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The Yunquera and Saucillo Units in the western Betic Internal Zone: regional significance

Las unidades de Yunquera y Saucillo en la parte occidental de la Zona Interna Bética: significado regional

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ABSTRACT

In order to gain in the understanding of the evolution of the Betics, particularly in its Alpine front, is important to know better its western tectonic Alpujarride units.

For this reason the Yunquera unit has been studied by analyzing its stratigraphic and tectonic context. This unit is a tectonic slice thrust by the Alpujarride Complex, to which it belongs. In turn, this tectonic slice was thrust over the Dorsal, and the latter was thrust over the Subbetic. During this thrusting, the bottom of the Yunquera unit was beveled, so that in its northern part only the higher stratigraphic levels remain, while to the south also lower levels are preserved. Part of this basal cut could also happen, during the later oblique thinning occurred in the Dorsal, which appears totally laminated in an area of this sector. These deformations happened during the progressive westward drift of the Internal Zone, whose advance was not homogeneous, but as segments, with greater displacement in the more southern ones. Although these deformations can be separated in several stages, actually they correspond to a continuous process spanning from the end of the Oligocene to the Burdigalian. According to its lithological characteristics, the Yunquera unit must be integrated in the upper Alpujarride unit, generally known as Jubrique or Los Reales, whose outcrops practically include all the western sector of this complex. This correlation allows for a better understanding of the structure and the tectonic evolution of this complex. In turn, the Saucillo unit, also present in this area, is clearly linked with the Intermediate units, tectonically situated between the Alpujarride and Malaguide Complexes. This unit is strongly affected by a fault zone formed during the stretching of the Dorsal. In this fault zone, tectonic rests of other units also can be found.

Keywords: Betic Cordillera; Betic Internal Zone; Alpujarride Complex; thrust; transpression.

RESUMEN

Conocer mejor las unidades tectónicas occidentales alpujárrides es importante para la comprensión de la evolución de las Béticas, particularmente de su frente orogénico alpino. Por ello se analiza la estratigrafía y el contexto geológico de la unidad de Yunquera. Esta unidad es una escama tectónica cabalgada por el Complejo Alpujárride del que forma parte. A su vez cabalga a la Dorsal y esta lo hace al Subbético. Por este cabalgamiento, la base de la unidad se encuentra muy biselada de manera que en su parte norte corresponde a niveles estratigráficos altos, conservándose otros más bajos al sur. Parte de ese cepillamiento basal pudo también producirse durante el

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corte oblicuo que sufrió la Dorsal que en ese sector quedó localmente laminada por completo. Todo ello se produjo en el contexto del progresivo avance de la Zona Interna hacia el oeste, el cual no se hizo de forma homogénea, sino según segmentos, con mayor desplazamiento de los más meridionales. Aunque estas deformaciones pueden separarse en varias etapas, realmente se produjeron en un cuadro de evolución continua que abarcó desde finales del Oligoceno al Burdigaliense. Por sus características litológicas, la unidad de Yunquera formó originalmente parte de la unidad alpujárride superior, generalmente conocida como unidad de Jubrique o Los Reales (este nombre se usa cuando se considera también a las peridotitas situadas en su base), cuyos afloramientos comprenden prácticamente todo el sector occidental de dicho complejo. Esta correlación de unidades permite una mejor comprensión de la estructura y evolución geológica del complejo Alpujárride. Por su parte, la unidad del Saucillo (que se encuentra afectada por una zona de falla formada durante el estiramiento de la Dorsal, en la que también hay restos tectónicos de otras unidades) es claramente relacionable con las llamadas Unidades Intermedias, tectónicamente situadas entre los complejos Alpujárride y Maláguide.

Palabras clave: Cordillera Bética; Zona Interna Bética; Complejo Alpujárride; cabalgamiento; transpresión.

Introduction

The differentiation in tectonic units of the Alpujarride Complex still hasn't earned a complete agreement in the scientific community, even though it is an important subject in the effort to gain a better understanding of the geological evolution of the region and its paleogeographical reconstruction.

There is a solid agreement in the understanding that the Alpujarride tectonic units are divided into three important thrusting groups of units (Aldaya *et al*., 1979), but the number, and even the distribution of the units comprising every group, varies in the interpretations of many authors. This is the case of the western part of the Alpujarride Complex, in which the units considered are different from one scientific paper to another. This means that this complex has not yet been clearly understood until today.

Moreover, in the Betic-Rif Internal Zone it is necessary to differentiate between the tectonic units formed in the first stages of the superposition of its complexes, and other tectonic units appeared during its westward drift, which occurred later from the end of the Oligocene- to the Burdigalian (early Miocene) (Andrieux *et al*., 1971; Boillot *et al*., 1984; Sanz de Galdeano, 1990; Jabaloy-Sánchez *et al*., 2019). This process of drifting strongly affected the present area of study, because it is situated just in the front of the Internal Zone, at the contact with the External Zone (the Subbetic). This drifting of the Betic-Rif Internal Zone was provoked by the opening of the Algero-Provençal basin in the western Mediterranean. During this opening, the Internal Zone was pushed westwards (Boillot *et al*., 1984; Guerrera *et al*., 2021; Martín-Martín *et al.,* 2000 a, b).

The Alpujarride Complex, one of the three main tectonic complex of the Betic-Rif Internal Zone, is located in a middle geometric position, having the Nevado-Filabride Complex below it, while the Malaguide Complex is thrust above it. The Nevado-Filabride Complex does not appear in the western area of the Internal Zone, since its westernmost outcrops are located immediately to the east of Granada. Both previous complexes were affected by the Alpine metamorphism.

The Malaguide Complex is well represented in the Málaga province (hence its name) and crops out abundantly in the studied area (Figs. 1 and 2). Its lithological sequences comprise Paleozoic, Mesozoic and Cenozoic sediments (Makel, 1985), only slightly metamorphosed in the lower parts of the Paleozoic sequences. This complex is also present in the Rif (Morocco) where it is called Ghomaride, and generally presents the same sequences. In that location, the Ghomaride complex is divided into three superimposed tectonic units, while in the Betics only one such unit is generally distinguished (apart from local thrust slices).

Moreover, both in the Betics and in the Rif, several units exist located tectonically between the Malaguide and the Alpujarride, which display intermediate characteristics. They pass from units whose lithological and metamorphic characteristics are very similar to the Alpujarride Complex, to others, situated in higher positions, changing progressively into having clear Malaguide aspects. These have been called the Casares and Federico units (these last in the Rif) by Didon *et al*. (1973), and Intermediate units by Sanz de Galdeano *et al*. (2001) and Sanz de Galdeano (2019). The same have also been called "Benarrabá

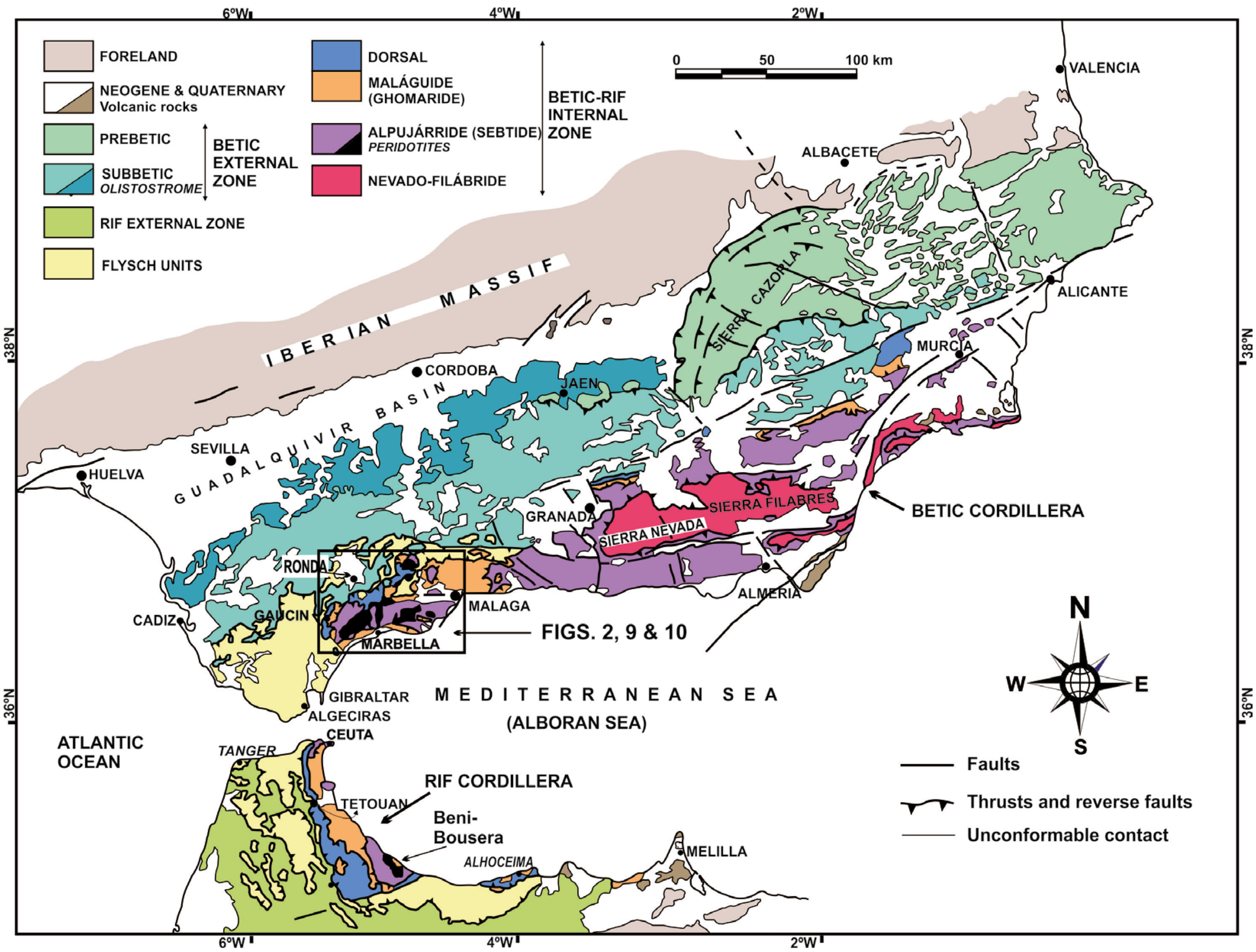

Figure 1.— Geologic scheme of the Betic and part of Rif Cordilleras, with the general distribution of the Internal Zone. The rectangle indicates the position of Figs. 2, 9 and 10.

