BOLETÍN GEOLÓGICO Y MINERO
2022, VOL. 133 (2), 195-223
ISSN: 0366-0176
http://dx.doi.org/10.21701/bolgeomin/133.2/009

Boletín
Geológico y
Minero

RESEARCH ARTICLE

Lithostratigraphy and structure of the Macael marbles (Betic zone, Spain)

Litoestratigrafía y estructura de los mármoles de Macael (Zona Bética, España)

Willem Arend Zevenhuizen[1]

[1] Calle Bédar, 9, 04008 Almería, Spain

Corresponding author: inyenster@gmail.com (Willem Arend Zevenhuizen)

Key points

The Macael marbles occur in a complex stack of imbricates with numerous recumbent folds and thrust slices

Detailed description of key outcrops is essential for documenting a geological area

More emphasis should be placed on structural geological criteria to unravel the tectonics of the Nevado-Filábride Complex

ABSTRACT

A complex stack of tectonic imbricates is mapped and studied in the Nevado-Filábride Complex of the Macael-Cóbdar area of the Sierra de los Filabres. The lithostratigraphy and geological structure are unravelled, documenting key outcrops in the heavily quarried area that is famous for its pure white marble. Four principal successive stages of deformation are recognized, based on careful field work. Initial SW-verging folding and thrusting was followed by extensional, top-to-the-NW shearing. Late N-verging folding and thrusting is also prominent. The resulting lithostratigraphic and tectonic subdivision is compared with some of the previous investigations in the area, which span over 6 decades. The findings assert the importance of using detailed local field data and the difficulty to apply a simple stratigraphic or tectonic model for this part of the Betic Zone.

Keywords: Betic Internal Zone; Folds; Lithostratigraphy; Nevado-Filábride Complex; Tectonic units.

Article History:
Received: 21/10/2021
Accepted: 07/05/2022

Puntos clave

Los mármoles de Macael se presentan en una pila compleja de imbricados con numerosos pliegues recumbentes y cabalgamientos

La descripción detallada de los afloramientos clave es esencial para documentar un área geológica

Se debe poner más énfasis en los criterios geológicos estructurales para desentrañar la tectónica del Complejo Nevado-Filábride

RESUMEN

Se cartografía y estudia un complejo apilamiento de imbricados tectónicos en el Complejo Nevado-Filábride del área Macael-Cóbdar en la Sierra de los Filabres. Se desentraña la litoestratigrafía y estructura geológica, documentando afloramientos clave en un área fuertemente explotada y famosa por su mármol blanco puro. Se reconocen cuatro etapas sucesivas principales de deformación, en base a un cuidadoso estudio de campo. El plegamiento y cabalgamiento inicial hacia el SW fue seguido por un cizallamiento extensional dirigido hacia el NW. Destaca también una deformación tardía asociada a plegamiento y cabalgamiento dirigido hacia el N. La subdivisión litoestratigráfica y tectónica resultante se compara con algunas de las investigaciones previas en el área de estudio, que abarcan más de 6 décadas. Los hallazgos apoyan la importancia de utilizar datos de campo locales detallados y la dificultad de aplicar un modelo estratigráfico o tectónico sencillo para esta parte de la Zona Bética.

Palabras clave: Zona Interna Bética; Pliegues; Litoestratigrafía; Complejo Nevado-Filábride; Unidades tectónicas.

Historial del artículo:
Recibido: 21/10/2021
Aceptado: 07/05/2022

1. Introduction

In southern Spain, the northern slopes of the Sierra de los Filabres, around Macael village, have been quarried for thousands of years for its coarse grained, pure white marbles. Over the past decades, large scale marble extraction has led to exceptionally good exposures, which render valuable information about the geological structure and deformation history. However, continuous excavation also poses problems, because exemplary structures may appear and disappear rapidly; in addition, the vertical quarry walls in a labyrinthine disposition are dangerous to sample and difficult to represent on maps.

The main purpose of this study is to document some currently accessible examples of typical geological structures. The predominant orientations of planar and linear structures in the area are also presented. The emphasis is on macroscopic geological structures, although some new quartz fabric microstructures are included. Time relation of quartz fabrics to folding was previously documented by Zevenhuizen (1989). The key locations where some of the photographs in this paper were taken are shown on a detailed map and in the supplementary material. Alternative partial views of some structures can be seen online through Google Street View and local topographic names are used in the text for offline field reference.

After a short description of the geological setting, the lithological succession is dealt with from bottom to top, and brought in relation to some geological structures in which they can be seen in the study area. Next, the deformation history is described in more detail, illustrated with additional examples of representative outcrops from the same area. Finally, the tectonic and lithological subdivision presented here is compared to previous papers and commented on in a discussion.

2. Geological setting

The structures and rocks described in this paper all occur in the Nevado-Filábride Complex as defined by Egeler (1963), which in paleogeographic reconstructions is considered as a part of the Alboran Domain (Balanya and García-Dueñas, 1987; Bessière *et al.*, 2021) or the southernmost extension of the Iberian Margin (Platt *et al.*, 2006; Gómez-Pugnaire *et al.*, 2012; Kirchner *et al.*, 2016; Van Hinsbergen *et al.*, 2020). The Nevado-Filábride Complex is sometimes subdivided into a lower Veleta Complex and an upper Mulhacen Complex (Puga *et al.*, 2002) and all the rocks in the eastern Sierra de los Filabres would belong to the latter. The tectonic contact with the overlying Alpujárride Complex is considered as a brittle-ductile extensional detachment zone (Galindo-Zaldívar *et al.*, 1989; Booth-Rea *et al.*, 2015); this same contact and the related deformation in the footwall have also been referred to as the Betic Movement Zone (BMZ) (Platt and Vissers, 1981).

Detailed maps and descriptions of the area around Macael and Cóbdar were first presented by Voet (1967), Kampschuur (1975) and Vissers (1981). Their work was simplified and summarized in the geological map sheet 1013 of the MAGNA project (García-Monzón *et al.*, 1975), in which all metamorphic rocks, notwithstanding their lithostratigraphic peculiarities, were ascribed to just four general formations in three superimposed tectonic nappe units. After careful fieldwork, this study mostly confirms and does not significantly redraw the lithological boundaries that were already shown on the MAGNA map, but it presents a more detailed lithostratigraphic description, geological map and corresponding subdivision (figures 1, 2 and 3), based on a more elaborate structural analysis (figures 4 and 5).

In the eastern Sierra de los Filabres, the rocks were metamorphosed in HP-LT conditions reaching peak pressures of ca. 1.8 GPa with temperatures ranging from 500 to 610ºC (Gómez-Pugnaire *et al.*, 1994), which evolved to IP-IT conditions during exhumation with some reheating and then retrogression (De Jong *et al.*, 2001). The HP-LT metamorphic event is dated at ca. 18-15 Ma (López-Sánchez-Vizcaíno *et al.*, 2001; Gómez-Pugnaire *et al.*, 2004, 2012; Platt *et al.*, 2006; Kirchner *et al.*, 2016). Rocks in the studied area were cooled below 200 ºC at 12.9 – 10.4 Ma (fission tracks on zircons; Johnson *et al.*, 1997), and below 105ºC at 11.6 – 4.4 Ma (fission tracks on apatites; Johnson *et al.*, 1997).

The stack of metamorphic rocks shows a complex deformation history with at least 4 generations of folds and movement along low-angle faults, which are named D3, D4, D5 and D6, and occasional small-scale relict structures of at least 2 previous deformation stages (D1 and D2). D3 initiated at the peak temperature of metamorphism. The intensity and geometries of resulting deformation structures are not homogeneous throughout the pile of rocks. The general structure conforms to a NE-dipping monocline of trans-

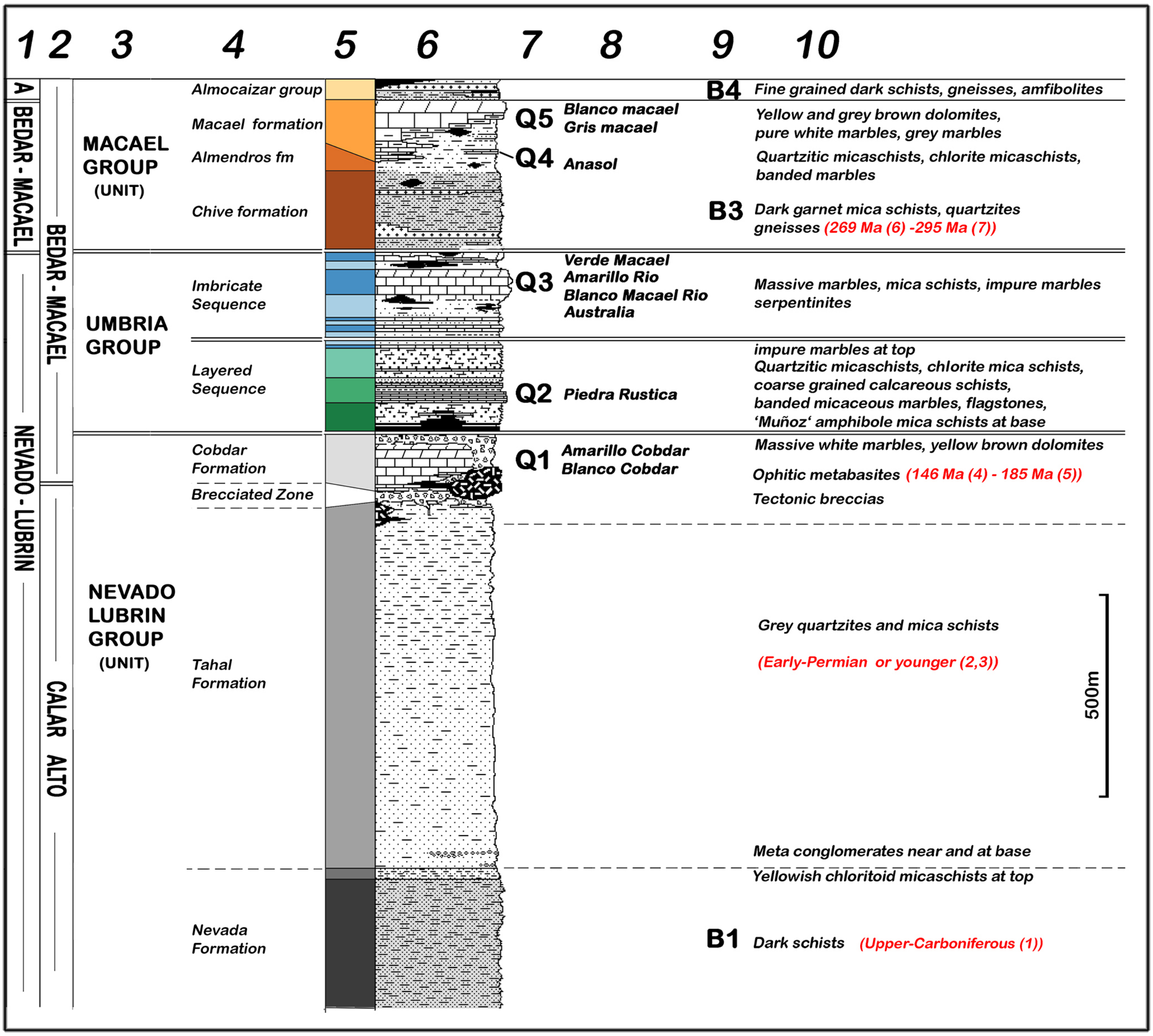

Figure 1. Lithostratigraphic column of the Nevado-Filábride Complex in the Macael-Cóbdar area. 1. Tectonic units according to García-Monzón *et al.* (1975), A= Almocaizar Unit. 2. Tectonic units according to García Dueñas *et al.* (1988). 3. Lithostratigraphic groups. 4. Lithostratigraphic formations. 5. Colours used in Geological Map of Figure 2. 6. Lithological column. 7. Main marble quarry levels. 8. Commercial names for quarried marbles. 9. Dark schists and associated rocks. 10. Lithological description. Age references: (1). Santamaría and Sanz de Galdeano (2018); (2). Jabaloy-Sánchez *et al.* (2018); (3). Jabaloy-Sánchez *et al.* (2021); (4). Hebeda *et al.* (1980); (5). Gómez-Pugnaire *et al.* (2017); (6). Priem *et al.* (1966); (7). Gómez-Pugnaire *et al.* (2012).

Figura 1. Columna litoestratigráfica del Complejo Nevado-Filábride en el área de Macael y Cóbdar. 1. Unidades según García Monzón *et al.* (1975), A= Unidad Almocaizar. 2. Unidades según García Dueñas *et al.* (1988). 3. Grupos de formaciones. 4. Formaciones. 5. Colores usados en el mapa de la Figura 2. 6. Columna litológica. 7. Niveles principales de mármoles explotados. 8. Nombres comerciales de mármoles explotados. 9. Esquistos oscuros y litologías asociadas. 10. Descripción litológica. Referencias edades: (1). Santamaría and Sanz de Galdeano (2018); (2). Jabaloy-Sánchez *et al.* (2018); (3). Jabaloy-Sánchez *et al.* (2021); (4). Hebeda *et al.* (1980); (5). Gómez-Pugnaire *et al.* (2017); (6). Priem *et al.* (1966); (7). Gómez-Pugnaire *et al.* (2012).

posed bedding (figures 2 and 4), with a complicated internal structure dominated by low angle faults and recumbent folds, which form a stack of imbricates. Fold structures and tectonic slices are typically in the order of tens of metres or hectometres and can easily be identified in good exposures, such as the quarries south of Macael. They are often too small to be evident on regional geological maps, but some can be followed for several kilometres. Because the apparent stratigraphy

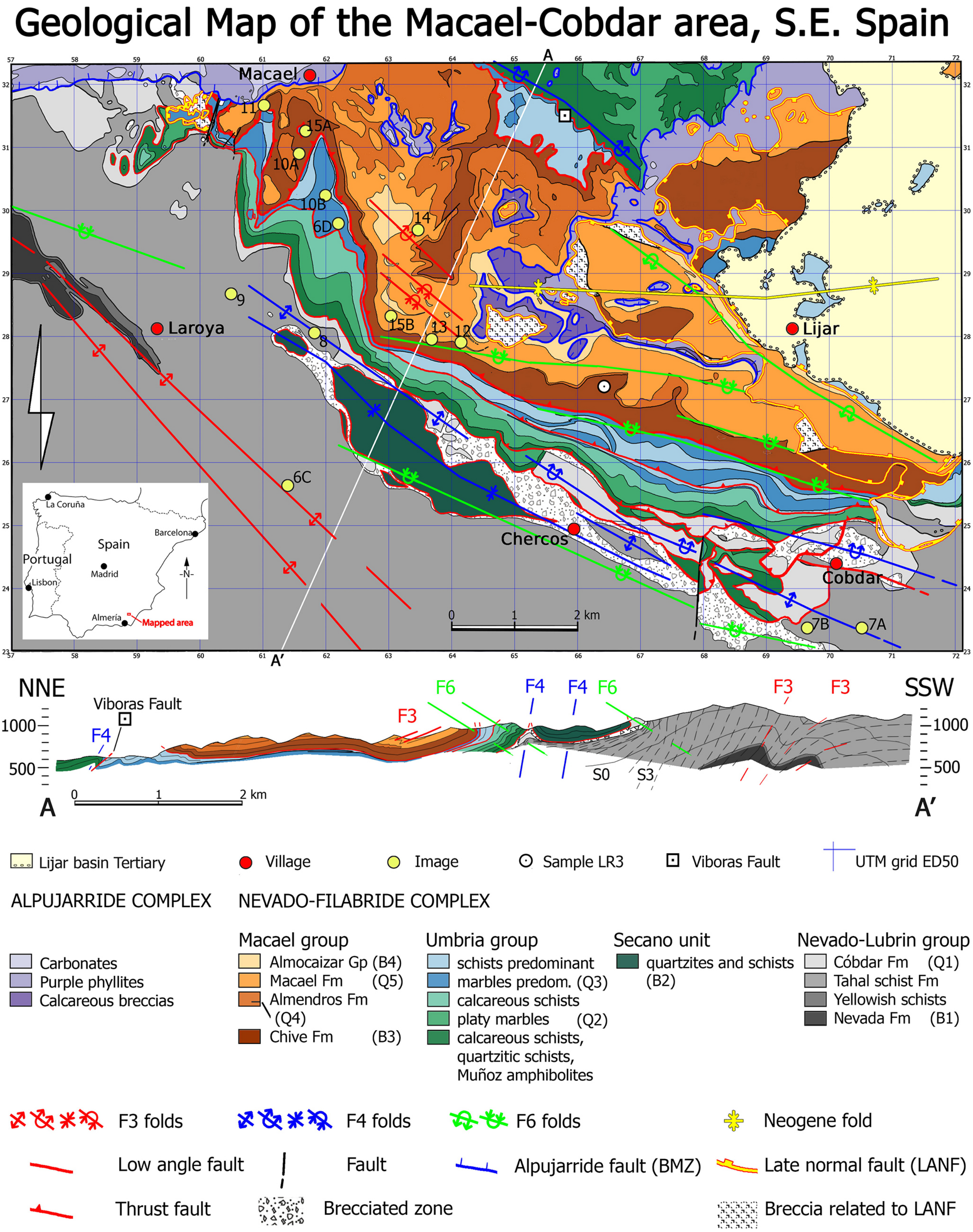

Figure 2. Geological map of the Macael-Cóbdar area. Cross section represented by white line. Yellow dots refer to spots where photos were taken (figures 6 to 15).

