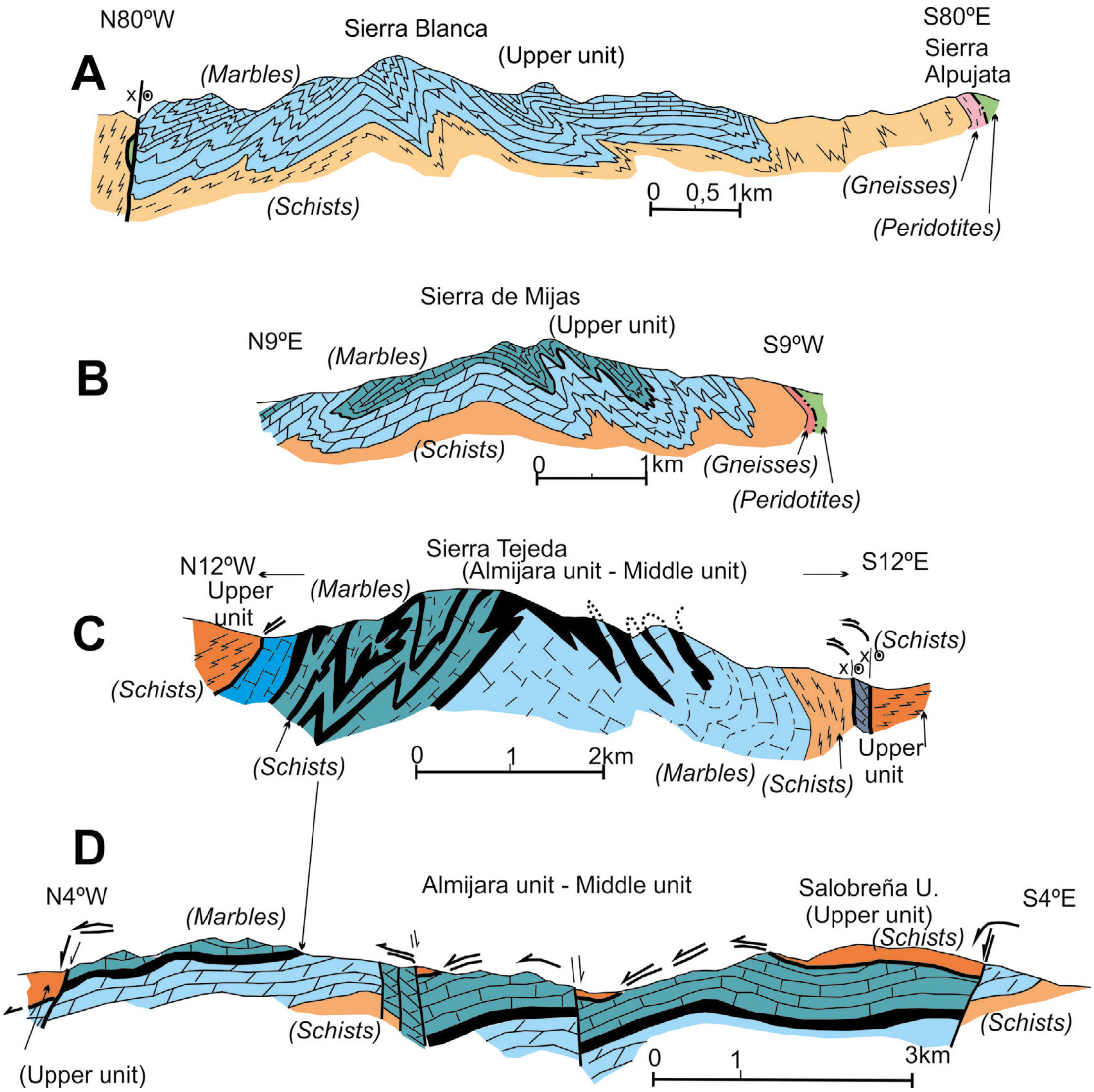

Fig. 3. Structure of: A. Sierra Blanca. Modified from Sanz de Galdeano and Andreo (1994). B. Sierra de Mijas. Modified from Sanz de Andreo & Sanz de Galdeano (1994). C: Sierra Tejeda. Modified from Sanz de Galdeano (1989). D. Sierra Almijara. Modified from Sanz de Galdeano and López-Garrido (2003). The position of these cross-sections is indicated in Figs. 2 and 4.

Over the Jubrique-Los Reales unit exist the above-mentioned Federico-Casares units. These constitute slices, variable in number, depending on the different places, with imbricate structures, which in turn underlie the Malaguide Complex.

From Málaga to Vélez-Málaga, the Alpujarride Complex does not crop out because it is covered by the Malaguide Complex (Fig. 1).

The sector from Vélez-Málaga to Motril

To the east of Vélez-Málaga, the Alpujarride Complex emerges again, and is practically the only complex that crops out there (Fig. 4). In this area the upper and middle Alpujarride units can be recognized, and these are divided into many local units.

Background

Boulin (1970) studied this region and described its lithological series. Elorza (1979) studied the area of Sierra Tejeda and also described the Benamocarra tectonic unit, whose attribution to the Alpujarride or to the Malaguide complexes is debated. Avidad & García-Dueñas (1981) differentiated the two main tectonic units existing in the area of Almuñécar and Motril. Lat-

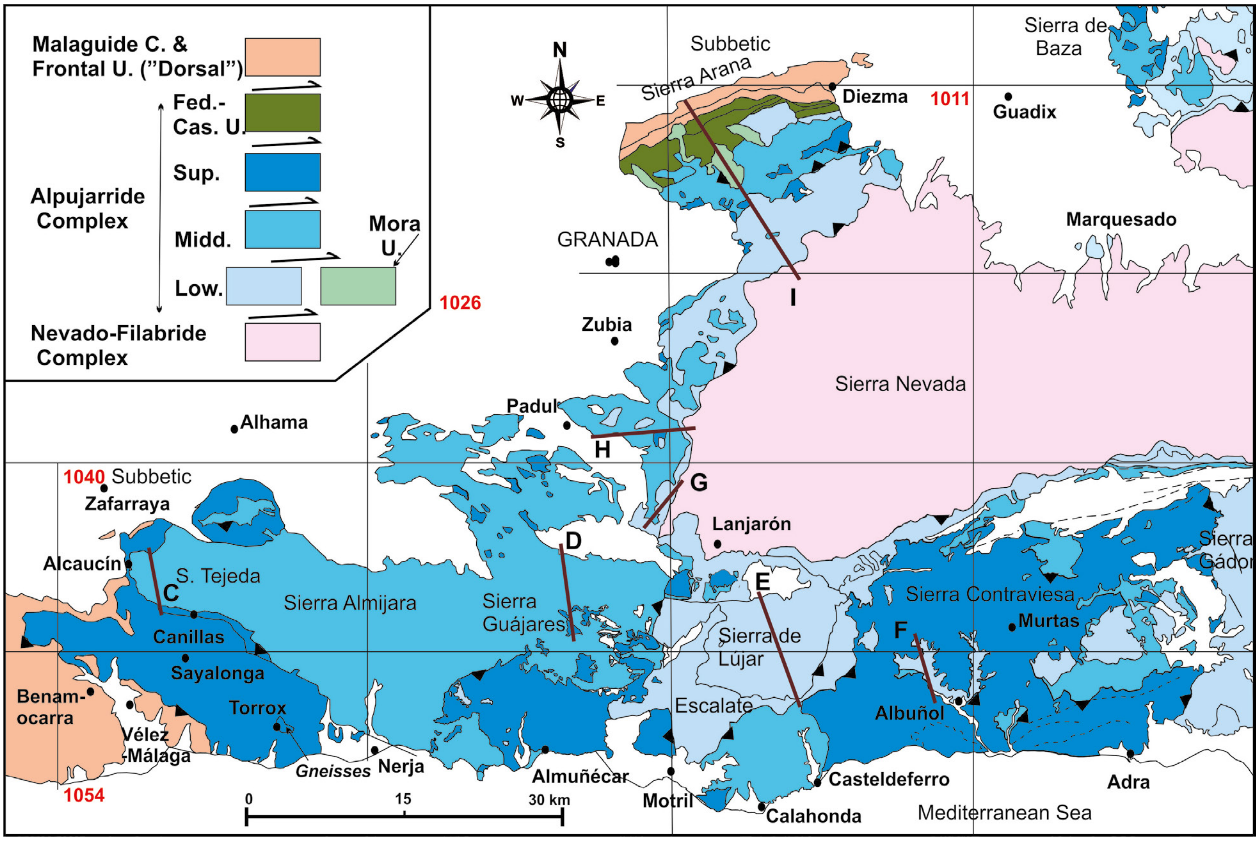

Fig. 4. Schematic map of the distribution of Alpujarride units in their central western sector. Red numbers indicate those of the geological maps at 1:50,000 scale. The position of the cross-sections C to I of the Figs. 3, 6 and 7 is indicated.

er, Alonso-Chaves & Orozco (2007) emphasized the importance of the extensional tectonic in this area.

