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Low-angle detachment faults vs. transcurrent structures in the Betic Internal Zone: the case of the Mecina fault and the system of faults south of the Sierra Nevada

Fallas de bajo ángulo vs. estructuras transcurrentes en la Zona Interna Bética: el caso de la falla de Mecina y el sistema de fallas del sur de Sierra Nevada

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ABSTRACT

The Mecina fault, located to the SW of the Sierra Nevada, affects the contact between the Nevado-Filábride and Alpujárride complexes. Later, its characteristics were extended to this entire contact, then defined as the detachment of Mecina, which has been interpreted as separating two tectonic levels: the upper one, the Alpujárride, widely fractured, and the lower one, the Nevado-Filábride, free of these deformations. But the features initially attributed to this fault need to be integrated with those of the dextral E-W faults band of the Alpujarran corridor. In this band, all the rocks, including those from the Nevado-Filábride, are clearly affected. In addition, to the W of the Sierra Nevada other deformations due to the enormous uplift there happened also affect the Nevado-Filábride complex. The tectonic laminations existing in this latter complex can be attributed above all to the effect of the faults band and the cited uplift. The prolongation of the proposed Mecina detachment under the Granada basin, as the main detachment level, is not supported by the evidence, nor is its continuation under the Betic External Zone.

Keywords: Betic Internal Zone; Extension; Tectonic detachments; Tectonic laminations.

RESUMEN

La falla de Mecina se sitúa al SO de Sierra Nevada y allí afecta al contacto entre los complejos Nevado-Filábride y Alpujárride. Posteriormente su significado se extendió a todo este contacto, definiéndose entonces el detachment de Mecina, un despegue que, según se interpreta, separa ambos complejos, ampliamente fracturado el superior, el Alpujárride, mientras que el inferior, el Nevado-Filábride, queda por debajo, sin sufrir esas deformaciones. Pero los rasgos inicialmente atribuidos a esta falla se deben integrar junto con los de la banda de fallas E-O dextrorsas del corredor de las Alpujarras. En esta banda todos los materiales allí presentes, incluidos los del Nevado-Filábride están netamente afectados. Además, al O de Sierra Nevada hay otras deformaciones debidas al enorme levantamiento allí producido que afectan también al Nevado-Filábride. Las laminaciones que se observan en este último complejo se pueden atribuir sobre todo a ambos rasgos. La prolongación bajo la cuenca de Granada del propuesto detachment de Mecina como el principal nivel de despegue no se observa justificada y, menos aún, su continuación bajo la Zona Externa Bética.

Palabras clave: Despegues tectónicos; Extensión; Laminaciones tectónicas; Zona Interna Bética.

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Introduction

Since 1984, the idea concerning a major tectonic detachment situated between the two lower complexes of the Internal Zone of the Betic Cordillera has been developed. This began with the interpretation of the characteristics of the tectonic contact between these complexes on the SW edge of the Sierra Nevada, where it was called the "Mecina fault". Later, the interpretation of the characteristics of this contact was spread regionally, and then came to be considered the Mecina detachment, which now refers to the entire contact of both complexes, then considered as the main feature, although not the only one, that controlled the extension in the Betic Cordillera. The accuracy of this idea, concerning the meaning of the initial description of the Mecina fault and its regional insertion, is discussed in the present study.

Antecedents

Throughout the last century, the different tectonic complexes forming the Betic Mountain Range were defined. A general idea of this division can be had, among many other articles, in Durand-Delga and Fontboté (1980) or in the book on the geology of Spain in relation to the Betic Mountain Range (Vera, 2004). There, the superposition and initial relationships of the tectonic complexes that form this mountain range are shown. However, the first superposition of these complexes was subsequently affected by new deformations. The following background information deals with the evolution of the ideas that interpret these new deformations.

The Mecina fault was defined by Aldaya et al. (1984) as extending from near Lanjarón (Granada province) to approximately Laujar de Andarax (Almería province) on the SW of the Sierra Nevada (see Figs. 1 to 3). For these authors, the Mecina fault included other faults and associated structures. This main fault is located between the Nevado-Filábride and Alpujárride complexes, at some points laminating lithological sequences even kilometres thick. The general displacement of the fault is deduced from striae of direction N230-250ºE and dextral character, with abundant extensional type features, an extensional detachment. On this basis, the above authors contended that these movements correspond to a notable transtension. They also cited E-W subvertical strike-slip faults to the south of the Sierra Nevada, in the Alpujarran corridor, that overlap the previous structures. These faults were subsequently described by Sanz de Galdeano et al. (1985).

Galindo-Zaldívar (1986) studied a sector of the SW of Sierra Nevada and there described the Mecina fault as low-angle dextral transtensional. Also, to the south of this sierra, this author pointed out normal faults with dextral components that affect materials of the Alpujárride complex and the Neogene sediments, as well as cited the presence of crushing bands, cataclasites.

Later, the characteristics of the Mecina fault began to be attributed to the entire contact of the two aforementioned complexes. García-Dueñas and Martínez-Martínez (1988) held that this contact is extensional (they called it "el Despegue Extensional de Filabres") and undergoes a thinning that exceeds more than 5 km in some verticals. Galindo-Zaldívar et al. (1989, 1991, 1996) described this fault as an extensional detachment with movement of the roof (the Alpujárride complex) towards the W/SW. That is, it was considered a detachment superimposed on a previous surface of thrusting of the Alpujárride complex over the Nevado-Filábride. In their review, these latter authors established the idea that the Alpujárride complex slides on the Nevado-Filábride, while the latter is not affected in its interior, or is affected very little. Then, these authors used the name Mecina detachment for this extensional contact with W movement, which, depending on the point, veers towards the NW or towards the SW. These authors also indicate that in the SW part of the Sierra Nevada there is high-angle NW-SE normal faults (such as the Nigüelas fault) that do not cut through the Nevado-Filábride complex; these were interpreted as less important faults that moved later. That is, in their interpretation, the Nevado-Filábride complex is not cut by faults. It remains unaffected except by the detachment between the two complexes and by some minor faults associated with it.

Jabaloy et al. (1992) described the displacements attributed to this Mecina Extensional System since the lower Miocene (Burdigalian), in which these authors estimated a minimum extension of 104%. Like the previous authors cited, the direction of displacement of the deformations was deemed to be towards the W-WSW, varying locally. Their figure 2 shows faults that affect the Sierras Alhamilla and Cabrera, as well as others in the Alpujarran corridor. According to these authors, the aforementioned displacements would be determined by the openings farther to the E in the Liguro-Balearic basin.

Martínez-Martínez (2006) pointed out the existence of a dextral strike-slip transfer fault zone, with a general movement towards the WSW. These faults are situated in the Alpujárride complex, just south of the Sierra Nevada. In this sense, it should be noted that, earlier, Sanz de Galdeano (1989) and later Sanz de Galdeano et al. (2010) described strike-slip faults in an E-W direction that affect the Nevado-Filábride and Alpujárride complexes in the Sierras Alhamilla and Cabrera (located to the E of Sierra Nevada), in addition to those reported by Sanz de Galdeano et al. (1985) south of the Sierra Nevada.

Madarieta-Txurruca et al. (2021), studying the NE faults of the Granada basin, separated high-angle faults from low-angle ones. The latter reach a depth of between 6 and 12 km, with deep movement that appears to coincide with the Mecina detachment. Later, Madarieta-Txurruca et al. (2024) examined the SW part of the Granada basin, extending the Mecina detachment there, even below the External Zone (under the Subbetic). The displacement was proposed to be towards the W or WSW, as in previous studies cited.

Geological setting

As indicated, the Mecina fault (Aldaya et al., 1984) was initially defined in the S part of the Sierra Nevada, where three localities with the name of Mecina are located (which from E to W are M. Alfahar, M. Bombarón, and M. Fondales, all in a similar geological situation). However, as indicated above, it was later considered to be a general detachment in a larger area of the Betic Cordillera.

This cordillera is divided (Vera and Martín-Algarra, 2004) into two main domains: the Internal and External Zones (Fig. 1). Furthermore, the Flysch units (or Campo de Gibraltar units) and the Neogene basins, these last developed on the previous domains, are distinguished.