Figura 2. Mapa geológico del área entre Macael y Cóbdar. Corte representado por la línea blanca. Los puntos amarillos indican donde fueron tomadas las fotos de este artículo (figuras 6 a 15).

Nijhuis	Voet	Garcia-Monzon et al (MAGNA)	Vissers	Garcia-Dueñas et al	De Jong & Bakker	Tendero et al, Nieto et al, Puga et al	Gomez-Pugnaire et al	Booth-Rea et al	Sanz de Galdeano et al	This paper, Macael Area
1964	**1967**	**1975**	**1981**	**1988**	**1991**	**1993,2K,2009**	**2012**	**2015**	**2016**	**2022**
	Huertecicas Altas Unit	Formacion Nevada			Huertecicas Altas-Almocaizar Unit	Sabinas Cover				Almocaizar Group B4
	Macael Marbles	Formacion Las Casas		Marmoles de la Atalaya Upper limb	Macael Marbles	Undiff. Marbles Mainly Ophiolite nappe		Huertecica Fm		Macael Marble Formation
	Almendros schists	Formacion Tahal		Formacion Tahal Upper limb	Calesas schists	Caldera Cover		Tahal Fm		Almendros Schist Formation
Graphite schist - tourmaline gneiss complex	Garnet-mica schist – Tourmaline gneiss sequence	Formacion Nevada		Formacion Montenegro	Aceituno schists	Caldera Basement	Tahal Fm/chive Fm	Montenegro Fm		Chive Formation B3
	Marble – calc schist sequence	Formacion Las casas		Formacion Tahal Lower limb	La Yedra 4 La Yedra 3		Marble calc schist Fm/Tahal Fm		Marbles and schists upper Fm	Imbricate Sequence Umbria Group
Las casas Marbles and Schists			Umbria de las canteras unit		La Yedra 2 La Yedra 1	Sedimentary sequence of the Ophiolite unit				Layered Sequence Umbria Group
Muñoz amphibole mica schists	albite – epidote amphibolites				Amphibolites	Ophiolite unit				
Atalaya Marbles	Cobdar marbles of the marble - calc schist sequence			Marmoles de la Atalaya Lower limb	Carrasca marbles	Sabinas Marbles	Marble calc schist Fm			Cobdar Marble Formation
Huertecica brecciated Marble zone		Formación Huertecica	brecciated zone	Formacion Huertecica	Carbonate breccias	Ophiolite unit Soportujar Fm	Meta evaporitic Fm	Huertecica Fm		Brecciated Zone
Tahal schist complex	Tahal schist	Formacion Tahal	Tahal schist	Formacion Tahal	Tahal schists	Sabinas/Caldera /Tectonic Melange	Tahal and meta evaporitic Fm	Tahal Fm	Tahal Fm	Tahal Schist Formation
Crystalline schists of Sierra Nevada	Crystalline schists of Sierra Nevada	Formacion Nevada	Nevada schist	formacion Montenegro	Velefique schists		Lower Fm	Montenegro Fm	Crystalline schists of Sierra Nevada	Nevada Schist Formation B1
				Formacion Aulago		Veleta	Lower Fm	Aulago Fm Ragua unit		

Figure 3. Table showing nomenclature used for the lithological sequence in the eastern Sierra de los Filabres by some previous publications and in relation to this paper. Shaded areas stand for presumably pre-Permian or dated as Upper Carboniferous dark rocks. Solid thick horizontal lines represent low-angle tectonic surfaces, (thrust faults and other low angle faults).

Figura 3. Tabla esquemática de los nombres de unidades usadas para la secuencia litológica en la Sierra de los Filabres oriental en algunas publicaciones anteriores y en relación a este artículo. Áreas sombreadas indican rocas oscuras presuntamente pre-pérmicas o datados como Carbonífero Superior. Las líneas gruesas representan contactos tectónicos (cabalgamientos y fallas de bajo ángulo).

has been affected by transposition of the foliation, isoclinal folding, low angle faults and thrusting, the recognition of these structures has consequences for the interpretation of the lithostratigraphy and vice-versa.

3. Description of the metamorphic rocks in the Macael-Cóbdar area

The succession of the Nevado-Filábride metamorphic rocks outcropping in the Macael-Cóbdar area is represented in the lithostratigraphic column of Figure 1 and the geological map of Figure 2. Both figures use corresponding colours. In this study, the term “Unit” or “tectonic unit” is occasionally used and defined as: major bodies of characteristic rock-sequences that are bounded by tectonic contacts. However, many small tectonic slices have not been named as individual units. On the other hand, lithological characteristics are understood to be more objective and indisputable. Bodies of metamorphic rock sequences purely distinguishable for their lithic characteristics are considered to represent lithostratigraphic units and consistently named “Group”, “Formation” and “Member”; (“Gp”, “Fm” and “Mb”). Economically viable marble exploitation is limited to a few characteristic levels of variable thickness, numbered Q1 to Q5 in ascending order (Figure 1). Commercial names for varieties of marble from each level are referred to in the text and Figure 1. The quarriable beds are found to be severely folded and imbricated internally, which makes it impossible to represent them in detail in Figure 2. The marbles are relatively undisturbed by late stage fracturing in the area south of Macael in the western half of the area, where they are exposed in a subhorizontal platform that has been largely exploited.

Four presumably Paleozoic layers of dark-coloured graphite -bearing rock have been num-

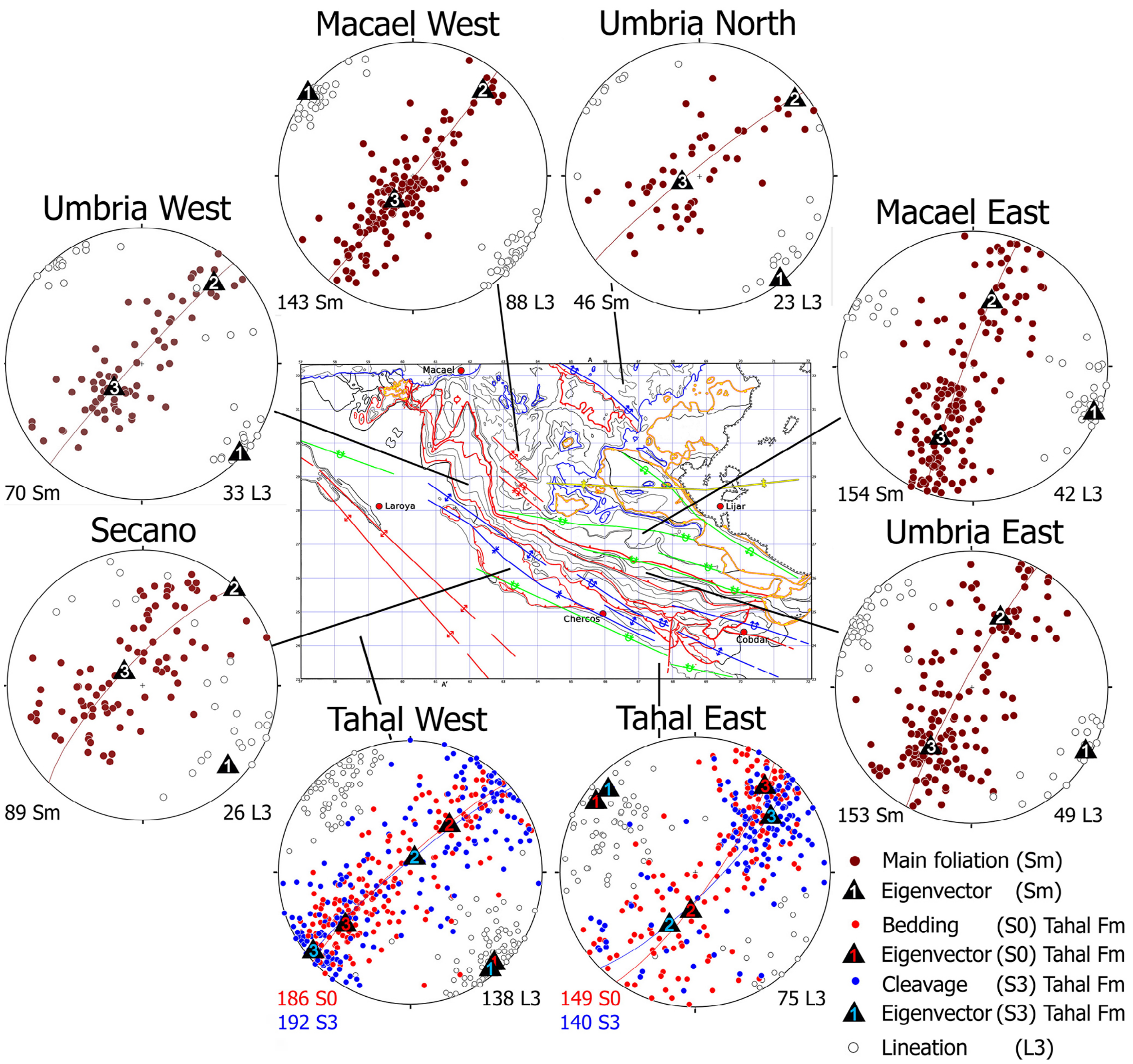

Figure 4. Lower hemisphere projection of poles to main foliation and related lineations. (Stretching lineations, intersection lineations and F3 fold axes), in different parts of the Macael-Cóbdar area. Poles to S3 and bedding in the Tahal Fm.

Figura 4. Proyección de polos de la foliación principal y lineaciones relacionadas. (Lineaciones de estiramiento, lineaciones de intersección y ejes de pliegues F3), en distintas partes del área de Macael y Cóbdar. En la Fm Tahal: polos a S3 y bandeado litológico.

bered B1 to B4 from bottom to top. Their distinction in the folded and imbricated stack has traditionally been essential for the geological interpretations of the Nevado-Filábride Complex, as the lighter coloured schists have most often been considered to be Permo-Triassic and the marbles as Triassic in age (Egeler and Simon, 1969; García-Monzón *et al.*, 1975; De Jong and Bakker, 1991). Some of these ages for specific levels in the stack have been confirmed by later research and are referred to in Figure 1, but there is no reason to apply these ages directly to all other similar rocks in different levels in the stack of heterogeneous, highly-deformed rocks. In other words, not all dark schists (B1 to B4) need to belong to one single formation with a single age, and the same holds true for all the lighter schists and all the marbles. The model in which the lithologies in the Nevado-Filábride stack are limited to four simple formations was introduced by Kampschuur (1975) and later followed by García-Monzón *et al.* (1975) (see Figure 3). However, detailed geological fieldwork does not corroborate any simple model for the eastern Sierra de los Filabres.

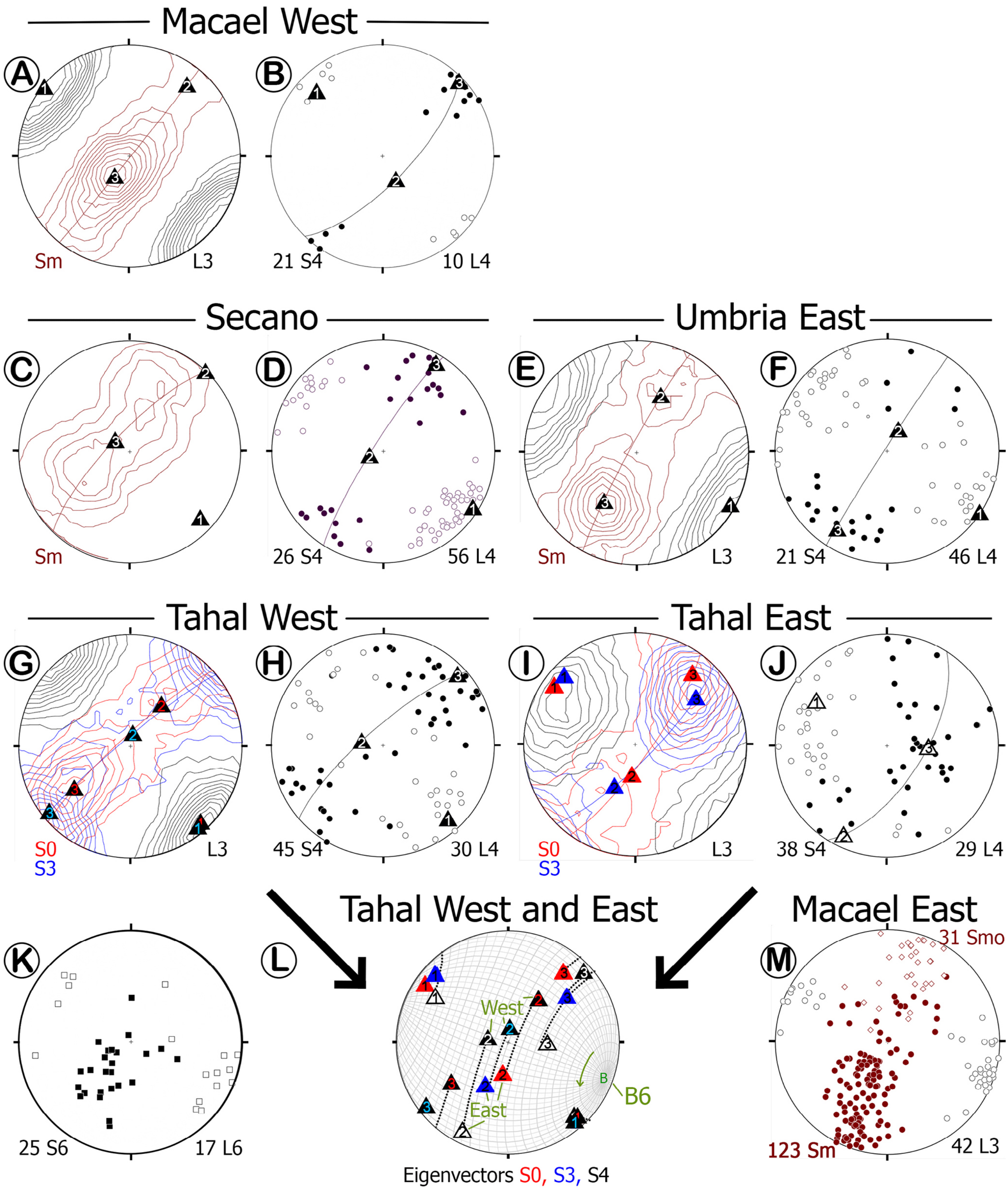

Figure 5. A to J: Contour plots of poles to main foliation (Sm) and related lineations (L3), compared with poles to upright F4 axial planes (S4) and lineations (L4) in some of the subareas of Figure 4. Means shown by eigenvectors (triangles). K: F6 fold axes and poles to associated fracture cleavages. L. Small circle rotation of eigenvectors of G to J by F6 folding to explain the relation between the western and eastern Tahal schist subareas. M: The steep and overturned main foliation in the eastern half of the Macael Unit and its dispersion, due to F6 folding.