Imbrications" by Balanyá (1991) and Balanyá & García-Dueñas (1991) (Benarrabá is a village situated near Gaucín, Figs. 1 and 2).

Background

One of the first divisions of the Alpujarride tectonic units in the western part of the Betic Cordillera corresponds to Hoeppener *et al*. (1964) and Dürr (1967) who distinguished, from bottom to top, the Blanca, the Ronda Peridotites, and the Casares units (in this case, the Casares unit comprises the later called Jubrique unit and the Benarrabá Imbrications) (Fig. 3). Later, Navarro-Vila & Tubía (1983) and Tubía (1988) distinguished the unit of Ojén at the bottom of the complex, with the Guadaiza unit above it, and the Los Reales unit on top of the Guadaiza.

Balanyá (1991) and Balanyá & García-Dueñas (1991) joined the Ojén and Guadaiza units into the Guaro nappe, and above it, they described the Bermeja unit (the peridotites), the Jubrique unit and, at the top, the Benarrabá tectonic imbrications. These authors grouped the last units, from Bermeja to the Imbrications, into the Los Reales nappe.

Sanz de Galdeano (2017, 2019) considered that the Guaro nappe does not have a real and independent existence, as it is the case with the Blanca and Mijas units (the Sierra de Mijas is situated farther to the East, Fig. 2). Instead, the author sees all these units as forming part of the Jubrique or Reales nappe (this last name is usually given when the peridotites situated at the bottom are also considered). Above them, the Intermediate units and the Malaguide Complex are located.

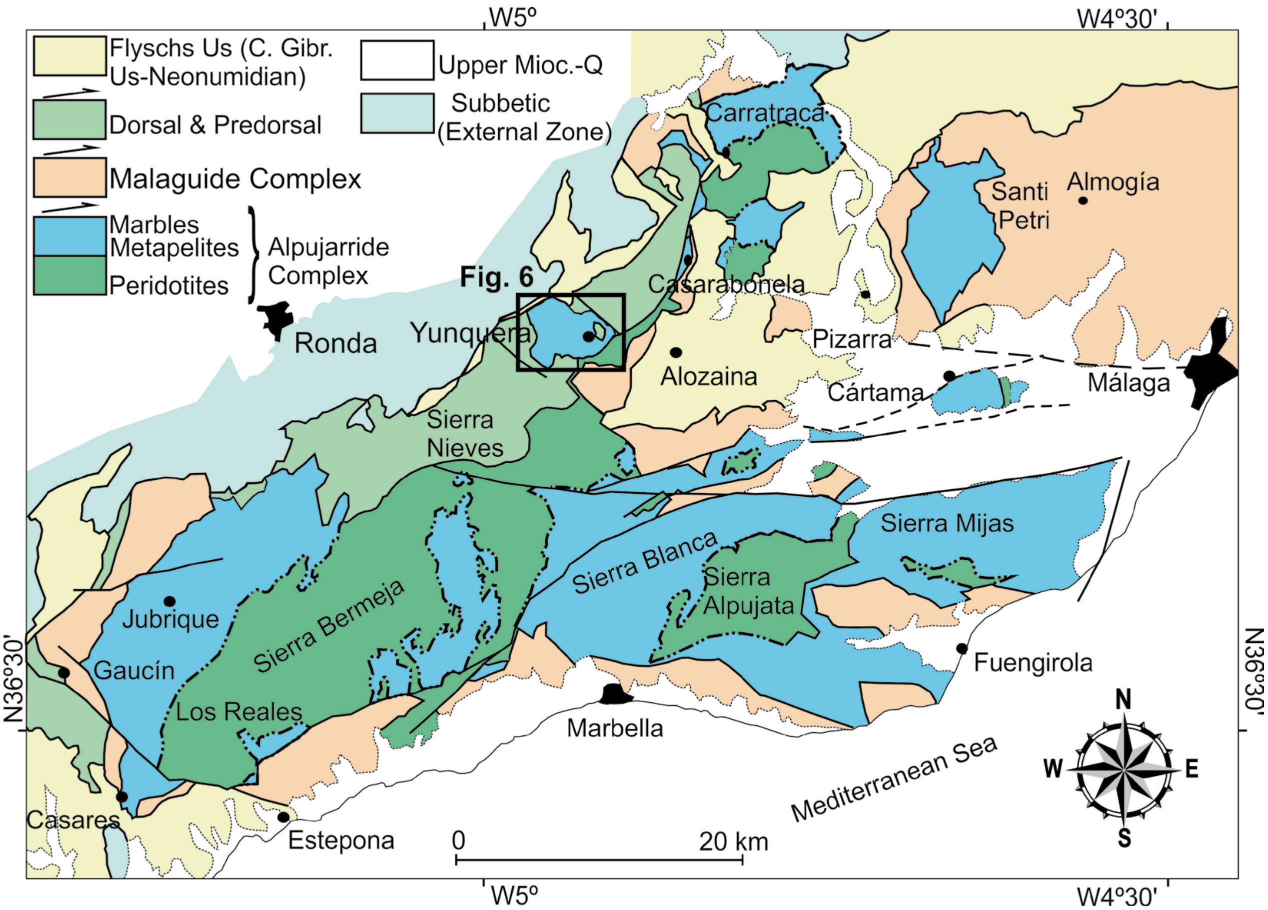

Figure 2.— Geologic scheme of the region in which the area of Yunquera (western area of the Betic Internal Zone) is located. All the peridotites associated with the Alpujarride Complex appear in it. The rectangle indicates the position of Fig. 6.

The Yunquera unit, although forming part of this region, is generally not cited in the previous divisions because it is situated immediately more to the N and its extension is reduced, approximately of 15-16 km^2. This last sector was briefly described by Blumenthal (1930). Dürr *et al*. (1960); Hoeppener *et al*. (1964), and later Dürr (1967) cited their existence as a tectonic unit.

Bourgois (1978) considered that in the area of Yunquera the Alpujarride Complex is formed by one unit type Los Reales, and, in the northern part, by another unit equivalent to the Casares unit (in the sense of Didon *et al*., 1973, that is, an Intermediate unit). Martín-Algarra (1987) used the name of Yunquera for the first unit, and that of Saucillo, for the second one. This author considered the possibility that the Yunquera unit was equivalent to the Blanca unit situated southwards (Fig. 2). These same names were later used by Del Olmo *et al*. (1991), although their geologic map was originally made in the year 1981. Finally, Esteban *et al.* (2005) studied the Yunquera unit, particularly from the petrologic point of view, describing also the process of exhumation and thermochronology. They indicate ages of T-t evolution from the Permian to the early-middle Miocene.

Geological setting

In this western area of the Betic Internal Zone, in addition to the Alpujarride and the Malaguide Complexes, it is necessary to cite the Dorsal (Figs. 1 and 2), which can be considered as the fourth tectonic complex of the Internal Zone, narrowly linked to the Malaguide Complex, so much so that the Mesozoic cover of this last complex, in some cases, cannot be distinguished from the Dorsal units. The Dorsal, present in the Betics and the Rif (Durand-Delga &

