# Post-orogenic exhumation of high-grade rocks in the Sierra de los Filabres, SE Spain



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### Abstract

The Internal Betics (SE Spain) have experienced a complex structural and metamorphic history of burial during the Alpine Orogeny followed by (post-)orogenic exhumation of high-grade rocks. Traditionally, the Nevado-Filabrides and Alpujarride are the two tectonic units that are used to reconstruct the Alpine orogenic history of the Internal Betics, whereas at the same in the field the boundary between the two is defined by a Miocene detachment that has emplaced the Alpujarride on top of the Nevado-Filabrides. This study presents an improved tectono-stratigraphic column of the upper part of the Nevado-Filabrides with a special focus on the structural position of the (ultra-)mafic oceanic mantle derived rocks and quantitatively defines the relation between burial and exhumation shear zones in the eastern Sierra de los Filabres, located in the eastern part of the Internal Betics. Analysis of kinematic (micro-)structures shows that there is a ~45 degree difference between the direction of contraction (top-to-NW) and subsequent extension (top-to-W). Moreover, the detachment that accommodated the main displacement during extension did not exactly localize in the burial related shear zones but instead occasionally crosscuts them. For this reason, on a local scale the detachment cannot be used as the boundary between the Nevado-Filabrides and Alpujarride. Alternatively, we propose that the (ultra-)mafic rocks observed in the Nevado-Filabrides represent an Alpine suture zone between the two units and therefore should be used as the boundary. The detachment creates a tectonic omission that cross-cuts this suture zone and in this way preserves slivers of low-grade Nevado-Filabrides in the hanging-wall and slivers of high-grade Alpujarride in the footwall. Simultaneous N-S compression perpendicular to the E-W extension has led to the formation of an E-W trending dome in which the high-grade Nevado-Filabrides and Alpujarride are exposed in the core and the low-grade equivalents at the margins.

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# Introduction

High-grade metamorphic rocks are often formed and exhumed within a single orogenic cycle (Ring et al. 1999). Among many potential mechanisms, one efficient mechanism to expose high-grade metamorphic rocks is by direct tectonic exhumation (Wernicke & Axen 1988, Lister & Davis 1989). Structures formed during such extensional exhumation (e.g. detachments) often overprint or reactivate the nappe-stack formed during the previous mountain building phase (e.g. Brun & Faccenna 2008). The overprint of the detachment complicates the reconstruction and interpretation of the geometry of the older nappe stack.

A good example to study the overprinting relationships between nappe stacking and extensional exhumation are the Internal Betics in southeastern Spain (figure 1). In this area, the Nevado-Filabrides, the Alpujarride and the Malaguide are three units containing rocks in different degrees of metamorphism, their tectonic contacts being often defined by extensional shear zones that formed during orogenic extension (e.g. Platt et al. 1984, Vissers et al. 1995, Jabaloy et al. 1993, Martínez-Martínez et al. 2002, Behr & Platt 2012, Lonergan & Platt 1995). At the same time, these three complexes are used as major units separating the Alpine nappe stack (e.g. Bakker et al. 1989, Augier et al. 2005c, Puga et al. 2011), often restored in plate-tectonic reconstructions of the whole western Mediterranean (e.g. Van Hinsbergen et al. 2014, Vergés & Fernàndez, 2012). Therefore, tectonic units bounded by (post-)orogenic collapse extensional structures, interpreted based on exhumation ages (Johnson et al. 1997, Zeck et al. 1992), are also used in the sense of a previously emplaced nappe stack. This general use may be correct at a regional scale, as detachments often reactivate and overprint nappe contacts in the Internal Betics (Martínez-Martínez et al. 2002, Augier et al. 2005a), but the overprint has never been structurally demonstrated in the Betics at the local scale, for example in the Sierra de Los Filabres, located in the eastern part of the Internal Betics.

This study aims to describe and explain the structural and metamorphic relationship between nappe stacking and subsequent exhumation along detachments in the Sierra de Los Filabres. We have carried out a field and microstructural kinematic and metamorphic study to derive an improved tectonostratigraphy and quantitatively define the cross-cutting relationships between burial and exhumation structures. The newly defined tectonic units together with the structural data may serve to propose a new interpretation for the Alpine evolution of the Internal Betics in the area of Sierra de Los Fillabres.