Figura 5. A hasta J: Diagramas de contornos de polos de la foliación principal (Sm) y lineaciones relacionadas (L3), comparados con polos a los planos axiales subverticales (S4) de pliegues F4 y lineaciones asociadas L4 . Medias representadas con eigenvectores (triángulos). K: Ejes de pliegues F6 y polos de planos axiales asociados. L: Rotación por círculo menor que explica la relación entre las orientaciones en las subáreas oeste y este de la Fm Tahal. M: La foliación principal Sm en posición subvertical a inversa y su dispersión a causa del plegamiento F6 en el área este de la unidad de Macael.

In the north and northeast, a brittle-ductile tectonic contact separates the metamorphic rocks of the Nevado-Filábride Complex from the overlying Alpujárride Complex. The latter complex is not described here. Relatively late low-angle normal faults within and between the metamorphic rocks of both complexes are predominant in the eastern half of the area, where they underlie and surround a basin of younger, non-metamorphic, Neogene sediments.

3.1. Nevado-Lubrín Group

In the NW, near the village of Laroya, the lowermost rocks crop out in a NW-SE trending anticlinorium that was described in detail by Vissers (1981). They are rather monotonous, dark graphite -bearing schists and quartzites, which are similar to the ones that appear further south and west in the cores of the Sierra de los Filabres and Sierra Nevada. They are called Nevada Schist Formation (following García-Monzón *et al.*, 1975) (B1 in figures 1 and 2). Their protoliths were dated as Late Carboniferous by Santamaría and Sanz de Galdeano (2018) using U-Pb on zircons (SHRIMP). The uppermost few meters of these rocks are different and made up of yellowish brown chloritoid-garnet micaschist, interpreted as a weathering zone or paleosol (Vissers, 1981).

The Nevada Fm is covered by a series of about 800 m of greyish micaschists and quartzites, rich in albite and chlorite and commonly known as the Tahal Schist Fm. Ocre-coloured weathering and small-scale open folding are conspicuous. On top of the supposed paleosol, lenses of metaconglomerate with a thickness of a few metres appear in the lower part of the Tahal Fm, for example about 6 kilometres south of Macael near Los Polillos (Figure 6C). The surfboard shaped pebbles of up to 40 centimetres are mostly composed of pure quartz but some quartzite pebbles are present. The Tahal Fm lacks other distinctive beds, but near the top minor intercalations of marble may occur, as well as bodies of amphibolites and blastophitic metabasites. Although contacts between the metasedimentary rocks and the mafic constituents are normally disturbed by brecciation and fractures, occasional neat contacts exclude a pure tectonic nature of the contact between both types of rocks. U-Pb ages on detrital zircons sampled a few kilometres south of the area indicate younger than Early-Permian ages for the Tahal Fm (Jabaloy-Sánchez *et al.*, 2018).

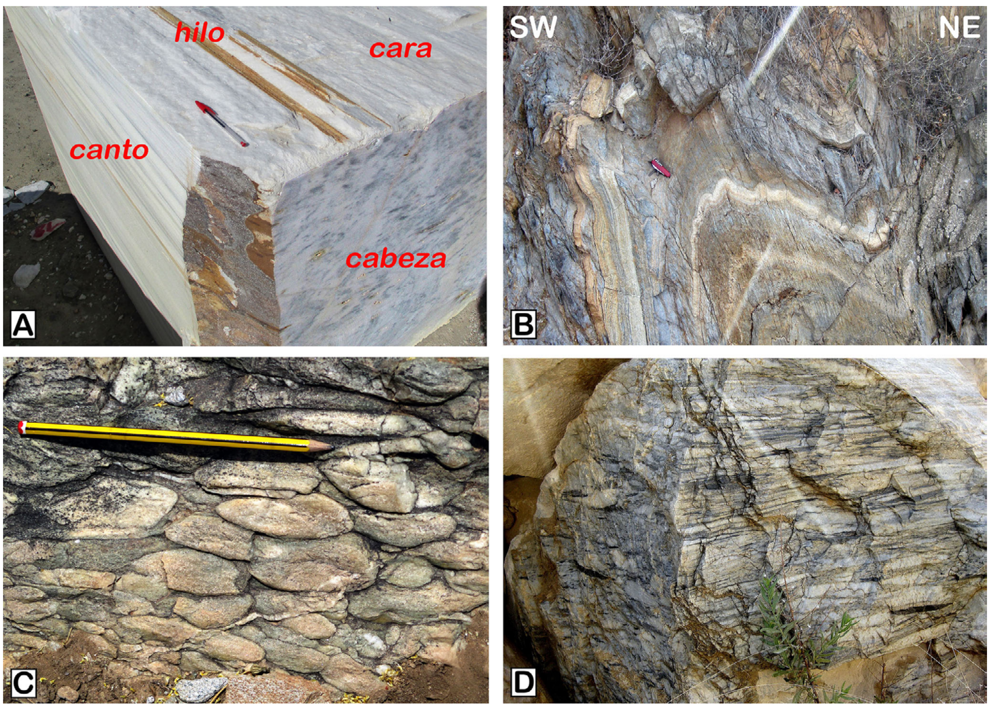

Figure 6. A: L-S-tectonite in Macael marble with local names for structural features. B: Typical small F3 fold in Tahal Fm. C: Pebble meta-conglomerate in Tahal Fm. D: Meta-conglomerate in Río marbles, Umbría Gp.

Figura 6. A: L-S tectonita en mármoles de Macael con la terminología local para los elementos estructurales. B: Pliegue típico F3 en Formación Tahal. C: Meta-conglomerado en la base de la Formación Tahal. D: Meta-conglomerado en Macael Río mármol, Grupo Umbría.

One or two generations of open to tight, mostly upright folds with an overall SW vergence are a common feature in the Tahal Fm (Figure 6B). Detailed structural analyses of Tahal schists were previously carried out by Langenberg (1972) in an area about 10 kilometres east of Cóbdar, and by Vissers (1981) to the west and southwest of this area. In this paper, and based on overprinting relations, the folds and concurring differentiated crenulation cleavage are ascribed to a third and fourth stage of deformation (figures 4 and 5).

The Tahal Fm is overlain by the Cóbdar Fm, but the contact is usually marked by an irregular series of calcareous breccias, known as the brecciated zone. It has often been referred to as the Huertecica Fm (García-Monzón *et al*., 1975; García Dueñas *et al*., 1988) or Meta-evaporitic Fm (Gómez-Pugnaire *et al*., 1994) (Figure 3). However, the brecciated zone is not a single formation in a lithological sense, but a chaotic rock ensemble or group of broken formations, without any constant thickness, composition, age or position.

The brecciated zone was described as an important decollement by De Jong (1991) and numerous minor tectonic slices in the zone and the adjacent formations confirm that it marks an important shear zone. This irregular mass of fractured rocks boasts thick accumulations in some places, whereas it wedges out completely elsewhere. Apart from fragments of the adjacent more common unbrecciated rocks, the damage zone typically contains carbonaceous rocks, sand, marl, blastophitic metabasites, pockets of gypsum, skapolite-rich rocks and fine-grained rocks resembling low grade phyllonites. However, most of these constituents can occasionally be found in underlying and overlying unbrecciated rocks and are not considered exotic elements. Therefore, the term “melange” in the sense of Festa *et al.* (2010) is avoided here. Gypsum and skapolite are indications of an evaporitic origin for at least part of the protoliths (Gómez-Pugnaire *et al.,* 1994).

Blastophitic metabasites with relicts of igneous structures and minerals are found as irregular, often shapeless, bodies from a few centimetres to several hundreds of meters, which seldom show clear undisturbed contacts with the surrounding rocks, although they sometimes grade into layered albite-epidote amphibolites that are more often in direct, relatively undisturbed, contact with the country rock. Light-coloured randomly oriented pseudomorphs after feldspar phenocrysts are clearly distinguishable from a pale green matrix. The rocks are normally strongly weathered, but some almost unaltered cores of dark olivine diabase are present north of the village of Cóbdar, where they are exposed in the core of a SW-verging F4 anticline in the top of the Nevado-Lubrín sequence (figures 2 and 7) These particular basic rocks have been subject to a considerable number of publications and have been classified as eclogites after gabbros and dolerites (Gómez-Pugnaire *et al.,* 2019) and troctolites and basaltic pillow lavas of an ophiolite sequence that yielded U-Pb SHRIMP ages on zircons of 185 Ma (Puga *et al.,* 2017 and references therein). Rocks from the same outcrop have been dated at 164-175 Ma by the K-Ar method (Portugal-Ferreira *et al*., 1988) and similar rocks near Lubrín also yielded a Rb-Sr isochron age of 146 Ma (Hebeda *et al*., 1980).

Cataclasites in the breccias sometimes show metamorphic minerals that have grown over a consolidated matrix (Nijhuis, 1964; Voet, 1967), but more often unconsolidated yellowish sand and marl make up an important part of the brecciated zone, looking like Cenozoic non-metamorphic rocks, or at least of a lower grade; hence the distinction of the Soportujar Fm of Puga *et al.* (1989). However, these rocks are not considered to be Cenozoic by most authors, who claim they are part of the same sequence (García-Monzón *et al*., 1975; De Jong and Bakker, 1991; Gómez Pugnaire *et al*., 2012 and Booth-Rea *et al*., 2015). From a regional point of view, the breccias typically appear in and on the top of the Tahal schists and under massive marbles of the Cóbdar Fm and they are affected by F4 folds (figures 2, 7 and 8). However, sometimes similar brecciated rocks occur on top of the Cóbdar marbles or even within or between series of adjacent, relatively undisturbed rocks. Ramifications fill cracks and faults that branch off from the main zone truncating the strata on top or below and bounding tectonic imbricates (Figure 7B). The breccias tend to be cut by later faults and fractures.

The brecciated zone is usually covered by massive marbles, here referred to as the Cóbdar Marble Fm, and elsewhere by dark-coloured graphitic schists and quartzites from the Secano Unit or layered rocks of the Umbría Gp. The Cóbdar Fm and the Secano Unit crop out on top of the brecciated zone as large elongated and often isolated bodies of rocks that stretch out for over several kilometres along the NW-SE trend. These rock bodies might alternatively be considered as

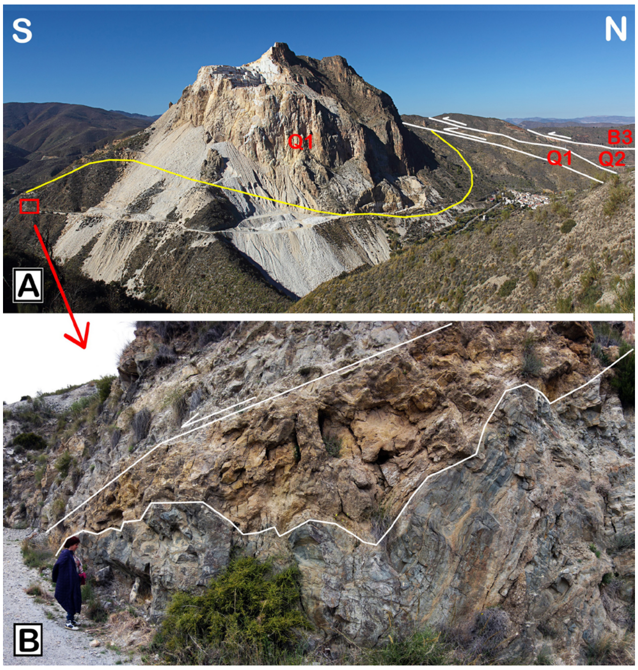

Figure 7. View looking W from the A-1100 road. A: General view of the massive marbles south of Cóbdar village. The yellow line marks the base of the marbles, folded by D4 and underlain by faults and breccias. Higher imbricates shown by white lines top right. B: detail of imbricate structures along the old road from Cóbdar to Chercos. Boudinaged and F4 folded metabasites (bottom) are covered by carbonaceous breccias which are truncated by late overthrusting of a slice of Tahal schists (top).

Figura 7. Vista mirando W desde la carretera A-1100. A: Vista general de los mármoles masivos al sur del pueblo de Cóbdar. La línea amarilla marca la base de los mármoles, plegada por D4 y encima de fallas y brechas carbonatadas. Imbricaciones superiores en la parte alta derecha. B: Detalle de imbricaciones en la antigua carretera de Cóbdar a Chercos. Budinaje y pliegues F4 en metabasitas (abajo), que están cubiertos por las brechas carbonatadas que a su vez están truncados por el cabalgamiento tardío de una escama de esquistos de Tahal (arriba).

mappable major tectonic slices within a greater damage zone that would comprise everything from the broken upper part of the Tahal schists up to the basal layered sequence of the Umbría Gp.

Perpendicular to the trend, in the SW-NE direction, the Cóbdar marbles wedge out quickly. Some of the thicker outcrops of the marbles are formed by hinges of major rootless recumbent F3 folds which in itself are overprinted by younger SW-verging and more upright F4 folds (figures 7 and 8) and WNW-verging F5 folds. The Cóbdar Fm is virtually absent southwest of the village of Macael along the AL-6104 Road to Laroya, where the Tahal schists are overlain by the layered sequence of the Umbría Gp, only separated by a thin layer of breccias. North of the village of Cóbdar, where the layered sequence of the Umbría Gp directly overlies the brecciated zone with relatively small outcrops of the Cóbdar Fm but abundant metabasites, this layered sequence has been interpreted as the metasedimentary cover of an ophiolite unit (Puga *et al*., 1989; Tendero *et al*., 1993).