More recent articles have been published on the area, though without consequential novelty in the differentiation of units. Also, Williams & Platt (2017) examined the Alpujarride Complex, with a special emphasis on this sector, but their tectonic interpretations are considered here to be incompatible with data directly observable in the field, as indicated above.

The lithological sequences

The higher Alpujarride tectonic unit in this sector is equivalent to the Jubrique unit and, although several names have been given, probably the main one used is Salobreña. Its lithological sequence is equivalent to that of the Jubrique unit although the peridotites are not visible, but gneisses exist, well expressed particularly in the area of Torrox, (Fig. 4), which Zeck & Whitehouse (1999) dated as Permian. Also Triassic metabasites appear, intercalated in the phyllites and in the marbles.

The middle unit is the Almijara unit (previously called the Herradura unit by Avidad & García-Dueñas, 1981). It does not present gneisses, and the dark schists are visible only locally. Light schists are abundant and the different formations of marbles are very well developed, with thicknesses at many points exceeding 1000 m.

Structure

The main structure of this sector is the thrust of the upper Salobreña unit over the middle Almijara unit (Fig. 4). Moreover, in some areas, tight folds appear with different vergences, in some cases opposite, as is the case of Sierra Tejeda (cross-section C of Fig. 3). Laterally, eastwards, the structure of folds is noticeably less tight (cross-section D of Fig. 3).

Prominent later faults have affected the original tectonic superposition of the units. This occurred for instance in the area situated from Alcaucín to Nerja (Fig. 4), where major NW-SE dextral strike-slip faults cut through the units, interpreted as a testimony of the extensional detachment of Sierra Tejeda by Alonso-Chaves & Orozco (2007).

To the west, situated over the Salobreña unit, lies the Benamocarra unit (in the area of Vélez-Málaga). This is formed by dark schists which towards the top progressively change to shales attributable to the Malaguide Complex. Elorza (1979) and other authors assigned this unit to the Alpujarride Complex owing to the presence of the aforementioned schists, considering that the Malaguide Complex lacks this type of metamorphic rock. However, given the total transition of these schists to the slates and lutites of the Malaguide Complex, it may be more accurate to consider the Benamocarra unit as belonging to this latter complex.

In the area between Nerja and Motril (Fig. 4), the Salobreña unit cuts that of the Almijara at different levels, in such a way that in some places the complete formation of marbles, and even part of the phyllites and schists of this latter unit, are tectonically laminated.

The sector situated to the south of Sierra Nevada and its prolongation to the east

In this sector, lower, middle, and upper Alpujarride tectonic units crop out (Figs. 4 and 5).

Background

For this sector, Aldaya (1969) distinguished, from bottom to top, in addition to the lower Lújar unit, the units of Cástaras, Alcázar, Murtas, and Adra. Aldaya *et al.* (1979) considered these same units and also indicated a general division of the Alpujarride Complex into three main groups of units.

Jacquin (1970) studied the Sierra de Gádor, describing its stratigraphy and structure, also including the unit of Felix.

Estévez *et al.* (1985), studying the structure of the Alpujarride units in the SW part of Sierra Nevada, disputed the existence of the Cástaras unit (considering it to be part of the Lújar unit). Orozco *et al.* (2004) described the structure of the Sierra de Lújar, interpreting it as having formed in an extensional process. Martín-Rojas (2006) studied the area of the Sierra de Gádor and its western prolongation, describing the structure and the stratigraphy.

More recently, Sanz de Galdeano & López-Garrido (2014 a, b) described, respectively, the tectonic window of Albuñol (Fig. 4) (where the Gádor unit, equivalent to that of Lújar, appears), and the structure of the Sierra de Lújar.

The lithological sequences

The upper unit of this sector has no particular changes in its lithological sequences compared with the previous sectors. It corresponds to the units of Murtas and Adra, defined by Aldaya (1969), but taken together because their lithological sequences are complementary. Perhaps the most appropriate name for this unit, which encompasses the two previous units, is Adra. In this new Adra unit, dark schists to marble formations appear, but no basal gneisses.

For the middle unit, the name of Calahonda can be used, this name referring to a village situated to the east of Motril, because only this unit appears in this locality (Fig. 4). Moreover, this unit crops out in several tectonic windows, although these can be considered as forming part of a single unit. Its lithological sequences are equivalent to that of the Almijara unit.

The lower Lújar unit (or Lújar-Gádor unit) has light schists at the bottom and phyllites above, and several thick formations of marbles measuring more than 1000 meters. The marbles show only a low grade of metamorphism, being practically limestones and dolomites at many points, with observable fossils.

The structure

The limit between this sector and the western one (practically coinciding with the meridian of Motril) is of interest because it is the western border where the lower Alpujarride units crop out. At this limit, the thickness of the units concerned is not conserved. Particularly the middle Almijara unit has undergone extreme thinning, to the point that has been completely laminated in some places.

A possible explanation for this thinning can be found in the structure of the sierras of Lújar and

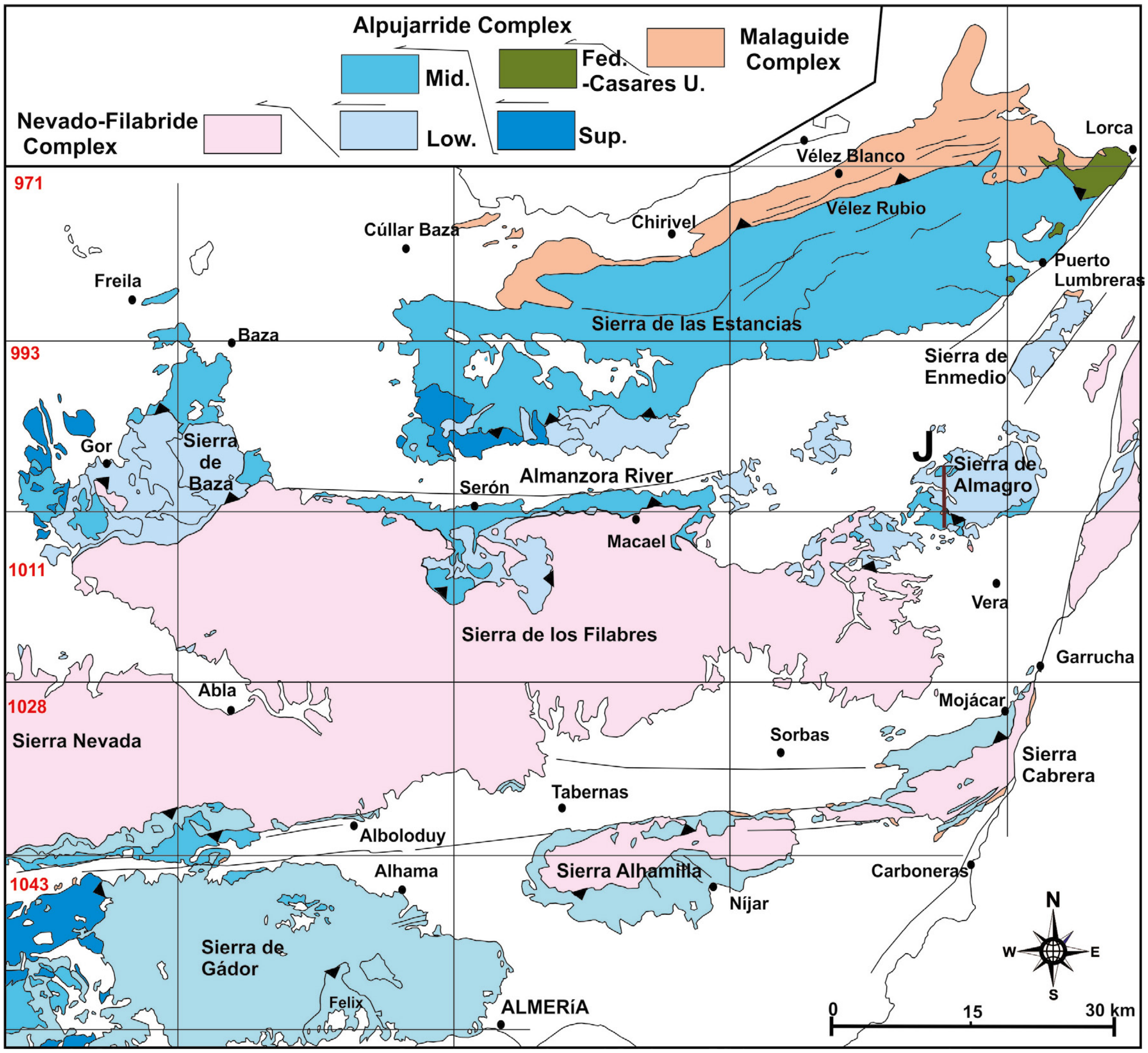

Fig. 5. Schematic map of the distribution of Alpujarride units in their central eastern part. Red numbers indicate those of the geological maps at 1:50,000 scale. The position of the cross-section J of Fig. 7 is indicated.