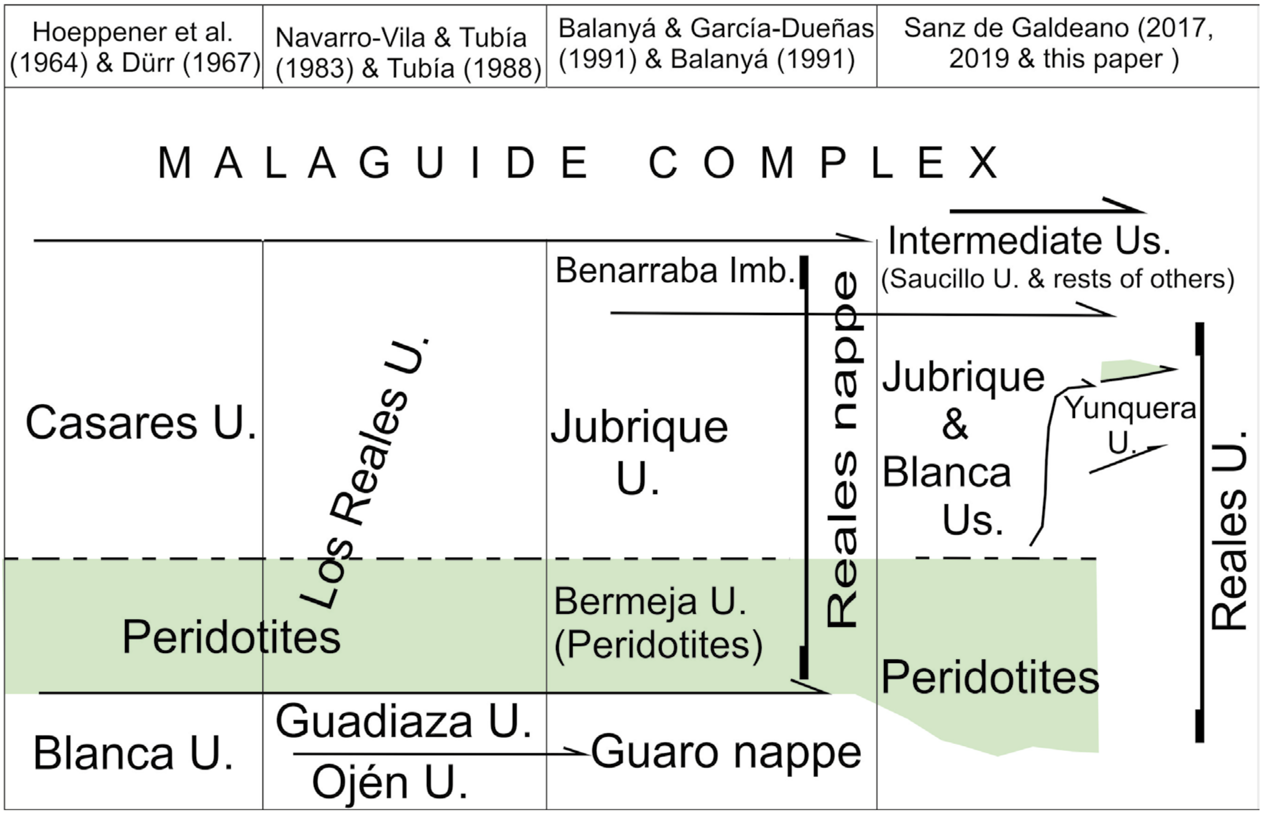

Figure 3.— Tectonic units proposed by different authors in the Western part of the Alpujarride Complex.

Foucault, 1967), is divided into many tectonic units. In the western part of the Betics, this complex was named Rondaides by Blumenthal (1928) and Frontal units (Serrano, 1998; Jabaloy *et al*. 2019), but for the moment, that of Dorsal is the more used one. Other units of this area correspond to the so called Predorsal, linked to the Dorsal, but paleogeographically occupying a more external position. In this article they have not being differentiated and are considered as forming a single ensemble.

In the study area, the Sierra de las Nieves and other neighboring mountains belong to the Dorsal (Fig. 2). This Sierra is mainly formed by Triassic-Jurassic carbonates, and it is thrust by the Alpujarride and Malaguide Complexes. The Dorsal, in turn, is thrust over the External Zone.

The External Zone corresponds to the Mesozoic and Cenozoic south and southeastern sedimentary cover of the Paleozoic Iberian Massif, and it is divided into Prebetic and Subbetic. The Prebetic is situated nearer this massif, and it is not represented in the study area. The Subbetic generally corresponds to marine sediments and in many places it can be further divided into Internal, Middle and External units, according to their regional position. In the study area it correspond to the Internal Subbetic, which is also called Penibetic.

Also, it is necessary to mention the units called Campo de Gibraltar, or more generally known as Flyschs units. They appear in the south of Italy, and pass from Tunicia to the northern part of the Rif (Alcalá *et al.,* 2013; Martín Martín *et al*., 2020), and are also present in the region of the Campo de Gibraltar, hence their name in the Betics. They correspond mainly to Cenozoic sediments tectonically superimposed over any other units previously cited. In the study area a particular type of these Flyschs units, the Neonumidian, is present. Moreover, near this area the *Formation d'Argiles à Blocks* (the Clays Formation with blocks) also appears. Both units are defined by Bourgois (1978). According to this author, these formations have an olistostromic character, presenting abundant kilometric olistoliths. The age of these formations is Burdigalian.

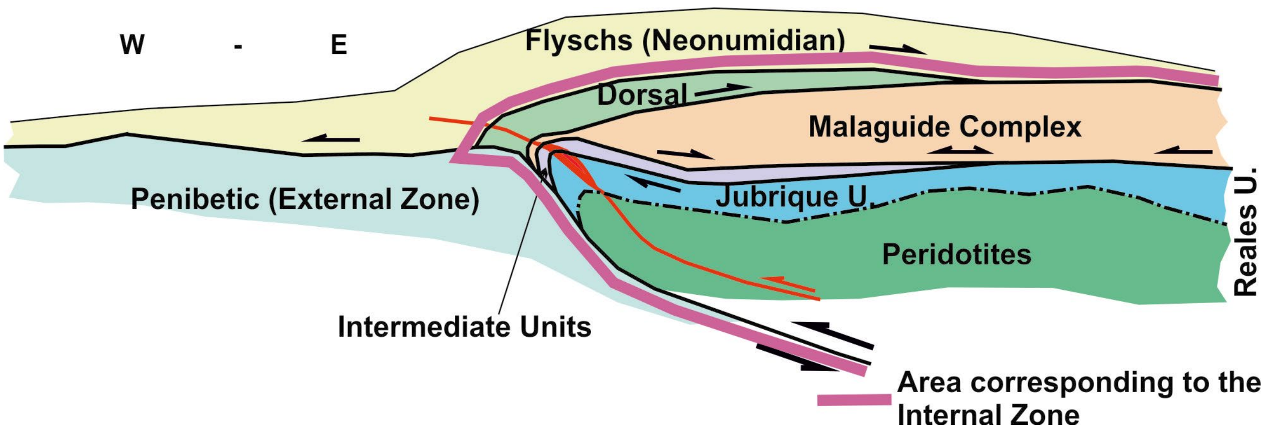

Figure 4.— Interpretation of the general structure of the Western Betic Internal Zone. The red line tries to indicate the approximate position of the immediately later thrust forming the Yunquera unit (red area).

To help in the understanding of the relations of the previous cited complexes and units, Fig. 4 present a simplified general scheme of their structure at the western end of the Betic Internal Zone.

Finally, three types of unconformable deposits can be mentioned: the Alozaina formation (Bourgois *et al*., 1972 a), the Brecha de la Nava – the Nava Breccias- (Martín-Algarra & Estévez, 1984), and the Millanas (Bourgois *et al*., 1972b) or Cártama formation (Sanz de Galdeano *et al*., 1993). A revision of these formations can be consult in Jabaloy *et al*. (2029). All of them have a lower Miocene age.

Aims of the article

Its first purpose is to describe the geometry of the Yunquera area. This description is mainly referred, but not exclusively, to the tectonic unit of this name. The second purpose is to try to reconstruct the kinematics able to produce this geometry and to identify the possible scenario in which the area was involved. Moreover, a comparison of the lithologic characteristics of the tectonic units concerned will allow to position them in relation with other units of this area, and it will also contribute to their paleogeographic reconstruction.

Lithologic sequences

The lithologic description is mainly centered in their appearance in the field, because previous articles, such as that of Del Olmo *et al*. (1991), Martín-Algarra (1987) and Esteban *et al* (2005) already provided details of their petrological characteristics. The description is made from bottom to top in every lithological sequence. The Alpujarride units (Yunquera and the peridotites) are described first, then that of intermediate character between the Alpujarride and Malaguide complexes (Saucillo Unit), and lastly the Malaguide. A few indications about the Dorsal/Predorsal units, the Flysch units (the Neonumidian unit) and the Subbetic are also given.

The Yunquera unit

Gneisses and schists

Towards the bottom of this formation there are gneisses, in which well formed feldspars can be seen, that are very abundant in some levels. This texture changes progressively towards the top, passing gradually to schists. There are also visible garnets, different types of micas, including biotite, and also sillimanite.

The dominant color is brown, with the exception of some gneisses in which the abundance of feldspar give the rock a generally lighter color. The conserved thickness of these rocks is very variable, from nothing in the northern parts of the unit, to more than 100 m in other parts. Originally they would have had more than several hundred of meters of thickness, but that which can be observed at present is much less due to tectonic and erosion effects.

The age attributed to the schists is Paleozoic, while that of the gneisses probably corresponds to the age of the emplacement of the peridotites, then forming an aureole to which the gneisses form part. This age is discussed, varying from the Aquitanian (Esteban *et al*., 2011) to the Permian (Sanz de Galdeano & Ruiz-Cruz, 2016).

Against the opinion of some authors (Del Olmo *et al*., 1991; Martín-Algarra, 1987) neither the schists nor the gneisses, contain intercalated levels of marbles in their interior. Only near the top of the schists these levels begin to appear, marking a short transition to the marbles. In this transition, a thin level of orthogneiss, about 30 cm thick (Fig.5A), exists near the kilometric point 36.7 in the road (A-366) to the E of Yunquera. In other places these levels of former volcanic rocks correspond to the Triassic, or Permian (Puga & Torres-Roldán, 1989).

Both types of rocks, paragneisses and schists have not been differentiated in Figs. 6 and 7, being indicated with the same color, because it is not possible to check at every point of this lithological formation, owing to the structure, the existence of soil cover, and the transitions from one type of rock to another.

Lower marbles

These marbles present different aspects. In some places they form thick levels, while in others the levels are much thinner. Generally they are dolomitic. In many places, though not always, they present interbedded levels of schists, whose appearance change towards the top, progressively decreasing in their apparent metamorphic grade.

Owing to tectonic reasons, the observed thickness of these marbles change from one point to another, but surely it formerly reached at least 150-200 m. The limit with the upper formation is conventional, and in the present work it has been situated at the occurrence of new and more abundant metapelitic interbedded levels.

Upper marbles with metapelitic and quartzite intercalations

The aspect of these marbles is more calcitic, although there are also levels entirely similar to those of the lower formation, i.e. dolomitic. The metapelites correspond to phyllites and calc-schists, which in many cases are not easily differentiable from thin dark marble levels.