### **Geological Background**

The Betic fold-and-thrust belt is generally described to be composed of two areas, an Internal part dominated by metamorphic rocks and Miocene sedimentary basins and a non-metamorphic External part (figure 1). The External Betics are made up of flysch-sediments deposited over the former southern margin of the Iberian continent, which locally were structurally emplaced over the Internal Betics during the Miocene (Banks & Warburton 1991).

The metamorphic rocks of the Internal Betics are traditionally subdivided into the Nevado-Filabrides, the Alpujarride and the Malaguide complexes (Vissers 2012). Their boundaries are defined by major extensional ductile shear zones (Lonergan & Platt 1995, Platt et al. 1984, Vissers et al. 1995, Galindo-Zaldivar et al. 1989, Jabaloy et al. 1993, González-Lodeiro et al. 1996, Martínez-Martínez et al. 2002, Behr et al. 2012). The Malaguide contains a non-metamorphic sedimentary sequence ranging in age from Permo-Triassic to Miocene (Lonergan 1993). The Alpujarride Complex contains rocks ranging in age from Paleozoic to Late Triassic metamorphosed during different tectonic events (Vissers 2012). This complex experienced a high pressure-low temperature (HPLT) metamorphic event with peak pressures of 15 kbar (Tubia & Ibarguchi, 1991) during the Eocene (Platt et al. 2005), followed by a high temperaturelow pressure (HTLP) metamorphism during the early Miocene (Platt et al. 2005, Monié et al. 1991). Exhumation by the detachment emplacing the non-metamorphosed Malaguide on top of the Alpujarride occurred before 18 Ma (Azañón & Crespo-Blanc 2000, Zeck et al. 1992).

The Nevado-Filabrides experienced a different PT-path than the Alpujarride (figure 2). The pressure during the Alpine HPLT-event was higher than in the Alpujarride (>18 kbar, Augier et al. 2005b, Puga et al. 2000). The HPLT-event has also been overprinted by a HTLP-event (Augier et al. 2005c, Bakker et al. 1989, De Jong 1993), but the tectonic setting in which this event occurred is debated. The increase in temperature has been related to rapid exhumation with isothermal decompression (Augier et al. 2006, Behr & 2005a, Augier et al. 2005c, Bakker et al. 1989), possibly in a subduction channel (Platt et al. 2006, Behr & Platt 2012, Kirchner et al. 2016, Booth-Rhea et al. 2015). Another explanation is that the rocks reached a second metamorphic peak both in pressure and temperature due to nappe-stacking (Puga et al. 2000, Li & Massone 2018).

Furthermore, there is no consensus on the timing of the metamorphic events. <sup>40</sup>Ar/<sup>39</sup>Ar dating gives an age for the HPLT peak of 48-30 Ma and exhumation between 20 and 14 Ma (Monié et al. 1991, Augier et al. 2005a). These results have been debated because there might be excess argon in the rocks due to fluid infiltration during the HPLT-event (Behr & Platt 2012, De Jong 2003), but in-situ dating of monazites gives similar ages of 40 Ma for the HPLT-event and 24 Ma for the HTLP-event (Li & Massonne

2018). Younger ages for the HPLT-event between 20-13 Ma are derived from laser probe analysis on garnets and U-Pb dating of zircons (Platt et al. 2006, Kirchner et al. 2016, Sánchez-Vizcaíno et al. 2001). Based on these ages, the HPLT-event was followed by very rapid exhumation (~0.8 cm/yr; Platt et al. 2006, ~1.2 cm/yr; Sánchez-Vizcaíno et al. 2001), since fission track ages show that exhumation of the Nevado-Filbarides complex was completed progressively from east to west between 12-8 Ma (Johnson et al. 1997, Vázquez et al. 2011).

#### Stratigraphy of the Nevado-Filabrides

Previous studies have defined the stratigraphic units of the Nevado-Filabrides in two main ways (figure 3).