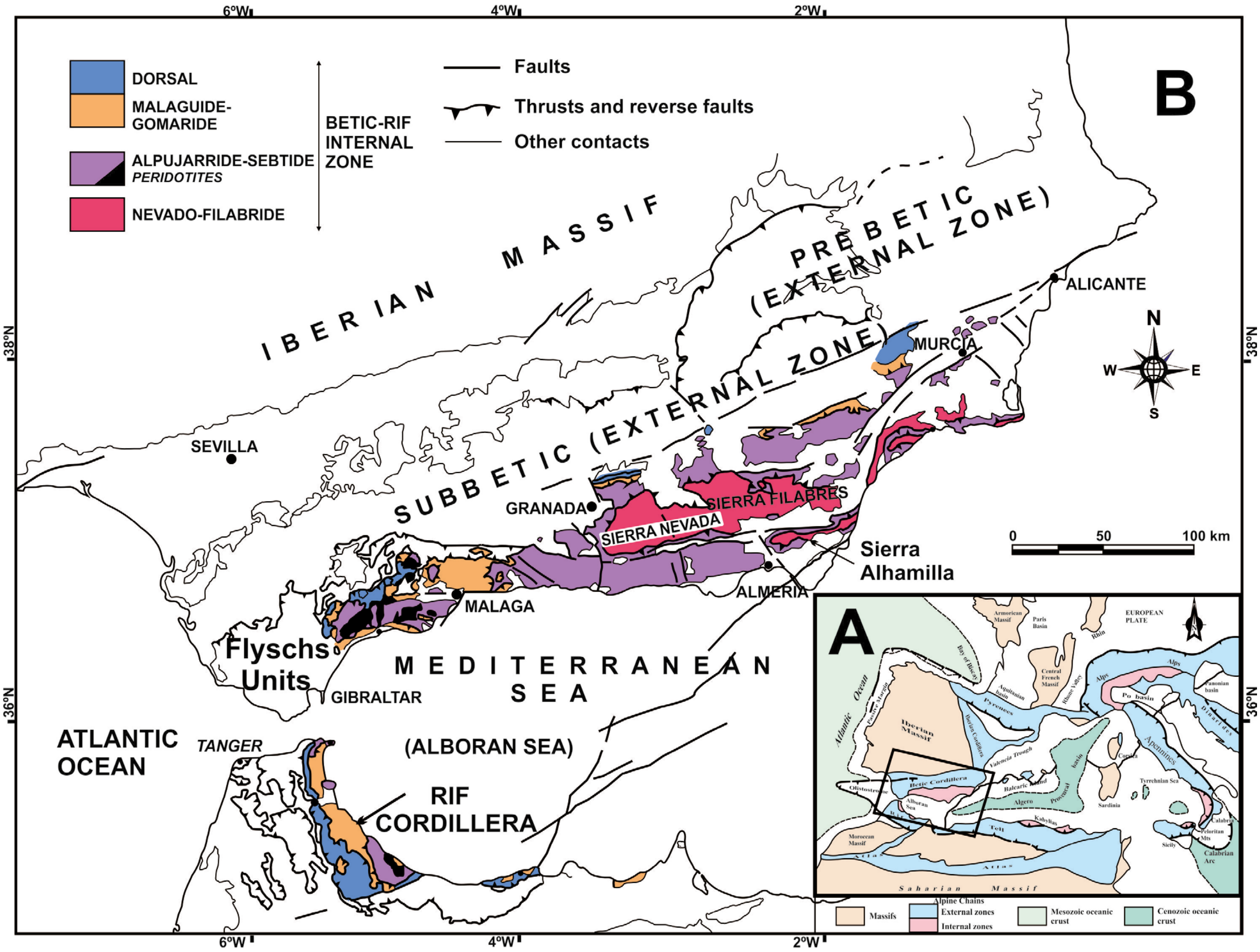

Figure 1.— A: Situation of the Betic Cordillera and the Rif in the western Mediterranean. The rectangle indicates the position of B. B: Distribution of the tectonic complexes of the Internal Zone in the Betic and Rif Cordilleras. Simplified from Sanz de Galdeano (2022).

The External Zone formed the Mesozoic and Cenozoic sedimentary cover of the S and SE part of the Paleozoic Iberian massif. It is divided into Prebetic and Subbetic, that latter having marine sediments of deeper facies than those of the former. It also has some outcrops of basic volcanic rocks.

The Internal Zone is formed by three tectonic complexes that, from bottom to top, are the Nevado-Filábride, the Alpujárride, and the Maláguide (Fig. 1). A fourth complex can be considered, the Dorsal, which is partly linked to the Maláguide and partly independent.

The Nevado-Filábride and Alpujárride complexes present alpine metamorphism, while the Maláguide is fundamentally sedimentary, except towards the bottom, which is somewhat metamorphic. The same is true of the Dorsal, which is generally not metamorphized.

The structure of the Nevado-Filábride complex is discussed because divisions of tectonic units/nappes have been made or, by the contrary, their existence has been contested. For example, Puga et al. (1974) distinguished two nappes, one at the bottom, the Veleta unit, and the other above, the Mulhacén unit. Martínez-Martínez et al. (2002) distinguished three, while Galindo-Zaldívar (1993) and Sanz de Galdeano and Santamaría-López (2019) have disputed the existence of these nappes, arguing that there is a continuity between the different formations of the original stratigraphic column. In any case, with regard to the Mecina fault, the key feature is the global stratigraphic succession, whether it is all a single unit or is formed by several superimposed units. In the Sierras Nevada, Filabres, Alhamilla, and Cabrera, this succession consists of the following lithological formations. The bottom consists of a succession of black schists, sometimes with quartzites, which have a thickness of more than 3500 m. These correspond to the Carboniferous and perhaps part of the Devonian (Santamaría-López and Sanz de Galdeano, 2018). Overlying these are light quartzites and lighter schists that progressively include marbles. Some places have large masses of basic rocks, even ultrabasic, and gneisses. The upper succession varies in stratigraphic thickness (in addition to variations due to tectonic causes), the maximum being about 2 km. Its age spans part of the Upper Carboniferous and Permian, reaching the Triassic, and only locally are other possible more modern materials.

The Alpujárride complex is divided into numerous tectonic units (Aldaya et al., 1979) that, together, can be divided into three groups: lower, middle, and upper. The lower ones are those that are fundamentally in contact with the Nevado-Filábride complex. A general lithological series of the Alpujárride are the following. At the bottom appear dark schists attributed to the Paleozoic, mainly to the Carboniferous, underlying phyllites (including also quartzites) from the lower/middle Triassic (although Ronda peridotites appear in the upper unit, under the schists in the SW part of the Internal Zone, these are absent in the area considered in the present study). The thicknesses of these metapelitic successions exceed 2000 m in some places. Over the phyllites, or in some cases over the schists, lie several formations of marble at some points measuring more than 1500 m. In these marbles, levels of schist and quartzite are locally interspersed. Their age corresponds to the upper Triassic, perhaps at some points reaching the lower Jurassic. Higher stratigraphic formations exist in some units, but do not concern the present study. In general, the units of the lower group have a lower metamorphic grade than those of the middle and upper groups.

The Maláguide complex (Durand-Delga and Fontboté, 1980) is made up of sediments ranging from the Paleozoic to the Neogene. In the area under study, this complex is practically absent only existing small outcrops in the Alpujarran Corridor and in the Sierras Alhamilla and Cabrera. Obviously, is not part of the contact of the Nevado-Filábride and Alpujárride complexes. The same applies to the Dorsal complex.

Main features of the geological evolution of the Betic Cordillera during the Alpine orogeny

Originally the Betic-Rif Internal Zone was located ENE of its current position (Boillot et al., 1984). There, at the end of the Cretaceous and especially during the Cenozoic, several stages of deformation occurred with the development of metamorphism and thrusting of the complexes (including tectonic units in the Alpujárride complex and, to a lesser extent, in the Maláguide).

At the end of the Oligocene/beginning of the Miocene, the Algero-Provençal basin began to open in the western Mediterranean (Durand-Delga and Fontboté, 1980; Boillot et al., 1984; Sanz de Galdeano, 1990, among others). Due to this opening, the Betic-Rif Internal Zone began to be expelled towards the west. At this time the initial superposition of its complexes and tectonic units had largely ended, although in this displacement some new thrusts occurred and readjusted those previously formed.

In this process of expulsion and drift, the Internal Zone collided obliquely with the Betic External Zone, which was deformed. This collision lasted from the lower Miocene to the Serravallian, progressively slowing down. This slowdown was greater towards the north, due to the greater resistance of the External Zone and its basement, and was less pronounced towards the south, where the Alboran Sea (western end of the Algero-Provençal basin) progressively opened at that time. Therefore, due to the different resistance found, the Betic Internal Zone was divided into several parts limited by bands of dextral faults in an approximate E-W direction (Fig. 2) (Sanz de Galdeano, 2020). One of these bands of faults, the main one and best delimited, is that of the southern Sierra Nevada, in the Alpujarran corridor (Fig. 3), as discussed by Sanz de Galdeano et al. (1985), which is of key importance in the present study.

Linked to this process of expulsion of the Internal Zone towards the west, readjustments occurred between the different previously thrust tectonic units, largely connected with the movements produced by the E-W fault bands just mentioned. These deformations and those that will occur later correspond to the topic discussed in this article.