Escalate. In Lújar an enormous northward reversed syncline appears (cross-section E, Fig. 6), and, as indicated Boulin (1966), the Escalate area, situated to the south, corresponds to the normal flank of the southern anticline. This structure was probably formed prior to and during the stage when the units were thrusting. The volume of this structure existing in the Sierra de Lújar, combined with the push of the upper Alpujarride unit caused the middle Almijara unit to thin and even become totally sheared in some places.

The same strong shearing occurs to the east, on the western border of the Sierra de Gádor (Figs. 4 and 5). This sierra also constitutes a large volume and the same phenomenon occurred in that area. This lamination is visible also in the tectonic window of Albuñol, where the Lújar-Gádor lower unit is directly covered by the Adra upper tectonic unit (cross-section F, Fig. 6), while, in between, the middle unit appears only in thin remnants.

The structure of the Sierra de Gádor is not complex, corresponding approximately to an anticline, although its southern border is thrust by the Felix unit (Fig. 5), probably a local duplication of the Lújar-Gádor unit, although Martín-Rojas (2006) proposed that it corresponds to an upper unit. Furthermore, to the SE of Alhama de Almería several slices verge northwards.

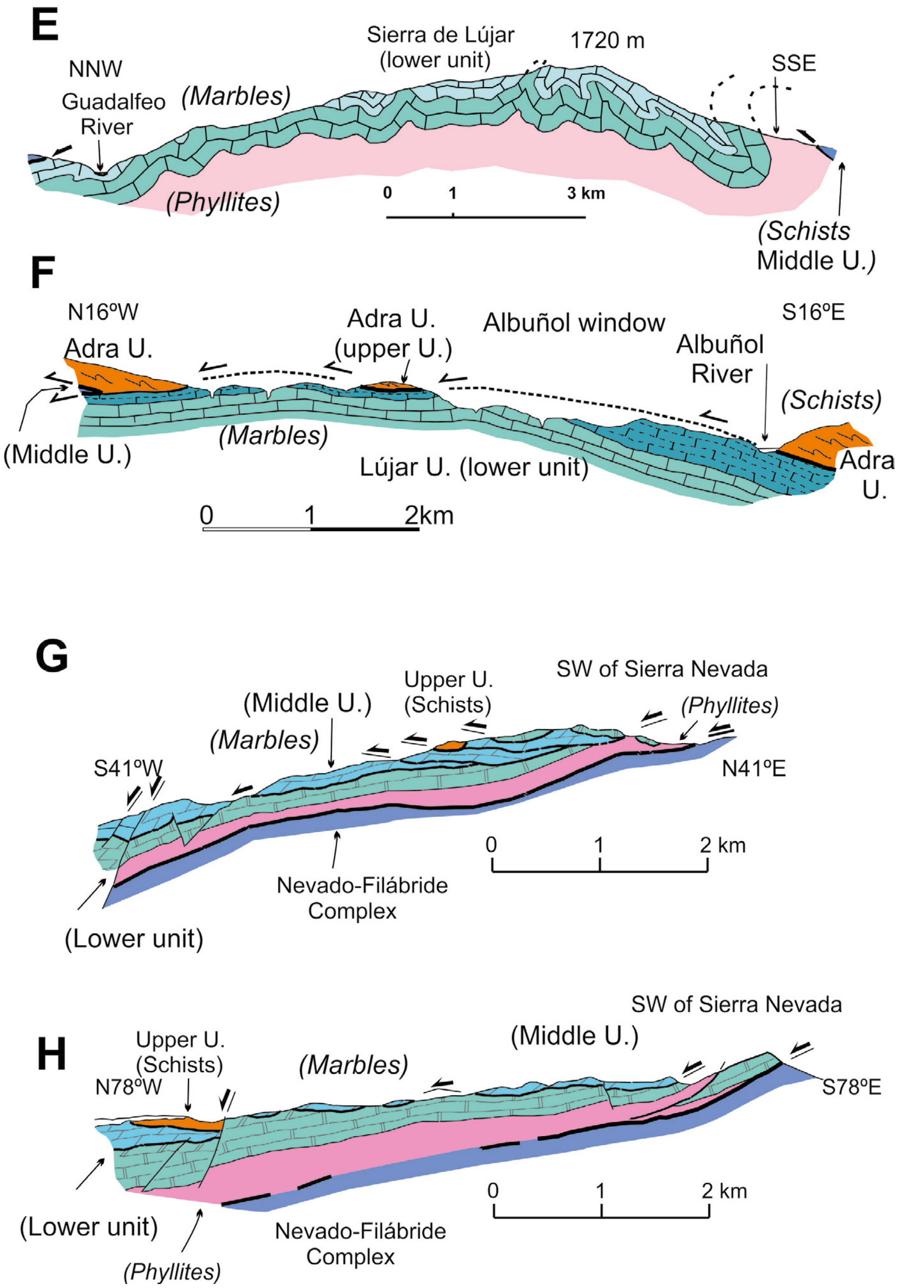

Fig. 6. Structure of: E. Sierra de Lújar. Modified from Sanz de Galdeano and López-Garrido (2014b). F. Tectonic window of Albuñol. Modified from Sanz de Galdeano and López-Garrido (2014a). G and H. SW of Sierra Nevada. Modified from Sanz de Galdeano and López-Garrido (1999). The position of these cross-sections is indicated in Fig. 4.

To the east of Sierra de Gádor lie the sierras Alhamilla and Cabrera, the latter reaching the coast in the area of Mojácar (Fig. 5). In both mountains, the Nevado-Filabride Complex crops out within their core, surrounded by Alpujarride lower units.

The sector of the western border of Sierra Nevada

This sector (Fig. 4) is the northern prolongation of the Vélez Málaga–Motril sector, in which the contact with the Nevado-Filabride Complex is well exposed. It is composed not only of the lower, middle, and upper units, each having different local names, but also of the Malaguide Complex, which crops out here, and furthermore of the Federico-Casares units which are visible in the western sector, previously described. In addition, a particular type of unit appears in several tectonic windows. The most important of these windows is called Mora, and this is the name used here.

Background

Gallegos (1975) studied the Alpujarride Complex in the SW of Sierra Nevada, and Foucault (1976) examined the area of Sierra Arana (NE de Granada). Ewert & Navarro Vila (1979) correlated the lower unit of this zone with the Lújar unit.

The lithological sequences

In this sector the lithological sequences of the three types of Alpujarride units (lower, middle and upper) correspond to those indicated above. In the upper unit, the basal gneisses are not represented, but the rest of the sequences are similar to those of the Jubrique or Salobreña unit. The middle and lower units have a great abundance of marbles. In the lower unit (the Padules unit of Sanz de Galdeano *et al*., 1995), the phyllites are well represented. A comparison of this lower unit with the Lújar unit shows great similarity (Ewert & Navarro-Vilá, 1979), perhaps with a lower metamorphic field aspect.

The Federico-Casares units are well exposed. The transition of their lithological characteristics from the Alpujarride to the Malaguide complexes is clear, progressively changing in metamorphic grade, lower in the unit situated in the higher position, in contact with the Malaguide Complex.

The Mora unit presents upper (perhaps also middle) Triassic rocks and Jurassic to Cenozoic sediments, but the lower levels are not visible. The Triassic rocks are composed of marbles with very low metamorphism, practically identical to those of the lower Alpujarride Padules unit. Probably, under a middle Alpujarride unit, both units, i.e. the Padules unit and that of the Mora, are stratigraphically continuous—that is, they are likely the same single unit.

The structure

The thrusting of the lower Alpujarride unit over the Nevado-Filabride Complex is clearly visible and the same is true of the corresponding thrusts of the middle and upper units, making their tectonic superposition clear. In the southwestern border of Sierra Nevada, this superposition is noticeably affected by slides caused by the Neogene uplift of Sierra Nevada (cross-sections G and H, Fig. 6).

On the northwestern edge of this sector the structure is more complex. There, in contact with the External Zone (the Subbetic), appear the Frontal units, which at the same time are situated above the Malaguide Complex (Sanz de Galdeano & López-Garrido, 2016), and this latter overlies the Federico-Casares units. In turn, these latter units thrust over the tectonic stack of the upper, middle, and lower Alpujarride units above mentioned. The cross-section I of Fig. 7 shows this structure, including also the position of the Mora unit.

While the tectonic superposition of the lower, middle, and upper Alpujarride units has a N or NW wards vergence, the Federico-Casares units have the opposite vergence, towards the S or SE. This different vergence may correspond to a later superposition, formed during the westward drift of the Internal Zone, in the early Miocene.

On the other hand, if the interpretation that the Mora unit is the same lower Alpujarride unit of this sector is correct, then this would be evidence that some Alpujarride units bear lithological sequences spanning Jurassic and Cenozoic formations.

