Revista de la Sociedad Geológica de España 32 (1)

ISSN (versión impresa): 0214-2708
ISSN (Internet): 2255-1379

THE LITHOLOGICAL SEQUENCE OF THE NEVADO-FILÁBRIDE COMPLEX (BETIC INTERNAL ZONE) IN THE SIERRAS NEVADA AND FILABRES

La secuencia litológica del Complejo Nevado-Filábride (Zona Interna Bética) en las sierras Nevada y de los Filabres

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Abstract: *The lithological sequence of the Nevado-Filábride Complex (Betic Cordillera, S Spain) in the sierras Nevada and Filabres can be divided into four formations. From bottom to top the first corresponds to dark schists and quartzites of about 3600 m thick. Above lie the quartzites of Benitagla and then the Tahal light schists, and at the top lies the schists and marbles Fm. The thickness of the upper formations is on the order of 2000 m. The passage between the formations is stratigraphic and transitional. The metamorphism is inverted, being of higher grade to the top. This feature led to the proposal of superposition of tectonic units, with a higher grade of metamorphism in the upper ones, but the tectonic contacts between these units, according to our data, simply do not exist. The deposit of the lower formation had a syntectonic-compressional character while the other ones formed in extensional and post-tectonic environment in relation to the Variscan orogeny. New faults then formed permitted the extrusion of igneous rocks, including some ultrabasic ones, which according to our scheme were extruded together with basic rocks, not linked to an oceanic crust.*

Keywords: *Betic Cordillera, Betic Internal Zone, Nevado-Filábride Complex, lithological formations.*

Resumen: *La secuencia litológica del Complejo Nevado-Filábride en las sierras Nevada y Filabres, puede dividirse en cuatro formaciones. De abajo arriba la primera corresponde a esquistos oscuros y cuarcitas, con un espesor de unos 3600 m. Encima están las cuarcitas de Benitagla y los esquistos claros de Tahal, y a techo se sitúa una formación de esquistos y mármoles. El espesor de las formaciones superiores es del orden de 2000 m. El paso entre formaciones en general es de carácter estratigráfico y transicional. El grado metamórfico está invertido de muro a techo. Este rasgo indujo a la propuesta de superposición de unidades tectónicas, con mayor grado metamórfico en las superiores, pero los contactos tectónicos entre estas posibles unidades, en nuestra opinión, no existen. El depósito de la formación inferior tuvo un carácter sintectónico-compresional mientras que las otras se formaron en régimen en extensión, ya post-tectónico, en relación a la Orogenia Varisca. Nuevas fallas formadas entonces permitieron la extrusión de rocas ígneas, incluyendo algunas ultrabásicas, que en nuestra opinión fueron extruidas junto con rocas básicas, no ligadas a una corteza oceánica.*

Palabras clave: *Complejo Nevado-Filábride, Cordillera Bética, Zona Interna Bética, formaciones litológicas.*

Sanz de Galdeano, C., Santamaría-López, A., 2019. The lithological sequence of the Nevado-Filábride Complex (Betic Internal Zone) in the sierras Nevada and Filabres. *Revista de la Sociedad Geológica de España*, 32 (1): 113-126.

Introduction and purposes

The Betic Cordillera, together with the Rif, are the westernmost Alpines ranges of the Mediterranean Sea. Its structuring occurred from the Cretaceous and particularly during the Cenozoic. According to its structure the Cordillera is divided into External and Internal Zones, furthermore of the Flysch units (Campo de Gibraltar units) and Neogene basins (Durand Delga and Fontboté, 1980). The External Zone corresponds to the sedimentary Mesozoic and Cenozoic cover of the S and SE border of the Iberian Paleozoic Massif, and according to its greater or lesser proximity to this massif it is divided into the Prebetic and Subbetic (Vera, 1988).

The Internal Zone is divided in four complexes that from bottom to top are: the Nevado-Filábride, the Alpujárride, the Maláguide and, related to the latter, the Dorsal. The Nevado-Filábride and the Alpujárride complexes were metamorphosed during Alpine orogeny. These two complexes present Paleozoic and Triassic successions as well as possible Jurassic and younger metasediments. On the contrary, the Maláguide Complex, which presents Paleozoic, Mesozoic, and Cenozoic formations, was only slightly affected by the Alpine metamorphism or not affected at all in many areas. The Dorsal, formed by Mesozoic and Cenozoic sediments was in general not metamorphosed.

The Nevado-Filábride Complex (NFC) has been divided into two or three tectonic units (depending on the authors; *e.g.*, Puga *et al*., 1974; Martínez-Martínez *et al*., 2002), although locally other units were proposed. In these divisions the different authors set different limits between the proposed tectonic units, shifting in each case to higher or lower positions in the overall NFC lithological sequence. In all these divisions, the tectonic units presenting higher grades of metamorphism are situated over other tectonic units with lower grades of metamorphism (nevertheless, until now, a generalized metamorphic inversion has not been considered in this complex).

Each proposed tectonic unit has its own lithological sequence, mainly formed, depending on the cases, by schists, quartzites and marbles. But if the NFC is considered altogether, then it would result the following: the bottom tec-

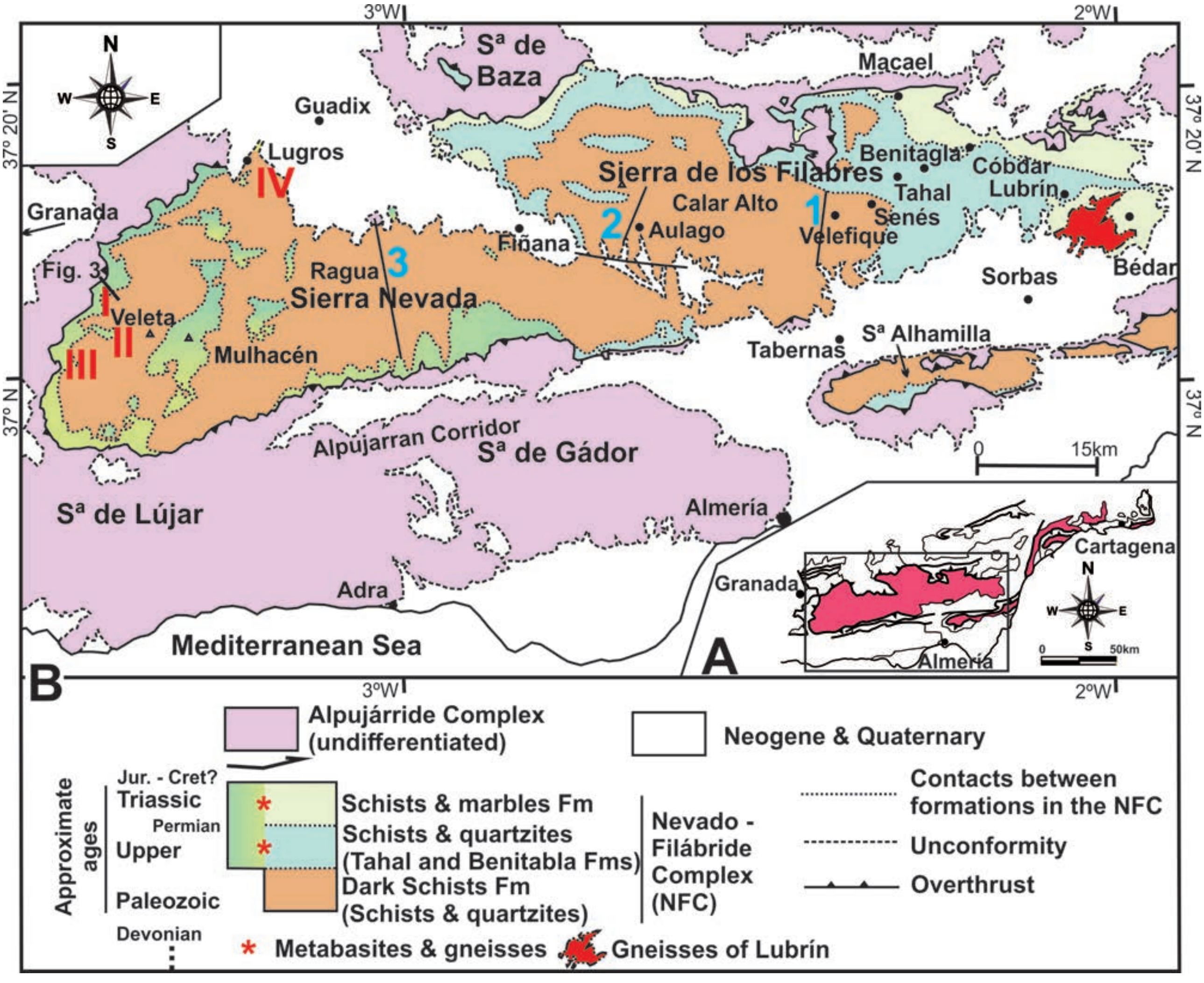
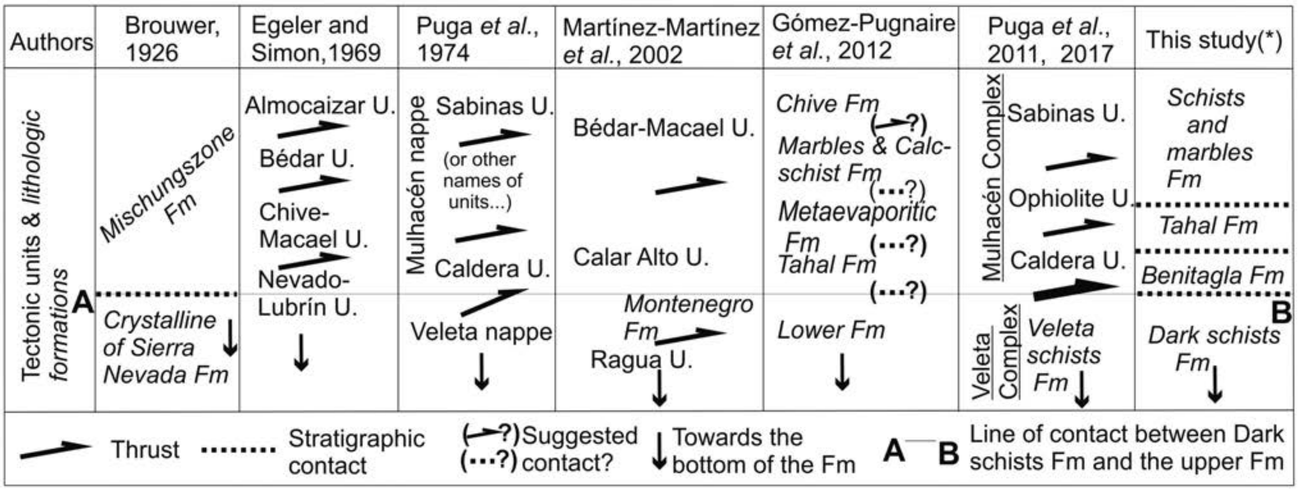