There are also quartzitic levels, at certain points reaching a thickness superior to 50 m. An interesting aspect is that in the study area the abundance of quartzites is more noteworthy in the western part, rather than the eastern part, indicating lateral changes of facies.

The greater conserved thickness of this formation is of the order of 150 m. And the attributed age, together with the lower marbles, is Triassic.

The peridotites

These rocks are the prolongation of the ultrabasic massif of Sierra Bermeja and other adjacent areas. They are called Ronda Peridotites, perhaps because this area corresponds to the Serranía de Ronda (Mountains of Ronda), although in that town this type of rocks is not present. According to Del Olmo *et al*. (1991) they mainly correspond to lherzolites.

Although it is difficult to calculate the thickness of the peridotites, considering the foliation (a kind of layering) existing in some places, not observed in the studied zone, it can surely surpass 1.5 km in areas as those corresponding to the North of San Pedro de Alcántara, South of Ronda. But this thickness is very variable depending on the places. Owing to tectonic reasons, in the studied area probably it is not superior to 300 m. They are tectonically situated over the Yunquera Unit and at their time are thrust by the Malaguide Complex.

The Saucillo unit

Under this name, rests of other units of intermediate character are actually also included, as is it mentioned a little later in this article.

Dark schists

They correspond to schists that, even though containing garnets, andalusite, biotite… their field appearance is very similar to the lutites and quartzites of the Paleozoic of the Malaguide Complex. Only they have a more schistose aspect, and in order to observe the aforementioned minerals, and others, it is sometimes necessary to look with care (when these minerals are visible, generally do not surpass 2-3 mm of size). These rocks, and the rest of the se-

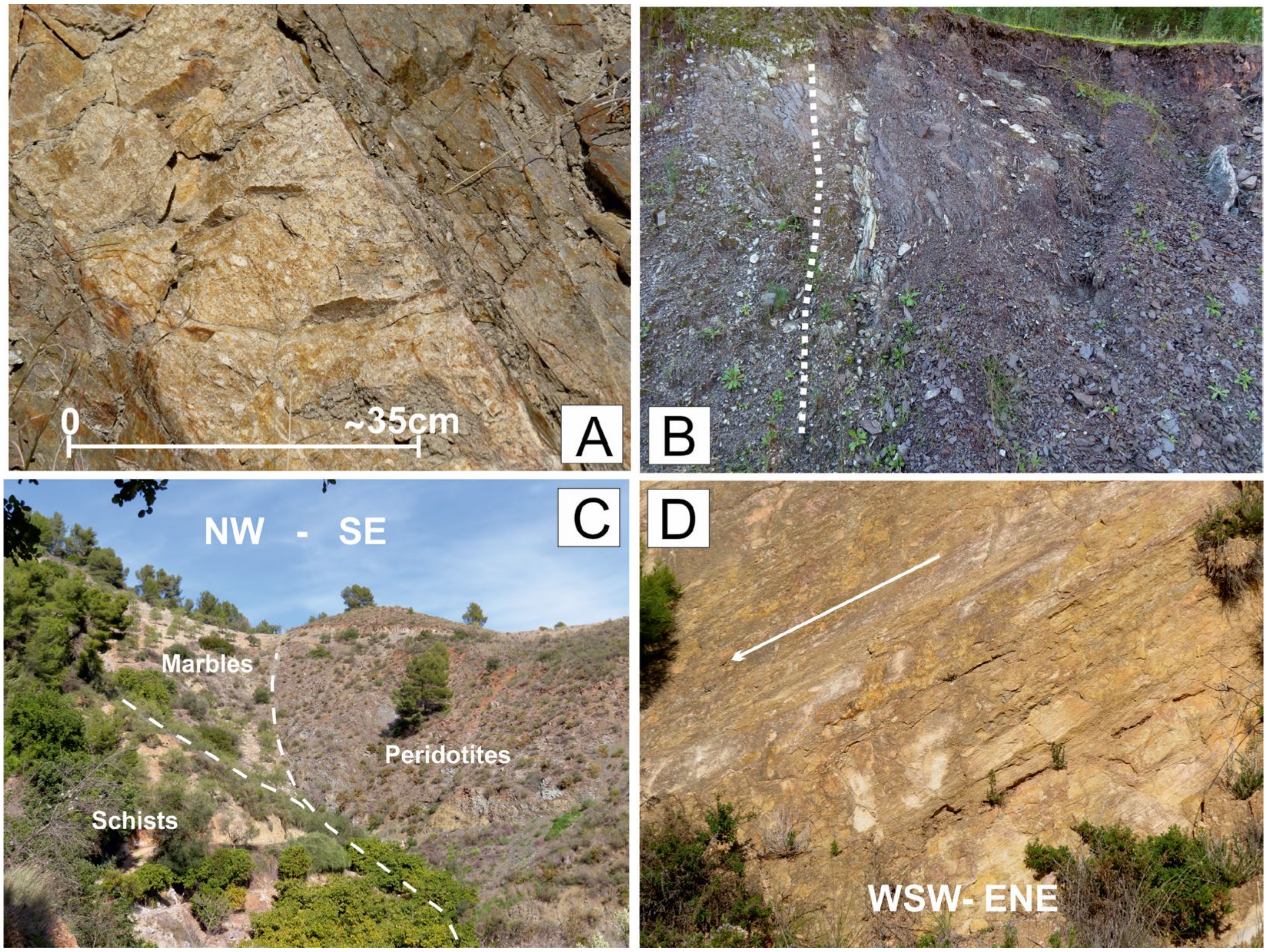

Figure 5.— A: view of the orthogneiss level situated near the top of the schists in the Yunquera unit. B: phyllites of the Saucillo unit. The white dotted line indicates the position of the vertical foliation, disposed in an ENE-WSW tectonic band. C: thrust of the peridotites over the Yunquera unit affected by an oblique dextral fault forming part of the later shear zone. D: oblique dextral fault in the contact between the Dorsal and the Yunquera unit. It is part of the shear zone that, among other effects, thinned and cut the Dorsal. The position of the photos are indicated in Fig. 6.

quence, are strongly affected by tectonic deformation, and the conserved thickness is very variable. Perhaps, at some locations, a little more than 100 m can be conserved.

Limestones are also included within these rocks, only slightly transformed in marbles, the "calizas alabeadas" (Silurian-Devonian), not distinguished in Fig. 6

Phyllites and quartzites

The color of these phyllites is variable, from red to violet (Fig. 5 B) and even yellow; and they present a marked schistosity. These are the main differences between these rocks and equivalent Malaguide Triassic formations, these latter lacking schistosity and having predominantly red coloration, not violet. The conserved thickness probably is not superior to 70 m. Regionally, their age are attributed to the lower Triassic (Delgado *et al*., 1981; Del Olmo *et al*., 1991; Jabaloy *et al.,* 2019)

The rocks of this unit are situated in the northern part of the study area (Fig. 6), the Las Morenas-Convento area, affected by a great strike slip zone. In this zone there are also rests of these same types of rocks, but they do not present a metamorphic aspect. As it is indicated later, a tectonic mélange of Intermediate units and even units of the Malaguide Complex exists in this fault zone. In this mélange the different rocks of the Saucillo Unit and of the Malaguide Complex can be found.

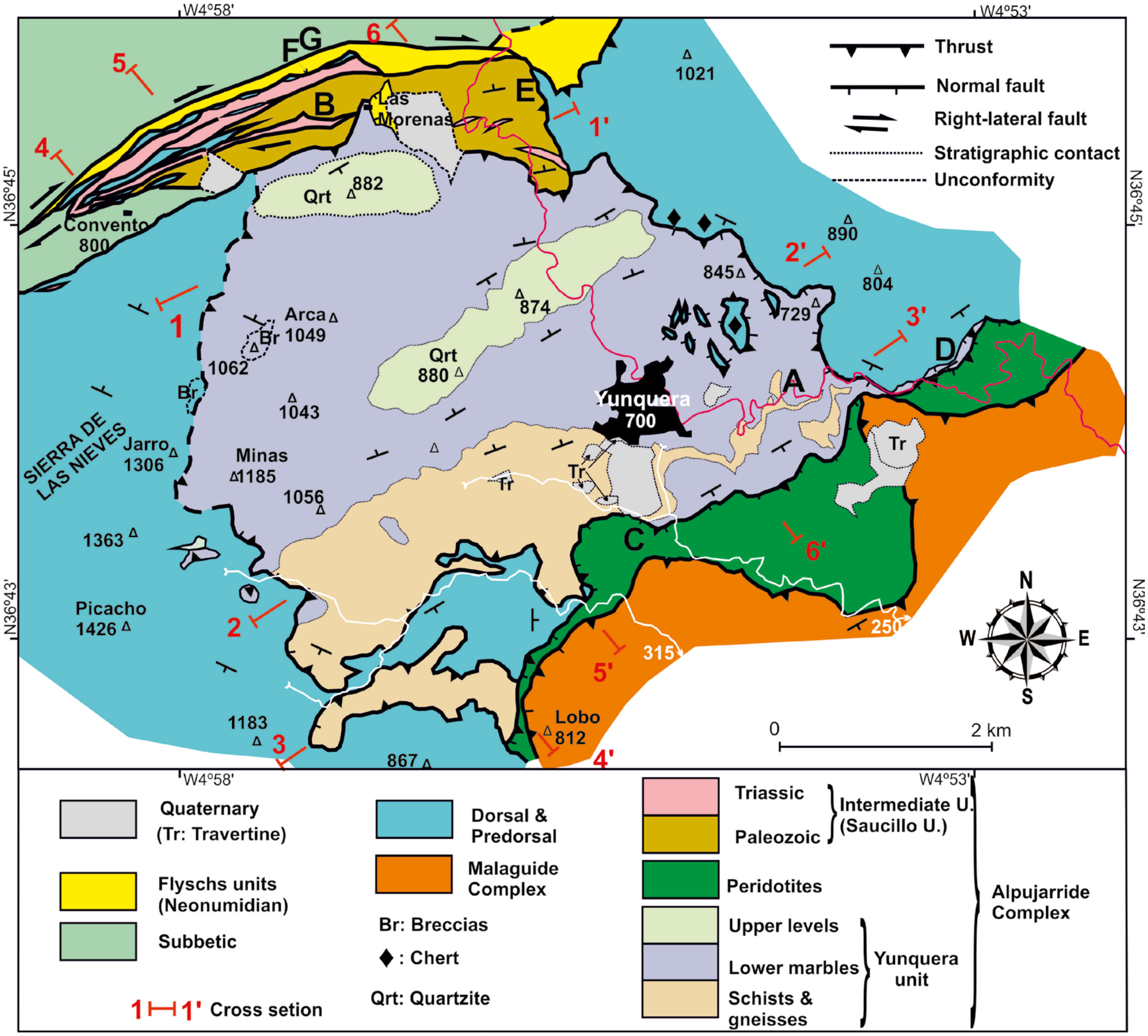

Figure 6.— Geologic map of the Yunquera area. Its position is indicated in Fig. 2. The situation of the cross sections of Fig. 7 are marked. Letters A to G correspond to the position of the photos of Figs. 5 and 8.