One terminology subdivides the Nevado-Filabrides in a Veleta Complex and a Mulhacen Complex (Puga et al. 1999). The Veleta Complex has a thickness greater than 1000m and is made up of graphite mica-schists covered with quartzites (Puga et al. 1999). The Mulhacen Complex is subdivided in three units, from bottom to top the Caldera, Ophiolite and Sabinas units, separated by ductile thrusts. The base of the Caldera unit is made up of graphite-mica-schists, overlain by quartzites, calc-schists and marbles with intercalations of orthogneiss (Puga et al. 2011). The Ophiolite Unit contains meta-ultramafic overlain by meta-gabbros, meta-dolerites and meta-basalts with pillow structures. The meta-ultramafic sequence contains serpentinites that are formed by metasomatization of the ocean floor before the first Alpine metamorphic event (Puga et al. 1999). A typical setting for metasomatism are slow-spreading ridges or hyper-extended margins (Dick et al. 2008, Péron-Pinvidic & Manatschal 2009). The geochemical composition of the meta-dolerites and meta-basalts indicate a MORB mafic composition (Bodinier et al. 1987) and these rocks are, therefore, interpreted as a dismembered and metamorphosed ophiolite sequence (Bodinier et al. 1987, Puga et al. 1999). The Jurassic age protolith of these rocks has been dated to 183-187 Ma (SHRIMP U-Pb on zircons, Puga et al. 2005, Puga et al. 2011, Puga et al. 2017), or to 146 Ma (Rb/Sr radiometric dating, Hebeda et al. 1980). Possibly, part of the meta-ophiolite is obducted between the HPLT and HTLP events (Puga et al. 2017). The top of the Ophiolite Unit is made up of calcschists, quartzites and marbles (Puga et al. 2011). In this meta-sedimentary sequence, possibly remnants of foraminifera of Cretaceous age are observed (Tendero et al. 1993). The Sabinas Unit contains graphite schists overlain by layers of marbles and non-graphite bearing schists interlayered with orthogneisses (Puga et al. 2011).

One other terminology defines three different units within the Nevado-Filabrides, from bottom to top the Ragua Unit, the Calar Alto and the Bedar-Macael Unit (Martínez-Martínez et al. 2002, Augier et al. 2005b, Booth-Rhea et al. 2015). The Ragua Unit is similar to the Veleta Complex, with a tectonic boundary

re-defined by Martínez-Martínez et al. (2002). The Calar Alto roughly corresponds to the Caldera Unit of the Mulhacen Complex. It contains a thick succession (>3500m) of schists that are subdivided into two formations: the darker Montenegro Schist and the lighter Tahal Schist (Martínez-Martínez et al. 2002). The Bedar-Macael Unit is equivalent to both the Ophiolite Unit and the Sabinas Unit, containing the meta-mafics and the meta-sedimentary sequence of calc-schists, marbles and mica-schists interlayered with orthogneisses. The Ragua Unit, the Calar Alto and the Bedar-Macael unit are separated by shear zones. Based on the inversed metamorphic gradient, the Ragua/Calar Alto shear zone is interpreted as a post-metamorphic thrust (Augier et al. 2005c, Behr & Platt 2012). A similar gradient is observed for the Calar Alto/Bedar-Macael (Augier et al. 2005c). Furthermore, the contractional character of the contact is also lithologically defined: the Late Carboniferous to Early Permian orthogneisses of the Bedar-Macael unit (Gómez-Pugnaire et al. 2004, Martínez-Martínez et al. 2010) are older than the presumed Permo-Triassic age of the Tahal Schist at the top of the Calar Alto (Martínez-Martínez et al. 2010).

#### Eastern Sierra de los Filabres

The area of interest of this study is the eastern end of the metamorphic dome of the Sierra de los Filabres (figure 4). At the core of the dome, the Calar Alto is exposed and at the flanks it is overlain by the Bedar-Macael Unit (Martínez-Martínez et al. 2002, Augier et al. 2005a, Augier et al.2005c). The two units contain remnants of mineral assemblages that indicate a HPLT event, but the amphibolite facies overprint is dominant (Bakker et al. 1989).

The lowest member of the Calar Alto that crops out in the dome is the light Tahal Schist. The schists are covered by a carbonate sequence (Bakker et al. 1989, De Jong et al. 2001). They are overlain by the Bedar-Macael unit which at its base contains meta-ophiolites and lenses of ultramafic serpentinite (Puga et al. 1999). The top of the Bedar-Macael unit contains a large orthogneiss body surrounded by graphitic garnet-mica-schists (De Jong et al. 2001). North of the dome, lower grade rocks of the Alpujarride cover the high-grade rocks of the Nevado-Filabrides.