The cited process of the opening of the Alboran Sea, to which the westward expulsion of the Betic-Rif Internal Zone is linked, practically ceased during the upper Miocene, in the Tortonian. Therefore, the compression in an approximate NNW-SSE direction was once again noticed in this region, brought about by the African plate and Eurasia approaching each other. This compression is responsible for the formation of major regional folds, notably the great anticlines that currently forms the Sierra Nevada and the Sierra de los Filabres, among others. This compression has also a practically perpendicular extension linked - that is, in the ENE-WNW direction. Added to these new structures was a conside-

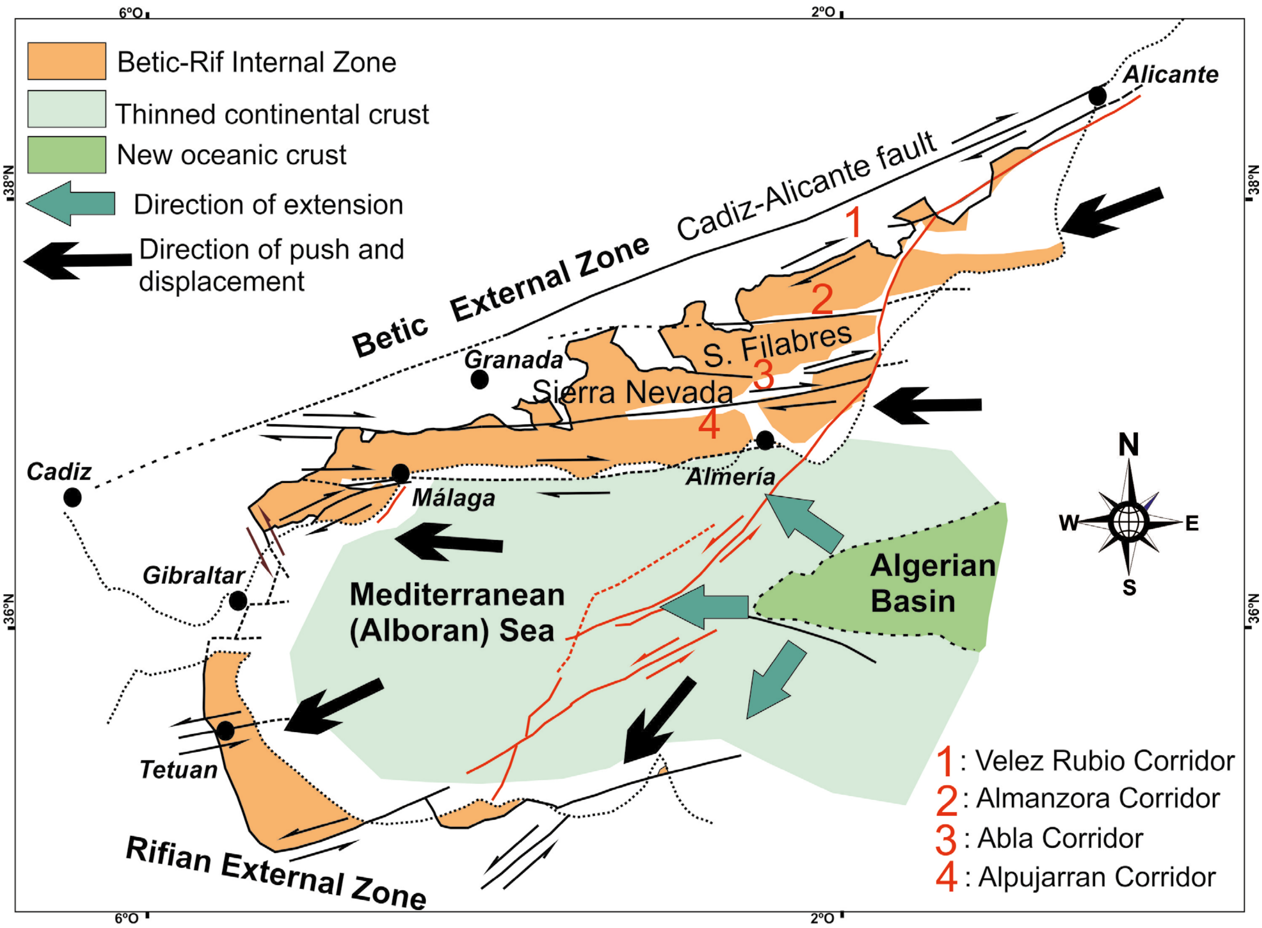

Figure 2.— Main corridors of approximate E-W direction into which the Internal Betic Zone is divided (formed by dextral strike-slip faults). Simplified from Sanz de Galdeano (2020).

rable regional uplift of the Betic Cordillera (Sanz de Galdeano and Alfaro, 2004).

Linked to the aforementioned last compression and extension, large normal faults have occurred in a general NW-SE direction and others, predominantly sinistral, NNE-SSW. The latter are well represented in SE Spain (such as the Palomares and Carboneras faults) and in the Alboran Sea (Fig. 1 and Fig. 2, red lines).

Analysis of the structures relatable to the Mecina fault

This fault is located on the SW edge of the Sierra Nevada. Given this situation, the present study analyses the structures present there but will first to deal with the structures farther to the E, in the Sierras Alhamilla and Cabrera, reaching the sea (Fig. 3), because what occurs in that eastern sector will help to provide an understanding of the structures of the southern Sierra Nevada.

The Sierras Cabrera and Alhamilla sector

The eastern edge of the Sierra Cabrera is cut by long faults (the Palomares and Carboneras faults) of NNE-SSW direction. These are major faults that cut the complexes of the Internal Zone. They were described by Bousquet and Montenat (1974) and later by numerous other authors, among which Larouzière et al. (1988) should be highlighted. These faults are sinistral with displacements of tens of kilometres and separate cortical segments of sharply different thicknesses, noticeably thinner on the eastern side. Their movements occurred mainly during the late Miocene to the present day. These fractures are cited for two reasons: they clearly cut the Nevado-Filábride complex and at the same time displace the E-W faults, the ones fundamentally discussed here.

On the S edge of Sierra Cabrera, the Nevado-Filábride and Alpujárride complexes are cut by dextral E-W faults (Fig. 4 and cross sections 1 to 3, Fig. 5). This happens both at the contact between these complexes and inside the Nevado-Filábride complex itself, affected by cataclastic bands in which many minor structures indicate the direction of the movement. The same occurs to the W, in Sierra Alhamilla. There, near the town of Lucainena de las Torres, the faults are concentrated on its N border and continue until its western end (Fig. 3 and cross sections 4 and 5, Fig. 5). On that N edge, the faults cut the two complexes, but the contact of their original thrust remains farther to the S, although affected by subse-

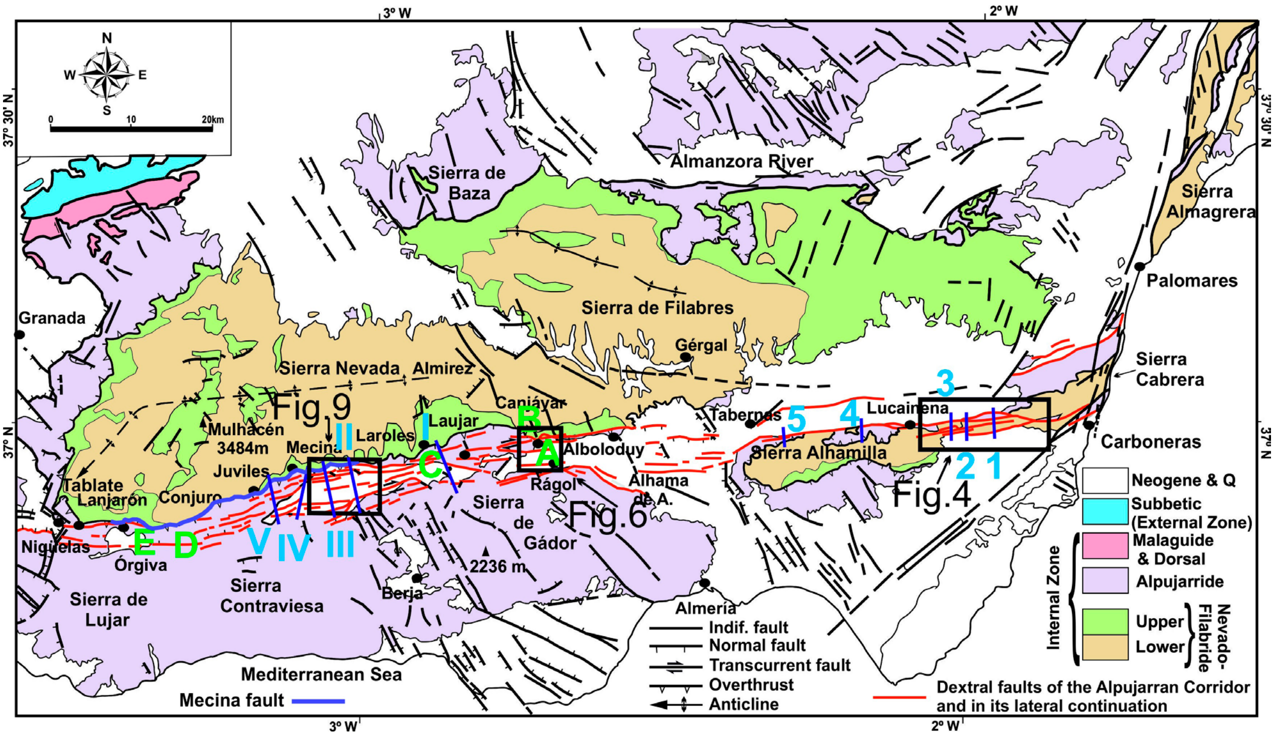

Figure 3.— General distribution of faults in the Alpujarran corridor. Simplified from Sanz de Galdeano et al. (2010). The location of the cross-sections in Figures 5 and 9 is indicated. Green letters indicate the position of the photos in Figures 7, 8 and 11. The rectangles indicate the position of Figs. 4, 6 and 9.