The sector of the northern of Sierra de los Filabres (Baza and Almanzora areas)

In this sector the general distribution of the Alpujarride units does not significantly change. It is divided in several areas:

Sierra de Baza area (Fig. 5)

Delgado (1978) studied this area and distinguished five tectonic Alpujarride units, which from bottom to top are: Tetica, Santa Bárbara, Quintana, Blanquizares, and Hernán Valle. The first three, Tetica, Santa Bárbara, and Quintana, can be assigned to the lower

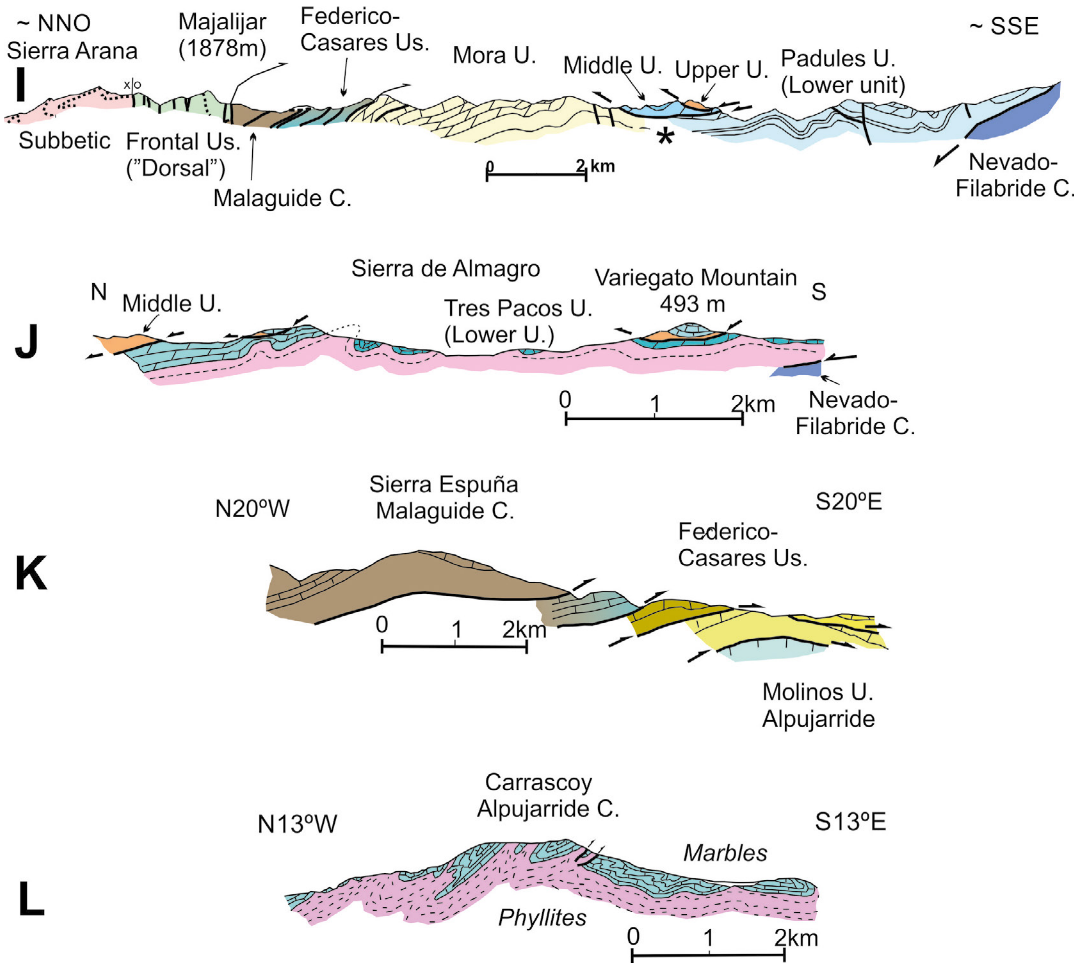

Fig. 7. Structure of: I. Mora area. Modified from Sanz de Galdeano (2022). J. Sierra de Almagro. Modified from García-Tortosa et al. (2002). K. Sierra Espuña. Modified from Sanz de Galdeano et al. (2000). L. Sierra de Carrascoy. Modified from Sanz de Galdeano et al. (1997). The position of these cross-sections is indicated in Figs. 4, 5 and 8.

*: possible transition from the Mora unit to the Padules unit.

Alpujarride units, while Blanquizares would correspond to the middle Alpujarride units, and Hernán Valle would form an upper Alpujarride unit.

The Santa Bárbara unit is striking for the great thickness of the phyllites and marble formations, showing some interbedded doleritic masses. Similar, but with lesser thickness conserved, are the Tetica and Quintana units. The Blanquizares unit has similar sequences, but apparently with a slightly higher grade of metamorphism. The Hernán Valle unit presents dark schists and quartzites, phyllites, and marbles.

These units form a well-defined thrust stack: the lower unit is situated over the Nevado-Filabride Complex in well-exposed contact, including a tectonic window located to the SE of the locality of Gor. Notably, great folds are visible in the marbles, particularly in the Santa Bárbara unit.

Almanzora area

Here, several parts can be considered, all located near the Almanzora River (Fig. 5). These parts lie directly to the north of Sierra de los Filabres, and also in the Sierra de las Estancias, and in the Sierra de Almagro. Further to the NE lies the Sierra de Enmedio.

North of Sierra de los Filabres: This sierra, situated to the east of the Sierra de Baza and south of the Almanzora River (Fig. 5), presents the same general thrust structure. Many local names have been assigned to their Alpujarride tectonic units.

Simon (1963), Vissers (1981), De Jong & Bakker (1991), Molina Cámara & Orozco (1983), among others, have worked on this sierra. Some names of these units include Almanzora, Ballabona-Cucharón, Variegato, Tetica, and Colorao.

Nonetheless, on the whole, only two different units can be distinguished, although locally some of these units are duplicated. The lower one, the Almanzora unit, has lithological sequences similar to other lower Alpujarride units, with phyllites and marbles, practically limestones, and interbedded metabasic rocks. Above lies the Variegato unit, formed by schists (comparable in aspect to Malaguide Carboniferous formations), phyllites, and marble (or limestone) formations, also including metabasic rocks.

According to its lithological sequences and tectonic position, the Almanzora unit is a lower Alpujarride tectonic unit, while the Variegato unit can be considered an upper tectonic unit, but also with some characteristics assimilable to the Federico-Casares units. This means that the middle and upper Alpujarride tectonic units are not represented with the characteristics discernible in more western sectors. That is, the Alpujarride Complex decreases in the metamorphic grade towards the east or northeast, a trend indicated by De Jong & Bakker (1991).

Sierra de las Estancias: To the north of the Almanzora river is the Sierra de las Estancias (Fig. 5). As in Sierra de los Filabres, several tectonic units are distinguishable. Vries & Zwaan (1967) and Soediono (1971) studied the lithological sequences of these units. Akkerman *et al.* (1980) separated, from bottom to top, the units Partaloa, Oria, and Montroy, the latter being equivalent to the Hernán Valle unit, cited above in relation to Sierra de Baza.

The Partaloa unit presents a Paleozoic sequence somewhat comparable to the Malaguide Carboniferous formations, and above lie phyllites and quartzites with gypsum followed by carbonatic formations, limestones, and dolomites. By virtue of its position, this unit can be attributed to the lower Alpujarride units. The Oria (or Blanquizares-Oria) unit presents dark schists and quartzites, phyllites, limestones, and dolomites, locally marbled. Metabasites are present in all the sequences. This unit can be considered to be a middle Alpujarride unit, although with a lower metamorphic grade. The Montroy unit has similar sequences and, according to its position, can be considered an upper Alpujarride unit, although its grade of metamorphism is clearly lower than that of the Jubrique/Salobreña unit. Finally, in the higher position, and under the Malaguide Complex, lie two Federico-Casares units, there called Peña Rubia and Tropeles (situated near Lorca) ensuring the paleogeographic passage to this last complex.

Sierra de Almagro: This sierra, situated to the SE of the Sierra de las Estancias (Fig. 5), was studied by Simon (1963, 1964), who distinguished, from bottom to top, the units of Almagro, Ballabona, Cucharón, and Variegato, with the Malaguide Complex above. Later, Egeler and Simon (1969) considered the three lower cited units as forming part of a new complex, the Ballabona-Cucharón Complex, but Bakker *et al*. (1989) changed this name to the Almagride Complex, restricting it to the Almagro unit.

Barragán (1993) distinguished the Almagro unit, above the Ballabona-Cucharón unit and at the top of the Variegato unit. García-Tortosa *et al*. (2002) considered these two first units to be really the same but corresponding to different parts of the same lithological sequences. These authors called it the Tres Pacos unit, with the Variegato unit above it, and discarded the idea of a new complex, Ballabona-Cucharón or Almagride.

The Tres Pacos unit is formed by schists, quartzites, and phyllites, together with a thick carbonatic sequence of limestones and dolomites having interbedded gypsum and pelites, also with basic rocks. For its position, directly above the Nevado-Filabride Complex, this is regarded as a lower Alpujarride unit. The Variegato unit is similar to that of the northern part of the Sierra de los Filabres. Above it lie several klippes of the Malaguide Complex.