Fig. 1.- Regional setting. A. Distribution of the Nevado-Filábride Complex (NFC) (in red) in the Betic Cordillera. B. General distribution of the main stratigraphic formations of the NFC in the sierras Nevada and Filabres proposed in the present work. Cross sections of Figure 2 are indicated by the numbers 1, 2, and 3, and also the position of the cross section of Figure 3 (near the western border of the figure), and that of the columns of Figure 5 (in red Roman numerals).



Authors	Brouwer, 1926	Egeler and Simon,1969	Puga *et al.*, 1974	Martínez-Martínez *et al.*, 2002	Gómez-Pugnaire *et al.*, 2012	Puga *et al.*, 2011, 2017	This study(*)
Tectonic units & *lithologic formations*	*Mischungszone Fm* A *Crystalline of Sierra Nevada Fm* ↓	Almocaizar U. Bédar U. Chive-Macael U. Nevado-Lubrín U. ↓	Mulhacén nappe Sabinas U. (or other names of units...) Caldera U. Veleta nappe ↓	Bédar-Macael U. Calar Alto U. *Montenegro Fm* Ragua U. ↓	*Chive Fm* (⟶?) *Marbles & Calc-schist Fm* (•••?) *Metaevaporitic Fm* (•••?) *Tahal Fm* (•••?) *Lower Fm* ↓	Mulhacén Complex Sabinas U. Ophiolite U. Caldera U. Veleta Complex *Veleta schists Fm* ↓	*Schists and marbles Fm* *Tahal Fm* *Benitagla Fm* B *Dark schists Fm* ↓

⟶ Thrust ••••••• Stratigraphic contact (⟶?)Suggested (•••?) contact? ↓ Towards the bottom of the Fm A—B Line of contact between Dark schists Fm and the upper Fm

Table 1.- Different proposed divisions of the NFC in tectonic units and lithologic formations, according to several authors. (*): Also in Sanz de Galdeano *et al.* (2016) and Sanz de Galdeano and López-Garrido (2016).

tonic unit would correspond to the lower part of the general NFC lithological sequence; the middle tectonic unit (if its existence is considered) would correspond to the lower part of the upper NFC lithological sequence; and the upper tectonic unit would correspond to the rest of the upper lithological sequence.

But not all authors accept the division of the NFC into tectonic units, but rather contend that it represents a single tectonic unit (Galindo-Zaldívar, 1993; Sanz de Galdeano and López-Garrido, 2016; Sanz de Galdeano *et al*., 2016), with a lithological sequence presenting moderate lateral and vertical stratigraphic changes.

Generally, the NFC has been studied using petrological data, and the different divisions in tectonic units have been proposed based on them. But the data of the lithological formations, the stratigraphic and tectonic aspects directly detectable in the field, have in many cases been considered subordinate to the petrological data or have even been disregarded.

The purpose of this work is to present an overview of the lithological sequence of the NFC (Fig. 1) in the sierras Nevada and Filabres. Here, the main stratigraphic formations are described, something that implies major divergences with respect to many previous descriptions, resulting in markedly different tectonic interpretations.

Background

Previous lithological and tectonic divisions of the NFC

In this work, articles dealing only with the NFC in the sierras Nevada and Filabres are commented. The southeastern and easternmost areas of this complex, those situated in the sierras Alhamilla, Cabrera, Almenara, Mazarrón, and Cartagena are generally not included (Fig. 1A). Particularly the latter two areas cited present different lithological sequences, partially older than those of the sierras Nevada and Filabres (Laborda-López *et al*. 2014). The different proposed divisions of the NFC in tectonic units and lithologic formations are summarized in Table 1.

Brouwer (1926) differentiated two main lithological formations (Table 1) in the *Penninic Betics*, as he called the NFC. The lower one, the Crystalline of Sierra Nevada (*Kristallijne Schisten*), is formed by a monotonous succession of dark schists with graphite, and quartzites, probably Paleozoic in age. The upper one, the Mixed Zone (*Mischungszone*), is formed by light schists, dark schists, mica schists, quartzites, marbles, gneisses, and metabasites (amphibolites and serpentinites). The above author contended that both formations originally had sedimentary continuity.

Fallot *et al*. (1959, 1960) found possible lithological unconformities situated between these two formations. These authors calculated the lower one to be more than 5000 m-thick but they expressed uncertainty about the autochthony or allochthony of the higher one. Egeler (1963) was the first to use the term Nevado-Filábride Complex, including in it the two aforementioned formations, and considering the possible existence of several tectonic units.

Nijhuis (1964) distinguished several tectonic units in the NFC, in the eastern sector of Sierra de los Filabres: the Nevado-Lubrín unit and, in an upper position, the Chive and Bédar units. In spite of this, the lithological column presented by this author, indicates a stratigraphic continuity between these differentiated tectonic units. Later, Helmers and Voet (1967) distinguished different tectonic units. Similar divisions were followed by Egeler and Simon (1969) (Table 1). The existence of similar units was considered by many other authors, such as Langenberg (1972), García Monzón and Kampschuur (1975), García Monzón *et al*. (1975a, b, c), Kampschuur (1975), Soto (1993), and Linthout and Vissers (1979).

In Sierra Nevada, Puga (1971) distinguished two great nappes, those of the Veleta and Mulhacén (Table 1). The Veleta nappe corresponds to the Crystalline of Sierra Nevada Fm of Brouwer (1926), while the Mulhacén nappe corresponds to the *Mischungszone* Fm, although locally part of the Crystalline of Sierra Nevada Fm is also assigned to the Mulhacén nappe. This latter nappe was divided in two units (Puga *et al*., 1974), which are the Calderas (bottom) and Sabinas units (top), although locally other names of units were indicated, even in some sectors differentiating three units. Martínez-Martínez (1984-85) and Gómez-Pugnaire (1988), among others, followed this differentiation of nappes. Later, based on the greater grade of metamorphism of the Mulhacén nappe, Puga *et al*. (2002) proposed the differentiation of the NFC into the Veleta and Mulhacén complexes.

Other divisions were proposed by Jabaloy and González Lodeiro (1988) and Jabaloy (1993) in the western part of the Sierra de los Filabres, divisions that differ from those presented by Navarro Vázquez and Velendo Muñoz (1979) in the same area. Many other studies published during the 1980s and 1990s refer to the same or similar nappes or tectonic units, but these are not cited here because they continued more or less in the same line.