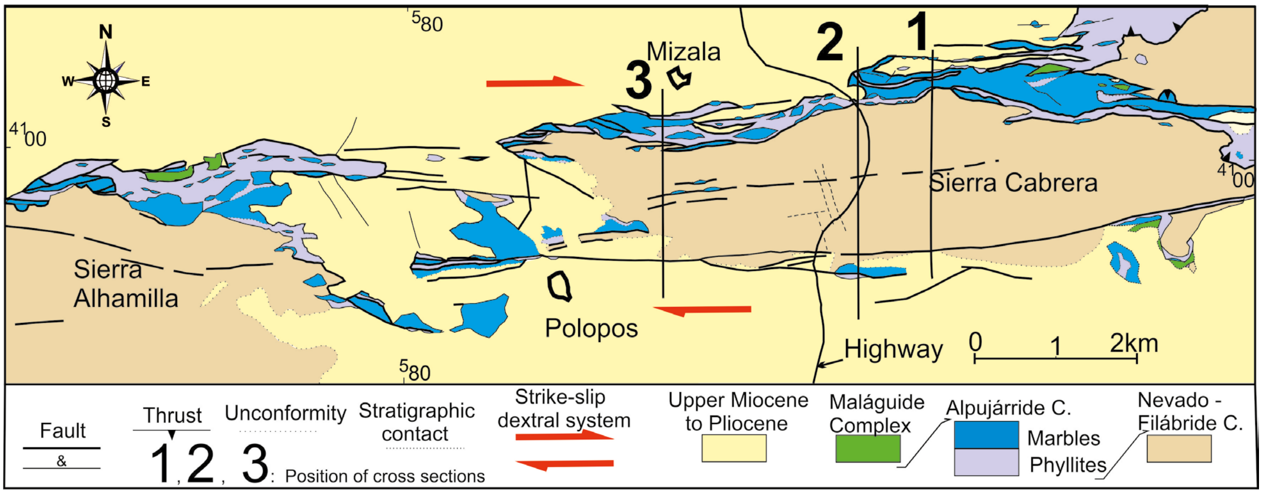

Figure 4.— Schematic geologic map of the S of Sierra Cabrera and the E of Sierra Alhamilla. Cross sections 1 to 3 of Figure 5 are situated in it. Its position can be seen in Figure 3.

quent displacements of the Alpujárride towards the W. However, the clearest displacements are concentrated in the E-W bands of the faults.

To the N and also to the W of the Sierra Alhamilla, dextral E-W strike-slip faults clearly affect sediments from the upper Miocene.

The Tabernas desert sector

The Tabernas desert is located between the Sierra Alhamilla, to the E, and the Alpujarran corridor, to the W (Fig. 3). In this sector, sediments from the upper Miocene and Pliocene crop out and are cut by long E-W dextral strike-slip faults (Sanz de Galdeano et al., 2010). There, the complexes of the Internal Zone do not crop out.

In addition to these E-W direction faults, the presence of normal NNW-SSE faults deserve mention in this sector. These faults form the western limit of the Sierra Alhamilla (Fig. 3). That is, they sink the sierra towards the W and continue towards the N up to Sierra Nevada, where they reach the Nevado-Filábride complex in the vicinity of the town of Gérgal, an area currently undergoing seismicity as clear testimony that this complex is affected and cut off there.

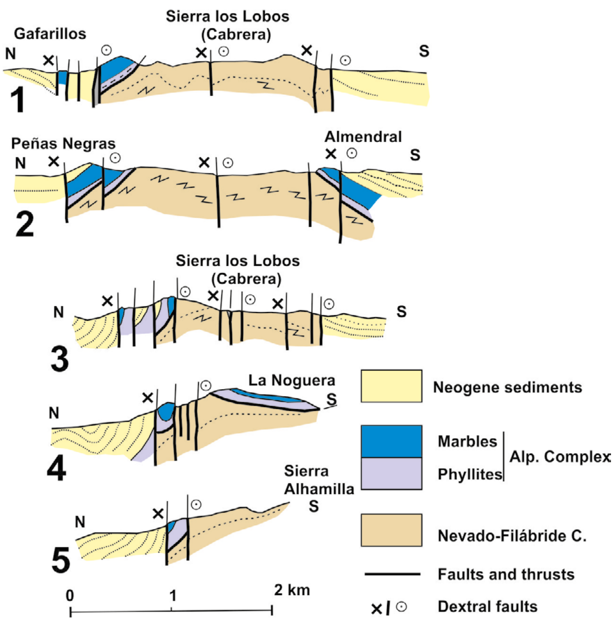

Figure 5.— Geological cross sections in the Sierras Cabrera and Alhamilla. Their situation is indicated in Figs. 3 and 4. Simplified from Sanz de Galdeano (1989).

The Alpujarran corridor

This corridor is a valley that has the Sierra Nevada to the N, while to the south has, from E to W, the Sierras Gádor, Contraviesa and Lújar (Fig. 3). Over 80 km long, it ends at Alboloduy and Alhama de Almería to the E and approximately Lanjarón to the W. In it, there are spectacular outcrops of many E-W dextral faults. These faults affect the entire width of the corridor, although they are more abundant on its northern edge, at the contact with the Sierra Nevada. They affect the Neogene sediments which occupy a large part of it as well as the materials from the Alpujárride and Nevado-Filábride complexes. The present discussion focuses on the N edge.

For its description, the N edge will be divided into three sectors that from E to W go from Alboloduy to Canjáyar, from Canjáyar to Juviles, and from Juviles to somewhat west of Lanjarón.

The Alboloduy to Canjáyar-Padules sector

Here, the original thrust contact between the Nevado-Filábride and Alpujárride complexes is highly tectonized. At many points, vertical E-W faults affects rocks of both complexes, forming sheets interspersed with each other like shuffled cards. The same occurs between the rocks from the Alpujárride and the red conglomerates from the Serravallian. The latter are turned vertical near the faults. In some places, the Alpujárride complex is even completely laminated, and the Nevado-Filábride schists come into direct contact with the red conglomerates (Fig. 6 and Fig. 7 A). All these rocks are heavily crushed, forming cataclastic bands. Photo B (Fig. 7) is another example of this. There the Alpujárride complex is reduced to a thin crushed sheet where Alpujárride marbles are preserved in an almond shape. At many points of this sector, similar features are visible, and numerous almost horizontal striae and minor structures indicate dextral displacements while later vertical or almost vertical striae appear, generally raising the northern block, helping to increase the relief.

The sector from Padules to Juviles

While at many points of the previous sector the E-W faults directly affect the visible contact between the two complexes, Nevado-Filábride

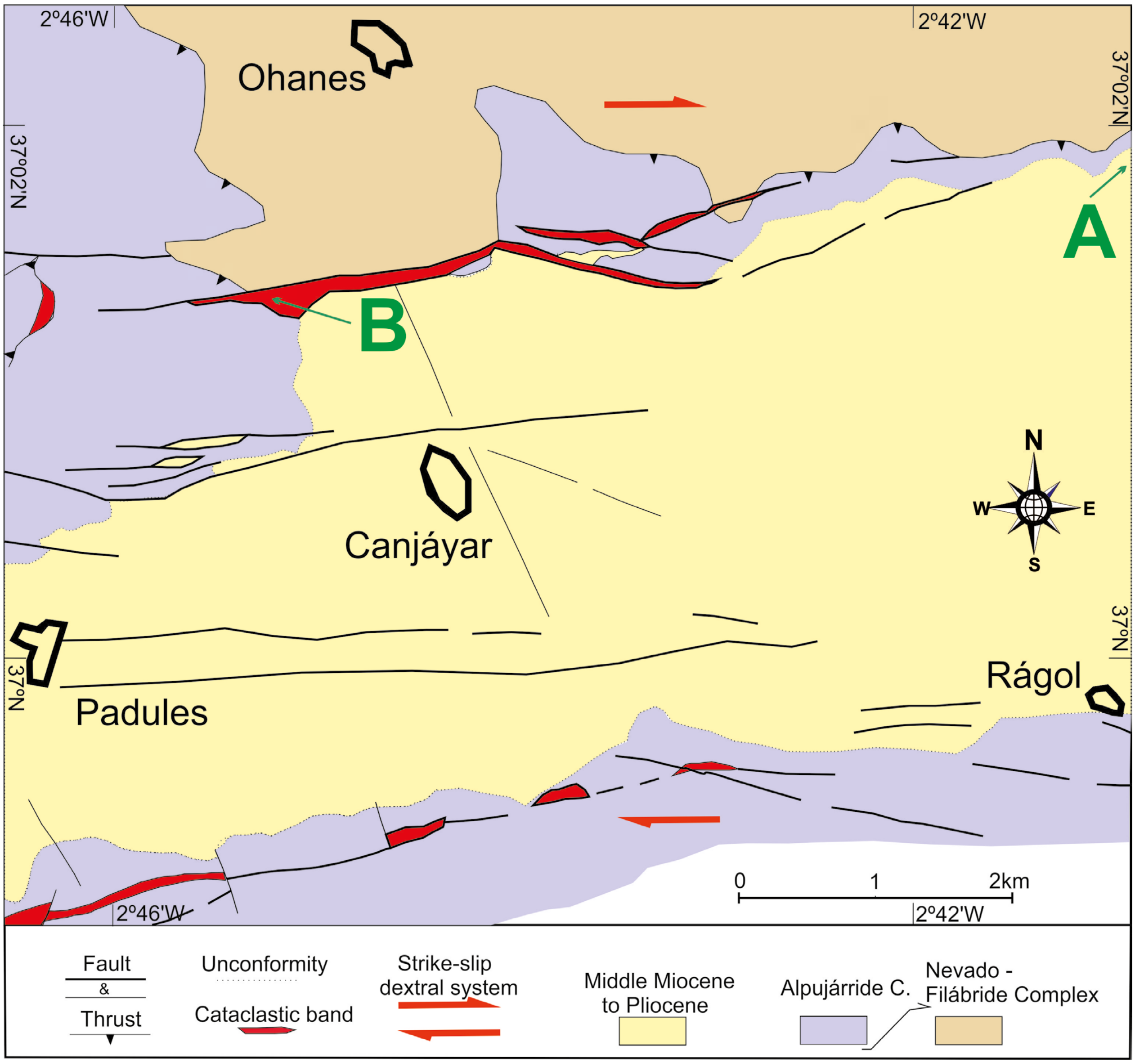

Figure 6.— Schematic geologic map of the area of Canjáyar in the Alpujarran corridor. The position of photos A and B of Figure 7 is indicated.