The metamorphic grade of these units is lower than in geometrically equivalent units situated more to the west. The thrusts are the more important structures, although noticeable E-W folds can also be found (cross-section J, Fig. 7).

Sierra de Enmedio: In this small, elongated mountain (Fig. 5) appears an Alpujarride unit with its northern part covered by a Malaguide unit. Here, Fernex (1962) distinguished three units, that of the Malaguide Complex, one of the Alpujarride, and a third, corresponding to the Nevado-Filabride Complex. Egeler and Simon (1969) considered only one unit under that of the Malaguide and attributed it to their Ballabona-Cucharón Complex.

The Alpujarride unit is formed by phyllites and quartzites locally with metaconglomerates and gypsum. Above, appear limestones as well as metabasites. Its metamorphic grade is very low, much lower than in equivalent western units, surely reaching a lower temperature during its development. This may explain why Egeler and Simon (1969) differentiated the Ballabona-Cucharón or Almagride Complex in this area.

In addition, there is a local slice, which is presumably the reason why Fernex (1962) individualized another unit.

The NE sector (Águilas-Mazarrón-Cartagena- Orihuela areas)

In this sector (Fig. 8), several areas can be considered: that of the arc of Águilas and Mazarrón, extending to the east in Cartagena-Cabo de Palos; and the areas of Sierra Espuña, Carrascoy, and Orihuela, situated more to the N and NE.

Arc of Águilas-Mazarrón

This area is complex and the attribution of several units to the Alpujarride or to the Nevado-Filabride complexes changes depending on the author. For instance, the mountain called Lomo de Bas, situated 12 km to the SW of Mazarrón (Fig. 8) and reaching the sea, has been attributed to one or another complex. Pavillon (1972) and Espinosa Godoy *et al*. (1974) posited that this mountain formed part of the Alpujarride Complex, while Álvarez & Aldaya (1985) and Álvarez (1987) ascribed it to the Nevado-Filabride Complex. Another unit, that of Cantal, was attributed by Álvarez & Aldaya (1985) to the Alpujarride Complex, while García-Tortosa *et al*. (2002) considered it to belong to the Nevado-Filabride Complex. In the present work, this latter interpretation is accepted. In this area, only two Alpujarride units are considered, although strongly affected by later faults.

The lower unit has Paleozoic schists, practically shales, that recall the equivalent Malaguide formations. Above, in both units, phyllites and quartzites as well as limestones and dolomites appear. Especially in the higher unit, conglomeratic layers are interbedded, in which pebbles and cobbles are hardly deformed.

Besides the thrusting of the units, the most outstanding feature is the tectonic arc of Águilas-Mazarrón, formed by the displacement of more than 60 km, caused by the sinistral strike-slip fault of Garrucha or Palomares. Thus, in the eastern block of this near N-S fault, the Internal Zone was pushed northwards, giving rise to the aforementioned arched shape while, at the same time, many other faults were formed in its interior. All this caused many deformations in the previous thrusting structures, provoking many difficulties in the correlating of the units.

Area of Mazarrón – Cartagena-Cabo de Palos

This area is the eastern prolongation of the previous one, although its structure is simpler. Here, Espinosa Godoy *et al*. (1974) and Gordillo Martín *et al*. (1974) described two Alpujarride units and another one belonging to the Ballabona-Cucharón Complex, situated in a lower position, which they called the Intermediate unit. García-Tortosa *et al*. (2000) distinguished two Alpujarride units, although at some points local slices could be considered to be other units. Also, locally, certain units have intermediate characteristics with the Malaguide Complex (Federico-Casares type units), for instance to the east of Cartagena.

These units present phyllites and quartzites, in some cases practically shales of various colors and carbonates, limestones, and dolomites. The units of very low grade of metamorphism, previously attributed to the Ballabona-Cucharón or Almagride Complex, here are included in the Alpujarride Complex.

The main structural element is the tectonic superposition of the units. Also, major folds appear, in some cases very tight, with predominant northwards vergence.

Sierra Espuña and Sierra Tercia: In Sierra Espuña, Paquet (1969) described four Alpujarride units, and similar divisions of units were proposed by Kampschuur *et al*. (1974) as well as Egeler (1974). Martín Rojas *et al*. (2007) also distinguished four units situated under the Malaguide Complex, where three of them can be considered Federico-Casares type units,

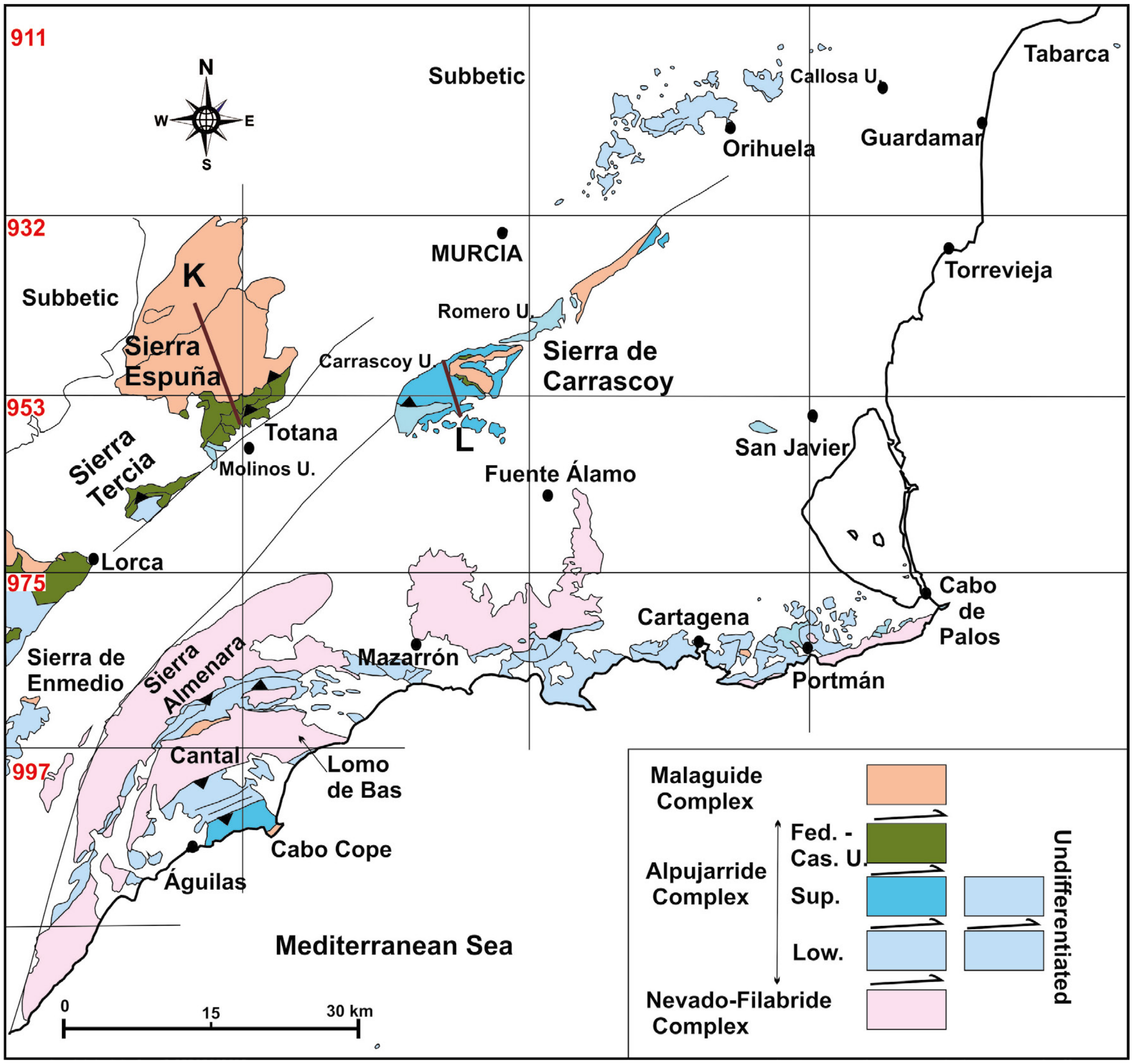

Fig. 8. Schematic map of the distribution of Alpujarride units in their eastern part. Red numbers indicate those of the geological maps at 1:50,000 scale.

whereas the lower one (Molinos unit) has a lesser degree of metamorphism, although greater than that of the above-mentioned Federico-Casares units. The Molino unit is formed by phyllites and quartzites, locally with gypsum, as well as marbles. The Federico-Casares units progressively change from a scant metamorphic grade to becoming more metamorphic in the lower unit.

The main feature of this area is the tectonic superposition of the units (cross-section K, Fig. 7), later affected by approximately E-W folding.

In the small mountain of Sierra Tercia, situated in the SW prolongation of Sierra Espuña (Fig. 8) appears an Alpujarride unit similar to the Molinos unit, but also showing dark schists and quartzites, attributable to the Paleozoic. Above, lie two Federico-Casares units.