However Galindo-Zaldívar (1993), who studied the central and western part of Sierra Nevada, detected no tectonic contacts (*e.g*., detachments, ductile shear zones), either between the aforementioned nappes of Veleta and Mulhacén, or in lower tectonic positions. For this reason, he considered the NFC, at least for this area, to be a single tectonic domain.

Martínez-Martínez *et al*. (2002) introduced the term Ragua unit to replace that of Veleta, considering that the upper limit of the Ragua unit, though indefinite in position, was lower than that of the Veleta unit (Table 1). At the same time, the Mulhacén unit was divided into the Calar Alto unit (making up part of the former Veleta unit and the lower part of the Mulhacén unit) and the Bédar-Macael unit in the higher position (comprising the upper part of the Mulhacén unit). These new limits were followed by Martínez-Martínez *et al*. (2010) and by Augier *et al*. (2005 a, b). For the latter authors the Bédar-Macael unit constitutes a complex ductile shear zone.

Gómez Pugnaire *et al*. (2000, 2004, 2012) and López Sánchez-Vizcaíno *et al*. (2001) presented a continuous lithological sequence formed by the superposition of the sequences of the tectonic units cited in previous articles, but the character of the contacts is not clearly indicated (Table 1).

Puga *et al*. (2011, 2017) offered a new arrangement within their Mulhacén Complex, proposing, from bottom to top, the units of Caldera, Ophiolite, and Sabinas (Table 1). In the Ophiolite unit these authors identified basic and ultrabasic rocks, considering the unit to be an oceanic spreading zone.

Recently, Sanz de Galdeano *et al*. (2016) and Sanz de Galdeano and López-Garrido (2016) studied two different sectors of the Sierra de los Filabres and, according to the structure and continuity of the lithological formations cropping out there, they concluded that, at least in this area, there is only one tectonic unit, presenting a thick and continuous lithological sequence.

Fossil and absolute dating in the NFC

In the eastern part of this complex (in Murcia province, not in the sierras Nevada and Filabres), Lafuste and Pavillon (1976) and Laborda-López *et al*. (2014) dated lower Devonian fossils in marbles. These are the oldest reliable ages known in this complex.

In Sierra de los Filabres, at an unclear place, Gómez-Pugnaire *et al*. (1982) dated by microfossils a possible Precambrian, but these data have not been confirmed and are presumably incorrect. Also in the northern part of Sierra de los Filabres, near the locality of Bédmar, Tendero *et al*. (1993) cited marbles having ankeritic “ghosts”, interpreted as possible Cretaceous foraminifers. Also in Sierra de los Filabres, Rodríguez-Cañero *et al*. (2017) dated conodonts as Bashkirian (323.2 to 315.2 Ma).

Radiometric dating in the NFC by Priem *et al*. (1966) gave an age of 269±6 Ma (Permian) in granite-gneisses in the E of Sierra de los Filabres (in the meta-pluton of Lubrín-El Chive). Andriessen *et al*. (1991) in Filabres reported ages ranging from the early Permian to Triassic in samples taken in gneisses interlayered among schists. Nieto (1996) proposed ages of 307± 30 Ma in orthogneisses. Also in these types of rocks, Gómez-Pugnaire *et al*. (2004) offered data indicating a late Carboniferous age (301±7 Ma), while Martínez-Martínez *et al*. (2010) gave ages of 304±23 Ma to 320±6 Ma. Also, Gómez-Pugnaire *et al*. (2012) and Ruiz-Cruz and Sanz de Galdeano (2017) reported early Permian ages (282±3 to 295±5 Ma and ~286 Ma respectively).

Except for the two first references cited concerning fossil dating, the rest of the references studied rocks belonging to the *Mischungszone*. However, Santamaría-López and Sanz de Galdeano (2018) studied detrital zircons from schist samples comprising from the lower visible parts of the Crystalline of Sierra Nevada Fm (the Dark schists Fm), to the higher part conserved of the *Mischungszone*. The maximum ages of deposition of these metasediments correspond to the (late) Carboniferous. Very recently, Jabaloy *et al.* (2018), also studying detrital zircons, obtained comparable results (Carboniferous and early Permian ages) although the exact stratigraphic positions of the samples studied is not clear for us.

The lithological sequence of the NFC

The description of the rocks presented below corresponds mainly to field data. Their mineralogical and petrological aspects have been repeatedly described in many articles (for instance De Jong, 1993; Gómez-Pugnaire *et al*., 2000, 2012; Puga *et al*., 2002; Booth *et al*., 2008); nevertheless a thorough description of their appearance and the field context is generally missing. The lithological sequence includes from base to top the following units (Table 1): Dark schists Fm, light quartzites of the Benitagla Fm, the mica schists with garnets of the Tahal Fm, and the Schists and marbles Fm.

The Dark schists Fm

These rocks make up a monotonous formation (the Crystalline of Sierra Nevada of Brouwer, 1926, Table 1) containing interlayered quartzites, abundant in several places, and absent in many others. This formation is well represented in both sierras, Nevada and Filabres, and geological cross sections can be made in many places, particularly in Velefique and Aulago areas, in Sierra de los Filabres, and in La Ragua sector in Sierra Nevada (Fig. 2). The structure in these two areas corresponds to two great anticlines, and the lithological sequence can be studied from their visible nucleus.

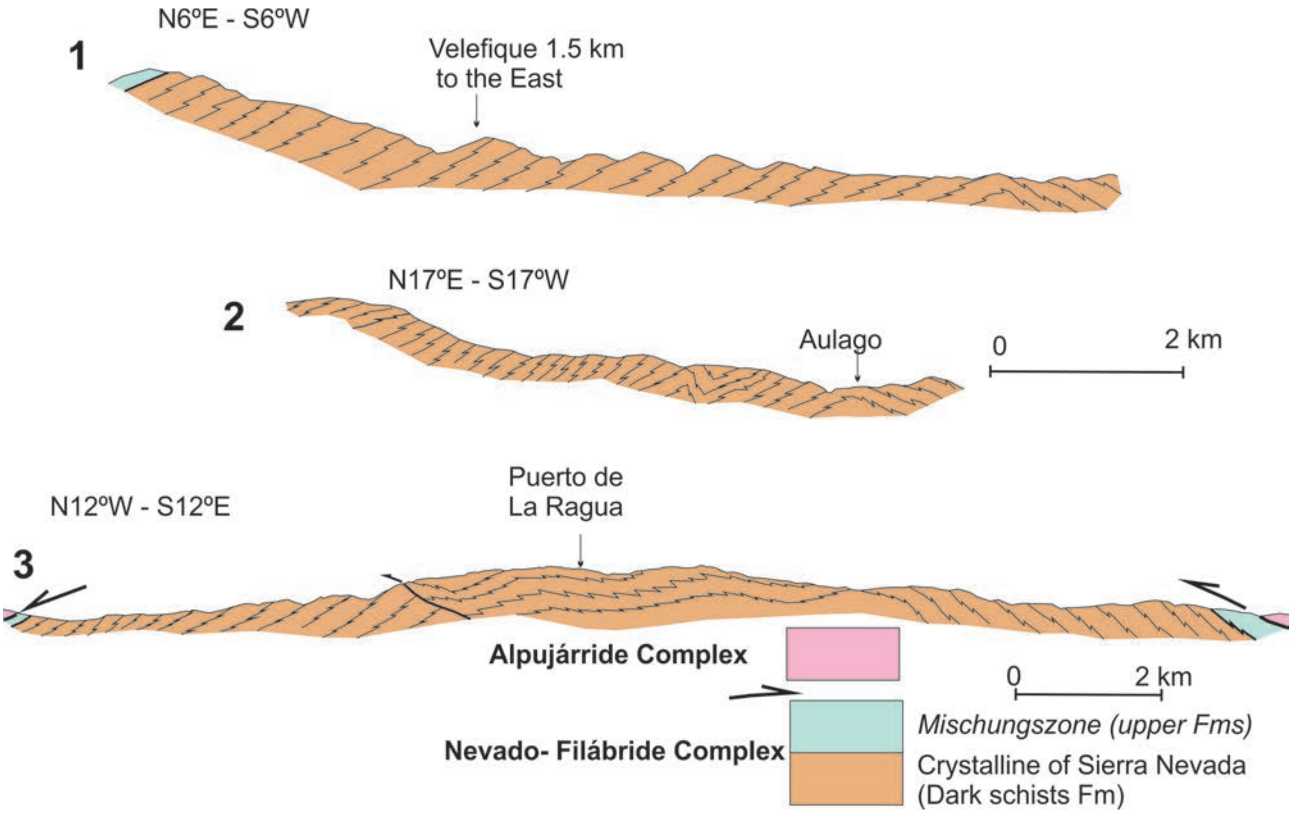


Fig. 2.- Geologic cross sections of the three sectors where the dark schists (the Crystalline of Sierra Nevada) are better exposed: Velefique (1) and Aulago (2) (Sierra de los Filabres) and La Ragua (3) (Sierra Nevada). The position of these cross sections is marked in Figure 1.