Also, carbonatic bodies whose attribution is really problematic can be found in this mélange. Probably the more abundant ones correspond to tectonic splinters originally belonging to the Dorsal/Predorsal units, but others could correspond to the Intermediate units, and even to the Malaguide Complex.

The Malaguide units

The plural designation of “units” used here refers to the fact that this complex appears in the southern part of the study area and also in the northern, in the strike slip area.

In the south it is formed by Paleozoic rocks, lutites, greywackes, and quartzites with a brown color. In this area more than 100 m of thickness is conserved.

In the strike slip area the Silurian-Devonian limestones (calizas alabeadas) (Mäkel, 1985) have been previously mentioned, although in this case they are slightly metamorphosed and situated in the Intermediate units. There are also red lutites and quartzites attributable to the Triassic, disposed in tectonically elongated bodies. Some carbonatic rests also could belong to this complex.

Moreover the described units, in this area there are others not directly studied, although their lithology is now very briefly indicated here, in order to complete the geologic context.

The Dorsal and the Predorsal (or Frontal Units)

At the bottom of the sequence a thick dolomitic formation appears. Above it there are limestones and dolomites, locally with marls, limestones with chert, and other higher formations. The age of these rocks spans from the upper Triassic to the Jurassic and up to the Cretaceous; even younger ages are cited in very local points. The limestones with chert, and some thin interbedded marl levels, correspond to the lower Jurassic. The total thickness of these formations, although variable, is in excess of a thousand meters.

In some areas, particularly those in contact with the Alpujarride units, the above mentioned rocks of the Dorsal have been metamorphosed, passing to marbles, calc-schists and even phyllites. For this reason, in some cases, it is not possible to distinguish them from equivalent Alpujarride rocks, the lower marbles of the Yunquera unit. This means that in some places the cartography here presented has the value of an interpretation rather than an exact determination.

In the Dorsal it is necessary to mention the existence of the Nava Breccias, unconformably deposited over the previous formations, made up by carbonatic clasts of the same domain, some of them metamorphosed, and someone of Alpujarride origin (Martín-Algarra & Estévez, 1984). According to these authors its age is lower Miocene. Del Olmo *et al*. (1991) called Jarro Breccias the deposits that lay over the Yunquera unit, which can be considered totally equivalent to the Nava Breccias (Martín-Algarra, 1987). In Fig. 6 two small outcrops of these breccias have been indicated, and they are significantly less than those indicated in the map of Del Olmo *et al*. (1991). In this area the thickness of these breccias is very variable, probably not reaching more than 10 m.

The Penibetic (Internal Subbetic, External Zone)

In the area of study only Cretaceous to Cenozoic limestones, marlstones and marls appear (Del Olmo *et al*., 1991). Most of the levels are of salmon color, but there are also others of white tones. Under these rocks, the Jurassic is mainly carbonatic.

The Neonumidian

This unit corresponds to a Flysch sequence, formed by sandstones, lutites, clays, locally conglomerates, and contains sedimentary klippes of variable lithology, such as microcodium limestones. The dominant color is brown. Although very similar in its field aspect to the Flysch units present in the Gibraltar area (Campo de Gibraltar units), its age is Burdigalian (Bourgois, 1978).

Finally, there are also alluvial and colluvial sediments, in many cases not indicated in Fig. 6.

Structure

It is previously known that the Malaguide Complex thrusts the Alpujarride Complex, and that, in the study area, unlike the structure indicated in Fig. 4, both complexes are thrust over the Dorsal, and the Dorsal lays over the Predorsal; then, both the Dorsal and the Predorsal lay over the Subbetic. Also, it is known that the Neonumidian occupies the higher tectonic position, and at the same time that the Yunquera unit is thrust by the Alpujarride peridotites.

Consequently, in this article, the description is centered on the structure of the Yunquera unit, as well as in that of the Saucillo unit, and in the important tectonic cut underwent by the Dorsal in this area, something that was not described previously.

Structure of the Yunquera unit

The structure of this unit can be deduced from the map of the Fig. 6 and the cross sections of Fig. 7. This unit is tectonically superimposed to the Dorsal, but the formations conserved at its bottom vary. In the northern part, the lower marbles of the Yunquera unit are directly in contact with the Dorsal, while in the southern part, the gneisses and schists are conserved, placed over the Dorsal. This means that the bottom of the Yunquera unit is cut in a beveling fashion.

The S-SE border of the Yunquera unit is limited by peridotites tectonically superimposed, but

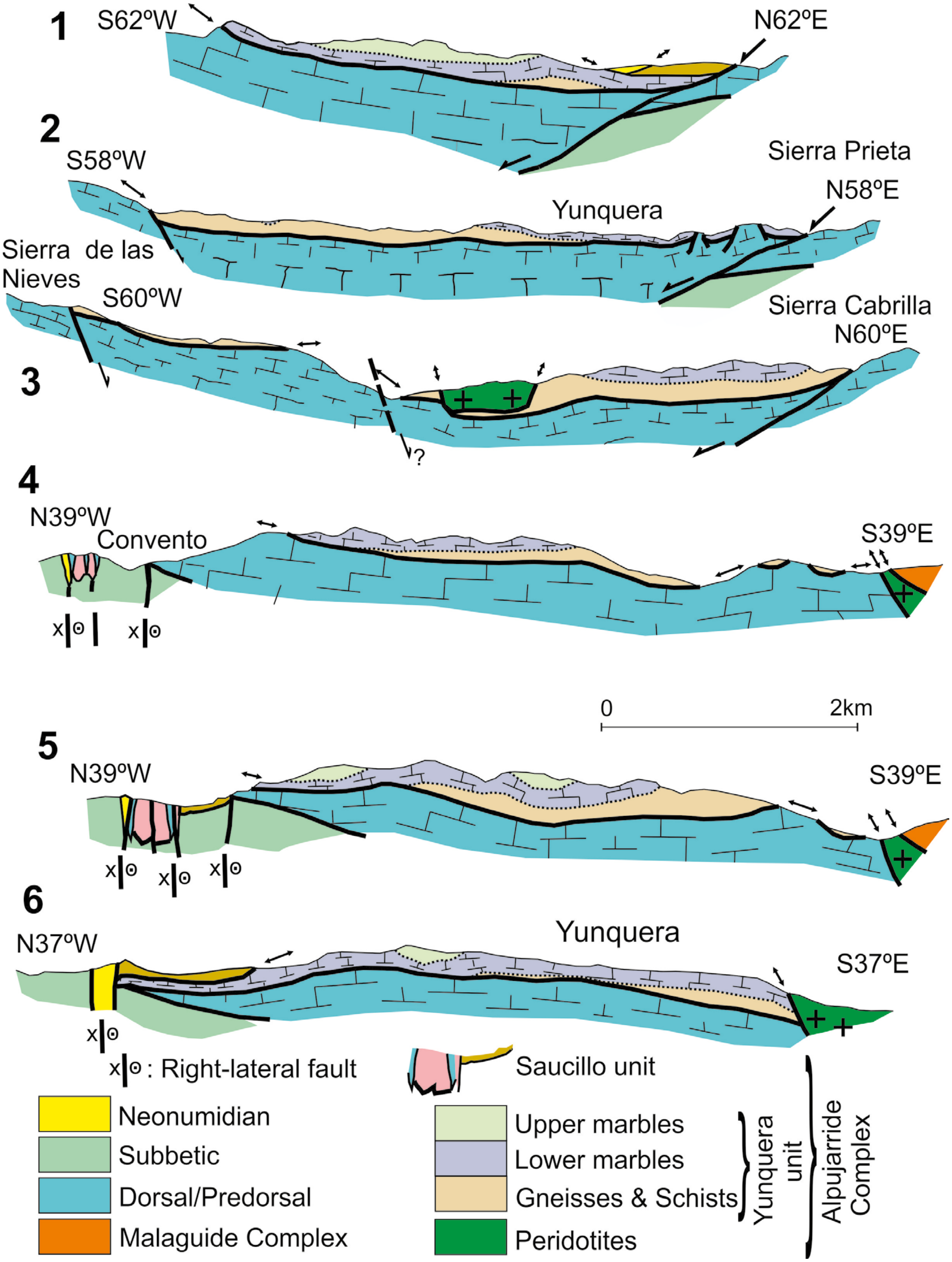

Figure 7.— Geologic cross sections of the study area. Their positions are indicated in figure 6. The symbol (x/o) indicates dextral strike slip faults.

the last movements observed at this contact (in the more eastern part of the studied area) correspond to an oblique-dextral fault (Fig. 5 C) with striae of 40º plunging to the SW (Fig. 5 D).