The lowermost marble quarry level Q1 in the study area is situated within the Cóbdar Fm. Q1 is made of massive white marbles, better known as Blanco Cóbdar, covered by massive dolomites with the commercial names Amarillo Cóbdar and Amarillo Triana (figures 1 and 2). Irregular masses of dolomite can also be found between banded layers of white calcite marbles. Locally, especially near fractures, calcite has been replaced by ankerite. Internal layering can be difficult to establish, but some dark blue, strongly banded and layered micaceous marbles with conspicuous black graphite-bearing carbonaceous boudins are usual (López Sánchez-Vizcaíno, 1994; De Jong and Bakker, 1991). Concordant beds of amphibolitic rocks are occasionally present. The marbles are often strongly fractured, especially at the base, where they are underlain by calcareous breccias and mafic rocks. The top of the marbles west of Cóbdar is composed of fine grained banded dolomites, which sometimes alternate with fine grained phyllites or phyllonites.

Apart from within the brecciated zone, blastophitic metabasites can occasionally be found within the Tahal schists or in direct contact with marbles, on top of which mafic rocks in the form of amphibolites at the base of the Umbría Gp are found. This suggests an original continuity of the rock sequence prior to disruption. At present, the Cóbdar marbles are always limited by tectonic contacts or breccias at the top, which implies that the Nevado-Lubrín Gp lithologies can be ascribed to a lower tectonic unit.

3.2. Secano Unit (B2)

Between Laroya and Chercos (Figure 2), an elongated lens-shaped body of dark-coloured graphite-bearing garnet schists and quartzites, alternating with light-coloured graphite-free varieties, crops out (here referred to as B2). It is well exposed along the A349 road from Macael to Tabernas.

It is considered as a separate tectonic unit because it shows an easily recognizable, distinct lithology, different from the underlying Tahal Fm from which it is always separated by tectonic breccias, faults and strongly deformed marble beds.

The limited and isolated outcrop is not covered by any other lithology. Although the graphite content and aspect show some similarities with the Nevada Fm (B1), rocks in the unit are richer in garnet and quartzites. Using the same name would have structural consequences for which no evidence has been found. It is totally devoid of carbonates, gneisses or amphibolitic rocks, which makes it different from the so-called basement of the Macael Unit (Chive Fm, B3). Apart from garnet, chloritoid is a characteristic constituent. Rare outcrops of meta-conglomerate provide evidence for a shallow depositional environment for the protolith.

The unit and the underlying brecciated zone form a major synform structure of a subhorizontal transposed main foliation (figures 4 and 8). There is a weak axial plane cleavage associated with the upright folds (Figure 5). The rocks are typically intersected by several sets of joints that result in a notable weathering in small, loose angular blocks covered by dark brown soils.

The nature of this dark horse in the stack is problematic and thus not represented in figures 1 and 3. In its present emplacement it occupies a position that is next to the layered sequence of the Umbría Gp, never under it. The peculiarities of this

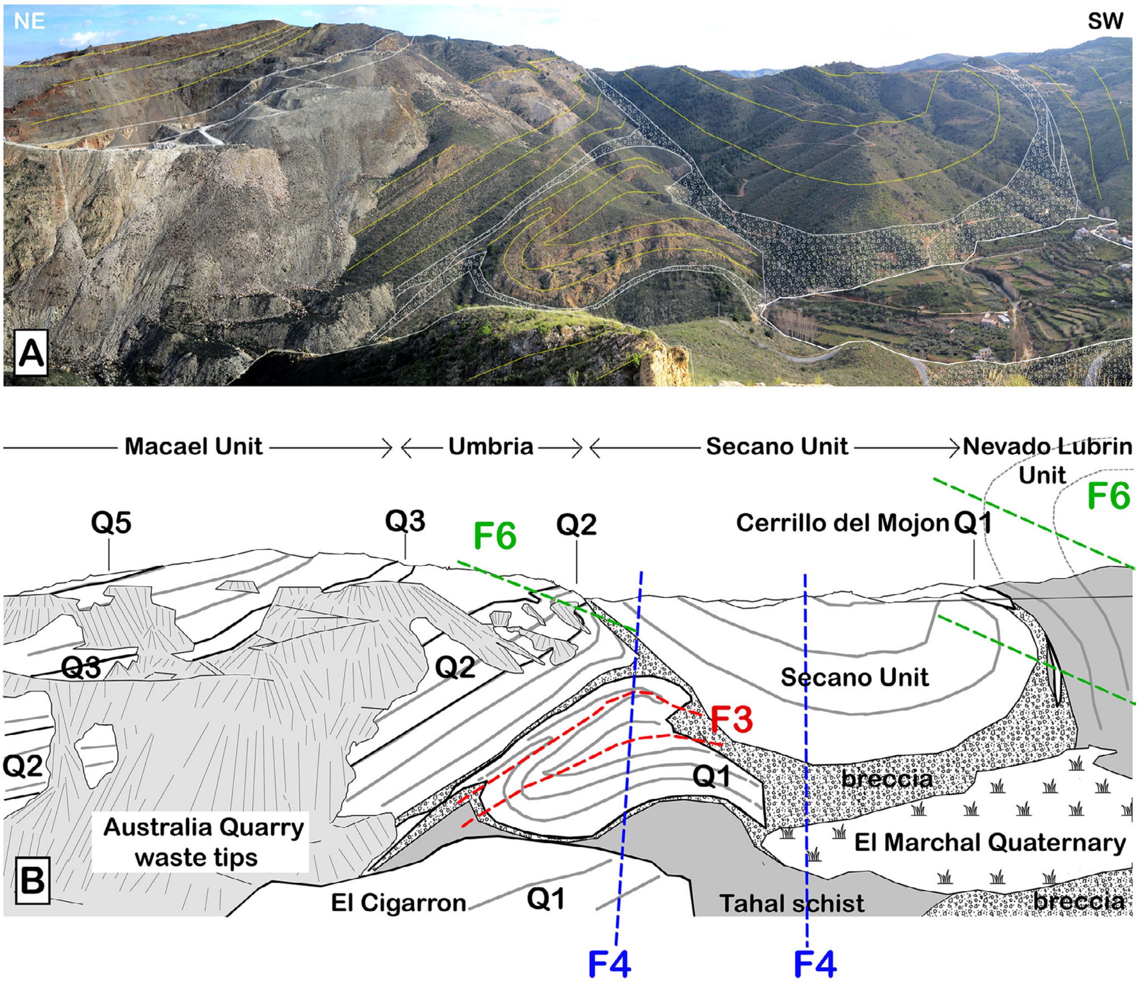

Figure 8. View looking SE from El Cigarrón mountain. 4 km south of Macael (2019). A recumbent F3 Z-fold in the centre is refolded by open upright F4 folds, which affect the Tahal schists, the brecciated zone, the Cóbdar marbles and the Secano Unit. The Umbría Gp rocks and the Macael Unit do not appear to be affected by F4 folds in this section. Both F3 and F4 fold generations are SW-verging. All structures are refolded by N-verging F6 folds, especially in the upper part of the section and on the right.

Figura 8. Vista mirando hacia el sureste desde la montaña “El Cigarrón”, 4km al sur de Macael. Un pliegue recumbente en forma de Z (F3) es plegado por pliegues con plano axial subvertical F4, plegando la formación Tahal, la zona brechificada, los mármoles de Cóbdar y la Unidad de Secano. Las rocas del Grupo Umbría y de la Unidad de Macael no parecen afectadas por los pliegues F4 en esta sección. Ambas generaciones de pliegues F3 y F4 son vergentes hacia el SW. Todas las estructuras están replegadas con vergencia hacia el N por pliegues F6, especialmente en las partes superior y derecha de esta imagen.

unit were a major topic of Linthout and Vissers (1979), who favoured a position under the adjacent Umbría Gp, leading to the distinction of their Umbría de las Canteras Unit. The graphite free rocks in the Secano Unit show similarities to some lithologies found in the eastern part of the area on top of the Cóbdar Fm, which have been ascribed to the Umbría Gp here. In other parts of the eastern Sierra de los Filabres, slices of quartzites found at the top of the Tahal Fm show some similarities. Meta-conglomerates among this B2 sequence and meta-evaporitic rocks in the adjacent brecciated zone make a parautochtonous position possible.

3.3. Umbría Group

A heterogeneous and strongly layered group of marbles, calcareous schists, quartzitic schists and amphibolites overlie the massive marbles of the Cóbdar Fm, from which they are separated by a fault. The name "Umbria de las Canteras Unit" was introduced by Linthout and Vissers (1979) for these rocks. However, similar rocks can be found NE of a reverse fault, about 4 kilometres east of the village of Macael, (referred to as Umbría North in Figure 4), where they occupy a higher position with respect to the Macael Gp. The characteristic sequence of lithologies thus occupies different positions in the stack and furthermore shows internal imbrications at the top. They are therefore not considered as one single lithostratigraphic formation or tectonic unit, but as a distinct lithostratigraphic group that crops out in several unnamed tectonic slices or imbricates.

Following the simplified lithological subdivision of Kampschuur (1975) into either schists or marbles, calcareous schists and alternations of schists and marbles have sometimes been interpreted as either Tahal (schists) or Las Casas (marble) formation. García Dueñas *et al*. (1988) and Gómez-Pugnaire *et al.* (2012) chose to include a large part of the Umbría Group in their Tahal Fm, leading to their structural geological interpretations (Figure 3).

The remarkable layered sequence that constitutes the lower part of the Umbría Gp can be followed for many kilometres and gives a deceitful suggestion of simplicity to the Nevado-Filábride Complex (figures 2 and 9). Typically, amphibole mica schists and amphibolites appear at the base, together with micaschists quite similar to schists of the Tahal Fm. These schists grade into coarse grained calcareous mica schists and conspicuous micaceous platy marbles (Q2) that often stand out as ridges, covered by a second series of coarse grained calcareous schists. The top of this group of lithologies is formed by several beds of impure marbles alternating with quartzitic schists, which have been imbricated and repeat themselves in recumbent isoclinal folds. They are referred to as the imbricate sequence of the Umbría Gp in Figure 1. Within the Umbría Gp, unusual Cr-rich minerals in bands would indicate shallow depositional environments according to López Sánchez-Vizcaíno *et al.* (1995) and Gómez-Pugnaire *et al.* (2000). This is coherent with the presence of meta-conglomerates in the impure marbles at the top (Figure 6D).

The albite epidote amphibolites at the base of the Umbría Gp show strongly sheared, yellowish spindles of epidote and colourless mica that constitute pseudomorphs after feldspar phenocrysts.

Q2 is a series of micaceous marbles that are quarried for flagstones that go by the names of "piedra rústica", "aleros" or even "cuarcitas". Square stacks of roughly hewn stones on pellets are a common sight at the access to the quarries. Although some of these stones are locally known as "cuarcitas" they are mostly micaceous marbles and dolostones. The marbles are typically dark bluish grey with fine white veins and dark brown replacement by ankerite along cracks, but some of the micaceous dolostones are green, or even almost white or gold tinged. Sometimes patches of green amphiboles are present.

The layered lower part of the Umbría Gp was referred to as the "Muñoz amphibole mica schists" and the original "Las Casas marbles and Schists" by Nijhuis (1964), and as the "La Yedra" 1 and 2 sequence of De Jong and Bakker (1991) (Figure 3). The same series was described as the sedimentary cover of an ophiolite unit by Puga *et al.* (2002). North of Cóbdar, where this sequence crops out in a subvertical position, ankerite-rich layers were interpreted as containing Cretaceous fossils (Tendero *et al*., 1993).

On top of the layered sequence, a series of impure blue and white marbles alternating with grey schists crops out. The marbles at this level in the stack seem to suddenly appear and disappear, typically because of isoclinal SW-verging folding and thrusting. These structural features in an alternating and apparently simple sequence of schists and marbles may lead to the conclusion that individual marble layers wedge out strictly

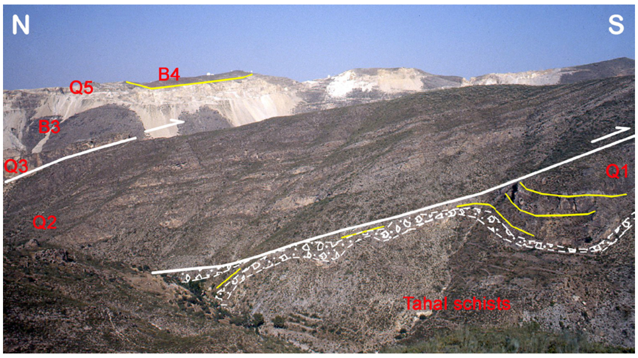

Figure 9. Looking east at the ridge south of Macael Viejo. (Picture taken in 1980). The continuous layered sequence of the Umbría Gp in the middle of the picture between low-angle faults is underlain by the highly irregular brecciated zone and Tahal schists and Cóbdar marbles Q1, (folded by F4 folds, bottom right) and overlain by the massive Río Marbles (Q3; Middle left at Macael Viejo). The ridge in the background represents the Macael Unit. The main quarry level of the Upper Macael marbles can easily be recognized by the waste tips. It is sandwiched between underlying dark schists and gneisses (B3) and under the dark schists and gneisses from the Almocaizar Gp (B4, top layer).

Figura 9. Mirando hacia el este sobre el Arroyo del Baile a la cresta al sur de Macael Viejo. (Foto de 1980). La secuencia continua de la parte baja del Grupo Umbría en el centro de la foto entre cabalgamientos se sitúa encima de la zona brechificada muy irregular y los esquistos de Tahal y mármoles Q1, (Plegados por pliegues F4, abajo a la derecha) y el cabalgamiento en la base de los mármoles masivos del Río, (Q3; centro izquierda en Macael Viejo). La sierra al fondo representa a la Unidad de Macael. El nivel principal de las canteras es reconocible fácilmente por las escombreras. Se halla encima de los esquistos oscuros y gneises (B3) y debajo de esquistos oscuros del grupo Almocaizar (B4, capa superior).

due to stratigraphic causes (De Jong and Bakker, 1991; Sanz de Galdeano *et al.*, 2016). One of these marble layers in the western half of the area attains a thickness of up to 40 metres and has been quarried intensively. It is the marble quarry level Q3 (figures 1 and 2). Level Q3 can be seen in the southernmost so-called “Australia” quarry, where it consists of an upper dolomite member, underlain by pure white marble, which grades downwards into blue micaceous marbles and calcareous schists. Although sometimes boudinaged or cut off by the overlying thrust of the Macael Unit, the Q3 layer can be followed for over 10 kilometres towards the east, as well as some 5 kilometres to the northwest in and around Macael Viejo, where it is known as the “Río marble”. The Q3 Río marble is made of irregular dolomite on top of white marble, but locally some grey micaceous marbles and beds with a metaconglomeratic aspect are present on top of these (Figure 6D). Marbles of the Q3 level have commercial names as “blanco Macael Río”, “gris Macael Río” and “Amarillo Macael Río”. The steep excavated slopes of the Umbría de las Canteras area show a major recumbent isoclinal antiform, which is cut off by the basal thrust fault of the Macael Unit (Figure 10). The Q3 Río marble can also be recognized in the Laroya river SW of Macael, where it is sandwiched between two serpentinite layers. It cannot easily be seen further west, which is probably due to the boudinage and the NNE-SSW normal faults related to D5 extensional movements.

In the southeastern part of the area, strongly deformed schists and quartzites, capped by dark grey layered marbles, are found on top of the massive calcite and dolomite marbles of the Cóbdar Fm. These rocks have been mapped in Figure 2 as belonging to the layered sequence of the Umbría Gp, but they also show a resemblance to some of the lithologies found in the Secano Unit. In their exposure on the southern slope of Cóbdar’s massive marble mountain, the rocks in this series have often been ascribed to the Tahal Fm (Voet, 1967; Gómez-Pugnaire *et al.*, 1994; Sanz de Galdeano *et al.*, 2016). However, the Tahal Fm typically lacks carbonaceous rocks and the general structure shows that they occupy a higher position in the stack on top of the Cóbdar Fm with which they are folded together in a major upright F4 antiform.