In the Velefique sector the thickness calculated is roughly 4000 m. The structure of this area is simple, the outcrops are very good, without major visible tectonic complications. However, the total thickness can fluctuate (depending on the mean values considered for the dip of the layers) between 3500 and 4500 m. If the average overall dip is considered to be 30º towards the N, the resulting thickness is some 3600 m. In this sector the sequence of dark schists is particularly monotonous, locally presenting quartzites. These rocks generally contain garnet, although this mineral is not visible in every layer. Garnet size tends to increase towards the top, particularly near the passage to the upper formation, the light Benitagla quartzites, situated in the lower part of the *Mischungszone* of Brouwer (1926) (Fig. 2 and Table 1). Locally, some schist layers do not present visible minerals, except for some micas. Only very locally there are intercalated schist layers of lighter tones. Generally, graphite is responsible of the black colour of the rock.

In the Aulago sector the nucleus of the same anticline presents the lower layers of the dark schists in the sierras Nevada and Filabres, the visible thickness there being on the order of 2500 to 3000 m (from the village of Aulago to the mountain pass in the N). However, there the top of the dark

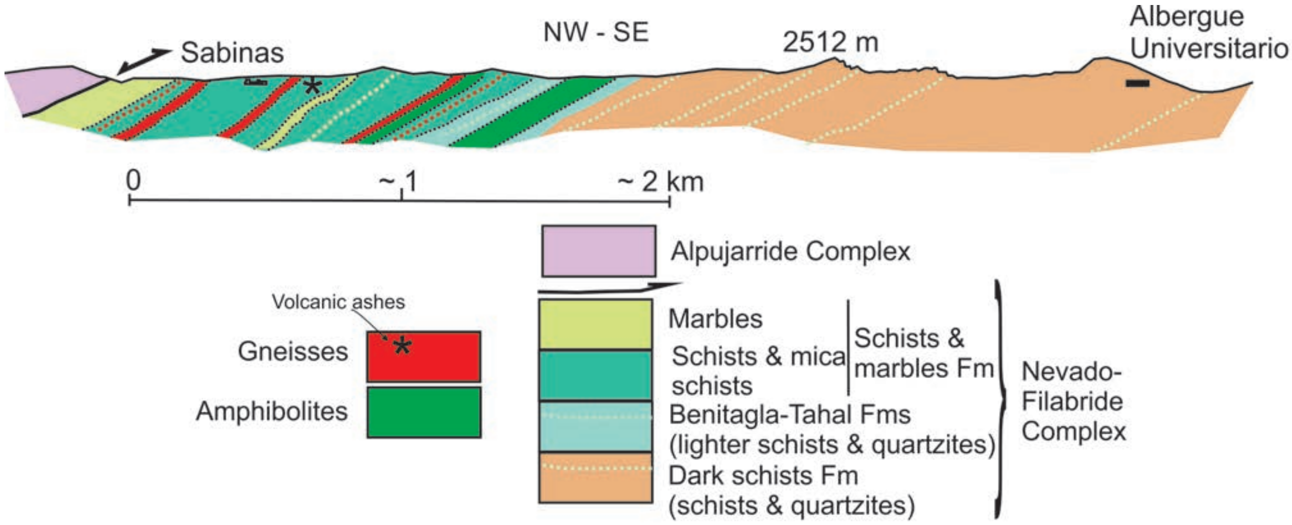


Fig. 3.- Geological cross section of the area of S. Francisco-Sabinas. Its position is marked in Figure 1.

schists is not visible. In this area the lithological sequence is not so uniform and the difference in lithological aspect is clear from bottom to top. Near the village of Aulago, in the core of the structure, the rocks have only an epimetamorphic appearance, while to the N, in the mountain pass, the rocks contain abundant garnets and other minerals, forming typical dark schists as in the Velefique area. This change in the aspect of the rocks is totally progressive from bottom to top and the tendency of the garnets is to be progressively larger in size and more abundant towards the top.

In La Ragua cross section (Sierra Nevada), both flanks of the anticline show the lithological sequence. This anticline is not simple, and its nucleus presents lesser folds comparing with the total size of the anticline. In the map, the northern flank occupies a wider area than does the southern flank. There are also faults that have not been thoroughly studied until the present. The thickness is apparently somewhat less than in Velefique sector. In La Ragua the lithological sequence is similar to that of Velefique, but with generally less metamorphic appearance. Rocks of laminar aspect are more abundant, particularly towards the core of the structure, showing a less metamorphic aspect than in those of the upper part of both flanks of the structure. Locally, interlayered schists and quartzites have lighter colours, the first practically with a lutitic aspect, showing apparent low-grade metamorphism. These intercalations are readily visible in the road going to the N from the La Ragua mountain pass. The garnet sizes progressively increase towards the top.

According to the data of Santamaría and Sanz de Galdeano (2018) this formation has a maximum (late) Carboniferous age.

The quartzites of Benitagla Fm and other equivalents

Close to the top of the Dark schists Fm, interbedded layers of light quartzites begin to appear, easily visible particularly on the roadside slopes. This transition from the schists to the quartzites is not sharp but progressive, with the quartzites becoming more abundant towards the upper part.

This transition varies depending on the site; for instance, to the west of Sierra Nevada, the first layers of light quartzites appear even more than 300 m below the top of the Dark schists Fm (Fig. 3). At the top the relative abundance is the opposite and finally the dark schists disappear, the quartzites alternating with light schists and other types of rocks (*e.g.*, gneisses, metabasites). In this sector, although abundant, the quartzites do not generally form a differentiated formation.

On the contrary, to the E, in the area of Senés-Tahal (Sierra de los Filabres; Fig. 4), the contact between the dark schists and the light quartzites present a much shorter transition. There, the quartzites locally reach a thickness of ~ 400 m, although laterally they markedly thin, changing to quartzites intercalated among light schists, as occurs in the western part of Sierra Nevada. Sanz de Galdeano and López-Garrido (2016) gave to these massive quartzites the name of Benitagla Fm. Benitagla is a village partially situated over these quartzites (although this is not the sector with the maximum thickness), because the villages nearest the maximum thickness, Tahal and Senés, are not situated over these quartzites.

These quartzites have a peculiar aspect in some areas, especially in the western part of Sierra de los Filabres, in the sectors of Escúllar, El Tesorero, and Charches (Fig. 4), although also in Sierra Nevada, but with lower thickness: part of these quartzites are not consolidated, maintaining the as-