In the cartography of this unit (Fig. 6) there are two aspects that are not precisely defined. The first one is found in its NW border, in the area of Jarro and Arca points. There, the dolomitic marbles of the Dorsal and those of the Yunquera unit are in contact, the latter ones sit over those of the Dorsal. Due to the similarities in terms of facies of the marbles in both units, the separation between these formations is only approximate. The uninterrupted forest mantle existing in that location contributes to this possible imprecision.

The second aspect corresponds to the small tectonic windows located to the NE of Yunquera (Fig. 6 and cross section 2 of Fig. 7). The existence of these windows is indicated in Bourgois (1978) and Del Olmo *et al*. (1991), although their shape and number varies. Here, a different shape is presented, although it is only one approximation. There really exist tectonic windows where formations of the Dorsal crop out, for instance marble limestones with chert, rocks that don't exist in the Yunquera unit. Some of these small windows are limited by faults, generally normal faults. But it is necessary to insist on the fact that the shape of these windows presented in Fig. 6 is only one approximation, mainly made to indicate their existence more than their detailed shape.

Structure of the Saucillo unit

This unit, in which there are also fragments of several other Intermediate units and of the Malaguide

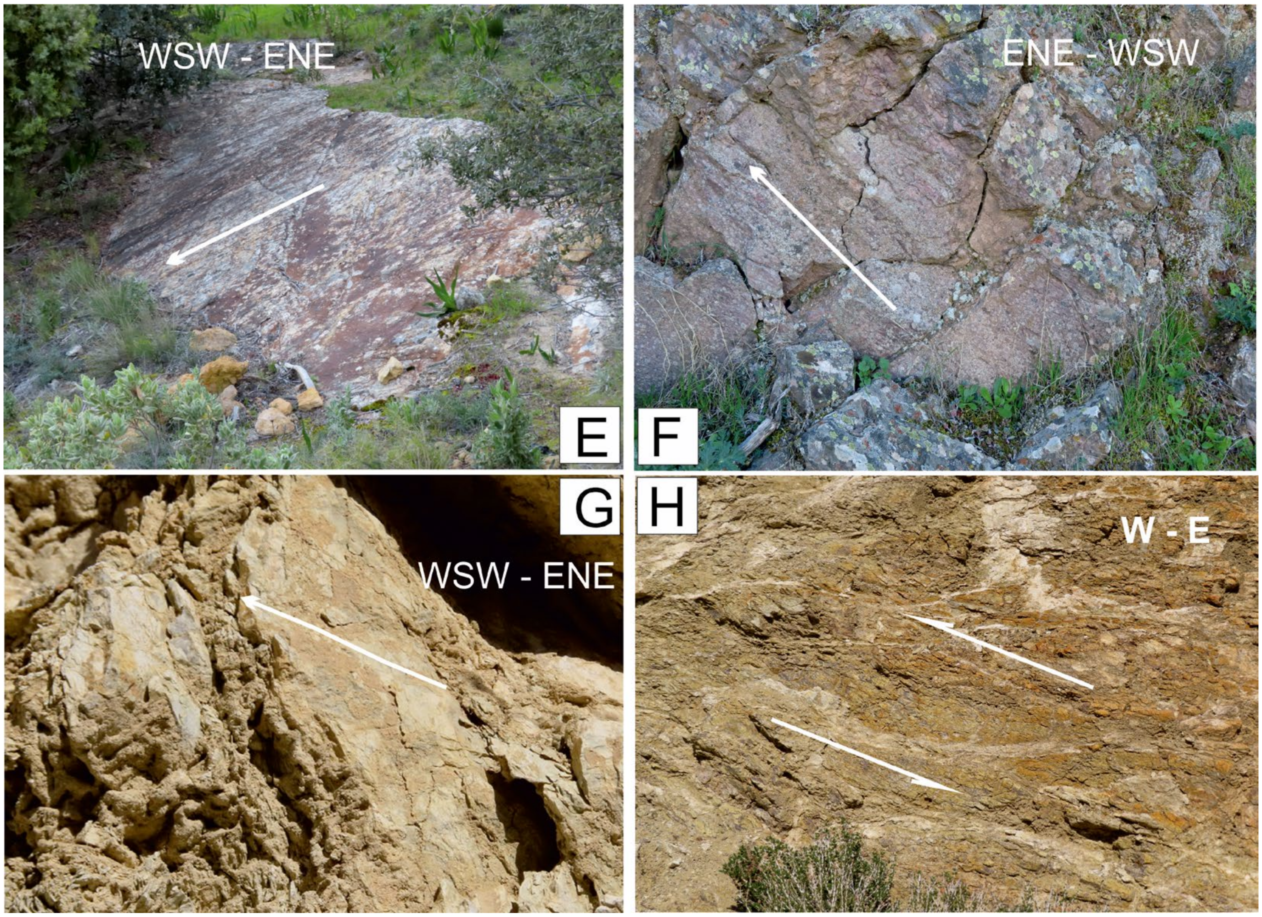

Figure 8.— E: low angle fault at the top of the Dorsal corresponding to the posterior shear zone. F: oblique dextral fault in quartzites/conglomerates of the Saucillo unit, in the shear zone affecting it. G: dextral fault in the Cretaceous formation of the External Zone, near the previous photo. Striae are practically horizontal, although in the photo seem to be inclined. H: fragile pseudo S-C structures in peridotites of the Majada Vieja unit trusting over the Cartama unit. Photos E to G are situated in Fig. 6, photo H in Fig. 10.

Complex, is located in the northern part of the study area. It is tectonically placed over the Yunquera unit and also over the Dorsal and Predorsal. In turn, the Neonumidian is thrust over the Saucillo unit and also over the Subbetic.

But this structure of superposition of units is at present almost entirely affected by a wide dextral strike slip fault zone (Fig. 6 and cross sections 4-6 of Fig. 7), forming vertical tectonic bands, a flower structure. The cartography of this area in Fig. 6 is only one approximation because, as it happens in other parts of the region, it is covered by forest and scrub, making it difficult to follow the contacts, even though it probably expresses the existing structure well enough.

It is worth to indicate that thin shreds of Neonumidian are located within this flower structure, together with those of the Saucillo unit, that is to say, the Neonumidian is also clearly imbricated in the structure.

Some kinematic indicators have been found in this area of the Saucillo unit. In its eastern part the bottom of the unit is observable, situated over the Predorsal/Dorsal. The contact corresponds to a low angle fault, with striae trending N50ºE, and plunging towards the SW (Fig. 8 E). More than 1 km to the west, striae with dip angles that vary from 45º to 0º (horizontal) can be found. Similar features exist in the nearest Subbetic formations (Fig. 8 F, G). Also, to the SW of the Convento, in the tectonic contact existing between the Dorsal and the Subbetic, equivalent structures have been found, including in between small remnants of the Saucillo unit and even of the Neonumidian, not indicated in Fig. 6, due to their small size.

The hidden cut of the Dorsal

In the study area the Dorsal appears at the E and NW borders of the Yunquera unit. In both sides the Dorsal is extensively exposed, forming mountains higher than 1500 m, while the area of Yunquera, in many areas is lower than 900 m (Fig. 6). That is to say, the area where the Yunquera unit is conserved corresponds comparatively to a depressed sector.

This depressed area does not correspond to a kind of flexure in which the Dorsal is solely bent; on the contrary, in this area the Dorsal is strongly sheared, in such a way that it disappears entirely in the sector of the Saucillo unit, being this last unit, and also practically the Yunquera unit, in direct contact with the Subbetic. This is expressed in the cross sections 4-6 of the Fig. 7. In this sense, Fig. 9 indicates the geometry of this shear cutting the Dorsal and puts it in its regional context.

The sense of displacement of this zone of thinning in which the Dorsal was cut, is the previously indicated one of N50º, plunging southwards. This measure has been obtained not only from the bottom and the splinters of the Saucillo unit, but also from other sectors, i.e. north of Jorox, in the contact between the Yunquera unit and the Dorsal, and between the Yunquera and the peridotites (Fig. 5, C and D).

Discussion

Two issues are examined here. The first one concerns the process of formation of the structures previously presented, and the second one is a discussion about the relationship of the Yunquera unit with the rest of the Alpujarride Complex in its western areas.

Different features of the formation of the alpine structures in the Yunquera area

The thrust of the Malaguide Complex over the Alpujarride Complex is the most important tectonic alpine feature in this region. The rest of the structures, though also important, must be considered linked to the effects related to the westward displacement of the Betic Internal Zone.

Regionally, the Dorsal is thrust over the Malaguide Complex, being the Alpujarride Complex in a lower position, as it happens in the Jubrique-Gaucín area, the more western part of the Internal Zone (Fig. 4). But on the contrary, this position of the Dorsal is not conserved in the Yunquera area. In fact, in the entire Sierra de las Nieves, i.e. in the study area, the Dorsal is widely thrust by the Alpujarride units, the Yunquera, the peridotites and the Saucillo units. And due to this superimposition of the Alpujarride Complex, the Dorsal underwent an important increase of temperature that likely has been the source of its metamorphism in the sector of contact with the Alpujarride.