The Calar Alto and Bedar-Macael unit are separated by a ductile thrust with a positive upward pressure and temperature gap of 6-8 kbar and 50°C (the Marchall shear zone, Augier et al. 2005c). The boundary between the Nevado-Filabrides and the Alpujarride is defined by the detachment (Platt et al. 1984, Bakker et al. 1989, Martínez-Martínez 2002). This detachment formed during the last exhumation phase from greenschist to brittle conditions and accommodated tectonic transport towards the west (Jabaloy et al. 1993, Martínez-Martínez et al. 2002, Augier et al. 2005b, Johnson et al. 1997). Coeval orthogonal N-S compression (Martínez-Martínez et al. 2002, Augier et al. 2005b) resulted in an a-type dome geometry (Jolivet et al. 2004).



**Figure 1** Geological map of the External and Internal Betics after Vissers 2012. Note the detachment that separates the low P/T series from the high P/T series. This boundary is often used as the equivalent of the Alpujarride/Nevado-Filabrides boundary.



**Figure 2** Compilations of PT-paths for the Alpujarride (left) and Nevado-Filabride (right) after Vissers (2012) and references therein. Although the calculated PT-paths show different peak pressures for the two complexes depending on the location, in the Easteren Betics the peak in the Nevado-Filabrides is almost twice as high as in the Alpujarride.



**Figure 3** Tectonostratigrpahic column of the Nevado-Filabrides after Puga et al. 2017. (a) The comparison between tectonostratigraphy of Martinez-Martinez et al. (2002) and Augier et al. (2005c) with the column of Puga et al. (2017). (b) the tectonostratigraphic column of the easteren Sierra de los Filabres of this study.



Figure 4 Geological map of the Sierra de los Filabres after Augier et al. 2005c. Red inset is the area of this study.

## Results

Based on field observations and micro-structural analysis we have improved the geological map (figure 5) and tectono-stratigraphy of the eastern Sierra de los Filabres (figure 2b). Four different units are recognized, from bottom to top: the Calar Alto, the Mafic Unit, the Bedar Unit and the Low Grade Unit (figure 6). These units roughly correspond to respectively the Caldera Unit, the Ophiolite Unit, the Sabinas Unit and the Alpujarride of Puga et al. (2017), respectively. They are separated by shear zones that genetically originate from different deformational events. The deformation events and shear zones are described in genetical chronological order after the rock description.

#### **Tectono-stratigraphy**

#### Calar Alto

The lowest member in the Calar Alto in the eastern Sierra de los Filabres is the Tahal Schist and is found at the core of the dome. The schists are dark-grey to grey, with a fine-grained matrix that contains quartz, feldspar and micas. Common porphyroblasts are garnet, and alusite, chlorite and cordierite (BT-TSC, BTJ-328, figure 7). Quartz also occurs in veins running subparallel to the main foliation. On top of the dark to grey Tahal Schist lies the Metallic Schist. It can be distinguished from the Tahal by the metallic lustre created by the micas on the foliation planes. The matrix of the Metallic Schist is similar to that of the Tahal Schist. However, the porphyroblasts tend to be larger in the Metallic schist. For example, garnetporphyroblasts may reach up to one cm in diameter (figure 17a). Throughout the Calar Alto, the schists are intercalated with lenses of dolomite marble (e.g. at the eastern entrance of Lubrin town) and metamafic rocks. The meta-mafics have retained an igneous texture. However, the mineralogy is no longer igneous: pyroxenes are unstable and almost fully replaced by kyanite, staurolite and amphiboles (BTJ-L226, figure 7 E-F). Towards the top, the Metallic schists gradually changes into different lithologies. At the southern margin of the dome, the matrix of the schists become more quartz-rich instead of mica-rich. They are dark grey and no longer have a shiny luster on the foliation planes. Cordierite porphyroblasts are abundant (BTJ-G161, BTJ-H175, BTJ-I187, figure 9). At the northern margin of the dome quartz is even more dominant and locally forms pure quartzites. The different lithologies at the top of the Metallic Schist are covered by dolomite marbles. At the boundary between the dolomite marbles and the schists, a breccia is observed with predominantly marble and some meta-mafic clasts (figure 17b). Just below this boundary, the Metal Schist has also dolomite in the matrix (BTJ-212, figure 8 A-B). The dolomite marbles

form the top of the Calar Alto. The dolomite minerals are recrystallized, and occasionally a foliation plane is developed. The dolomite marbles are most distinctive in the landscape just north of the Lubrin-El Marchal road where they make up the top of the hills.