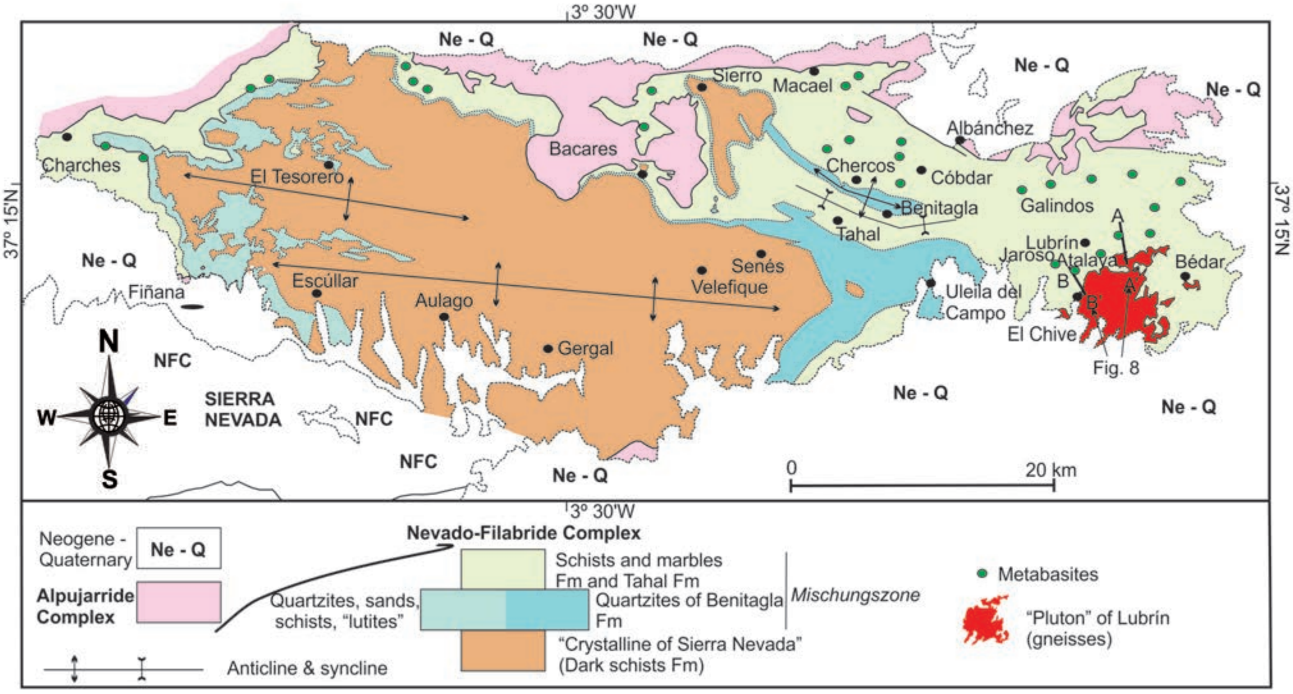


Fig. 4.- Highly simplified geological map of Sierra de los Filabres. The position of the quartzites of Benitagla Fm and other equivalent ones are highlighted. The areas corresponding of the stratigraphic columns of figures 6 and 7 are indicated (for Figure 6 see their names in the western part of the figure and for Figure 7 in the central-eastern part). Also the position of the cross sections of Figure 8 is indicated (as 8A and 8B, see the eastern part of the figure).

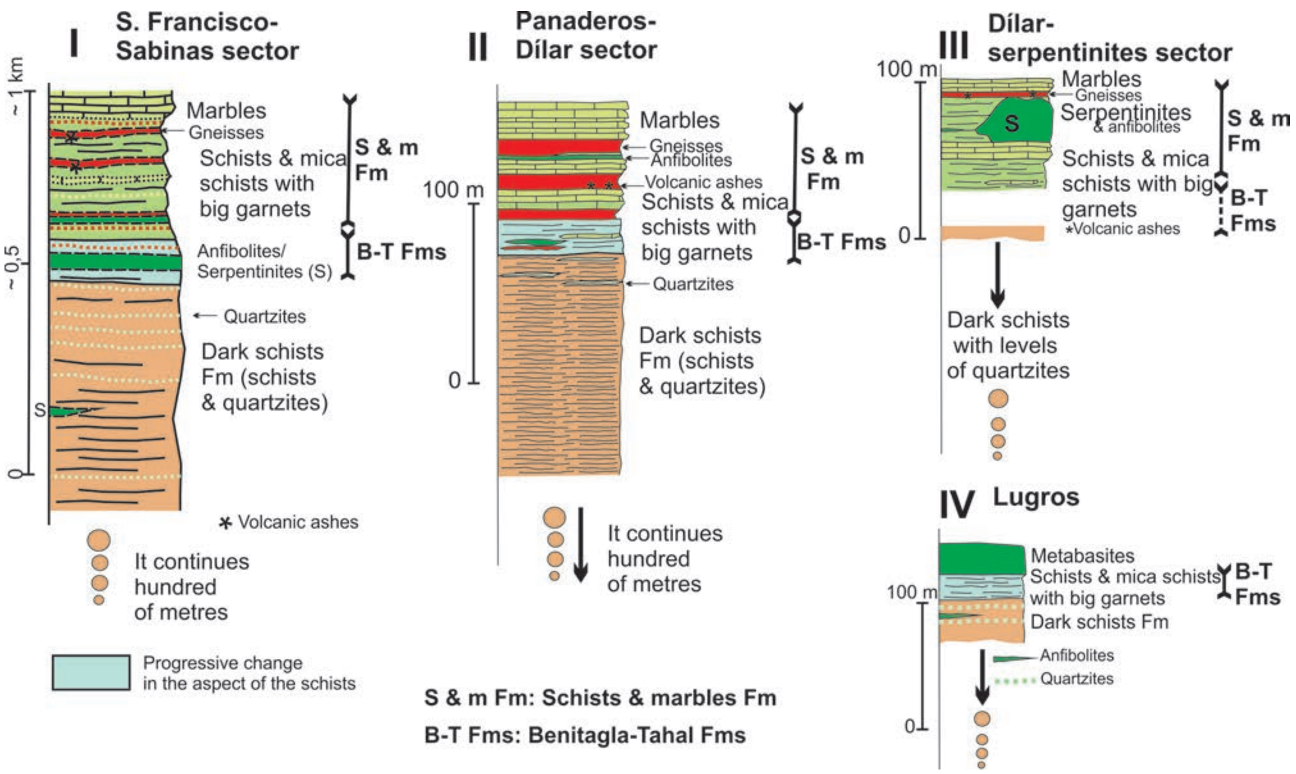


Fig. 5.- Stratigraphic columns in the western Sierra Nevada. I: in San Francisco-Sabinas area. II: Panaderos area, south of San Francisco. III: Río Dílar area. IV: in the area of the E of Lugros, indicating the position of two outcrops of metabasites. Their position is indicated in Figure 1.

pect and the looseness of sand. Laterally and vertically the transition between quartzites and sands is visible for a few meters. This feature was indicated by Fallot *et al.* (1960) and much later by Sanz de Galdeano and López-Garrido (2016). Moreover, these rocks bear light schists sometimes with garnets, reaching 1 cm or more in diameter, together with other levels of apparent lutites. These features are not restricted to the lower quartzites laterally equivalent to the Benitagla Fm, but they are visible also in higher positions. These rocks have even been found among the marbles (Sanz de Galdeano and López-Garrido, 2016). Within the sands and the quartzites, cross-stratification can be observed, and the measurements made indicated a sense to the N80ºW.

Moreover, in the sectors where the presence of sands and "lutites" are abundant, local layers of limestones (hardly metamorphic) appear in such a way that in some places they have been dated as Bashkirian (Rodríguez-Cañero *et al*., 2017).

The Tahal Fm

Over the quartzites of Benitagla, a formation crops out containing mica schists with garnets, and interlayered quartzites, (Tahal Fm; Nijhuis, 1964). From the area of the Tahal village towards the E (Fig. 4), this formation presents great thickness, clearly more than 500 m. To the W these values are lower, and the Benitagla and Tahal formations cannot be differentiated and form a single ensemble.

The sizes of the garnets and other metamorphic minerals visible in the Tahal Fm vary depending on the layers (in some cases the garnets can reach more than 5 mm, while in adjacent layers they can be very small or even imperceptible in the field). However, on the whole, the size of visible minerals, particularly the garnets, tends to increase towards the top, although laterally these sizes also change.

These schists are generally grey to greyish blue, varying from light to dark tones. In some layers, white mica is abundant and the rock can be considered to be a micacite. Locally the schistosity can be largely undulating (particularly towards the top) owing in part to the mineral's grain size.

Near the top, this formation begins to intercalate thin layers of marbles and calc-schists, preluding the following formation.

The Benitagla and Tahal formations, according to the data of Santamaría and Sanz de Galdeano (2018) have a maximum late Carboniferous age. Probably they do not reach the Permian, because some age data of the next formation still indicate probable terminal Carboniferous ages (*e.g.*, Gómez-Pugnaire *et al*., 2004; Martínez-Martínez *et al*., 2010).

Gómez-Pugnaire *et al.* (2012) indicated the existence of a metaevaporitic Fm (Table 1) situated over the Tahal Formation. In the field it is not clearly distinguishable, but this presence of metaevaporitic sediments could indicate the passage to marine restricted conditions (see the discussion).