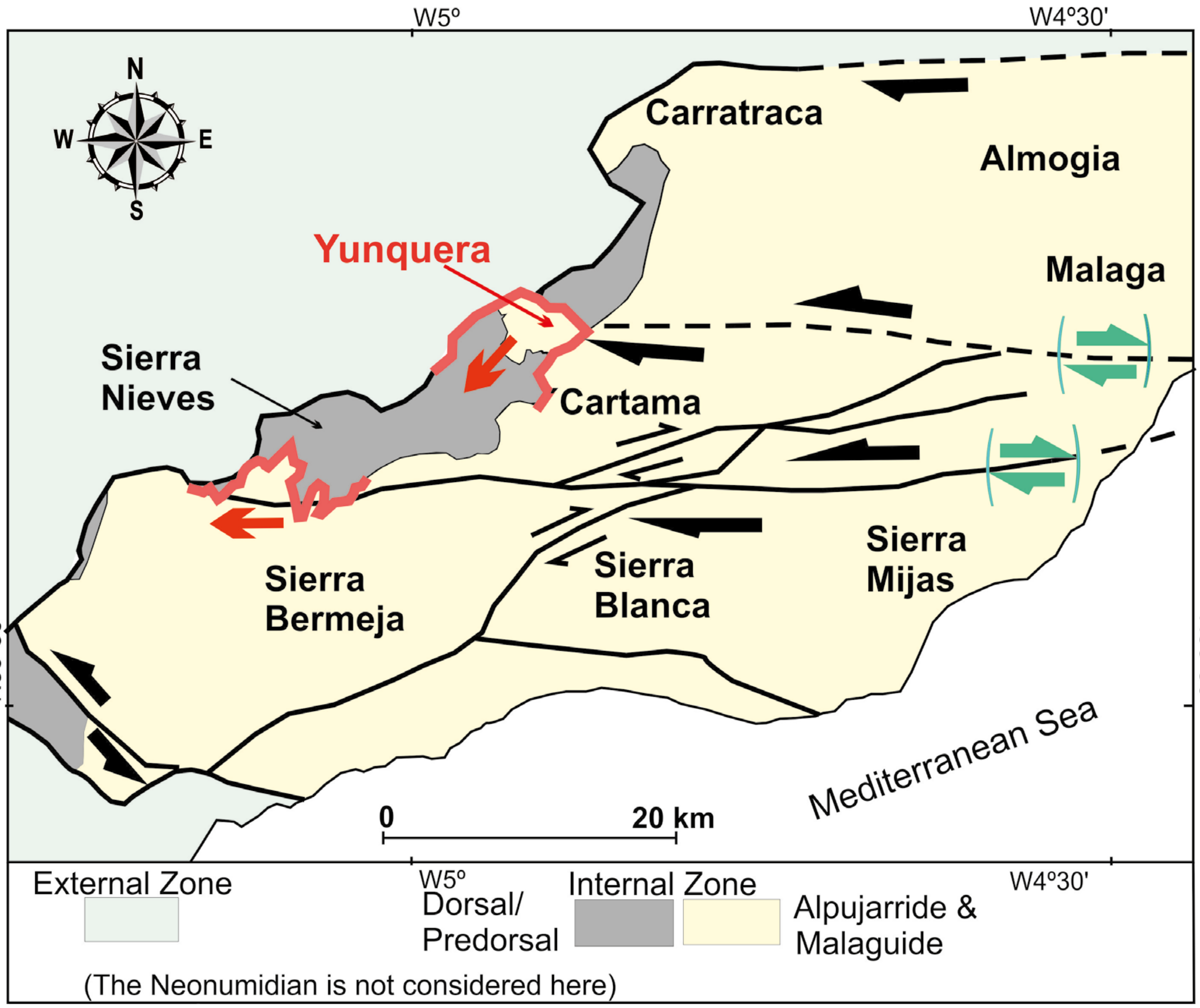

Figure 9.— Tectonic scheme in which the oblique cuts (in red) underwent by the Dorsal in the Yunquera area and to the south of the Sierra de las Nieves are indicated. The red arrows indicate the local directions of displacements. In green, the relative displacements of the fault blocks are marked.

The reason for this “abnormal” thrust of the Alpujarride Complex over the Dorsal is to be found in the gradual and progressive westward displacement of the Internal Zone occurred during the end of the Oligocene and part of the lower Miocene. This movement first caused the thrust and the final embedding of the Dorsal against the Subbetic, but, simultaneously, the pressure exerted by the Alpujarride and Malaguide Complexes continued, culminating into also thrusting over the Dorsal.

But the evolution of deformation in this area was not yet finished: after the thrusting of the Alpujarride Complex over the Dorsal, and also linked to the progressive westward drift of the Internal Zone, the previously mentioned thinning and cut of the Dorsal began. This happened because this drifting of the Internal Zone was not homogeneous. The displacement was greater in the area of Yunquera compared with the sector located directly to the NE. This differential movement produced the thinning of the Dorsal. The cut had a sense of displacement of N230º (N50º, top to the SW), also coincident with the direction obtained in the fault zone affecting the Saucillo unit. Both aspects were linked. In fact, this fault zone begins exactly in the zone of the cut of the Dorsal.

The aforementioned differential displacement implied in the cut of the Dorsal is here interpreted as produced by the movements of very important regional E-W dextral strike slip faults (Figs. 2, 9 and 10) which facilitated in each case a greater advance of the southern segments of the Internal Zones in relation to those situated in the northern sectors (Sanz de Galdeano, 1996 and 2020). This happened in the study area and also to the south of the Sierra de las Nieves (Fig. 9), where the Dorsal forms a reversed syncline whose southern part is metamorphosed by the thrust of the Alpujarride Complex (Dürr, 1967, Piles Mateo *et al*., 1978; Martín-Algarra, 1987), (there the Jubrique/Los reales unit is represented not only by the peridotites but also by the rest of its lithological sequence).

As indicated previously, the Yunquera unit is a local duplication of the Alpujarride domain. In the study area, before its individualization, the Yunquera unit occupied the frontal part of the Alpujarride Complex during the thrusting over the Dorsal (Fig. 4, area in red color). In its advance, and superimposition, the basal part of the Yunquera unit was partially cut, being at the same time progressively embedded. Then the whole of the Alpujarride domain also thrusted over this embedded sector, forming the "small" slice of the Yunquera unit.

But probably, the present bevelling of the bottom of the Yunquera units was formed in two stages, first during its emplacement, and, partially, later during the cut and shearing of the Dorsal, something that also affected this unit.

The Saucillo unit (also containing rests of other Intermediate units) is situated over the Yunquera unit. In this regard, it has the same tectonic position than the Intermediate units in the area of Gaucín (Didon *et al*., 1973; Sanz de Galdeano *et al*., 1999 and 2001), where they are also placed over the Jubrique-Los Reales Alpujarride unit. But the difference is that the Saucillo unit is tectonically placed over the Dorsal, contrarily to what happens in the area of Gaucín (Fig. 4).

The position of the Neonumidian unit is generally clear: it is tectonically placed over the rest of the units, but it is involved in the northern strike slip shear zone, inside which it locally appears forming thin vertical splinters.

The age of formation of the different structures

The thrust of the Malaguide Complex over the Alpujarride Complex was the first structure that formed, regionally, as it pertains to the present study. It is related with the main alpine tectonic structuring of the Betic Internal Zone, and took place before the end of the Oligocene (Durand-Delga & Fontboté, 1960, 1980), although several authors thinks that it continued till the end of the Aquitanian (Martín-Algarra, 1987; Jabaloy *et al*., 2019). This affirmation, the first main alpine structure, would be false if the emplacement of the peridotites occurred during the Aquitanian (Esteban et al. 2011, among other authors) or in any Cenozoic times, but for Sanz de Galdeano & Ruiz-Cruz (2016) this happened many time before, at the end of the Carboniferous, beginnings of the Permian. In fact, analyzing the regional position of the peridotites, they are situated under the Jubrique unit, even when they thrust, for instance, the Dorsal in the Sierra de las Nieves or the Blanca unit in the Sierra Alpujata.

This was, the final Oligocene - Aquitanian, the initial moment, while the last moment of structuring in the study area corresponds to the thrust of the Neonumidian over the rest of the tectonic units and the cut of the Dorsal.

As pointed out before, the Neonumidian is considered Burdigalian (Bourgois, 1978) and immediately during this time it was tectonically emplaced. This is confirmed approximately 20 km to the E, in a sector located to the north of Cártama, where the Neonumidian thrusts over early marine Burdigalian sediments (Sanz de Galdeano *et al*., 1993), abruptly cutting their sedimentation. Moreover, the Neonumidian is included in the form of splinters in the strike slip fault zone of the Saucillos area, something that occurred during the Burdigalian, probably not reaching the Langhian.

Consequently, the interval of time in which the studied structures were formed spans from the end of the Oligocene to the Burdigalian. And the image obtained is that their formation was a continuous and not interrupted process.

On the whole, this process can be described as follows:

Just before the end of the Oligocene the main structuring of the complexes of the Betic Internal Zone was achieved (the Nevado-Filabride Complex was thrust by the Alpujarride Complex, and this last by the Malaguide Complex). Immediately, the process-es of the westward drift of this Internal Zone began, and the Betic External Zone underwent its oblique impact. This was the moment of the superimposition of the Dorsal/Predorsal over the External Zone, the Subbetic. But the westward drift continued and, with the Dorsal embedded against the Subbetic, then, the Malaguide and Alpujarride complexes (together with the Intermediate units) thrust over the Dorsal in the study area, and metamorphosed it partially.

According to the age proposed by Martín-Algarra & Estévez (1984) for the Nava Breccias (containing metamorphic clasts inherited from the Dorsal) and the age of the Alozaina Formation (Bourgois *et al*., 1972a), this thrust of the Alpujarride Complex occurred during the Aquitanian. But the process of structuring continued (because the westward drift continued), and then, during the Burdigalian, the Neonumidian arrived, it thrust over the rest of units and, at the same time, the Internal Zone broke in important E-W dextral strike slip faults. This was the time when the Dorsal was totally cut in the Yunquera area, moving its southern part to the SW and, directly related to this, the strike slip zone affecting the Saucillo area also was formed.