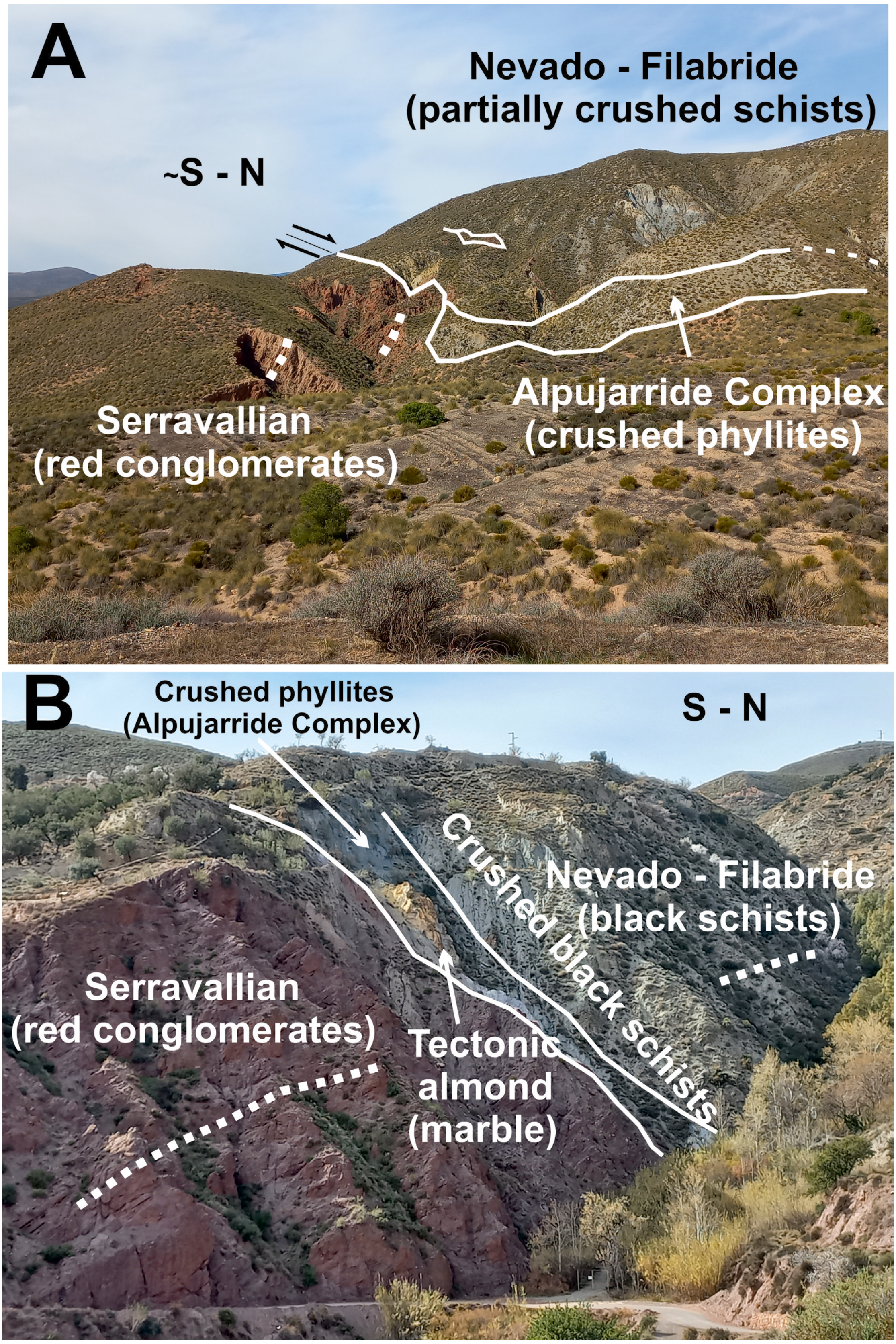

Figure 7.— Two points of interest in the Alboloduy to Canjáyar sector. A: contact between the Nevado-Filábride complex and the Serravallian red conglomerates. The Alpujárride complex, heavily crushed, is locally laminated. The fault is almost vertical. Note the strong dip of the red conglomerates. The photo was taken N of Rágol. B: Contact between the Nevado-Filábride complex and the red conglomerates. From the Alpujárride complex, a narrow band of cataclastic rocks remains that are lost laterally. A tectonic almond of marbles can be discerned in that band. The fault is almost vertical. The view, oblique, is located to the N of Canjáyar. The position of these photos is indicated in Figs. 3 and 6.

and Alpujárride, in this sector the original thrust between the two are better preserved and the E-W strike-slip faults in most cases are located farther to the S. Thus, photo C (Fig. 8) shows the thrust of both complexes as well as an E-W fault to the south that cuts through the Alpujárride at the surface, but this fault extends to the W where it visibly affects the two complexes. This same fault can be followed farther to the E, to Laujar de Andarax, where is visible a normal fault scarp that cuts Quaternary sediments and has practically vertical striae (Martínez Martos et al., 2017), but at other points it shows striae that are almost horizontal with dextral displacement. That is, over many kilometres at the surface, this fault affects only the Alpujárride rocks and other recent sediments, but laterally is located affecting the contact between the two complexes.

The general structure of the corridor in this sector is illustrated by cross-sections I to V (Fig. 10), situated in Figs. 3 and 9. The faults affect all the materials of the corridor, as in the previous sector. Also, bands of intense cataclasis appear, some shown in the cross-sections of the aforementioned figure.

The Juviles sector to the west of Lanjarón

As in the previous sector, the E-W dextral strike-slip faults also exist, but for the most part they appear to involve only rocks from the Alpujárride complex on the surface, and the original thrust between the two complexes is largely conserved, although affected by movements on its surface. Photo D (Fig. 11) depicts these features: rocks from the Alpujárride complex are on top, with finely crushed phyllites at the base, while below lie schists from the Nevado-Filábride complex, of which all of the upper lithologic sequence is absent at some points. There the absence may exceed 1000 m.

The minor structures observed show displacements towards the W or WSW, coinciding with those indicated by Aldaya et al. (1984). In the ancient Conjuro iron quarry, west of Juviles, Alpujarride marbles have normal and vertical faults, and at the contact between the two complexes, striations have a rake of 90º and others measure about 30º towards the west, on an almost vertical surface.

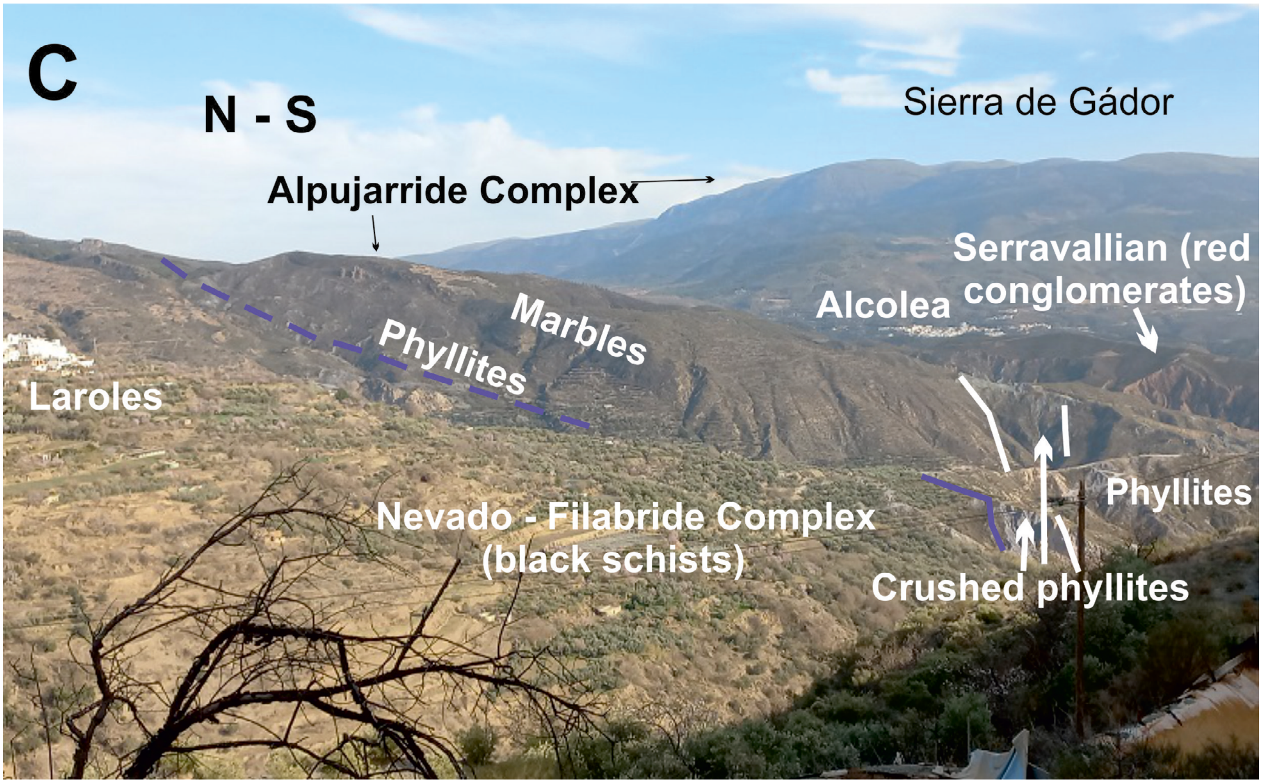

Figure 8.— Photo C, in the Canjáyar to Juviles sector: contact between the Nevado-Filábride and Alpujárride complexes in the Laroles sector. The thrust is visible, and to the south a vertical fault with an E-W direction cuts the Alpujárride on the surface and extends to the W, where it cuts through the two complexes at the surface. Its situation is indicated in Figure 3. The original trace of the Medina fault is indicated in blue color.