The Schists and marbles Fm

This formation corresponds to a succession of marbles, alternating with schists (Figs. 1 and 4 to 7). The marbles form different groups of layers of variable thicknesses and lengths, and in some cases the groups of layers are more than 15 m-thick but in others no more than several cm. In many cases the

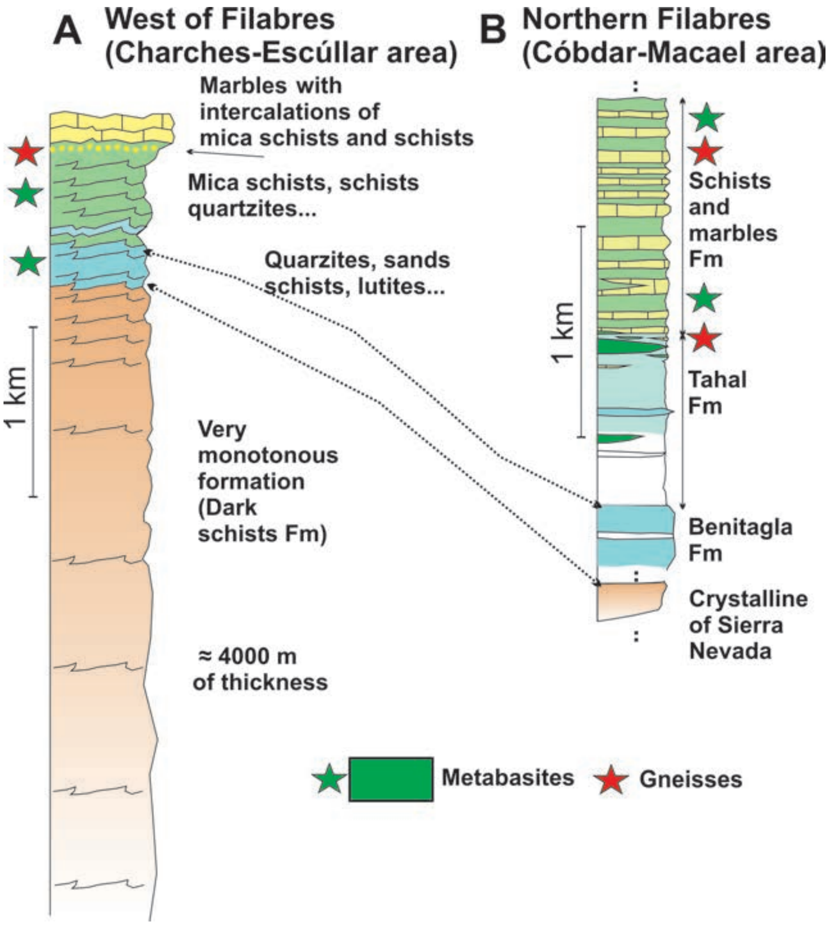


Fig. 6.- Stratigraphic column of the W part of Sierra de los Filabres (area of Charches-Escúllar) and of the central part of the northern part of Sierra de los Filabres (area of Cóbdar-Macael). The place names can be seen in Figure 4.

layers of marbles laterally disappear, generally changing previously to calc-schist. In other cases, one single level laterally splays into several others and vice versa.

The schists, generally light-grey but locally also dark-grey, and also mica schists, are intercalated among the marbles. Generally, garnets abound, varying in size from several cm to mm. Even locally, near the village of Cóbdar, some layers of the metadetritic rocks contain centimetric porphyroblasts of feldspar, giving rise to gneisses, although laterally these disappear in distances of less than 100 m, changing to mica schists with garnets.

This formation exceeds 1 km in thickness in the area of Cóbdar-Macael (Sanz de Galdeano *et al*., 2016). This is probably the area where the preserved thickness is greatest. The proportion of marbles in relation with the metadetritic rocks is widely variable, being the area lying between Macael and Lubrín, where the abundance of marbles is highest.

Locally, the marbles (and in some places even the schists) are mineralized by iron oxides, being exploited at several points (*e.g.*, El Marquesado, Piletas, El Tesorero). No other rocks situated in higher positions are visible or conserved.

The ages of this formation according to the previous data of Andriessen *et al*. (1991), Gómez-Pugnaire *et al*. (2012), Ruiz-Cruz and Sanz de Galdeano (2017) and Santamaría and Sanz de Galdeano (2018) is Permian, although some data of Gómez-Pugnaire *et al*. (2004) and Martínez-Martínez *et al*. (2010) indicate a Carboniferous age. This last age corresponds to igneous rocks interbedded in this formation. Other data even indicate the possibility of the presence of Cretaceous metasediments (Tendero *et al*., 1993). Probably this formation comprise all the Permian (even perhaps the very terminal Carboniferous), the Triassic and possible younger metasediments.

A brief presentation of the igneous rocks existing in the sierras Nevada and Filabres

Interlayered with the two previous formations (Figs. 1 and 3 to 8), from the Benitagla quartzites upwards, there are metabasites and gneisses. In general, they are more abundant near the top of the Tahal Fm, and equivalent layers, and in the upper formation of schists and marbles.

The gneisses, orthogneisses, generally present visible feldspar crystals and in many places small tourmaline prisms appear. In some places several layers of gneisses remain unconsolidated, as in Sierra Nevada, several km W of the ski resort (Sol y Nieve), visible in the slope along the road. Also, among other places, these appear to the E of the village of Lubrín, at the bottom of marbles. These layers must correspond to cinerites. The ages of these gneisses, as indicated previously, range between the terminal Carboniferous and Permian.

In the area of Lubrín-El Chive, the eastern part of Sierra de los Filabres (Figs. 4, 7 and 8) a pluton is exposed, with rocks that are now orthogneisses. It intruded in the rocks of different formations, even reaching the marbles and schists of the upper formation, although part of their rocks covers the orthogneisses. As indicated previously, this pluton has been dated as Permian (Priem *et al*, 1966, having 269±6 Ma). Other data indicate ages of the order of 300 Ma.

The metabasites are particularly abundant in the upper part of the Tahal Fm arrayed in different bodies, but many others also appear within the upper formation of marbles and schists. We know only one outcrop of ultramafic rocks embedded in the dark schists, corresponding to the "Barranco de San Juan" serpentinites on the western edge of Sierra Nevada. They are situated more than 300 m below the top of the dark schists and have a lenticular shape, adapted to the general arrangement of the layers.

At many points (particularly in the Sierra de los Filabres, but also in Sierra Nevada) the metabasites correspond to bodies varying from several cm to hundreds of m in thickness. Particularly in slopes sides of recent roads is easy to see these rocks intercalated among schists, mica schists, and marbles. Now they correspond to amphibolites, although at some points, even structures such as vacuoles are preserved. In some cases, when the body is more than 20 m-thick, the edges of the body present a clear metamorphic texture, while the interior preserves a texture typical of a basalt, even with disoriented feldspars. Clearly these rocks correspond to former basic volcanic extrusions interlayered in metasediments.

Several outcrops, more abundant in the eastern part of Sierra de los Filabres, although also present in Sierra Nevada, are considered to have been former ultrabasic rocks, at present metamorphosed (García-Monzón and Kampschuur, 1975; Puga *et al*., 2011, 2017; Jabaloy *et al*., 2015; Laborda-López *et al*., 2018). Examination of these outcrops reveals that most (though not all) contain layers of schists and marbles interlayered in the interior of these bodies, probably the metasediments indicated by Puga *et al*. (2011, 2017). This occurs for instance in the outcrop of El Jaroso, several km S of Lubrín, and to the SE and E of this village, as well as in the proximities of the village of Bédar. These layers of metasediments are well preserved and their surfaces generally do not present features of tectonization after their formation. The possible meaning of these interbedded layers is discussed below.

In some cases, peridotites/serpentines laterally occupy the same position within the lithological sequence as other bodies of metabasites. This happens for instance in the outcrop of the river Dilar (SW of Sierra Nevada), where there is an abandoned quarry. There the serpentinites, with a maximum thickness of roughly 40 m, change laterally to much thinner metabasites distributed along several km. At the top and the bottom of these serpentinites lie thin layers of metabasites, and also several of gneisses.

Another unexpected feature is the presence of giant "drops" of metabasites. That is, isolated bodies of this type of rock embedded within schists and marbles of the upper formation. The size varies from several m to several dozens of m. They appear to be completely separate from other meta-igneous rocks and have been seen approximately 8 km to the WNW of Lubrín (Sierra de los Filabres).

The ages of these rocks are deduced from those of the metasediments in which they are situated. According to Santamaría and Sanz de Galdeano (2018) they have a maximum age of late Carboniferous. The gneisses, also interlayered, indicate ages ranging from the Carboniferous and especially the Permian, although Puga *et al*. (2011 & 2017) even signalled Jurassic ages.

Discussion

Significance of the Dark schists Fm

The maximum deposition age estimated by Santamaría-López and Sanz de Galdeano (2018) for the dark schists sedimentary protolith, is late Carboniferous, not older, in spite of the enormous thickness of this formation (*e.g.*, ~3600 m in the Velefique area). This age is in fact consistent with the data reported by Lafuste and Pavillon (1976) and Laborda-López *et al*. (2014) for the lower Devonian in limestone marbles in Murcia province, underlying dark schists.