This is, approximately, the sequence of deformation in the study area, a continuous sequence, practically uninterrupted during the entire process.

The relationship of the Yunquera and Saucillo units with the rest of the Alpujarride Complex in its western part

As indicated in the background, the Yunquera unit has been compared to the so called Reales or Jubrique and Blanca units. These comparisons were made taking into account the respective tectonic positions and the lithologic sequences.

The tectonic position is clear for the Yunquera unit. It is a slice situated under the whole mass of the Alpujarride Complex in this area. Regarding the lithologic sequences existing in this Alpujarride western area, there is great similarity between all of the outcrops. In all the areas indicated in the figure 10, there are gneisses in the lower parts of the metapelitic sequences (with the exception of the units located in the western frontal areas, the Intermediate units, mainly situated to the west of Jubrique). In many locations, peridotites are found under these gneisses, suggesting that the gneisses were the aureole covering the peridotites.

Only in the sectors of Santi Petri, Cártama (Mon, 1971; Chamón *et al*., 1978) and Yunquera (see Fig. 10 for these names), the peridotites are not visible under the gneisses. In the eastern part of the Cártama sector there are peridotites located over the Cártama unit thanks to a thrust of fragile character (the Majada Vieja unit, Mon, 1971) (Fig. 8 H). This superposition is here interpreted as being due to the effects of two dextral faults limiting the Cártama sierra. In the Yunquera unit the absence of visible peridotites is interpreted as the effect of its beveled bottom. In the other two sectors, Santi Petri and Cártama, the peridotites are not visible because the erosion is not deep enough to allow for them to be seen. But very probably they exist.

The area of Sierra Blanca (and the equivalent of Sierra de Mijas) has been considered a unit thrust by the Guadaiza unit. But the Guadaiza unit does not exist as a separate tectonic unit (Sanz de Galdeano, 2017), rather, it is the same Jubrique /Los Reales unit. And Sierra Blanca and Mijas actually correspond to huge reversed folds, representing to the top of the lithologic sequences, whose lower parts are directly located to the south (Sanz de Galdeano & López-Garrido, 2016; Sanz de Galdeano, 2019). This means that both sectors had originally the peridotites at their bottom and, directly above the peridotites, the gneisses and the rest of the sequence are there.

Over the gneisses, in every sector of this western Alpujarride region, there are brown schists and, above them, phyllites. But the thickness and even the aspect of the phyllites are variable. For instance, in the Jubrique area to the west of the Genal River, more than 100 m of thickness of these rocks can be seen, having gray blue color. More or less the same happens in the Carratraca area, while in other sectors, for instance in Yunquera, these rocks practically do not exist under the marbles. However, this feature probably results from the combination of lithologic facies and metamorphic degree.

The marbles are not conserved in all the sectors of this region. For instance, in Santi Petri area they have being tectonically cut for the superimposition of the Malaguide Complex. Nevertheless, in Sierra Blanca and Mijas they are greatly conserved. But on

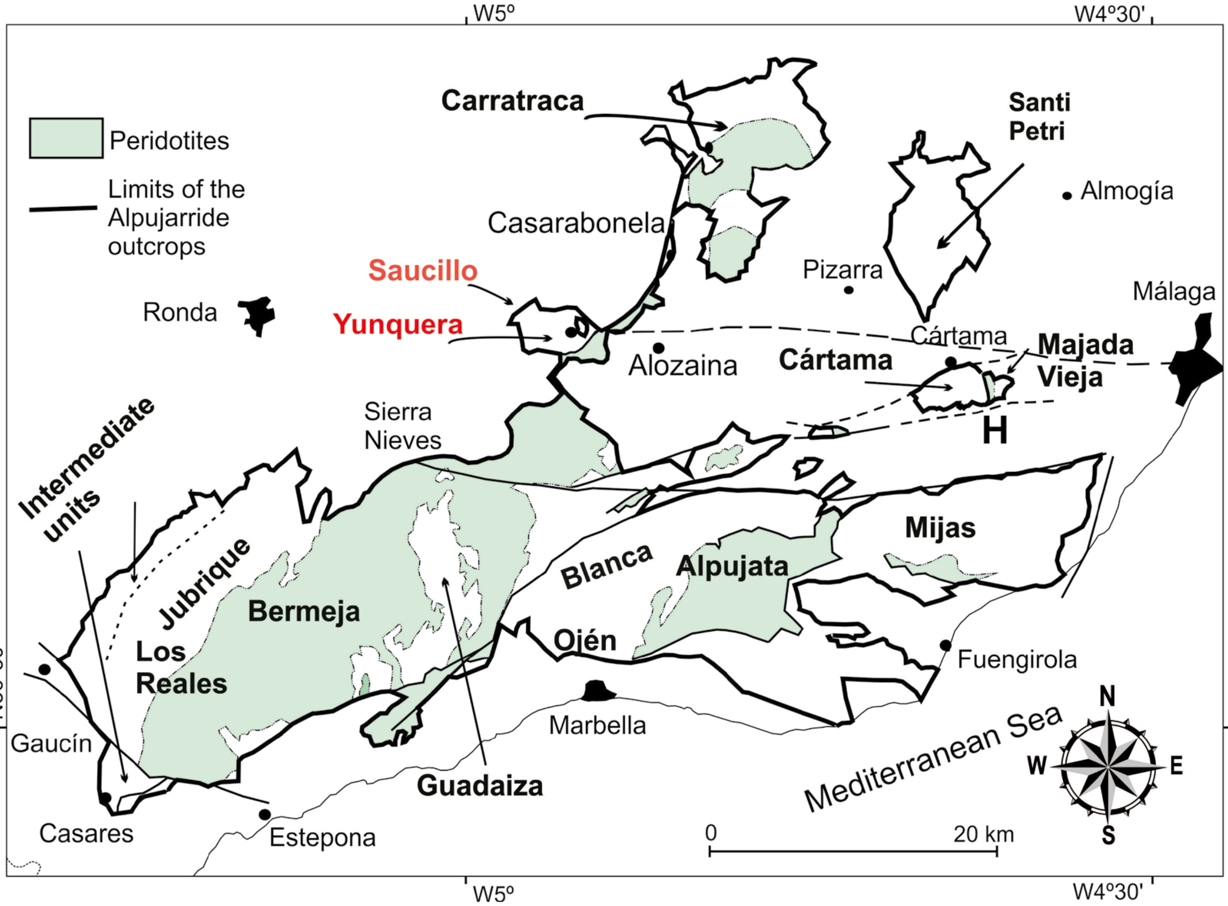

Figure 10.— The western area of the Betic Internal Zone, with the names of the main Alpujarride outcrops of this region. The position of photo H is indicated.

the whole, these marbles are equivalent in all of the sectors of this region.

The revision of the lithologic sequences of this western part of the Alpujarride Complex, allows for the conclusion that inside it (apart from the Intermediate units) the different outcrops existing are in reality equivalent, although the Yunquera unit can be differentiated as a tectonic slice.

Regarding the Saucillo unit, this one is easily correlatable, as it was done, with the Intermediate Units (or Benarrabá imbrications), occupying the same tectonic position. In the Saucillo area, rests of several of these units actually also exist, although very tectonized inside the strike slip fault zone.

Conclusions

The Yunquera tectonic unit corresponds to a big slice, differentiated within the upper unit of the Alpujarride Complex in the western part of the Betic Internal Zone. Its lithologic sequences present gneisses at the lower visible part (probably indicating the former existence of lower peridotites), something common in this sector of the Alpujarride Complex. Both features were previously known.

The brown schists located over the gneisses pass towards marbles in a stratigraphic transition, alternating both types of rocks, but there aren't any intercalations of marbles in lower positions. Within the marbles there are metadetritic intercalations, changing facies laterally, in some places from quartzites to phyllites.

The bottom of the Yunquera unit is beveled. This happened probably during the initial thrust, and perhaps also later, when the Dorsal was tectonically cut and sheared. This cut is important, in such a way that the Dorsal is entirely laminated in one sector of the

Yunquera area. The cut is linked to the westward drift of the Internal Zone, a not homogeneous advance made by differentiated segments, with more important displacements in the southern ones. In this westward advance, the Dorsal thrust over the Subbetic, and during the prolongation of this advance, the Dorsal was embedded in it. However, the Alpujarride and Malaguide complexes continued their advance and also thrust over the Dorsal. This is an opposite tectonic position to that existing in the western end of the Internal Zone, in the area of Gaucín-Jubrique.

Linked to the cut of the Dorsal is the strike slip fault zone, in which the Saucillo unit is located, a unit that actually contains rests of other Intermediate units and even of the Malaguide Complex.

All these structures were formed from the end of the Oligocene until the Burdigalian, probably before the Langhian. The oldest time boundary corresponds to the regional thrust of the Malaguide Complex over the Alpujarride Complex, while the youngest ones are coeval to the thrust of the Neonumidian, the cut of the Dorsal and the strike slip zone of the N of the study area. But it all occurred within a continuous and progressive process.

Regionally, the Yunquera unit –although differentiated as a tectonic slice- can easily be integrated within the ensemble of the western Alpujarride outcrops, which can be denominated with the general name of Ubrique/Los Reales unit.

The Saucillo unit, and the tectonic rests linked to it, clearly corresponds to the Intermediate units, better observable to the SW in the area of Benarraba-Gaucín-Casares, which is regionally situated between the Malaguide and Alpujarride complexes.

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