In this sector, just to the E of Lanjarón the contact is almost vertical (Fig. 11, E). There the Nevado-Filábride schists are clearly cut and the structure of the formations of the Alpujárride complex is adapted to a vertical movement.

The corridor ends a short distance W of Lanjarón upon reaching the Tablate ravine. There, the formations of the Nevado-Filábride complex are cut by a fault of almost N-S direction (~N10ºE) that sinks the Alpujarride rocks with respect to those of the Nevado-Filábride. In that sector, the upper part of the lithological sequence of the Nevado-Filábride is almost completely laminated, and, at the head of the ravine, cataclastic bands that developed in the schists sink towards the west. Several bands or a single one can be considered, as it anastomoses and divides locally. This fault clearly differs from those that form the Alpujarran corridor. Also farther west, to the NE of the town of Nigüelas, this same structure is repeated, with a fault in the same direction, almost N-S. However, slightly farther to the N, the contact between the two complexes becomes superposition, with the upper lithological sequences of the Nevado-Filábride becoming notably thinned. These almost N-S faults are conjugated with other well-developed NW-SE normal faults in the Granada basin. Here, in the Dúrcal-Nigüelas sector, the throw approaches 800 m, according to the displacement undergone by shallow marine sediments from the upper Miocene. At once, these data indicate that their displacement has occurred since that age.

E-W faults extend farther W in the Lecrín valley and continue in this direction to the N of other mountains occupied by the Alpujárride complex; however, although they serve to show how this set of faults continues, they move away from the visible contact between the two complexes.

The laminations of the high formations of the Nevado-Filábride lithological sequence

Figure 3 shows that the distribution of these formations is irregular. These are well represented in the Sierra de Filabres, especially in its E, N and NW parts. In the upper part of this sierra, erosion has been able to eliminate most of the high formations without any discernible tectonic feature being involved. In Sierra Nevada, in two sectors the high forma-

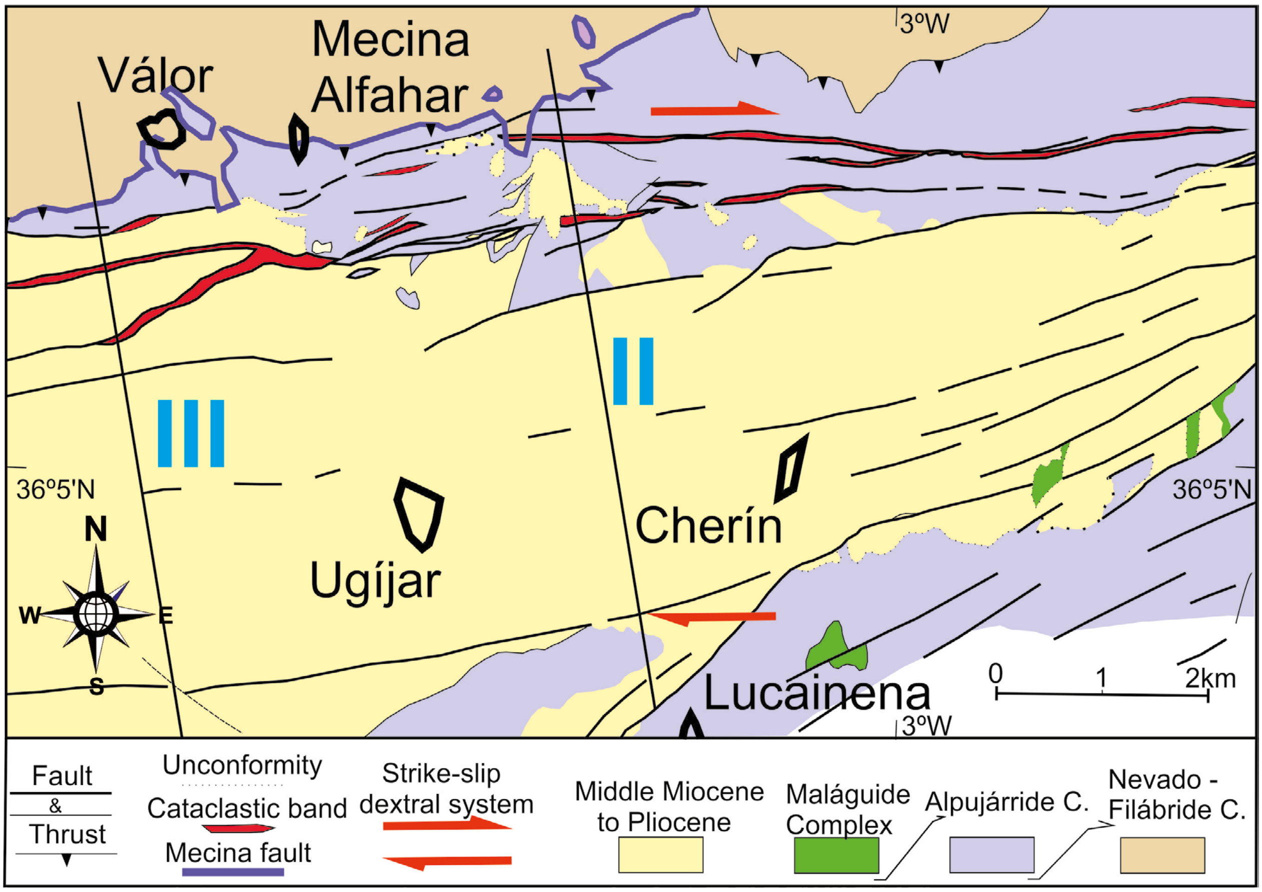

Figure 9.— Schematic geologic map of the area of Ugíjar in the Alpujarran corridor. The position of cross sections II and III of the figure 10 are indicated. The original trace of the Medina fault is indicated in blue color

tions are well preserved. One is the Mulhacén peak sector (3484 m a.s.l.), where, high formations of the Nevado-Filábride lithological sequences, hundreds of meters thick, are preserved and a tight syncline structure appears, partly faulted. The other sector is the Almirez peak area, where thicknesses of the high formations, of the order of 1000 m, are preserved at some points. In these sectors what is missing of the lithological sequences can be attributed to erosion.

By the contrary, on the southern edge of the Sierra Nevada, the upper formations of the Nevado-Filábride lithological sequence become thin, to the point of disappearing at some points. (Fig. 3). In this sector, lamination becomes greatest and furthermore, cannot be attributed to a simple erosive process. On the N edge of this sierra, these high formations are almost completely missing, but at this location the disappearance can be attributed largely to erosion