This thickness and the lithology of this formation (the Dark schists Fm/Crystalline of Sierra Nevada) greatly recall the facies Culm, generally early Carboniferous in age, being a syntectonic formation, *i.e.* syntectonic with the Hercynian/Variscan orogeny. Given these similarities, the metasediments now forming the dark schists can be interpreted as a syntectonic formation deposited during the Variscan stages affecting the region.

The former stratigraphic relations

The change from the dark schist to the light quartzites of Benitagla and other equivalent layers is, as indicated,

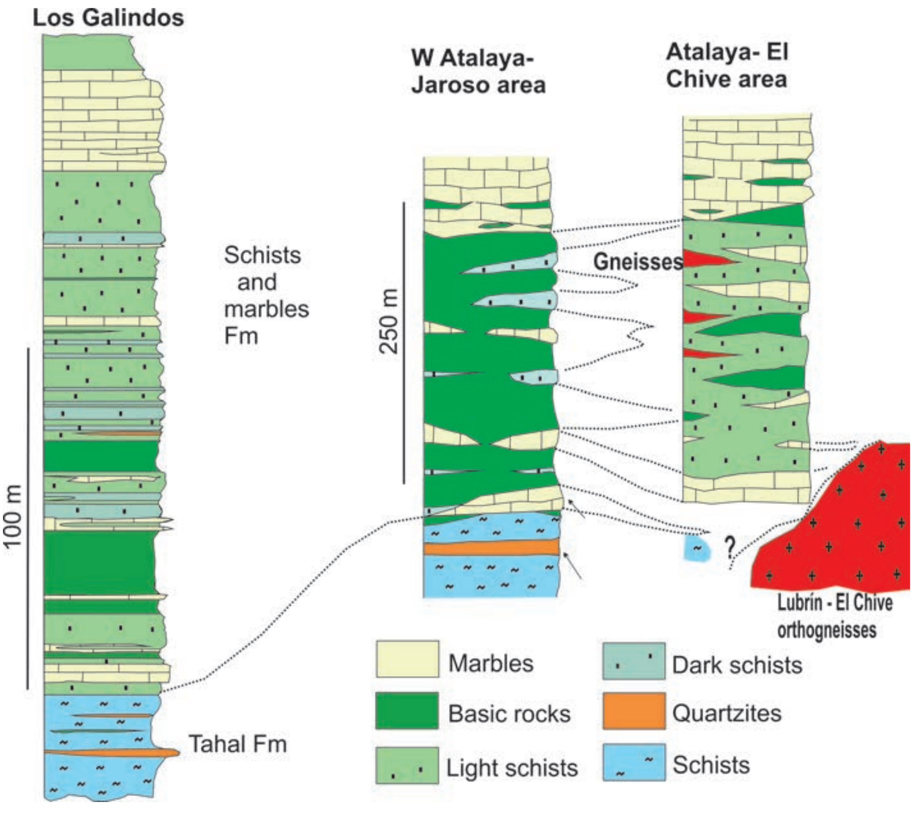


Fig. 7.- Stratigraphic columns in the area of Lubrín-El Chive. The positions of the points Galindo, Atalaya, Jaroso and El Chive are indicated in Figure 4.

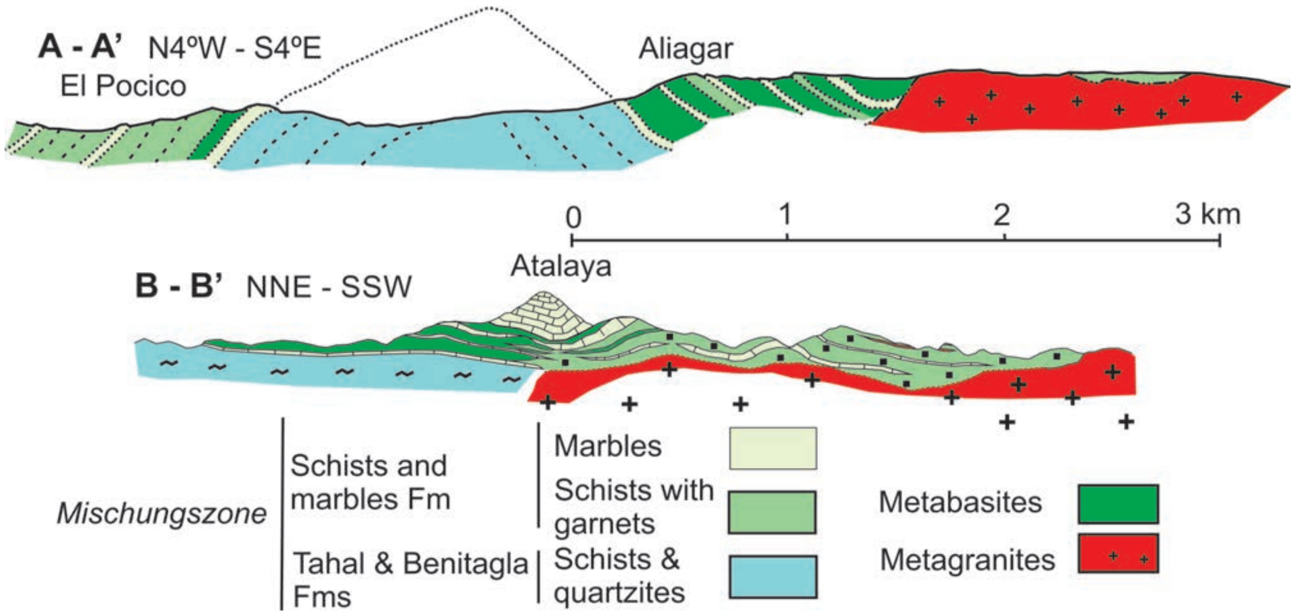


Fig. 8.- Geological cross sections of the Lubrín-El Chive sectors. Their positions are indicated in Figure 4 (see in the right part of the Figure 4).

transitional. Several authors (Fallot *et al*., 1960; Gómez-Pugnaire *et al*., 2012) have cited the presence of conglomerates. Although we have not detected them, certainly they must exist. This feature could be interpreted as an unconformity, probably local in character.

As indicated previously, light quartzites begin to appear interlayered with the dark schists until being the dominant lithology. That is, the passage is transitional, indicating a progressive change in the depositional environment. The previous conditions forming the facies Culm of the dark schists finally disappeared.

Particularly in the Benitagla sector the quartzites are thick (approximately ~400 m). The interpretation is that they corresponded to a delta with a major channel supplying the sands. Laterally the input of sand diminished, being thinner and alternating with lutites (future schists) poor in organic material. Another possibility is that these quartzites could correspond to a turbiditic deposit. This is an open question.

Although few measurements are available for the direction of the currents (to the N80ºW), the probable clockwise rotation of the NFC, as occurred in other places of the Internal and External Zones (Osete, 1992; Platzman *et al*., 2000), perhaps approaching 90º, would imply a supply of sands from the N (but this interpretation is based on two successive hypotheses).

Above the Benitagla quartzites the schists of Tahal also reach maximum thickness (more than 500 m) in the eastern sector of Sierra de los Filabres, coinciding with the position of the aforementioned older delta. Apparently this was the area of a larger supply of sediments, coinciding with greater subsidence. In the rest of the sierras Nevada and Filabres, schists and quartzites alternate with variable thickness, less than in the Benitagla-Tahal area. The metaevaporitic formation of Gómez-Pugnaire *et al.* (2012) probably indicated the prelude of restricted marine conditions and the first interlayered carbonate layers, at present marbles, which began to appear over the previous schists (formerly lutites) of the Tahal Fm, marked the beginning of a clear marine transgression represented by the schists and marbles formation.

Existing geodynamic conditions

On the whole, a major change occurred in the geodynamic conditions existing from the deposit of the metasediments of the first formation (now the dark schists of the Crystalline of Sierra Nevada) and the beginning of the deposit of the upper formations (*Mischungszone*). The metasediments giving rise to the dark schists correspond to a synorogenic formation deposited during the Carboniferous, while, on the contrary, the upper formations were deposited after the Variscan orogeny, changing to a distensive context that facilitated the progressive marine transgression.

The distension/extension process was facilitated by the formation of deep faults, a feature that permitted the extrusion of the igneous rocks. This is why the orthogneisses extruded during this time are situated among the upper formations. The same occurred with the metabasic rocks not visible in the dark schists, with the exception of the serpentinites of Barranco de San Juan, these latter rocks probably corresponding to a body that did not reach the surface. Also the meta-pluton of Lubrín-El Chive intruded in this context.