#### Mafic Unit

The lowest part of the Mafic Unit is made up of white, calcite marbles intercalated with meta-mafic layers up to 1 metre thickness. Most of these meta-mafic layers are isoclinally and asymmetrically folded together with the marbles, others are intruded into the marble (figure 18a). Occasionally chilled margins are visible at the contact between the marbles and meta-mafics (figure 18b). A large body of meta-mafic rocks overlies the white marbles. Most of the meta-mafics are amphibolites with large stretched feldspar grains (figure 18c). Chlorite and epidote, together with plagioclase and amphiboles form the foliation (BTJ-438 an BTJ-H172, figure 10). Towards the top of the mafic body serpentinite lenses occur which contain veins filled with asbestos. Talc is often found close to the meta-mafic rocks. At various places, the top of the meta-mafic body is a mylonitic white schist with kyanite and zoisite making up the foliation (BTJ-15, figure 11). The meta-mafic rocks are covered by a meta-sedimentary sequence. The content of this sequence varies and can contain thin layers of quartzite and marbles (both dolomitic and calcitic), but the bulk is made up of calc-schist and coarse garnet-mica-schists. The calc-schists contain a small amount of siliciclastics and this makes them easily distinguishable from the white marbles at the bottom of the Mafic Unit. The coarse-grained garnet-mica-schists contain garnet-porphyroblasts up to 1 cm in size and often have mica-rims surrounding them (BTJ-C118 and BTJ-655, figure 18d).

#### Bedar Unit

The bottom of the Bedar Unit is made up of para-gneisses and garnet-mica-schists. The colour of the paragneiss varies from brown to grey whereas the garnet-mica-schists are more orange. The matrix of the paragneiss is made up of quartz and feldspar. Garnet porphyroblasts are common, but usually are smaller than the garnets in the schists at the top of the Mafic Unit. Veins of quartz and/or feldspar are abundant (figure 19a). The paragneisses and garnet-mica-schists are the host-rock of a large orthogneiss body. The orthogneiss is strongly foliated and the feldspar porphyroclasts give in many places an augengneiss texture (figure 19b). Tourmaline is abundant in the orthogneiss (figure 19c and BT-74 figure 13). At the western side of the Sierra de Bedar, on top of the ortho- and paragneisses, several meters of fine grained grey schists similar to the Tahal and Metalic schists of the Calar Alto are observed. On the eastern side of the Sierra de Bedar, the gneisses are covered by meta-mafic rocks. They are predominantly foliated

amphibolites with garnet porphyroclasts (BTJ-E148 figure 13) but along the road from Bedar to La Serena lenses of serpentinite bodies are observed. The top of the Bedar Unit is made up of a massive succession of dolomite marbles. The dolomite minerals are recrystallized and at places a foliation developed in the marbles. Most of the Sierra de Bedar is made up of these dolomite marbles.

#### Low Grade Unit

The Low Grade Unit is mainly found in the north of the study area (figure 5). Black and purple phyllites are the lowest lithologies of this unit. The matrix of the phyllite is predominantly made up of fine grained quartz and with fine grained micas on the foliation planes (BTJ-K212, figure 14). Above the phyllite lenses of dolerite are found (figure 20a). The dolerite contains large grains of olivine which are partly breaking down into serpentine. Well-developed feldspar grains make up the matrix of the dolerite (BTJ-660A, figure 14). Gypsum lies on top of or is folded around the dolerite (figure 20b). The fabric of the gypsum is often mylonitic and the thickness varies between 1- 20 meter. The highest lithology of the Low Grade Unit is a dolomite. Since it is the most resistant lithology of the unit it makes up most of the hilltops in the north of the studied area. coordinates of the samples of the thin-sections are in the appendix. tectono-stratigraphic column (figure 3). For large-scale cross section (x-x) see figure 6. For the small-scale cross sections (in blue) through the shear zones, see figure 25-29. The Figure 5. Geological map of the studied area in the eastern Sierra de los Filabres, part of the Internal Betics, southeast Spain (see inset). See for the lithologies of the different units the





**Figure 6** N-S cross section. See the geological map (figure 5) for locality. Symbology of the shear zones and colours of the tectonic uits as in the geological map. The detachment (solid black) cuts all the other shear zones with a top-to-W motion.



**Figure 7** Thin sections of the Calar Alto. A, C and E in plane polarized light, B, D and F in crossed polarized light. A and B: BT-TSC crenulation foliation in the Tahal schist. C and D: BT-TSC twinned cordierite in crenulated Tahal Schist. E and F: BTJ-328 cordierite in fine-grained matrix.