A NE dipping reverse fault, here called the Viboras fault, 3 kilometres east of Macael (Figure 2, named in the cross section), is interpreted as an upthrust of a layered series of amphibolites, schists and marbles (Umbría North in Figure 4), showing similarities to the layered sequence found further south. The hanging wall shows an upright SW-verging F4 fold. The structure postdates the recumbent D3 folds and is sealed by the present contact with the Alpujárride Complex.

3.4. Macael Group

This group of lithologies shows some singularities that make it distinguishable from other elements in the Nevado-Filábride Complex. Most formations in the group can be followed for tens of kilometres along a NW-SE trend, but important changes can be seen perpendicular to it, going from SW to NE. A basal fault zone can be recognized, which truncates rocks of the footwall (Figure 10) and probably also the basal lithologies of

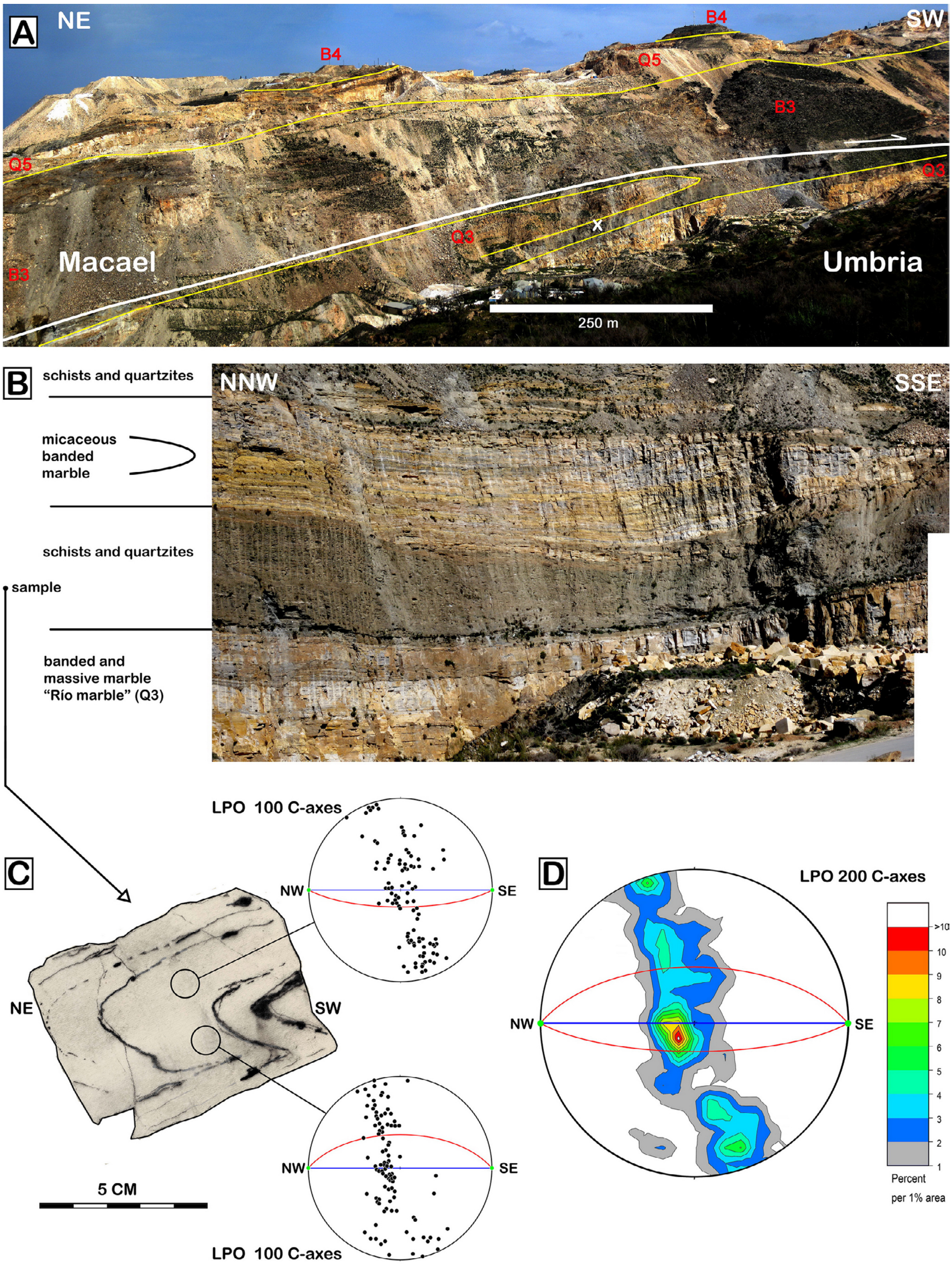

Figure 10. A: View of the 'Umbría de las Canteras' slope of the Río Macael, 2km south of Macael looking SE parallel to the fold axes. A large-scale SW-vergent recumbent antiform in Río Marbles at the top of the Umbría Gp is cut off by the basal contact of the Macael Unit (white line). White x shows position of sample shown in C. B: detail of the recumbent isoclinal antiform of the previous picture. C: Sample of small fold in quartzite taken at white x in A and Quartz C-axes diagram of opposing limbs, parallel to extension lineation and perpendicular to axial plane. D: Composite asymmetric C-axes orientations from sample shown in C.

Figura 10. A: Vista de la ladera llamada Umbría de las Canteras en el Río de Macael, 2km sur del pueblo y mirando paralelamente al eje de los pliegues. Un gran antiforme cerrando hacia el suroeste en la parte alta del Grupo Umbría es cortado por el cabalgamiento de la unidad de Macael (línea blanca). La "x" blanca señala la ubicación de la muestra en C. B: Detalle del antiforme de A.C: muestra de pequeño pliegue en cuarcita, tomada en lugar señalado con x en A. y diagramas de ejes-C de cuarzo de los flancos, paralelo a la lineación de extensión y perpendicular al plano axial. D: diagrama compuesto de ambos flancos de la muestra C.

the hanging wall towards the NE, so this group of rocks can be ascribed to a separate tectonic unit; the Macael Unit. The basal fault of the Macael Unit has traditionally been considered a thrust fault (Voet 1967; García Monzón *et al*., 1975; De Jong and Bakker, 1991).

The lowermost part of the Macael Gp consists of often graphite -bearing, dark grey, compact quartzitic schists (B3) that include bands of orthogneisses (Figure 11). Strongly boudinaged dolomitic marbles and skarn type rocks form a minor constituent. Gneisses in these outcrops (Gómez-Pugnaire *et al*., 2012) and elsewhere in the Nevado-Filábride Complex have rendered Permian radiometric ages (Priem *et al.,* 1966; Nieto *et al.,* 2000; Martínez Martínez *et al.,* 2010). The host rock was traditionally ascribed to the Paleozoic basement of the Macael Unit (Voet, 1967; Egeler and Simon, 1969; García-Monzón *et al*., 1975; Gómez-Pugnaire *et al.,* 2000, Figure 2a; Nieto *et al.,* 2000) and as an equivalent of the Upper-Carboniferous Nevada Fm, which, however, lacks orthogneisses. Here the rocks are referred to as a distinct formation; the Chive Fm. Gómez-Pugnaire *et al*. (2012) introduced this name for outcrops of dark schists and gneisses 20 km to the SE, but then did not recognize them as such in the Macael area and incorporated them in their Tahal Fm. Their subsequent radiometric dating of the gneisses 2 km North of Chercos led to the single report of occurrences of orthogneisses in the Tahal Fm and a decisive argument for attributing Paleozoic ages to the entire Nevado-Filábride Complex (see Figure 2, sample LR3 of Gómez-Pugnaire *et al*., 2012) (see also Gómez-Pugnaire *et al*., 2019).

Going north-eastwards, the graphitic schists of the Chive Fm become gradually thinner and lack gneissic bands, which make the formation more difficult to recognize. The thinning is thought to be related to wedging out against the basal thrust of the Macael Unit. Further to the northeast, about 3 km east of Macael, the Chive Fm and the entire Macael Unit are cut off by the relatively steep NW-SE trending Viboras Fault (Figure 2, cross section A-A').

Upwards, the Chive Fm changes into graphite-free schists, banded quartzites and calcareous schists that were called the Almendros Schist Fm by Voet (1967). The Almendros Fm is often considered as an equivalent of the Tahal Fm (García-Monzón *et al*., 1975) (Figure 3), but it typically shows marble and chlorite amphibole mica schist bands that are absent in the Tahal Fm and no conglomeratic beds have been found. Therefore the original name used by Voet (1967) is preferable. The Almendros schists grade upwards and laterally into micaceous grey marbles that form the base of the overlying Macael marble Fm. Lenticular bodies of serpentinite of several tens of metres are common, especially near the contact with the marbles. The Almendros Fm is almost absent in the SW outcrops but quickly thickens perpendicular to the trend going NE, where a band of layered marble in the middle of the Almendros Fm is quarried, here labelled as Q4.

Q4 consists of a single isolated micaceous marble layer amid a sequence of micaschists. The conspicuous multi-coloured banded marble is commonly known as "Anasol" or "mármol cipolínico". Its only active quarry is situated about 3 kilometres SE of the village of Macael, where the normally 4 metre thick layer has been exposed as a series of NE-verging tight recumbent folds. In this study, these folds are considered to be part of the overturned limb of a major SW-verging fold affecting the whole of the greyish green Almendros Fm and overlying marbles. The resulting asymmetric fold in the overlying Macael marbles can be easily recognized 500 metres south of the Anasol quarry and, following the trend 1 km to the NW, along the A-349 road. It was described as a D3 fold by Kampschuur (1975). The entire structure is thought to be largely responsible for the considerable thickening of the greyish Almendros schists SE of Macael, stacked as incompetent material behind the isoclinally folded thick marbles situated to its SW.

The marbles that cover the Almendros schists have been intensely quarried and are here referred to as the fifth quarry level Q5; by far the most important quarry level of the region. It reaches its greatest thickness of about 60 metres in the SW but it is only a few meters thick in the urban area of Macael, where it is devoid of white marble. There, the Macael marble Fm consists of a bluish grey marble member at the base and a yellowish brown dolomite member at the top. South of the village, a high quality pure white marble and greyish brown dolomite can be found sandwiched between the lower and upper members, so that often 3 or even 4 members can be recognized in the quarries. Contrary to the Q1 and Q3 quarry levels, there are no irregular patches of dolomites within the white marbles; dolomites and marbles are clearly separated in neat layers (figures 12 and 13). The top yellow

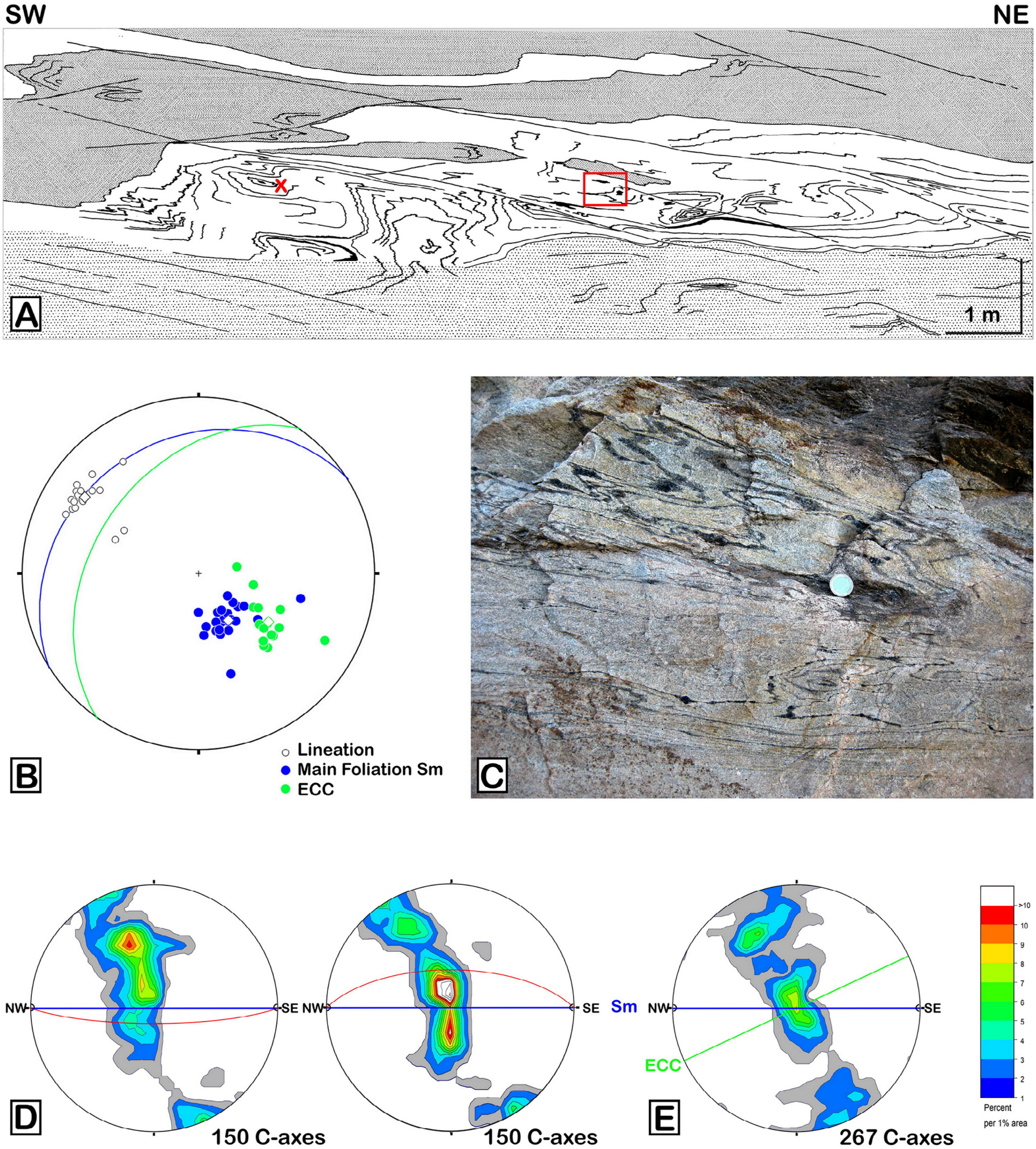

Figure 11. Outcrop of strongly refolded mylonite along the Al-6104 road to Laroya, 500m SW of Macael. A: Drawing of the road section in the year 1986. Dark grey top layers: dark schists (B3). White middle layers: quartzitic tourmaline orthogneiss, sampled by Andriessen *et al*. (1991, Location 2). Light grey bottom: Quartzite. Red x: Location of sheath fold represented in D. Red Rectangle: location of C. B: Lower hemisphere projection of stretching lineations, poles to bedding, and Extensional Crenulation Cleavages. C: Detail of A, photographed in the year 2018. D: Asymmetric quartz C-axes fabric in upper and lower limb of a sheath fold. E: Quartz C-axes fabric in dark schists of the same outcrop, showing perpendicular relation to Extensional Crenulation Cleavage (ECC).