The extension, according to the data of Gómez-Pugnaire *et al*. (2004) and Santamaría-López and Sanz de Galdeano (2018), among others, began at the end of the Carboniferous, near the beginning of the Permian, before than in the Alpujárride Complex (Sanz de Galdeano, 1997). This age is contradicted by Puga *et al*. (2011, 2017) who proposed a Jurassic age, based on data of ultrabasic rocks. However, in our interpretation, these data likely correspond to rejuvenated ages or, in some cases, may be new extrusions of this latter age. In fact, the extension continued during the Triassic and probably lasted during the Jurassic and perhaps the Cretaceous.

The significance of the ultrabasic rocks

The significance of the ultrabasic rocks is controversial. For Puga *et al*. (2011, 2017) these rocks form their Ophiolite unit. According to these authors, it consists of numerous tectonic slices, metric to kilometric in size, of eclogitized mafic and ultramafic rocks associated with oceanic metasediments, derived from the Betic oceanic domain. They developed from the Early to Middle Jurassic (185–170 Ma), just at the beginning of the Pangaea breakup between the Iberia-European and the African plates. For Jabaloy *et al*. (2015) and also Laborda-López *et al*. (2018) the ultramafic rocks derived from mantle peridotites exhumed from the sea floor in a continental passive margin or oceanic basin. Now, according to these same authors, they form a superposition of thin tectonic units.

The presence of interlayered metasediments in many of their outcrops guarantees that the mafic and ultramafic rocks were extruded during the sedimentation period. The problem is to know whether they were formed in an oceanic domain or in an extension process more limited in its effects, facilitating the extrusion of basic rocks.

The field relationships of these rocks let us to conclude that the tectonic slides and the thin tectonic units proposed do not exist and also negates the existence of a well-developed oceanic basin later disposed in tectonic slides. However, the problem is now to accept that the ultrabasic rocks could directly reach the surface without previous magmatic differentiation. This differentiation exists in reality, given that many of the associated rocks correspond to former basalts, but in some cases the differentiation was not complete and part of these rocks were extruded on the surface of the basin of sedimentation directly as ultrabasic rocks. This is a petrological problem to be resolved, but the field evidence indicates the coexistence of basic and ultrabasic rocks interlayered among sediments at different stratigraphic heights, and in some outcrops both types of rocks laterally coexist in the same layers. The ultrabasic rocks appear to have been dragged by the basaltic magmas and extruded together. This interpretation would require periods of major extension and opening of the fractures/faults.

Our present interpretation contends that both types of rocks, basic and ultrabasic, extruded because of the extension process, without a clear open oceanic basin and tectonic slices or units linked to the contact of these rocks (in any case, more studies in these aspects would be welcome). During this process of extrusion the sedimentation continued.

On the existence of the previous proposed tectonic units

The fundamental feature to justify the division in tectonic units of the NFC is the decrease of the metamorphic degree from the higher levels of the general lithological sequence to the lower ones situated in the visible bottom, this being perceptible both from petrological data as well as by direct examination in the field. This explains the differentiation of the above-mentioned units of Veleta and Mulhacén, or La Ragua (~ Veleta), Calar Alto, and Bédar-Macael, together with lesser units, such as the Ofiolite unit.

Even in the Crystalline of Sierra Nevada, in the Dark schists Fm, this decrease is visible. Probably for this reason Martínez-Martínez *et al*. (2002) differentiated a high part in these schists which they named the Montenegro Fm (Table 1), and considered it part of the Calar Alto unit. This proposal of division has the problem of physically establish a limit, *i.e.* the contact, between the two units Ragua and Calar Alto. In the cross sections made in the dark schists (Fig. 2), and anywhere else, a continuous transition within the lithological sequence can be detected. Even within the lower part of this sequence the decrease of the grade of metamorphism is directly visible, to such a degree that in the vicinity of Aulago (the lowest part visible of the Dark schists Fm) some rocks have almost a sedimentary look.

The same difficulty arises in situating the limit between the formerly proposed units of Veleta and Mulhacén. The possible position of this limit is generally situated in places where the layers are well exposed and no tectonic limit is visible (a reason to move the limit sought to a lower position –when was proposed the Ragua unit– although with the same completely imprecise result).

For all the other limits between units the problem is similar. The tectonic limit between the Calar Alto and Bédar-Macael units, according to our data, cannot be located anywhere. The same applies to the limits of the Ofiolitic unit proposed by Puga *et al*. (2011, 2017). These authors might argue that the borders themselves of the ultrabasic rocks constitute the limits, a debatable contention, but in any case these rocks disappear laterally, and in these positions none tectonic limit can be identified.

One argument used to explain the difficulty in situating the limits of the units is the pervasive presence of shear surfaces, even shear zones (the unit of Bédar-Macael is considered to be a shear zone; Augier *et al*., 2005 a, b). In this interpretation the proposed omnipresence of shear structures would erase the contact between the units. Certainly, some surfaces bear these characteristics, but generally they correspond to displacements among layers that only locally affect the lithological sequence. This is to be expected, particularly in a complex in which the main type of deformation is, in our interpretation, the simple shear. However, there is an immense difference between accepting the existence of small shear surfaces and considering that practically the entire lithological sequence, at least the upper formation, the Schists and marble Fm, forms an intricate shear zone. This is not observed in the field (the description of part of the structures of this formation can be seen in Sanz de Galdeano *et al.,* 2016). On the contrary, the former stratigraphic relations between layers are readily visible, even in this proposed Bédar-Macael unit interpreted as a shear zone.

Another consideration negating the existence of the proposed tectonic units is that the stratigraphic formations of the lithological sequence of the NFC maintain their geometric relations in the sierras Nevada and Filabres for more than 130 km in length, with only local exceptions caused by faults (Sanz de Galdeano and López-Garrido, 2016). This would not be expected if the proposed units exist, that is, owing to the process of thrust between two tectonic units, part of both units is usually cut off, resulting in contact different formations along their contact surface. This does not occur in the sierras Nevada and Filabres.

Moreover, in many cases, the limits of the proposed units, according to the maps published, traverse the lithological formations, but without displacing them. This, initially seeming illogical, indicates the existence of errors. In short, the proposed limits are artificial. The conclusion is that all the proposed limits of the tectonic units cannot be demonstrated, and in some cases they can be clearly demonstrated not even to exist.

Consequently, another explanation must be found for the distribution of the different degrees of metamorphism, higher in the upper part of the lithological sequence. In our interpretation, this in reality is an inverted metamorphism that is especially related to the P-T distribution linked to the Alpine subduction process underwent by the NFC. However, this issue lies beyond the scope of the present paper.

The significance of the sands and "lutites"

The presence of sands and "lutites" interlayered among quartzites and schists is another problem to be studied, but also lies beyond the scope of the present study. This is presumably related to the different distribution of P, T, and time in the subduction process.

Moreover, the grade of metamorphism in the NFC varies from one sector to another, probably being higher to the NE of the Sierra de Filabres than in the rest, being particularly low to the W part of Filabres. All these features remain to be studied.

Conclusions

The lithological sequence of the NFC in both sierras, Nevada and Filabres, shows clear uniformity, although with some lateral changes. In these sierras, four formations can be differentiated. The lower one is formed by dark schists and quartzites of about 3600 m in thickness. Above lies the Benitagla Fm of quartzites and the Tahal light schists, which laterally cannot be differentiated as two formations. On top, the higher formation is composed by schists and marbles. The total thickness of the upper formations is around 2000 m.

The change from one formation to another is stratigraphic in nature, generally showing a transitional lithological character. According to the dates previously indicated, the ages of the NFC lithological sequence range from the Carboniferous to the Triassic, perhaps reaching the Jurassic if not the Cretaceous.

The metamorphic degree increases progressively from bottom to top, being inverted. This feature has been interpreted as corresponding to a superposition of tectonic units, with a higher grade of metamorphism to the top, but the different tectonic contacts between the proposed units cannot be found. According to our data, they simply do not exist.

The sedimentation of the protolith of the dark schists had a syntectonic character, while the rest of the formations was deposited in a post-tectonic increasing extensional environment, facilitated by new faults that permitted the extrusions of acid and basic, even ultrabasic, igneous rocks. This new process occurred from the terminal Carboniferous/Permian. According to the field data, the ultrabasic rocks were extruded together with the basic rocks, not linked to the generation of an oceanic crust.

Acknowledgments

This work is a contribution of the project DAMAGE (AEI/FEDER CGL2016-80687-R) of DGICYT, and the research group RMN-370 of the Junta de Andalucía. We thank the professors M. Martín-Martín (Alicante), A. Folguera (Buenos Aires) and B. Bádenas (editor) whose corrections and suggestions have clearly improved this article.

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Manuscrito recibido el 4-10-2018
Recibida la revisión el 18-1-2019
Aceptado el manuscrito revisado el 11-2-2019