**Figure 8** Thin sections of the Calar Alto. A, C, E and F are in plane polarized light, B and D in crossed polarized light. A and B: BTJ-212 the boundary between the Metallic Schist and the Dolomite Marble. Dolomite is part of the matrix of the schist. C and D: BTJ-N249 chloritized Metallic Schist. E and F: BTJ-L226 staurolite and kyanite in a non-foliated amphibolite. F is rotated 90 degrees compared to E to see the pleochroism of the staurolite and kyanite.



**Figure 9** Thin sections of the Calar Alto. A, C and E in plane polarized light, B, D and F in crossed polarized light. A and B: BTJ-G161 fine grained quartz-rich Metallic Schist. C and D: BTJ-H175 cordierite porphyroblasts in the Metallic Schist. E and F: BTJ-I187 quartz-rich Metallic Schist with shear bands indicating top-to-N sense of shear.



**Figure 10** Thin sections of the Mafic Unit. A, C and E in plane polarized light, B, D and F in crossed polarized light. A and B: BTJ-438 amphibole and epidote making shear bands in a amphibolite. C and D: BTJ-438 garnet with feldspar and muscovite in the strain shadow. Inclusions indicate syntectonic growth of the garnet. E and F: BTJ-H172 epidote, chlorite and feldspar in a garnet pseudomorph of the amphibolite.



**Figure 11** Thin sections of the Mafic Unit. A, C and E in plane polarized light, B, D and F in crossed polarized light. A and B: BTJ-15 feldspar and zoisite making up the matrix of the 'white schist' at the top of the amphibolites. C and D: BTJ-15 kyanite growth parallel to the zoisite foliation. E and F: BTJ-C118 almost completely retrogressed garnet in a garnet-micaschist of the Schist Member.



**Figure 12** Thin sections of the Mafic Unit. A, C and E in plane polarized light, B, D and F in crossed polarized light. A and B: BTJ-C118 compositional layering in a garnet-mica-schist of the Schist Member. C and D: BTJ-655 feldspar and chlorite in a garnet pseudomorph in a heavily chloritized garnet-mica-schist. E and F: BTJ-655 unstable garnet with chlorite and feldspar in the reaction rim.



**Figure 13** Thin sections of the Bedar Unit. A and C in plane polarized light, B and D in crossed polarized light. A and B: BT-74 large tourmaline grains in a orthogneiss. C and D: BTJ-E148 amphiboles forming shear bands in a well-foliated amphibolite with garnet porphyroblasts.



**Figure 14** Thin sections of the Low Grade Unit. A, C and E in plane polarized light, B, D and F in crossed polarized light. A and B: BTJ-K212 well-foliated, fine grained purple phyllite. C and D: BTJ-660A large unstable olivine grain with serpentinite veins cutting through in a dolerite. E and F: BTJ-660A pyroxene and amphiboles in a plagioclase matrix with an igneous texture.



**Figure 15** Thin sections of the Jauro & Pocico shear zone. A, C and E are in plane polarized light, B, D and F are in cross-polarized light. A and B: BTJ-437 amphibole and chlorite in a amphibolite lense caught in the shear zone. C and D: BTJ-1193 feldspar and chlorite in a schist close to the shear zone. E and F: BTJ-1185 non-foliated amphibolite block caught in the Jauro shear zone.



Figure 16 Thin section of BTJ-16 of the El Pocico shear zone. A in plain polarized light, B in cross polarized light. Large grains of chlorite grow in the quartzite next to the shear zone.



Figure 17 Pictures of the Calar Alto. a) Large garnet porphyroblasts in the Metallic Schist. b) Non-foliated amphibolite clasts in the breccia at the base of the Dolomite Marbles





**Figure 19** Pictures of the Bedar Unit. (a) Quartz and felspar veins in the paragneiss. Garnets are generally smaller than in the garnet-mica-schist of the Mafic Unit. (b) Augengneiss above an ultra-mylonite in the orthogneiss. (c) Tourmaline grains are abundant in the orthogneiss.







Figure 20 Pictures of the Low Grade Unit. (a) Heavily fractured dolerite. (b) Gypsum mylonite around dolerite blocks.