Figura 11. Afloramiento de milonita replegada fuertemente en la carretera AL-6104 a Laroya, 500m al suroeste de Macael. A: Dibujo detallado del corte en el año 1986. Gris oscuro superior: esquistos oscuros B3. Áreas blancas: ortogneises con turmalina, muestreada por Andriessen *et al*. (1991, Location 2). Gris claro inferior: cuarcita. “X” en rojo: lugar de muestreo de pliegue en vaina representada en D. recuadro rojo: lugar de la foto C. B: Proyección de las lineaciones de estiramiento, polos de la foliación principal y polos de clivaje de crenulación extensional (ECC). C: Detalle del afloramiento dibujado en A, fotografiado en 2018. D: Fábrica de ejes-C de cuarzo con un patrón asimétrico, tanto en el flanco superior como en el inferior del pliegue en vaina. E: Fábrica de ejes-C de cuarzo en esquistos oscuros (B3) del mismo afloramiento, agrupados en una guirnalda perpendicular con respeto al plano del clivaje de crenulación extensional.

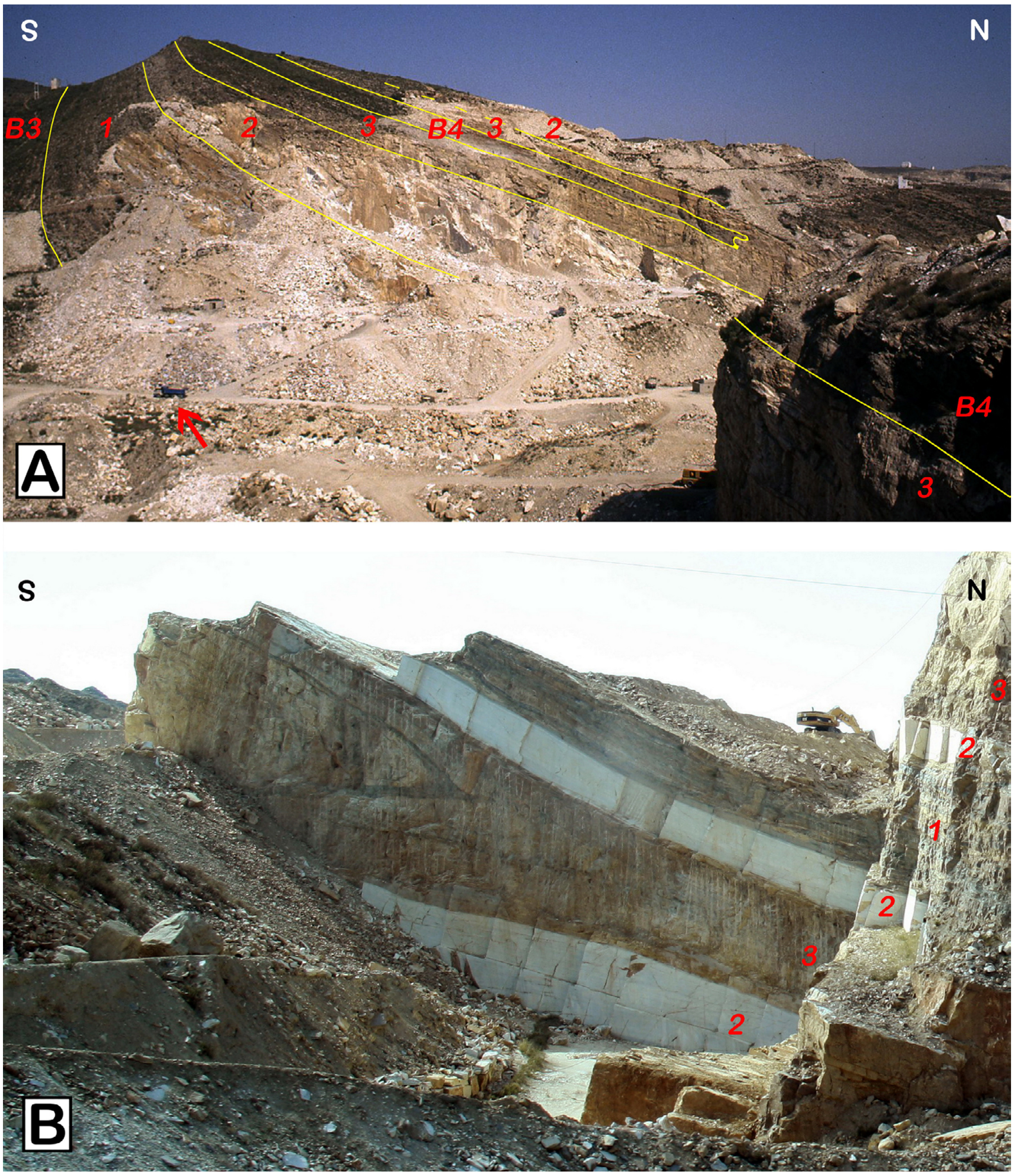

Figure 12. Recumbent isoclinal “hairpin” synform at the base of the Macael marbles (Q5) in the western Rambla de la Orica quarry. A: Situation in 1980, looking NW, parallel to the fold hinge. The core of the NE-closing synform is marked by fine-grained Almocaizar schists (B4), which are also exposed in the foreground on the right. The thick lower limb shows the normal succession of blue-grey marbles, white marbles and brownish dolomitic rocks, labelled 1-3 respectively. Scale marked by a truck (arrow) driving south along the then unpaved A-349 road. B: Detail of the same fold in 2017, as seen from the A-349 road. The lithological succession on the right contains part of a second higher isoclinal recumbent antiform.

Figura 12. Sinforme recumbente en la base de los Mármoles de Macael (Q5) en la cantera de la Rambla de la Orica occidental. A: Situación en 1980, mirando hacia el noroeste, paralelo a la charnela del sinforme. El núcleo del pliegue contiene esquistos de grano fino del grupo Almocaizar (B4), que están también expuestos en el primer plano de la foto a la derecha. El grueso flanco inferior está formado por la sucesión normal de mármoles azules, mármoles blancos y dolomías marrones, numerados 1, 2 y 3 respectivamente. Escala indicada por un camión (flecha) en la carretera A-349, entonces sin asfaltar. B: Detalle del mismo pliegue sinforme en 2017, visto desde la carretera A-349, con capas de un antiforme isoclinal superior a la derecha.

marbles are often boudinaged and capped quite abruptly by dark coloured B4 mica-schists, but sometimes without a fault contact. The blue marbles at the base are usually micaceous and layered and grade into the underlying greyish schists known as the Almendros Fm. The lowermost member of blue marbles is only massive in the southwest, where these have been extensively quarried in an area known as “Los Azules”. The subdivision in four members from bottom to top; blue, white, grey-brown and yellow-brown (or 1, 2, 3a and 3b respectively), enables us to recognize the intricate

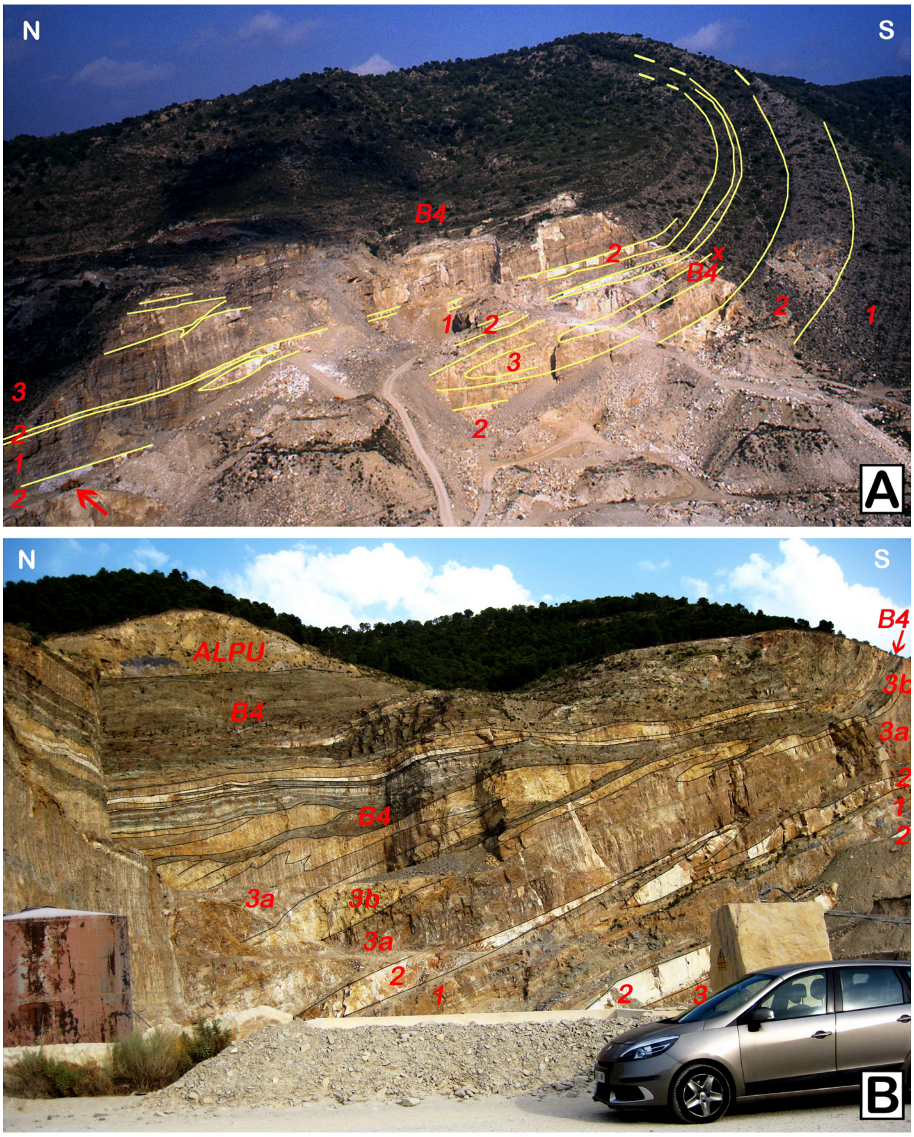

Figure 13. Recumbent isoclinal folds in the Macael marbles in the eastern Rambla de la Orica quarry. A: Situation in 1980, looking east over the A-349 road. Figure 12A was taken from the point marked by red x. Excavator bottom left (red arrow). 1: blue micaceous marbles. 2: white marbles. 3a: dark brown dolomites. 3b: light brown dolomites. The SW-verging isoclinal (F3) recumbent folds are overprinted by a mayor late (F6) N-verging fold. B: Detail of the left half of A; situation in 2017, as seen from the A-349 road. The SW-verging recumbent folds in the Macael marbles are truncated by the highest part of the Macael marbles and the Almocaizar schists (B4), which in turn are overlain by Alpujárride Complex purple phyllites and carbonates (top left). The cores of the recumbent synforms also contain dark-coloured Almocaizar schists (B4).

Figura 13. Pliegues isoclinales recumbentes en los Mármoles de Macael en la cantera oriental de la Rambla de la Orica. A: Situación en 1980, mirando hacia el este hacia el otro lado de la carretera A-349. La Figura 12A fue tomada el mismo año desde la 'x' roja. Excavadora en el fondo de la izquierda. 1:Marmoles azules fajeados. 2: Mármoles blancos. 3a: Dolomías marrones oscuras. 3b: Dolomías marrones claros. Los pliegues isoclinales vergentes hacia el suroeste están replegados por un pliegue tardío (F6) vergente hacia el Norte. B; Detalle de la parte izquierda superior con la situación en 2017, visto desde la carretera A-349. Los pliegues vergentes hacia el suroeste se hallan cortados por la parte superior de los mármoles de Macael y esquistos de Almocaizar, que tienen una orientación más horizontal. A su vez son cabalgados por rocas carbonatadas y filitas purpuras del Complejo Alpujárride. Los núcleos de los sinformes recumbentes también están formados por esquistos de Almocaizar (B4).

SW-verging F3 recumbent folding and thrusting in the outcrops of the vertical walls of the quarries south of Macael (figures 12, 13 and 14).

The top few metres, underneath the overlying heterogeneous sequence of the Almocaizar Group and the Alpujárride Complex, commonly show extremely tight folds with varying vergences and isolated boudins, which are cut by numerous low-angle faults (figures 13B and 14).

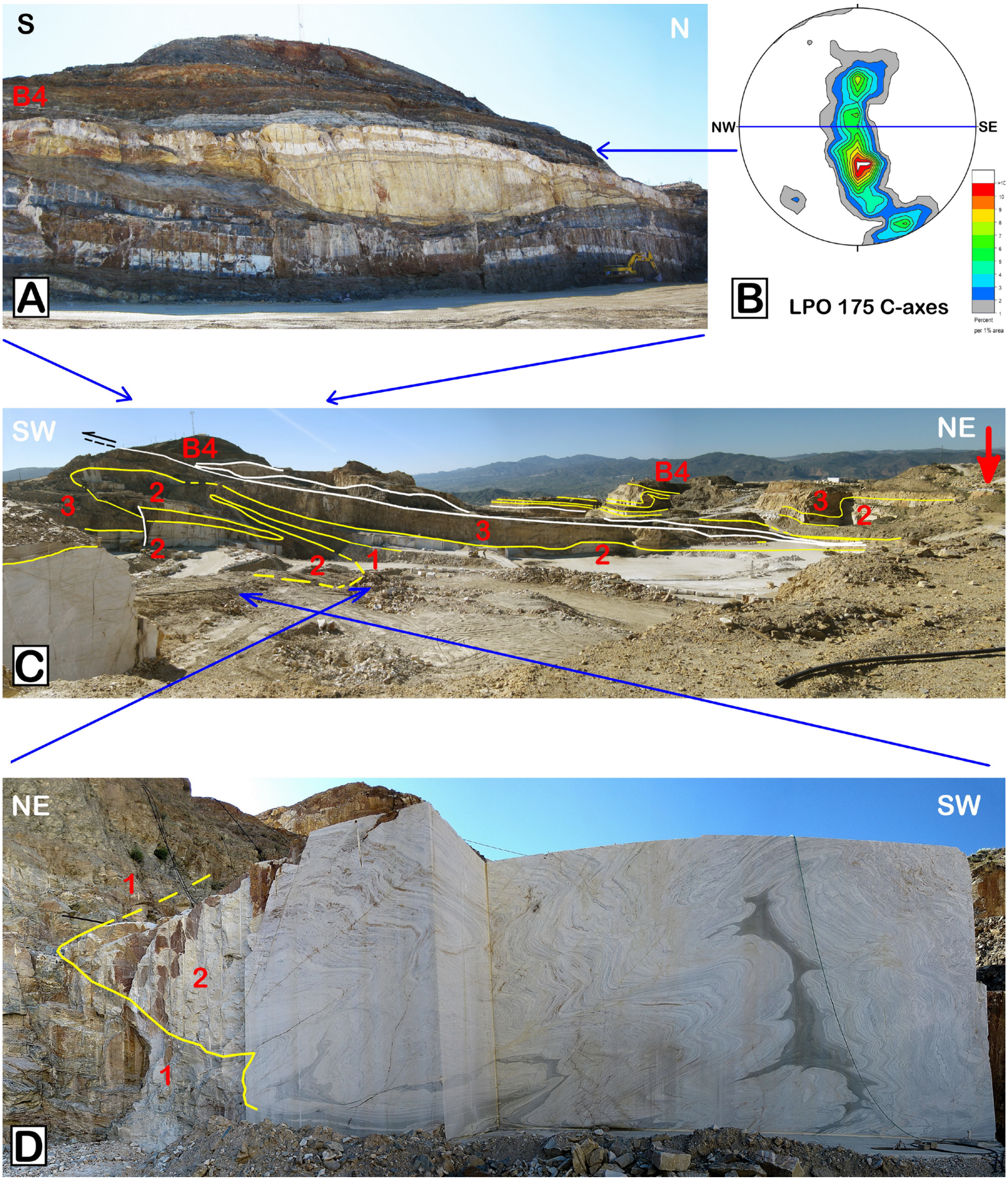

Figure 14. Alta Hoyos quarry operated by Cosentino, 3 km SE of Macael. A: Detail of top left of Figure C. Top of the Macael marbles, showing boudinage and extreme folding. B4: Almocaizar Gp, represented by grey orthogneisses (bottom), dark schists and amphibolites (top). Excavator for scale bottom right. B: Asymmetric Quartz C-axes pattern taken from B4 dark schists at this location. C: General view of the quarry with SW-vergent recumbent folds and thrusts. White lines: tectonic contacts. Yellow lines: lithological banding. 1. Blue micaceous marble. 2. White marble. 3. Dolomitic marble. B4: Almocaizar Gp. Arrow top right is the Cosentino viewpoint. D: SW-vergent synform in white marble. Outline of dark patches demonstrate older folding. White marble (Q5) quarry front height is about 10 m.