Sierra de Carrascoy

This mountain is situated near the city of Murcia. Kampschuur (1972) contended that, in this sierra, under a unit of the Malaguide Complex, lay one Federico-Casares type unit, the Pestillos unit, an Almagride unit, the Carrascoy unit, and at the bottom an Alpujarride unit. Sanz de Galdeano *et al.* (1997) maintained this differentiation, although attributing the Carrascoy unit to the Alpujarride Complex.

In the Carrascoy unit, dark lutites appear, perhaps belonging to the Paleozoic. Above these are phyllites and quartzites, with the top being limestones, some displaying Muschelkalk facies. The unit also contains gypsum and dolerites.

Apart from the thrusting of the units, major E-W folds appear (cross-section L, Fig. 7). In addition, there are N-S folds, probably formed by the effect of the large sinistral strike fault (Fig. 8) which cut through the W and NW border of the sierra.

The area of Orihuela, including the isle of Tabarca

The outcrops making up this area encompass the small island of Tabarca and some outcrops being situated in Callosa and Orihuela (Fig. 8). All these units were attributed by De Jong (1991) to the Almagride Complex. Martín-Rojas *et al*. (2007) also described them.

A common characteristic of all the units of this area is their low metamorphic grade, for which they were placed in the Ballabona-Cucharón or Almagride Complex. Their general sequence is formed by phyllites, practically shales, with different colors from bluish-gray to red and violet, locally containing gypsum and quartzites. Above, lie limestones, dolomites, and marls, in some cases with Muschelkalk facies. The total thickness of these sequences reaches several hundred meters.

The outcrops in this area are separated by Quaternary sediments and therefore at every site several tectonic units have been differentiated, each with its own name. However, probably only three different tectonic thrusting units exist.

Discussion of the main features of the Alpujarride Complex

From the exposure of the different units forming the Alpujarride Complex, several aspects need to be discussed.

The paleogeographic relations between the Alpujarride and Malaguide domains

The Federico-Casares units, Imbrications of Benarrabá or Intermediate units, which are variable in number in each sector, are situated as tectonic slices between the two complexes. These have a higher metamorphic grade than does the Malaguide Complex but lower than in the subjacent Alpujarride Complex. This feature is visible both in the Paleozoic and Triassic formations.

This progressive transition of the metamorphic grade, the stratigraphic sequences as the intermediate tectonic position of these units support the contention that they form the original paleogeographic passage from one to another complex. In this way, the former relations established between the ancient Mesozoic basin making up the present Malaguide Complex and that of the present Alpujarride Complex are confirmed (Sanz de Galdeano *et al*., 2001; Martín-Martín *et al*., 2006). Furthermore, the Benamocarra unit may indicate the original transition between the lowest Paleozoic levels of the two complexes.

The tectonic position of the Ronda Peridotites

The position of the peridotites in the Alpujarride Complex deserves attention because it defines diverse tectonic units. That is, the fact of whether these peridotites do or do not thrust over certain Alpujarride formations determines whether several tectonic units exist (as some authors have proposed and as indicated in the previous section) or do not exist.

The discussion of their position centers on the area of Guadaiza River and on Sierra Blanca.

In the Guadaiza River, a detailed analysis of the geometry of the contact of the peridotites with the Alpujarride (Sanz de Galdeano, 2017) formations indicates that the Ronda Peridotites are really underneath what was previously called the Guadaiza unit or Guaro unit (Fig. 2 B, cross-sections 1 and 2), although these units were originally defined as thrust by the peridotites. That is, these proposed units have the same position as that of the Jubrique unit, over the peridotites (A of Fig. 9); in fact, they form part of the Jubrique unit, and their differentiation as separate and independent units cannot be justified.

However, the discussion of the structure of this area does not end with the above affirmation because, in this sector of the Guadaiza River, it is necessary to consider the presence of a great outcrop of orthogneisses. These are interpreted by Esteban et al.

(2011) and Tubía et al. (2013), among others, as dynamothermal rocks produced by the thrusting of hot peridotites over the Alpujarride sequences (their proposed Guadaiza unit). This thrust, in their interpretation, happened during the early Miocene. However, this formation of orthogneisses does not underlie the peridotites, but rather, on the contrary, overlies them as well as also part of the Paleozoic Alpujarride sequences. Consequently, these gneisses cannot be a sheet formed by the thrust of the peridotites (see the aforementioned cross-sections 1 and 2 in Fig. 2 B). This outcrop corresponds to a former igneous acidic formation from the Carboniferous-Permian, as indicated by Acosta-Vigil *et al*. (2014) as well as Sanz de Galdeano & Ruiz-Cruz (2016); it is completely independent and situated over the peridotites (B and C of Fig. 9).

Nevertheless, on the NE border of Sierra Blanca and on the south of Sierra de Mijas (Fig. 2), the Ronda Peridotites are clearly situated over the Alpujarride sequences, schists and marbles. However, in the Sierra Blanca, moving laterally to the west, this thrust is progressively absorbed and finally in the SE part of the Sierra Blanca, SW of Sierra Alpujata, the original contact between the peridotites and the Alpujarride sequences is preserved, with the peridotites occupying a lower position and having gneisses-migmatitic aureole in between (D of Fig. 9) (Sanz de Galdeano & López-Garrido, 2016 b). That is, at that location in the SW of Sierra Alpujata, the contact between the peridotites and the Alpujarride sequences of Sierra Blanca does not constitute a thrust (Fig. 2 B, cross-sections 3 -5).

In addition, the peridotites of Sierra Alpujata did not thrust alone to the northern part of Sierra Blanca, but rather constitute the bottom of the Alpujarride formations of Sierra Alpujata, from which they are separated by a migmatitic aureole. That is to say, the cited thrust is an alpine thrust of an Alpujarride unit, which previously had peridotites at its

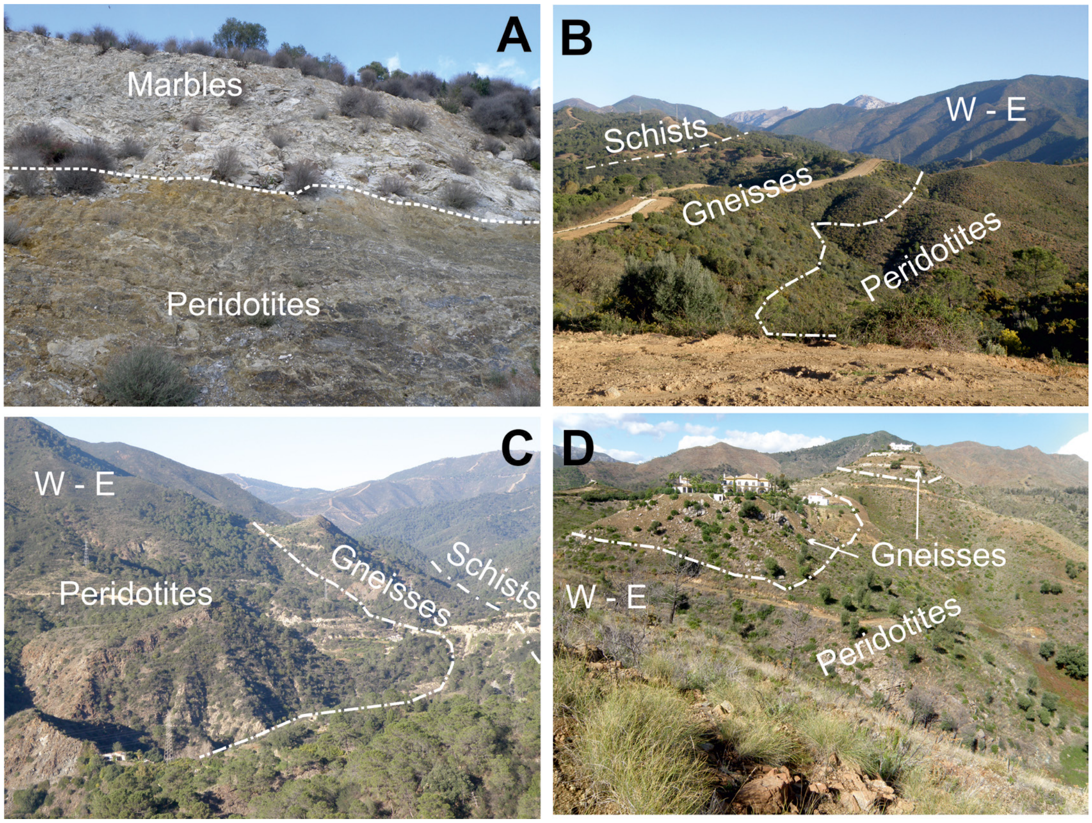

Fig. 9. A: Marbles situated over peridotites in the area of La Zagaleta (E of Benahavís and W of the river Guadaiza). Nearby, basal conglomerates can be discerned over the peridotites and under the marbles. B: Gneisses clearly situated over the peridotites in the Guadaiza area. C: View to the N of Istán, in which the gneisses, dipping to E, overlie the peridotites. D: Gneisses –migmatites over the peridotites in the SW part of Sierra Alpujata, SE part of Sierra Blanca.

base. The Sierra de Mijas shows no thrust (although the peridotites overlie the formations of this sierra) and corresponds only to a northward reversed structure, as can be noted even in the marbles of this Alpujarride outcrop. This signifies that, for this area of Sierra Blanca and Mijas, the superposition of the peridotites corresponds to later alpine structures, and the former relations between the Alpujarride sequences and the peridotites is visible to the SW of Sierra Blanca, with the peridotites appearing at a lower position.