#### **Deformation Phases**

#### D1

The first deformation phase (D1) is represented by isoclinal folds with axial planes subparallel to the original bedding. At places the tight isoclinal folding forms compositional layering. The isoclinal folds make an axial plane foliation parallel (S1) with a general E-W strike (figure 21) and fold axes (F1) have an E-W trend (figure 22). Only relicts of HPLT-metamorphism associated with D1 are preserved. In the Calar Alto, the non-foliated meta-mafics are kyanite bearing (BTJ-L226, figure 8 E-F). In the Mafic Unit, the kyanite and zoisite paragenesis at the top of the meta-mafic body (BTJ-15, figure 11) are also remnants of the HPLT-event during D1. There are no shear zones observed that are related to this phase of deformation.

#### D2

Asymmetric folds are associated with the second deformation phase (D2). Occasionally, asymmetrically folded D1 folds indicate the relative timing between the two phases. The axial planes of the asymmetric folds developed a foliation plane (S2) which is observable throughout the field area. The ESE-WNW-strike of the S2 is subparallel to S1 (figure 21). The fold axes of D2 have an ESE-WNW trend with a plunge predominantly towards the ESE (figure 22). Metamorphism under amphibolite facies during D2 almost completely overprinted the HPLT-event of D1 affecting the lowest three units in the eastern Sierra de los Filabres. In the Calar Alto, the cordierite and garnet porphyroblasts in the Metallic Schist formed during this event. In the Mafic Unit this is expressed by the paragenesis of feldspar, garnet and epidote in the amphibolite body and the garnet porphyroblasts in the mica-schists. The garnet grew synchronously with the development of S2 (BTJ-438, figure 10 C-D). The amphiboles in the orthogneiss, the garnets in the paragneiss, similar amphibolites as in the Mafic Unit and the presence of a foliation in some of the dolomite marbles indicate that amphibolite facies metamorphism is dominant in the Bedar Unit.

The prograde sense of shear criteria related with D2 show an overall tectonic transport of topto-NW (figure 23 & 24). They are observed throughout the Calar Alto, Mafic Unit and Bedar Unit, but strain localized in two main shear zones.

#### D2 shear zones

The Jauro & Pocico and the Cuatro Amigos shear zones that form the Calar Alto/Mafic Unit and Mafic Unit/Bedar Unit boundaries respectively are generated during D2. Only relicts of stretched minerals indicative of prograde metamorphism are preserved in these shear zones. In general, they have an NW-

SE trend. At present day, the Jauro & Pocico shear zone crops out in two shear zones at the margins of the dome due to D3-folding (figure 5).

The Jauro part of the shear zone is located at the southern boundary of the dome. In the east, the shear zone is overturned and dips towards the south. Towards the west, the dip gradually changes from sub-vertical to south dipping. It emplaces the calc-schists and garnet-mica schists of the Mafic Unit in the south on top of different members of the Calar Alto unit in the north. The shear zone localized mainly in calc-schists and calcite marbles (see figure 25). In the east (figure 25.1), the Jauro shear zone is overturned and dips towards the north. Here, the Tahal Schist is observed above the shear zone. Below the shear zone, well-foliated, subvertical amphibolites are found. Lenses of poorly foliated amphibolite (BTJ-437, figure 15 A-B) are observed within the shear zone itself, at places with a cataclastic fabric. They differ from the amphibolites more away from the shear zone by their smaller grain size. More to the west (figure 25.II), the shear zone is subvertical. Here it separates the Metallic Schist in the north from foliated amphibolites, folded together with garnet-mica-schists, in the south. In the shear zone itself, large non-foliated blocks of amphibolite (BTJ-I187, figure 15 E-F) are observed. In the west (figure 25.III), the shear zone is not overturned and dips towards the south. Here it separates the Dolomite Marbles of the Calar Alto in the north from the foliated amphibolites of the Mafic Unit in the south. The shear zone localized in the marbles creating sheath folds and in silicilastic schist (BTJ-I193, figure 15 C-D). Close to the shear zone, again blocks of non-foliated amphibolites are observed. West from this point, the Jauro shear zone is no longer traceable. Here, it is crosscut by several poorly exposed normal and reverse faults.