Figura 14. Cantera Alta Hoyos de la empresa Cosentino, 3km SE de Macael. A: Detalle de la parte superior izquierda de C. Parte superior de los mármoles con fuerte budinaje y plegamiento. B4: Grupo Almocaizar formado por ortogneises grises (inferior) y esquistos oscuros y anfibolitas (superior). Excavadora en el fondo a la derecha. B: Fábrica de ejes-C de cuarzo de la muestra tomada en esta colina. C: Vista general de la cantera con pliegues vergentes hacia el suroeste y cabalgamientos. Líneas blancas: contactos tectónicos. Líneas amarillas contactos litológicos. 1. Mármol azul fajeado. 2. Mármol blanco. 3. Dolomías. B4. Grupo Almocaizar. La flecha superior derecha indica el Mirador de Cosentino. D: Pliegue sinforme vergente hacia el suroeste con el núcleo en mármol blanco. Las vetas grises evidencian pliegues más antiguos. La altura de la pared vertical de mármol es de cerca de 10m.

3.5. Almocaizar Group B4 (subgroup of the Macael Group)

Fine grained schists, quartzites, amphibolites and gneisses constitute the top of the Nevado-Filábride Complex. This series was originally named Huertecicas Altas Unit by Voet (1967) and later rebranded as the Almocaizar Unit by Helmers and Voet (1966) in reference to a similar group of lithologies about 30 km further SE in the Sierra de los Filabres. The schists are often graphite -bearing and typically show a myriad of tiny garnets. These schists can sometimes be found in the core of the recumbent synforms (figures 12 and 13), which are exposed in the quarries, where they grade into the top dolomite member of the Macael Fm. For this reason no separate tectonic unit is considered here. More typically, the rocks of this group are found on top of the strongly deformed highest few metres of the Macael Fm (figures 13 and 14). The group is rich in banded grey and green biotite and amphibole rich gneisses and amphibolites. Subordinate pyroxene-bearing rocks and marbles have been found. These lithologies are well represented in the central part of the area on top of the Macael Fm and are overlain by a brittle contact with rocks of the Alpujárride Complex (figures 2 and 13B). Some of the gneisses were analysed by Nieto (1996) and Nieto *et al.* (2000), and interpreted as metavolcanic rocks, but no radiometric dates are available, in contrast to the better known gneisses of the B3 sequence.

4. General observations on the structure

The stack of metamorphic rocks shows a complex deformation history with several generations of folding and movements along low-angle faults, postdating peak temperature metamorphism. The intensity, style and geometry of resulting deformation structures are not homogeneous throughout the pile of rocks. Although some regional tectonic events can be distinguished, here named D3 to D6, it is sometimes difficult, and probably not necessary, to ascribe individual structures from an outcrop to a specific phase of deformation. A temporal overlap of some D3-D4 and D5 structures is probable. Although later reorientation could have taken place, a contractional D3-D4 event with SW-directed folding and thrusting and an extensional, late-D3 to D5 event with top-to-the-NW movement along low-angle faults provide an explanation for many deformation structures in the study area. An important, yet later, N-verging D6 event is also distinguished.

4.1. Main foliation and related structures (D3)

Most rocks in the studied area can be classified as gently, North-dipping, L-S tectonites, with a NW-SE linear component. The internal fabric is axial planar of large SW-verging recumbent folds and becomes more prominent in the higher parts of the stack. Figure 6A represents the typical aspect of D3 deformation in Macael marble. About 1800 field measurements of planar and linear D3 structures are documented in Figure 4, summarised in several subareas.

The planar element of the tectonites (Sm) is defined by both schistosity and lithological banding (mainly transposed bedding), which make between them a small and often not distinguishable angle. The linear element in the structure is an intersection lineation and/or a stretching lineation, which is strongly developed in the hinges of tight to isoclinal recumbent folds. The folds associated with these tectonites tend to be recumbent and intrafolial with axial plane cleavages parallel or at a small angle with the main gently North-dipping foliation.

Tectonites are different below the brecciated zone. In the Tahal and Nevada fms, both bedding and a differentiated crenulation cleavage can be distinguished, often in upright position (figures 4 and 6B). In the Tahal Fm, in this part of the Sierra de los Filabres, the angle between both planes is variable depending on the lithology and tightness of local folds. Eigenvectors show a mean angle of 15 to 30 degrees between bedding (S0) and S3 cleavage (figures 4 and 5), and an overall SW-verging asymmetry. The cleavage in the Tahal Fm has been tentatively considered as S3 after finding rare older rootless folds (F2) that affect an even older schistosity (S1). S3 in this paper coincides broadly with the S2 defined by other authors (Vissers 1981; Augier *et al.*, 2005; Booth-Rea *et al.*, 2015; Jabaloy-Sánchez *et al.*, 2019). S3 cleavages typically postdate the minerals formed during peak temperature metamorphism. Flattening of pebbles in Tahal metaconglomerates (Figure 6C) predates S3. Over large parts of the northern Sierra de los Filabres, S3 cleavages typically dip steeply north or south, but this is the result of late F6 folding. S3 cleavages turn subhorizontal towards the south and eventually dip S-wards on the southern slopes of the Filabres range (cross section in Figure 2 and Vissers, 1981).

In the metamorphic rocks above the brecciated zone, the main gently North-dipping foliation (Sm) has also been named S3, as this foliation shows a similar relative timing in the metamorphic record as in the Tahal Fm, broadly starting during peak temperature metamorphism.

Mostly recumbent F3 folds tend to be highly cylindrical on a kilometric scale and are dominantly SW-verging. They trend N130E in the northwestern part of the area and N110E in the east (Figure 4). Fold hinges are roughly parallel to the stretching lineations, although in some folds it is possible to observe a small angle between the fold axis and pre-existing lineations folded around the hinge (Zevenhuizen, 1989). Hinge orientations for open and isoclinal folds are similar, and SW-NE shortening related to folding and a SE-NW extension with predominantly top-to-the-NW shearing may have been partly contemporaneous, as can be shown by a detailed study of quartz Lattice Preferred Orientation and folding (Zevenhuizen, 1989; Porkolab *et al*., 2020). Most asymmetric quartz fabrics postdate F3 folds and show top-to-the-NW simple shearing, but symmetric fabrics and SE-directed asymmetric quartz LPOs have also been found. Individual fold hinges of major folds can sometimes be followed over several kilometres. NE-verging F3-folds are quite rare and are usually situated in the lower limbs of major SW-verging folds. Even rarer are curvilinear hinges or sheath folds, although these have been observed on a small scale (Figure 11). Detailed observation of the sheath folds, in the gneissic outcrop 500 meter southwest of Macael, shows that they have developed parallel to the hinges of refolded SW-verging folds (see Figure 11). Following Reber *et al.* (2012), these structures are interpreted as relatively small scale flow perturbations around planar weaknesses acting as slip surfaces. In this outcrop, Lattice Preferred Orientation of quartz and Extensional Crenulation Cleavages in the more schistose beds all indicate top-to-the-NW shearing.

In the Rambla de la Orica quarries, on both sides of the Al-349 road (figures 12B and 13B), there is important flattening posterior to folding. Figure 13B is considered paradigmatic for the prevalent geological structure. The exposure shows a series of SW-verging flattened folds that are overridden by a ductile shear zone, maybe a thrust fault, with the underlying folds acting like a duplex to a roof thrust. The structures are thought to reflect a ductile to brittle deformation transition. The main foliation in the overlying marbles, the Almocaizar rocks of the Nevado-Filábride Complex and the overlying Alpujárride rocks are parallel to the thrust or shear zone. The few metres of marbles within the shear zone show very tight folds with varying vergences and isolated boudins that are cut by numerous low-angle faults (figures 13B and 14A). Considering the prevalent orientation of the folds under the shear zone in this outcrop and elsewhere in the area, a top-to-the-SW component of simple shear or thrusting of the hanging wall is plausible. However, deformation has been 3D with coeval SE-NW extension parallel to fold hinges (Zevenhuizen, 1989), and movements clearly continued after folding, so other directions cannot be ruled out.

Similar structures can be observed at all scales in many outcrops. Shear zones are more horizontally orientated than axial planes of F3 folds and imbricates, but this angle is mostly not perceptible outside the outcrops of the quarry area. A comparable structure is the basal thrust plane of the Macael Unit, which postdates the recumbent F3 folding phase as shown in Figure 10. Initial overthrusting of the Macael Unit during a previous deformation event was suggested by De Jong (1993), and cannot be excluded. However, in the present study no reason has been found to single out this particular contact as different from or much older than those of many other tectonic slices within the area.

Going in a north-easterly direction, more open but still recumbent folds are found that overprint older folds. Several generations of recumbent folds are present here (Figure 14). The younger folds are associated with thrusts, such as in the Cosentino viewpoint in the Alta Hoyos quarry (Figure 14C). In this outcrop, the highest part of the Macael Unit and the Almocaizar lithologies show intense deformation (Figure 14A), similar to that observed in the Rambla de la Orica quarries (Figure 13B).

Further North, steeper dipping axial planes of F4 folds can be found as well as the SW-verging fold associated with the Viboras reverse fault. This is thought to indicate younging of the structures towards a NE hinterland, and no clear temporal break between the D3 and D4 events needs to have been present.

4.2. D4 imbricates

Orientations of F4 fold axes follow the same NW-SE trend as F3 folds and are also SW-verging and accompany SW-directed imbrications. Over 300 field measurements of D4 structures are documented in Figure 5. F4 folds tend to be only prominent in certain areas or specific levels of the imbricate stack. F4 folds show axial planes at variable angles to transposed bedding, with often steeply dipping axial plane cleavages. F4 folds refold the main foliation, and can commonly be seen to overprint previous folds and sometimes deform older thrust contacts. However, some low-angle tectonic surfaces were active during or after D4 folding (Figure 9), where shortening led to movement along pre-existing faults rather than folding. F4 folds are especially prominent in the higher part of the Tahal Fm (Figure 8), where sometimes F3 and F4 folds can be difficult to distinguish (see Langenberg, 1972). Upright F4 folds are quite rare in the Macael Unit, but become more prominent towards the NE.

The present Nevado-Filábride Alpujárride contact cuts off D4 folds in the North and is folded by F6 folds in the central part of the area. Characteristic purple phyllites (locally known as "Launa") are usually the basal rocks of the overlying Alpujárride Complex, but locally, calcareous breccias can be found at the contact. These calcareous rocks were formerly ascribed to a separate tectonic complex by Voet (1967), called the Ballabona-Cucharon Complex, but were later incorporated in the Alpujárride Complex. The intense ductile and brittle deformation of the top marbles within the Macael Unit and the reduced grain size of the Almocaizar series might bear some relation to the contact with the overlying Alpujárride Complex.

4.3. D5 structures

Folds with axes perpendicular to the regional trend are grouped under D5 structures. These structures are not as common as F3, F4 or F6 folds and it is sometimes difficult to establish their timing with respect to D3 or D4 structures.

Rare tight asymmetric folds with NE-SW trending axes perpendicular to the general trend have been interpreted as related to top-to-the-WNW displacements. They are more common in rocks near the brecciated zone, and also in and on top of the Cóbdar marbles. Open, probably rollover-type folds with axes at high angles to the trend and associated with normal faults and foliation boudinage can be found south and southwest of Macael (Figure 15). The strike of these normal faults is N010E to N020E. The resulting extension direction would be WNW-ESE, making a small angle with the older NW-SE stretching lineations associated with the main foliation (Figure 15C). It can be seen that, at this stage of deformation, brittle failure in dolomite is coeval with more ductile behaviour in pure white marbles and layer parallel shearing in more micaceous bands. Extensional Crenulation Cleavages and S-C fabrics that affect the S3 main foliation can at least partly be ascribed to D5.

4.4. D6 structures

Over large areas, S3 axial plane cleavages in the Tahal schist formation tend to be subvertical (Figure 4), but their present upright position is at least partly the result of large scale, late stage folding, here referred to as D6. From a regional point of view, most of these upright axial plane cleavages can be tracked southwards, and there they become subhorizontal and folded over the EW axis of the (Tortonian) Filabres anticlinorium to eventually dip south (Vissers 1981). In addition, cleavage refraction and lower strain can further explain the usually wider opening angles of F3 folds and steeper position of axial plane cleavages in the Tahal Fm over the northern slope of the Sierra de los Filabres.

North-verging F6 folds affect all previous structures in metamorphic rocks and affect the tectonic contact with the Alpujárride Complex (figures 8 and 13) all along the northern limb of the Filabres Anticlinorium (Vissers, 1981; Jabaloy-Sánchez, 1991). F6 folds typically show subhorizontal and subvertical limbs and are especially prominent in the eastern half of the area. An irregular fracture cleavage can be present in the subvertical limbs (Figure 5K). F6 folds are largely responsible for cleavage fans of F3 and F4 folds in the Tahal Fm. In general, this late stage of N-verging cascading folds has given rise to local steep or subvertical dips. The Tahal schists in the eastern half of the area are normally in an overturned position and dip SW as a result of stronger F6 folding. The difference in orientation of S3 and S4 planes between the western and eastern subareas can be explained by small-circle rotation over 70 degrees around a 110º/10º F6 fold axis (Figure 5L and M).