In addition, in the NW part of Figure 2 A, in the Sierra de las Nieves, the peridotites clearly thrust the Nieves unit. This unit belongs to the Frontal units (although its attribution is debated). Nevertheless, it is necessary to consider that this thrust, as in the sierras Blanca and Mijas, corresponds not only to the peridotites, but also to the full unit of Jubrique-Los Reales, meaning that this unit thrusts over the Sierra de las Nieves, with the peridotites at its bottom. This structure is clearly somewhat younger, of Alpine age, formed much later than the emplacement of the peridotites under the Jubrique-Reales unit.

The conclusion for the tectonic position of the Ronda Peridotites is that they constitute the tectonic sole of the Alpujarride Jubrique-Los Reales unit and only in some places are they affected by later Alpine thrusts and folds. In all these cases, they move together with the rest of the Jubrique-Los Reales unit. Consequently, the previously proposed units in this area, together with the Ronda Peridotites, really form a great unit, i.e. that of Jubrique or Jubrique-Los Reales.

Despite the data presented, the above interpretation might not be accepted, as it contradicts previous authors. The surest way to settle the debate would be to remap both sectors in detail, as has been done in this paper.

The geometry and number of the tectonic Alpujarride units in the different sectors

The shape of the Alpujarride units is highly variable. Some of its units form decakilometric volumes composed mainly of carbonatic sequences. They form the following sierras: Blanca and Mijas, in the western part; Tejeda-Almijara-Guájares, Lújar, and Gádor, aligned parallel to the E-W Mediterranean coast; and Baza, to the NW of the Filabres (their respective positions are indicated in Figs. 2, 4, and 5). These volumes constitute major convex reliefs that have affected the geometry of the superposed units.

This is true of the sierras of Lújar and Gádor, the two comprising part of the lower Alpujarride units. The volume of both sierras caused the middle units thrusting them to be totally sheared in some places—the lower units constituted a physical barrier while the upper units contributed to the shearing of the middle units.

In addition to these cases, the Alpujarride units are usually sheared both at their bottom as well as at their top. The schistose and phyllitic formations are commonly sheared and the same happens with the marbles, these being cut in many places at different levels, as in the sierras Tejeda-Almijara and Guájares.

Also, the number of the Alpujarride units in each sector is not constant, as indicated above. In the western part, only the upper unit is visible, the Jubrique unit (apart from the Yunquera slice and the Federico-Casares units, these latter with a variable number in each subsector).

From Vélez-Málaga to Almería, to the west of Sierra Nevada and in the Sierra de Baza, the general distribution of the Alpujarride units involves the superposition of three superposed groups of units. And each group can be locally divided into several units, whose independent existence proves debatable in some cases.

The proposal of the differentiation of the Ballabona-Cucharón Complex

To the east of Sierra de Gádor and to the east of Sierra de Baza, the division into three groups of units (lower, middle and upper) begins to be questionable, because the characteristics of the units (according to their geometric tectonic position) differ from the equivalent units lying more to the west. Towards the east they show a progressively lower metamorphic grade, in some cases becoming very low, at least with regard to the temperature that they underwent. This feature is presumably the basis for the proposed differentiation of the Ballabona-Cucharón or Almagride Complex.

However, the units of this Almagride Complex occupy the same position as those of the Alpujarride Complex, being situated between the Nevado-Filabride Complex below, with another Alpujarride unit or directly the Malaguide Complex on top. The only difference is the metamorphic grade. Certainly, this proposed complex presents basic rocks and some Muschelkalk facies, as in the Subbetic, but these rocks and facies are also present more to the west in other equivalent Alpujarride units. According to these characteristics, it seems unnecessary to consider this new complex.

The differentiation of the Alpujarride and Nevado-Filabride complexes

Generally, the tectonic superposition of the Alpujarride Complex over the Nevado-Filabride is clear, based on the different lithologies and grades of metamorphism. Nevertheless, Gómez-Pugnaire *et al.* (2012) compared the Nevado-Filabride and Alpujarride lithological sequences examining the hypothetical possibility that they were mutually a mere continuation. In this case, the contact could be a simple stratigraphic surface, but this interpretation poses insurmountable problems. For instance, the lower Alpujarride Lújar unit is situated directly over the Nevado-Filabride and its phyllites are situated over marbles or schists of the Nevado-Filabride, but in the southern part of this unit, under the Triassic phyllites, schists attributable to the Carboniferous-Permian clearly differ from the coetaneous schists of the Nevado-Filabride Complex. Thus, in this sector each complex has clearly different coetaneous rocks. This is reason enough to rule out the aforementioned possibility.

The meaning of the Mora unit and its paleogeographical significance

The Mora unit presents Mesozoic and Cenozoic sedimentary formations, and, as indicated, are probably assimilable to the lower Alpujarride units. Also, their sedimentary formations can be compared with those in the Frontal units, and even with other equivalent formations in the Subbetic. This aspect has been discussed in Sanz de Galdeano (2019, 2022), who concluded that the Frontal units also formed a sedimentary cover of some Alpujarride units. If this is correct, the Mora unit, moreover to be assimilable to the lower Alpujarride units, at the same time corresponds to part of the Frontal units (Fig. 10). This implies that the Frontal units were originally situated at the W end of the Alpujarride and Malaguide complexes and, at the same time, ensured the passage to the Subbetic at the end of the Triassic, beginning of the Jurassic.

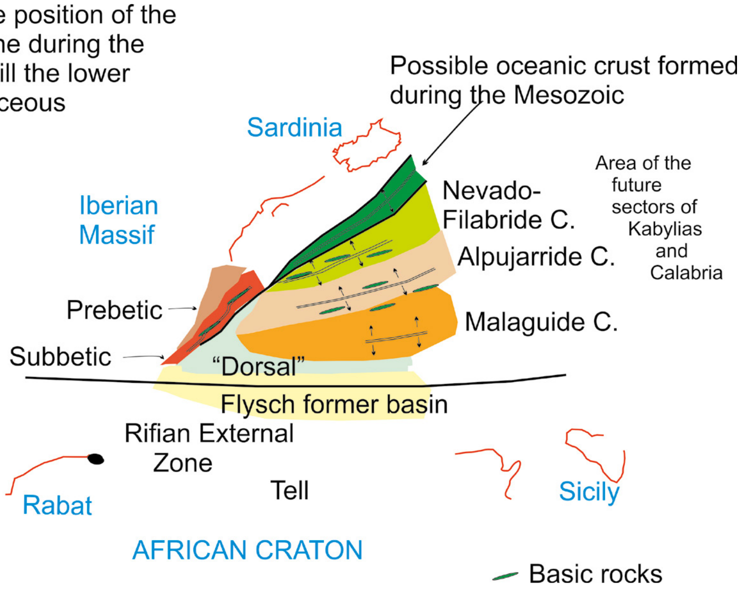

Fig. 10: Attempt at paleogeographical reconstruction of the distribution of the former basin of the Betic-Rif Internal Zone in the surrounding region, Iberia and NW of Africa. Modified from Sanz de Galdeano (2022).

The tectonic evolution of the Alpujarride Complex

Figure 10 is a hypothetical reconstruction of the paleogeography of the western Mediterranean during part of the Mesozoic to the Early Cretaceous, in a context of progressive extension. This situation changed when the Bay of Biscay began to open, with Iberia then rotating counterclockwise and pushing to the SE. From that moment the Betic-Rif Internal Zone began to be deformed and structured, which took place fundamentally during Alpine orogeny (Martin-Algarra *et al*., 2004) and its present shape was acquired in several stages.

It is generally accepted that the tectonic superposition of the complexes forming the Betic-Rif Internal Zone was practically complete at the end of the Oligocene-early Miocene, when the Algero-Provençal basin began to open in the western Mediterranean Sea (Boillot *et al*. 1984). From this time, this opening provoked the westward push and drift of this Internal Zone, which obliquely collided and deformed the External Zone of the Betics and, immediately afterward, that of the Rif.

In this westward drift (Guerrera *et al*., 2021, among other authors) the Internal Zone underwent new deformations: major E-W dextral strike-slip faults formed segmenting the Internal Zone (Figs. 11 and 12). Moreover, in the area of contact with the Betic External Zone, new tectonic units were formed, having eastward vergences, as opposed to the previous vergences, which had northwesterly vergences.