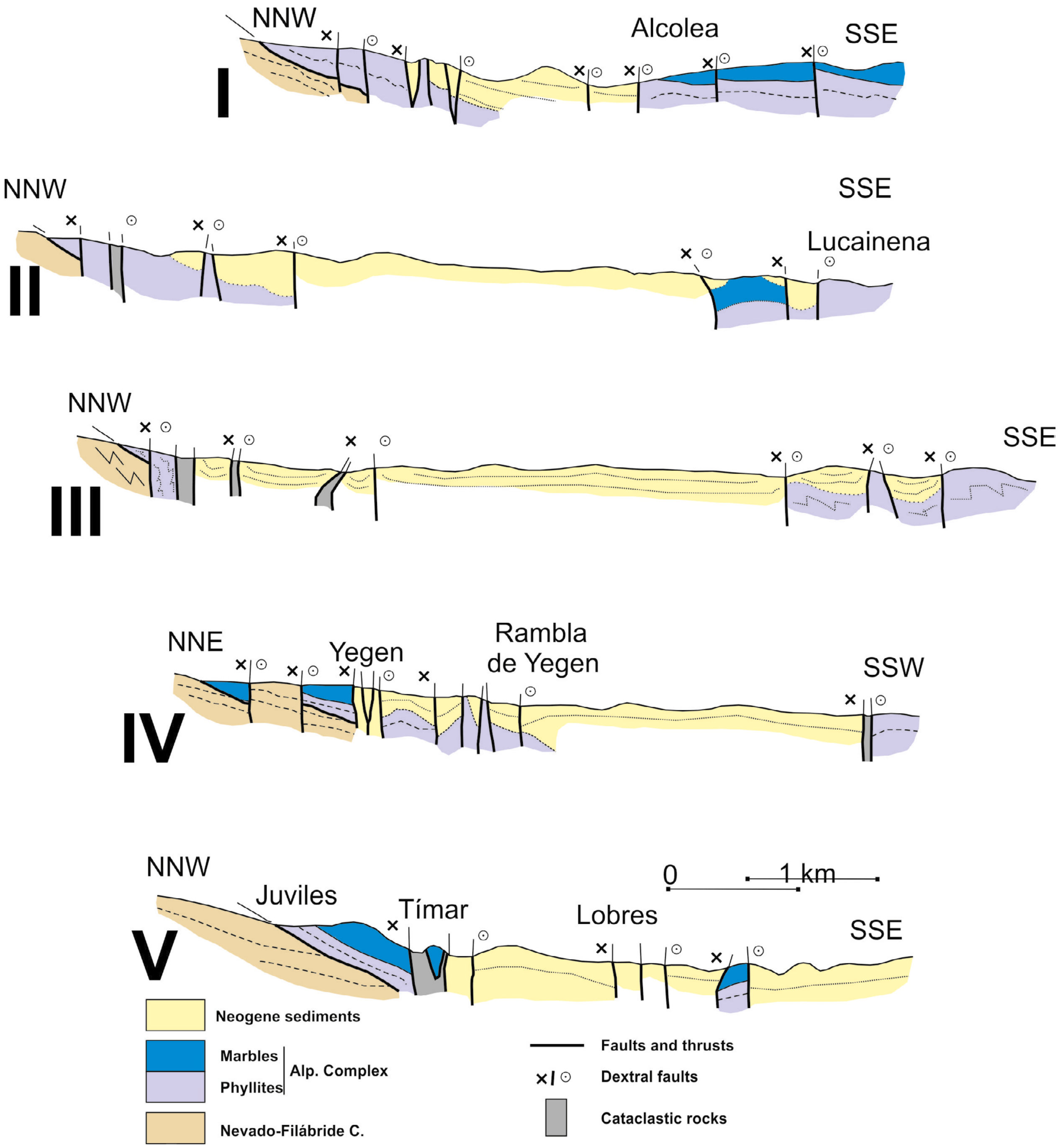

Figure 10.— Geological cross-sections in the Alpujarran corridor. Their situation is indicated in Figure 3 and in part in the Figure 9. Simplified from Sanz de Galdeano et al. (1985).

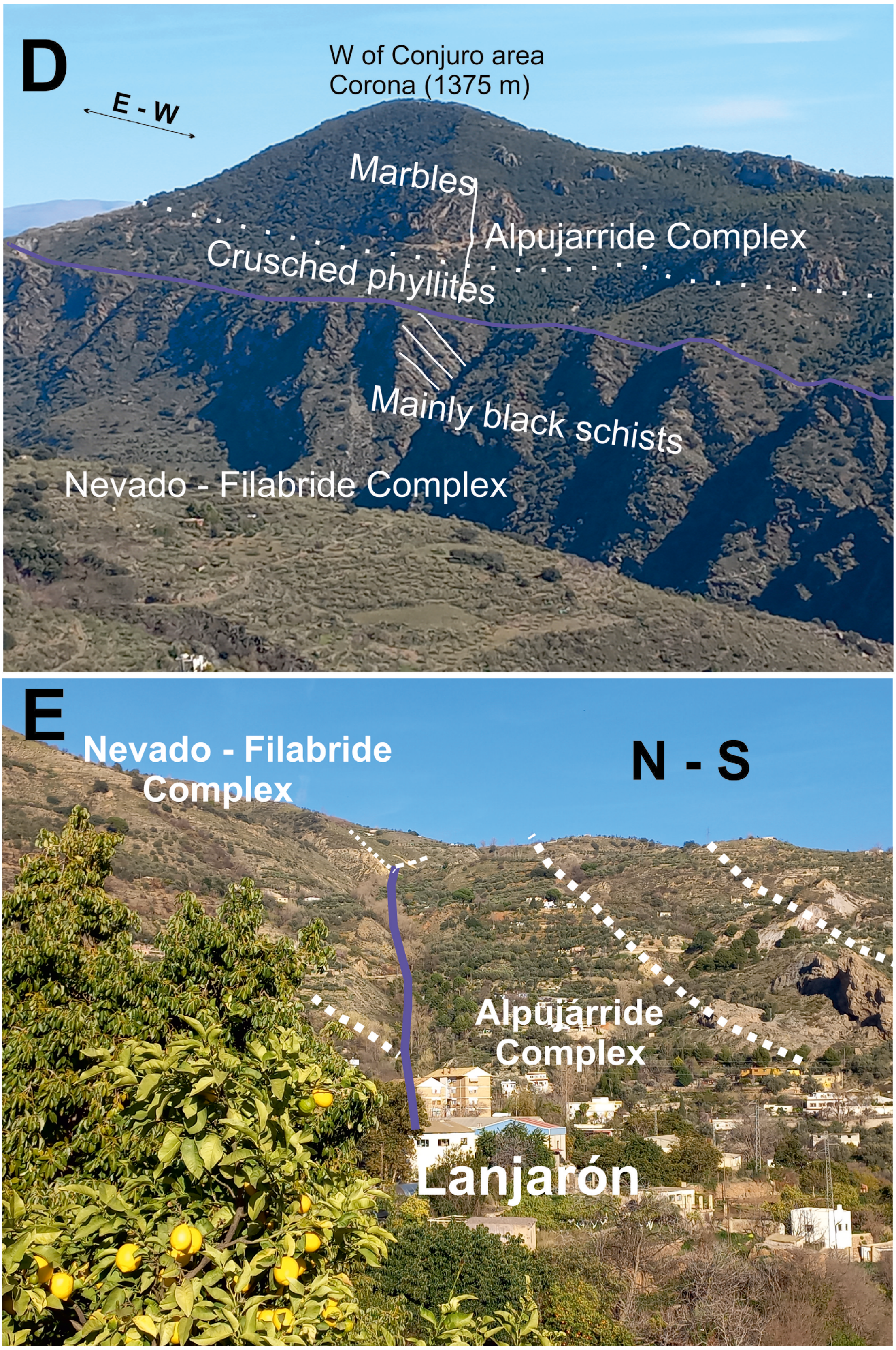

Figure 11.— Two points of interest in the Juviles to Lanjarón sector. D: part of the contact between the two complexes W of the Conjuro mines. This contact is that of thrusting, although it was clearly affected later. In that sector it has a dip of about 30º to the S. Note how schist layers dip more and are cut by the thrust. There, practically no high formations of the Nevado-Filábride sequences are preserved. E: view of the contact between the Nevado-Filábride and Alpujárride complexes to the E of the town of Lanjarón. The contact is almost vertical. Note that the prolongation of the Nevado-Filábride schist layers that must collide with the contact. Also note the curved arrangement of the Alpujárride rocks, a possible adaptation to the vertical throw of the fault. Its situation is indicated in Figure 3.

and also to a fault that marks that limit, currently hidden under Neogene and Quaternary sediments.

On the western edge of the Sierra Nevada the high formations are generally thinned, but not homogeneously: the thinning is generally greater the closer the contact is to the Alpujárride complex. That is, these formations are thinned the farther W they are, while towards the E more thickness are preserved, and there the missing thickness may have been carried away by erosion.

Finally, it should be noted that on the N edge of the Sierra Alhamilla, where the main E-W faults are concentrated, the high formations are missing, being preserved farther south (Fig. 3). In the Sierra Cabrera, the opposite is true, as the main faults appear on the southern edge, and the high levels are missing.

Discussion

In the interpretation that the Mecina fault forms part of a general detachment between the complexes Nevado-Filábride and Alpujárride, the Mecina detachment, the idea maintained is that the Nevado-Filábride is almost not affected or only in its upper parts.

The validity of the initial hypothesis of the Mecina fault

The interpretation proposed by Aldaya et al. (1984) was fundamentally accurate. Indeed, in the sector that goes from Lanjarón to the towns named Mecina in the south of Sierra Nevada, the contact between the Nevado-Filábride and Alpujárride complexes shows movements towards the W and SW. The contention that E-W right-hand strike-slip faults are present farther south is also valid, as clearly shown by Sanz de Galdeano et al. (1985) and Martínez-Martínez (2006).

These faults, from E to W, cut through the Sierras Cabrera and Alhamilla, the so-called Tabernas desert, and the Alpujarran corridor. In these sierras, both the Nevado-Filábride and Alpujárride complexes are cut, including the original thrust contact between them. The same occurs to the south of the Sierra Nevada, where in some places the contact between the two complexes is clearly affected by the aforementioned faults. In other cases, the faults are located farther to the south without directly affecting the Nevado-Filábride at the surface, although laterally some of those faults clearly affect it. Also, these E-W faults extend farther W to beyond the contact between the two complexes, passing through the south of the Granada basin and continue even farther W until they reach the Subbetic. That is, this set of E-W faults, generally vertical, clearly affects the two complexes and the Neogene sediments above them, which are from the middle and upper Miocene, even Messinian and Pliocene, while the latest observed movements are practically vertical, sinking the southern block (Martínez-Martos et al., 2017).

The age of the movements of the E-W faults of the Alpujarras corridor

One question is whether these E-W faults are contemporaneous with the detachment towards the W and SW of the Mecina fault or whether they are later and, above all, whether this detachment from the SW of the Sierra Nevada is genetically linked to the band of E-W faults. In this sense, the displacements of these faults and the Mecina fault are congruent and can have been formed in the same stress system. But previous studies (Aldaya et al., 1984 and Galindo-Zaldívar, 1986) lean towards the interpretation that the E-W faults were formed later.