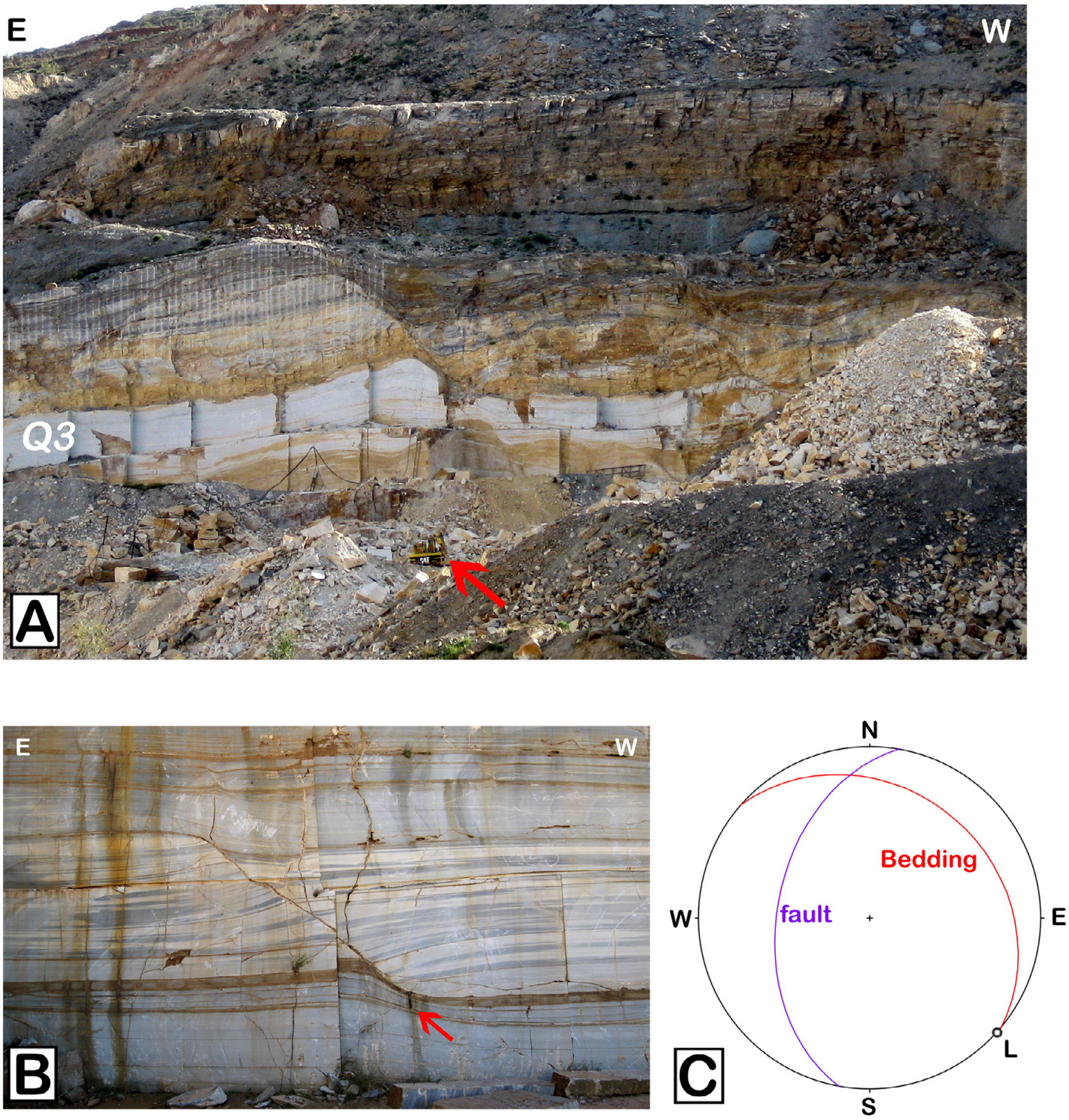

Figure 15. A: Extensional structures in the Río marbles, looking S and indicating westward sense of movement for the hanging wall. Picture was taken in 2017 facing the back of the Serpentinite Virgen del Rosario Quarry, 800m south of Macael. Excavator at bottom shows scale. B: Foliation boudinage in micaceous marble. Cañailla-Azules quarry 4 km SSE Macael. Hammer for scale (arrow). C: Lower hemisphere projection of planes and extension lineation of B.

Figura 15. A: Estructuras extensionales en los mármoles del Río, mirando hacia el sur e indicando movimiento hacia el oeste para el bloque de techo. Foto de 2017 del fondo de la Cantera de serpentinita Virgen del Rosario, 800m al sur de Macael. La excavadora al fondo indica la escala. B: Budinaje en mármol cipolínico, Cantera Cañailla-Azules, 4 km SSE de Macael. Martillo señalado con la flecha. C: Representación de la falla extensional, bandeado litológico y lineación principal de estiramiento.

D6 deformation was essentially brittle and dominates in the eastern half of the study area, where fracturing has seriously diminished the possibilities of profitable quarrying.

F6 folds were studied by Voet (1967), who related them to northwards late thrusting along Low Angle Normal Faults (LANF). Gravity gliding or mass slumping was thought to have placed rocks of the Nevado-Filábride Complex on top of Alpujárride phyllites (Egeler and Simon, 1969; Helmers and Voet, 1969; Molina-Cámara and Orozco, 1986; Jabaloy-Sánchez, 1991). The present study has found that the structures described by these authors can be followed further to the southeast, within the Nevado-Filábride Complex. Northeast of Cóbdar, LANFs even affect the rocks from the Cóbdar and Tahal fms in a listric fault. Within the studied area, the Neogene sediments of the Líjar Basin are always found uncomformably on top of these “late thrust masses” and they never cover Nevado-Filábride rocks unaffected by LANFs.

5. Discussion on the lithostratigraphic and tectonic subdivision of the Nevado-Filábride Complex in the Macael-Cóbdar area

The present study brings forward that, in the Macael-Cóbdar area, there is a thick stack of multiple tectonic slices and imbricates (figures 1 and 2). Keybeds and detailed lithostratigraphic differences in the area can be recognized, traced and mapped to reveal geological structures like isoclinal folds and thrust faults on a mesoscopic scale (figures 10, 12, 13 and 14). Similar structures may be present in other areas of the Nevado-Filábride Complex. In general, extrapolation of specific local structures to other parts of the Sierra de los Filabres or the Betic Zone is not feasible and lies beyond the scope of this paper. However, the detailed study of the present paper does provide insights regarding previously published interpretations of the Nevado-Filábride Complex and its subdivision in lithostratigraphic and tectonic units in the Macael-Cóbdar area of the eastern Sierra de los Filabres. Figure 3 provides an overview, in chronological order, of the subdivisions proposed by various studies of the area. The overview is primarily based on the similarities in the lithological characteristics recognized by the authors.

The original definition of the Nevado-Filábride Complex by Egeler (1963) as "a Complex of tectonic units, which are characterized by a medium grade metamorphism of Alpine age" was based on the geology of the eastern Sierra de los Filabres. The concept of tectonic units was part of this definition but not further specified according to any structural geological criteria. The dual name for the complex reflects the lithological composition of the units; combining typical Sierra Nevada elements (dark schists of supposedly pre-Permian age) with typical Sierra de los Filabres elements (light schists and marbles of supposedly Permo-Triassic age). This assumption of age relations has tectonic implications when abnormal superpositions are observed. Nevertheless, structural geological field observations should prevail because of the uncertainty about many age relations.

A detailed map and description of the area around Macael and Cóbdar was first presented by Voet (1967), following a similar geological analysis in the eastern Sierra de los Filabres by Nijhuis (1964). In their work, individual lithostratigraphic formations in the stack were given different names, but similarities and repetitions of the supposedly Paleozoic and Permo-Triassic rocks are interpreted as thin, superimposed nappe-sheets, each of which keeping a normal position. This interpretation was taken for granted, simplified and summarized in the geological map sheet 1013 of the MAGNA project (García-Monzón *et al.*, 1975), in which all metamorphic rocks, notwithstanding their litho-stratigraphic peculiarities, are ascribed to just four general formations in three superimposed tectonic nappe units (Figure 3).

Subsequently, careful geological mapping and structural analysis by Vissers (1981) and De Jong and Bakker (1991) led to the recognition of a more detailed lithostratigraphy and fault contacts in the lower part of the stack. This is generally confirmed by the present study and documented for the rocks of the Umbria Gp.

A basal thrust plane can be found in the Macael Unit in the sense of Voet (1967) and De Jong and Bakker (1991) (Figure 10). However, in this study, no clear distinction can be made into a Huertecicas Altas or Almocaizar Unit as described by these authors.

García-Dueñas *et al.* (1988) proposed a tectonic subdivision of the higher part of the Nevado-Filábride Complex into a Bédar-Macael Unit and a Calar Alto Unit, in which the former constitutes a N-verging fold nappe (see the repetition of formation names in the "upper limb" and the "lower limb" in the column dedicated to the paper in Figure 3). The basal thrust of this fold nappe is drawn directly under the supposedly inverted, non-brecciated Cóbdar ("Atalaya") marbles. In this model, the brecciated zone corresponds to the normal limb of the lower Calar Alto Unit. However, the analysis of this mayor recumbent fold structure of the Bédar-Macael nappe was based on recurrences and stratigraphic polarity, but vergence of small-scale folds could not be used, as is stated by Soto (1991, p103). Actually, field observation shows that the overall SW fold vergence in the Macael-Cóbdar area contradicts this tectonic model and a more detailed analysis of the lithostratigraphic sequence does not corroborate that the Cóbdar marbles and Umbría Gp rocks constitute the inverted limb of the different rocks in the Macael Unit. These same arguments against such a fold nappe were already brought forward by De Jong (1993). An additional argument against the proposed Bédar-Macael fold nappe is the ill-defined lower boundary of the unit, which is referred to as a thrust, but is situated amidst an irregular and partially broken series of marbles and other rocks without clear differences in lithology between the hanging wall and the footwall. Thus, without a better definition, the widely used "Bédar-Macael Unit" only seems to refer to all the metamorphic rocks from the Nevado-Filábride Complex above a poorly defined fault in the higher part of the brecciated zone and below the Alpujárride Complex. In this way the unit corresponds to a group of formations or lithologies, rather than a tectonic unit. The denomination "Marchal Shear zone" is alternatively used by García-Dueñas *et al.* (1988) to include their entire Bédar-Macael Unit and the top of the underlying Calar Alto Unit. In the Macael-Cóbdar area, this shear zone would correspond to the Betic Movement Zone (BMZ) in the sense of Platt and Vissers (1981).

The present study does confirm the existence of inverted limbs of recumbent isoclinal folds at the scale of hundreds of metres, as can be seen in figures 10, 12 and 13. Therefore, fold nappe structures could exist in the area and the general SW vergence of recumbent folds could be an indication of their orientation.

Puga *et al.* (1989) proposed the distinction of an ophiolite unit in the Macael-Cóbdar area, underlain by the Caldera Unit and overlain by the Sabinas Unit. However, this interpretation was based on geochemical analysis of metabasic rocks and the geological observations and subdivision in local units in Sierra Nevada and their generalisation, but not on local structural geological criteria or detailed lithostratigraphic observations in the Sierra de los Filabres. In this way, in the Macael-Cóbdar area, the relative position and assignation of the proposed tectonic units are either ambiguous or even contradictory in subsequent papers of Puga *et al.* (1989), Tendero *et al.* (1993), Nieto *et al.* (2000) and Puga *et al.* (2009), and do not correspond to their accompanying schematic lithostratigraphic column. Field observation shows that the reported sedimentary cover of the proposed ophiolite unit corresponds to the layered sequence of the Umbría Gp, which is actually separated from its supposedly magmatic base by the underlying Cóbdar marbles that are ascribed to their contradictory overlying Sabinas Unit in the aforementioned papers.

An ophiolite unit would imply quite a different lithostratigraphic column and tectonic subdivision than the one proposed, but it will be difficult to decide where to draw its boundaries. It is important to note that mafic and ultramafic rocks only constitute a very small portion of the volume of metamorphic rocks and they are normally embedded in metasedimentary rocks. The ophiolite unit would have to consider including the Cóbdar marbles, meta-evaporitic rocks associated with the brecciated zone and possibly all the Umbría Gp rocks, including meta-conglomerates. The small bodies of serpentinite rocks that can be found throughout the stack are usually intimately interbedded with other rocks without any signs of major faults or tectonic movement, and some metabasite bodies show neat contacts with the Tahal Fm, so that a tectonic emplacement for all of them also seems unlikely.

Gómez-Pugnaire *et al.* (2012) recognise repetitions in the metamorphic stack, as can be seen in their Figure 3, but do not elaborate on the geological structure. They suggest that the entire Nevado-Filábride Complex consists of Paleozoic or older rocks. Although this cannot be ruled out, their conclusion relies heavily on radiometric dating of one single sample of orthogneiss (LR3) from the Chive Fm about 2 km North of Chercos (Figure 2). The protolith of the gneiss in this outcrop was interpreted as a magma intruded into the Tahal Fm by Gómez-Pugnaire *et al.* (2012), and subsequently by Gómez-Pugnaire *et al.* (2019, p278). Contrary to this, the host rock in the same outcrop had been previously ascribed to the pre-Permian basement of the Macael Unit (Voet, 1967; Egeler and Simon, 1969; García-Monzón *et al.,* 1975; Nieto *et al.,* 2000; Gómez-Pugnaire *et al.,* 2000, Figure 2a), which is also supported by the present study. Therefore, the radiometric age of 295 Ma from sample LR3 does not confirm a Paleozoic age for the Tahal Fm because this formation does not crop out at the site of the sample. Instead, the reported radiometric age determination confirms the Paleozoic age of the Chive Fm, as first reported by Priem *et al*. (1966). Moreover, Gómez-Pugnaire *et al.* (2012) do not consider the possibility of thrusting along low angle faults or local inversion by isoclinal folds, as has been documented in this study.

Sanz de Galdeano *et al.* (2016) group all the rocks above the Tahal Fm, including the brecciated zone, in one single, undifferentiated and continuous Marble-Calc-schist formation, in which different lithologies can be ascribed to "changes in sedimentary realms". The geological structure is then stated to be "coherent and not particularly complex". Their conclusion that in the area around Macael there are no tectonic units and that the structure is not complex comes quite a long way from the original definition of the Nevado-Filábride Complex by Egeler (1963) as "a Complex of tectonic units, which are characterized by a medium grade metamorphism of Alpine age". Unfortunately, Sanz de Galdeano *et al.* (2016) document hardly any planar and linear structural data and no stages of deformation are recognised. Furthermore, no reference is made to some of the most relevant papers about the area, and which are mentioned above and in Figure 3.

Most of the previous studies mentioned above have in common that their emphasis is on lithological differences or similarities and supposed ages of the metamorphic rocks. Although this has tectonic implications, few structural details or criteria are presented in these papers to discuss tectonic subdivisions.

After carrying out exhaustive fieldwork, the present study advocates a different approach by documenting some factual macroscopic structures in detail. The description of a detailed lithological succession in combination with the analysis of a large number of structural data also gives a better understanding of the structure. Some valuable information published by previous authors has also been summarised and discussed here. All these contributions pretend to provide a concrete basis for further study and interpretation of the area.

6. Conclusions

Fieldwork is essential and gratifying in this area, where previous and present geological investigations have been confronted by a varied lithostratigraphy and a wide range of well-exposed geological structures. In the exceptional outcrops in the quarries, a diverse lithology, isoclinal recumbent folds and overthrusts are common features. This leads to the conclusion that any apparent simplicity of the structure of the metasedimentary rocks of the Nevado-Filábride Complex of the Betic cordillera is deceitful and that the original, although limited, definition of Egeler (1963) is still preferable.

An indiscriminate grouping of the metamorphic rocks into a few general formations or poorly defined tectonic units does not do justice to all the information that the outcrops have to offer. Following Voet (1967), different names are proposed for different lithostratigraphic elements in the metamorphic stack. In addition, multiple subhorizontal tectonic contacts, as well as generally transposed bedding and isoclinal recumbent folding, make a subdivision into a few homogeneous tectonic units incomplete.

A better approximation to the prevalent structure is to consider it as a complex metamorphic stack of imbricated tectonic slices separated by tectonic contacts, with both constrictive movements towards the SW as well as extensional movements parallel to the predominant NW-SE lineations.

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