The general structure of the Alpujarride Complex reached at the end of the Oligocene-early Miocene, just after the superposition of the tectonic units, is presented in a simplified sketch in Fig. 11 A. In this reconstruction, the superposition of the groups of units is oblique and not complete. That is, the middle units do not completely cover the lower units, and the upper units do not entirely cover the middle units. The result is that the lower units do not continue indefinitely under the middle ones and, similarly, these last under the upper ones. This means, for instance, that under the upper unit in the western end of the Alpujarride Complex, the lower units are not present, and the middle ones are only partially present (cross-sections of Fig.11 A). Subsequent movements during the drift process partially rotated the Alpujarride complex while newly formed E-W faults cut through it (Fig. 11 B).

Later, from the middle Miocene, the evolution of the Alpujarride Complex should be considered together with that of the other complexes of the Internal Zone. The processes that occurred from this time to the present (extension, compression, uplift, and new faults; some of these in red in Fig. 12) lie beyond the scope of the present study.

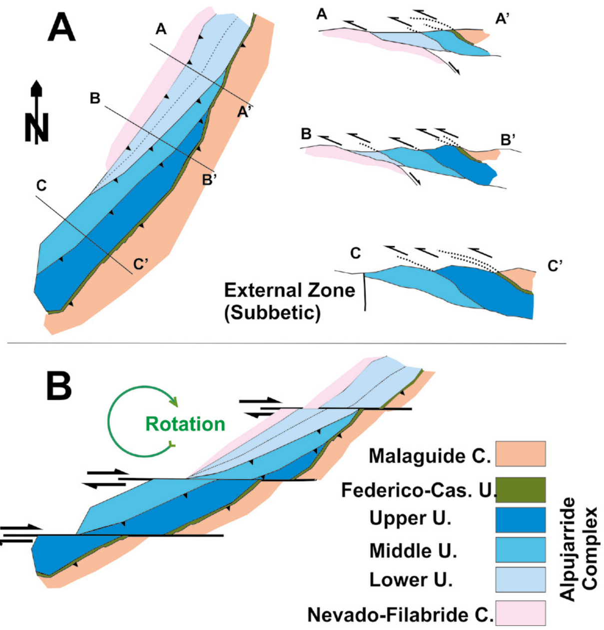

Fig. 11. A: A very rough reconstruction of the general structure of the Alpujarride at the end of the Oligocene-early Miocene, indicating the probable relative positions of the three main groups of its units. No group of units reaches the complete length of the complex. The cross-sections show this unequal distribution. B: The same reconstruction, later cut during the westwards drift of the Betic-Rif Internal Zone and somewhat rotated.

On the decrease in metamorphic grade towards the NE in the Alpujarride Complex

This progressive change of the metamorphic grade has been previously indicated. This decline probably indicates that the collision was less powerful, and particularly that the temperature reached was lower, to the northeast in the Betic-Rif Internal Zone. This is the reason why the Federico-Casares type of units (the Intermediate units) have a greater development in the NE area of the Alpujarride Complex. There they correspond to the previously proposed Almagride Complex.

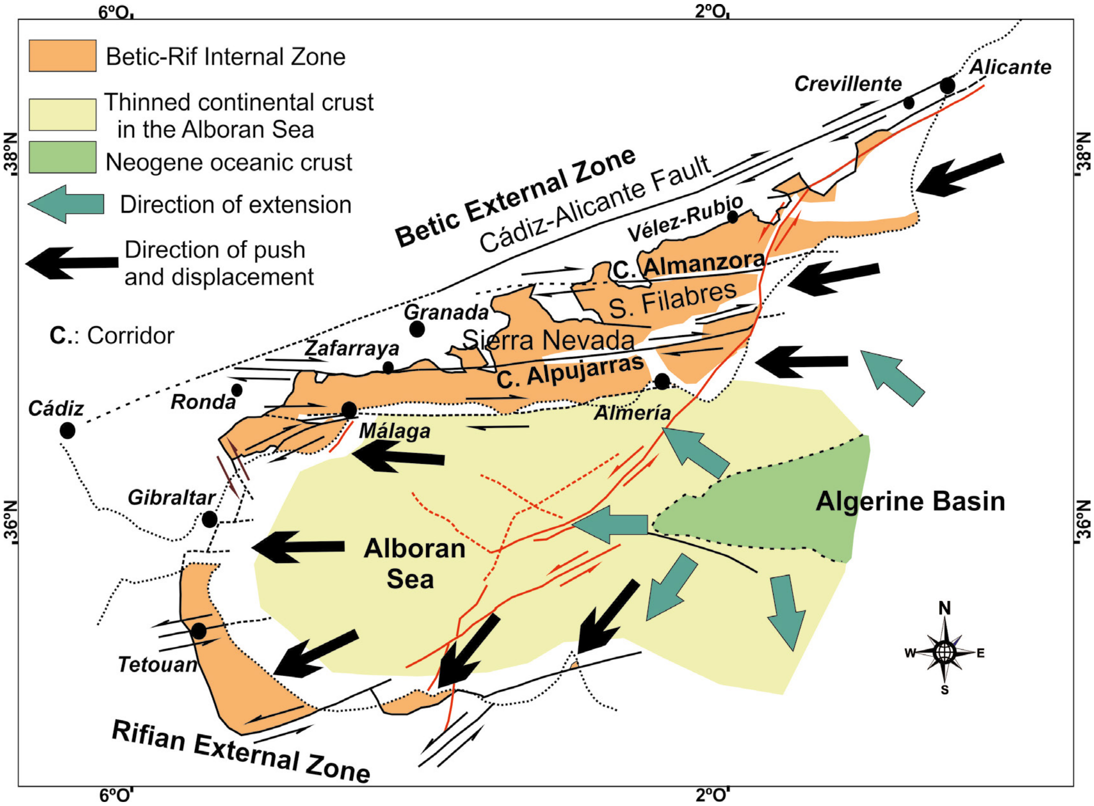

Fig. 12. Present position of the Betic-Rif Internal Zone. The faults cutting it are indicated. The color red corresponds to some of the middle-upper Neogene faults. The direction of displacement and extension during the drift and the opening of the Alboran Sea is indicated. Taken from Sanz de Galdeano (2022).

Regionally, it is necessary to take into account that the metamorphism of the Betic-Rif Internal Zone was not an isolated phenomenon. It formed part of a long band of collision/subduction joining the Alps. This band was not submitted to the same degree of deformation (varying the P and T conditions) in every place, although, on the whole, it corresponds to the same system of structures. Rather, at present, this band is formed by several metamorphic areas now apparently isolated: the Kabylias (in Algeria), the Peloritani Mountains (in Sicily), Calabria, and, more to the north, the sectors of the island of Elba and the zone of Carrara (in the Italian Peninsula), continuing even to the SW Alps. All these areas were practically alienated before the processes of opening of the Algero-Provençal and the Tyrrhenian basins (Sanz de Galdeano, 2022).

Conclusions

The Federico-Casares units (or Intermediate units) confirm the progressive paleogeographical transition between the Malaguide and Alpujarride complexes.

The differentiation between the Alpujarride and Nevado-Filabride complexes are generally clear and the possibility that some of the Alpujarride units correspond to the prolongation of the Nevado-Filabride sequences can be rejected because formations of the same ages and different characteristics exist in the two complexes in adjacent units.

The Mora unit is likely equivalent to lower Alpujarride units, and has sedimentary Jurassic to Cenozoic formations. This is important because it indicates the existence of formations of this age in some Alpujarride units. Also, they can be correlated with the Frontal units, partially situated not only as the cover the Malaguide Complex, but also as part of the cover of the Alpujarride Complex.

The Ronda Peridotites cropping out in the western part of the Alpujarride Complex (and also in equivalent sectors in the Rif) are situated under the upper Alpujarride unit (the Jubrique or Los Reales unit), forming, during the Carboniferous, a metamorphic aureole in contact with its Paleozoic formations. The tectonic superposition of the peridotites in the sierras Blanca, Mijas, and Nieves corresponds to later alpine structures, involving not only the peridotites but also the rest of the upper Alpujarride unit. The Ronda Peridotites were situated previously under the Jubrique unit from the Carboniferous.

The shape of the Alpujarride units is highly variable. Many of them are cut and beveled at different positions in their lithological sequences, to the point of locally disappearing in some cases. At some points, they form enormous bulks, particularly visible in their carbonatic formations, locally revealing very tight folds.

The differentiation of the Ballabona-Cucharón or Almagride Complex is not necessary. This proposed complex occupies exactly the same position as the entire set of units of the Alpujarride Complex, but it is partially justified by the clear and progressive lesser metamorphic grade towards the NE. As a consequence, the differentiation in three groups of tectonic units, lower, middle and upper, of this complex, progressively loses meaning towards the NE.

The tectonic superposition among the Alpujarride groups of units is not complete. That is, the lower units are not totally situated under the middle units, and these under the upper ones. Therefore, in the more western part of the Alpujarride Complex, under the upper unit (with the Ronda Peridotites at the bottom) no other lower Alpujarride tectonic units appear, at least in part.

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