For clarification of these aspects, it may be useful to examine the distribution of the degree of lamination undergone by the formations of the upper lithological sequence of the Nevado-Filábride complex (Fig. 3). It has been indicated above that these formations are well preserved to the E, N and NW of the Sierra de los Filabres. Moreover, it has been pointed out that in the Sierra Nevada the conservation of these formations is notably uneven. Thus, in the upper part of this sierra, around the highest peak, Mulhacén, these formations are well preserved and the missing sequences can be attributed to erosion. The same applies to the Almirez Peak area. On the contrary, south of the Sierra Nevada, in some places, for example from Órgiva to Conjuro, the high formations are markedly laminated or have even disappeared.

That is, observation indicates that the lamination is much greater where the E-W faults are located (and in the western edge of the Sierra Nevada, as shown below). In the Sierras Cabrera and Alhamilla the entire upper part of the Nevado-Filábride lithological sequence is missing at many points, even some lower formations. In the south of the Sierra Nevada this sequence is absent or extremely thin at numerous points, to a much greater degree than in the high parts of this sierra. That is, the degree of lamination is undeniably higher in the sectors of contact with the E-W faults.

These faults moved first during the early Miocene, particularly during the Burdigalian (Sanz de Galdeano, 1990) and continued during the middle Miocene (this is congruent with the proposed displacement of the Mecina detachment from the Burdigalian, Jabaloy et al., 1992). Later, at the beginning of the upper Miocene, owing to the NNW-SSE compression, the Sierra Nevada anticline began to form, its relief progressively emerging. The new movements began to have a vertical component, although certain eastern sectors (such as in the Tabernas desert and in Sierra Alhamilla) still show notable horizontal movements. Thus, the process of lateral movement of the E-W faults band of the Alpujarran corridor has spanned a long period, from the Burdigalian to the Tortonian south of the Sierra Nevada, and even the Pliocene farther to the E. In general, we are facing a change in the E-W fault regime. From the Burdigalian to the middle Miocene, even later in some places, these faults were of dextral character, but later they changed their regime to normal, contributing, for example, to the uplift of the Sierra Nevada.

These features lead to the following interpretation: the Mecina fault in its original sense is part of a set of structures linked to the E-W faults controlling the Alpujarran corridor. In their movement, they affected both complexes. Thus, in the Alpujárride, in some sectors there is thrust slices congruent with these displacements, in addition to affecting the contact between their units and the contact between the two complexes, clearly cutting them in many points. Moreover, the high formations of the lithological sequence of the Nevado-Filábride complex were laminated by the faults band, while farther to the N the lamination is minimal or absent.

The important uplift of the western border of Sierra Nevada

The aforementioned Sierra Nevada uplift was not limited to its southern edge. On the western border of the Sierra Nevada, the upper formations of the lithological sequence of the Nevado-Filábride complex are quite strongly laminated, this weakening as the distance from the contact increases. This occurs not only in the formations of the Nevado-Filábride complex, but also in those of the Alpujárride units there existing (García-Dueñas and Comas, 1971; Sanz de Galdeano and López-Garrido, 1999, 2000) that have slipped and laminated to a substantial degree. This edge of the Sierra Nevada has risen some 3000 m with respect to the Granada basin. In this sense, it has been pointed out that to the W of Lanjarón two normal faults of NNE-SSW direction cut the formations of the Nevado-Filábride, while units of the Alpujárride complex show notable slips. Farther to the N, these faults have not been detected, although the slip has been found at the contact between the two complexes as well as between the Alpujarride units. Moreover, along this western border of Sierra Nevada, in the Alpujárride complex there are faults which possibly cut deeply into the Nevado-Filábride, but this is not evident on the surface. That is, the lamination of the upper formations of the lithological sequence of the Nevado-Filábride complex on the W border of the Sierra Nevada can be explained by the enormous uplift there from the Tortonian, which is clearly later than many of the movements of the E-W faults band of the Alpujarran corridor.

The existence of different levels of detachment and importance of extension

But the existence of local detachments between Alpujarride units or in the contact between the two complexes, and in deeper positions, is not refuted here. In this sense, detachments are cited within the Nevado-Filábride itself (García-Dueñas et al., 1988) while others must exist below this complex, probably the more important ones. However, the idea of the existence of a general and dominant Mecina detachment is not supported by evidence.

But since the extension in the Betic Cordillera was largely linked to the movements of the proposed Mecina detachment, now it should be reinterpreted taking into account the overall features of the Betic Cordillera and the Alboran Sea. That is, the Alboran area no doubt underwent a clear extension during the early and middle Miocene (Soto et al., 1996; Torné et al., 2000; Talukder et al., 2004) (Fig. 2). Over this process, the Alboran crust thinned, affecting the southernmost part of the Betic Internal Zone. In this sense, the faults band of the Alpujarran corridor facilitated the relative W displacement of the southernmost part of the cordillera in relation to the part located directly to the N, where the Sierra Nevada is located. This displacement gave rise to a net stretching towards the W and WSW in the region (although at the same time in the westernmost part, notable compressions occurred, in the area of the Gibraltar arc). Later, when the opening of the Alboran Sea ceased, a NNW-SSE compression resumed. This compression formed large anticlines, notably the Sierra Nevada anticline, and brought with it a perpendicular extension clearly manifested (among other places) in the Granada basin, including the set of faults on the W border of the Sierra Nevada, which reach the sea in the S. These new faults also facilitated stretching and extension in a practically E-W direction, also coinciding with the previous stretching. Besides, the very existence of these anticlines shows the need for an important detachment located in a deeper position

The lower base level at which the E-W extension occurred has been deduced using the record of seismic data referring to the position, depth, and magnitude of the earthquakes. In relation to this, Morales et al. (1997) indicated that in the Granada basin the hypocentres on average does not exceed 20 km in depth, although some are deeper. Similarly, Galindo-Zaldívar et al. (1999) pointed out the occurrence of several deeper earthquakes in the Granada basin, even of the order of 30 km, although most of these were located at depths of 10 to 20 km. These data point to the existence of detachments to roughly 20-30 km deep, clearly below the contact between the Nevado-Filábride and Alpujárride complexes. Madarieta-Txurruka et al. (2021) have proposed, also on the basis of the seismicity under the Granada basin, that the Mecina detachment may be located at a depth of 6 to 12 km and have conjectured that it corresponds to the position of low-angle normal faults. Nevertheless, even with their data, certain points on the SSE of Granada have hypocentres located at depths that exceed the possible position of the Mecina detachment. Later, Madarieta-Txurruka et al. (2024) have expanded their interpretation of the aforementioned detachment, extending it under the External Zone, under the Subbetic, crossing the oblique transcurrent tectonic contact between both zones. But, according to the reinterpretation now presented, clearly limiting the significance of the proposed Mecina detachment, its prolongation under the External Zone has even less real basis, since no clear data support this conjecture.

Conclusions

The data of the Mecina fault, as defined by Aldaya et al. (1984), clearly show the features of the contact between the Nevado-Filábride and Alpujárride complexes to the SW of Sierra Nevada. This fault is one of the many faults that form the E-W fault band. In this band of faults, moreover the creation of many E-W faults, generally vertical, other previous ones moved again, such is the contact between the two aforementioned complexes. This is the case of the Mecina fault. Consequently, this fault needs to be integrated regionally within the band of dextral strike-slip faults forming the Alpujarran corridor, faults that extend from the sea, to the E, and continue farther to the W of the Sierra Nevada.

This band of faults clearly cut through the Nevado-Filábride and Alpujárride complexes as well as the Neogene sediments. This means that the contact between these two complexes does not constitute an insurmountable barrier. In fact, at numerous points the Nevado-Filábride complex is cut by faults E-W and of other directions. This is clearly visible in the Sierras Cabrera and Alhamilla, and also in the same southern border of Sierra Nevada. According to the total length of this band of faults, of the order of 200 km they can be expected to cut deeply into the crust.

This band of faults was fundamentally dextral and moved mainly from the Burdigalian to the middle Miocene, although in the easternmost part, the transcurrent movements lasted longer. The change of the type of movements of these faults was due to the new compression established between Iberia and Africa of NNW-SSE direction. This compression created new reliefs and these faults moved in many cases as normal, particularly in the Sierra Nevada, facilitating the rise of its relief, which is currently a clear antiform.

The high formations of the Nevado-Filábride lithological sequence are heavily laminated in some sectors, particularly along the S border of the Sierra Nevada and its W limit. In the first case, the lamination can be attributed to the action of the faults band of the Alpujarran corridor and in the second case to the enormous uplift of the W border of the Sierra Nevada, on the order of 3000 m.

The hypothesis of the prolongation of the Mecina detachment as a general and dominant feature under the Granada basin has no strong data to support it, since a considerable number of earthquakes occur below this proposed detachment, indicating the existence of other deeper detachments. In addition, the contention of prolonged detachments under the External Zone lacks currently justifiable support.

Finally, the Neogene extension of the Betic Cordillera is controlled by three factors: one involves the opening of the Algerian basin, the W end of which reaches the Alboran Sea, this resulting from a notable cortical thinning. Linked to this process, the second refers to the stretching of the faults band of the Alpujarran corridor (in addition to the action of the other corridors), particularly in the Internal Zone. Finally, the third is related to the approximately E-W extension perpendicular to the current NNW-SSE compression that affects the region from the Tortonian.

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The author of this article declares that he has no financial, professional or personal conflicts of interest that could have inappropriately influenced this work.

CRediT AUTHORSHIP

Carlos Sanz de Galdeano: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing.

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