The El Pocico part of the shear zone forms the northern part of the Jauro & Pocico shear zone and dips to the north. The angle of the dip is subvertical in the east and becomes more shallow (~50°) towards the west. It separates the Mafic Unit in the north from the Calar Alto in the south. The main lithologies found in the shear zone are quartzites and amphibolites. In the east (figure 26.1) the shear zone is very steeply north dipping. The footwall is made up of the Metallic Schist and the quartzites of the Calar Alto. In the hangingwall the non-foliated amphibolite, dolomite marbles and part of the Metallic Schist (BTJ-212, figure 8 A-B) of the Calar Alto are observed. They are cross-cut by E-W striking normal faults. More to the east (figure 26.11, 111, IV) the shear zone is more shallow dipping towards the north. In the footwall, lithologies of the upper Calar Alto are observed: quartzite, dolomite marbles and non-foliated amphibolites. The orientation of the foliation in the footwall varies along the fault, but in general it is north dipping. Quartzite mylonites and amphibolite mylonites define the shear zone itself. In the hanging-wall, foliated amphibolites, garnet-micaschists and calc-schists of the Mafic Unit overly the shear zone.

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The Cuatro Amigos shear zone form is located at the southern side of the dome. In the west, this shear zone is parallel to the Jauro shear zone. In the east it curves towards a NNW-SSE strike. Here, the shear zone is overturned and dips towards the NE. Towards the west the dip gradually changes from NE to subvertical to normal S dipping. Near El Chive the shear zone is again overturned and is shallow Ndipping. In the east, calc-schists and thin layers of calcite marble together with garnet-mica-schists are caught in the shear zone. More to the west, the orthogneiss and paragneiss of the Bedar Unit are sheared as well as the amphibolite of the Mafic Unit. In the east (figure 27.I) the Mafic Unit lies on top of the Bedar Unit. In the Mafic Unit, the hinge of the south-vergent asymmetric fold that overturns the shear zone is observed within the amphibolites. North of this hinge, the sense of shear is top-to-NW, whereas south of the hinge the sense of shear has changed towards top-to-SE. More to the west (figure 27.II) the shear zone has become subvertical. Towards the north, the foliation in the garnet-mica-schists is still overturned and steeply dips to the north. Up the main road from El Marchal towards Bedar (figure 27.III) the Cuatro Amigos shear zone is southwardly dipping. In the hanging-wall, the orthogneiss of the Bedar Unit is observed with a fabric that is at places ultra-mylonitic. Below the shear zone lie the coarse garnet-mica-schists and calc-schists of the Mafic Unit. West of El Chive (figure 27.IV) the Cuatro Amigos is again overturned and shallowly north-dipping. The amphibolites and the calcitic marbles of the Mafic Unit are on top of the paragneiss of the Bedar Unit.

#### D3

The third deformation phase (D3) is characterized by symmetric up-right folds. These folds have a subvertical axial plane cleavage (S3) with a rough E-W orientation (figure 21). The fold axes (F3) are shallow plunging E- or W-wards (figure 22). The D3-folds create the E-W trending dome of the Sierra de los Filabres but are also observed on meter-scale. The metamorphic conditions during D3 are of low-amphibolite/greenschist facies. N-S oriented chlorite is occasionally observed (e.g in the Metallic Schist, figure 9 E-F), but no significant shearing in a N-S direction is observed.

#### D4

The D4-folds have a sub-horizontal axial plane (S4, figure 21) and a flat lying fold axis (F4, figure 22). These folds are best developed where an older foliation plane (often S1) is close to vertical. The metamorphic conditions during D4 are low-amphibolite/greenschist facies to brittle conditions ans is observed in all four units. The schists of the Calar Alto in the core of the dome are all chloritized and the chlorite grains have grown with a roughly E-W preferred orientation (BTJ-TSC, figure 7 A-D and BTJ-H175, figure 9 C-D). Closer to the Jauro & Pocico shear zone, the chlorite grains become more pronounced in the foliation planes and are stretched in an E-W orientation (BTJ-I187, figure 9 E-F, BTJ-N249, figure 8 C-D). D2-garnets in the Mafic Unit are often partially or even fully replaced by retrograde metamorphism (BTJ-438 and BTJ-H172, figure 10). Also the garnet-mica-schist at the top of the Mafic Unit have a strong chlorite overprint (BTJ-C118, BTJ-655, figure 11 E-F and 12). In the Bedar Unit and the Low Grade Unit chlorite growth mainly occurred close to the bounding shear zones.

Retrograde stretching lineations are associated with the vertical flattening of D4. They are observed throughout the studied area and have an E-W trend with a dominant top-to-W sense of shear (figure 23 & 24), making a ~45° angle with the older prograde stretching lineations. Shearing affected all four units, but initially the strain mainly localized in the D2-shear zones. Here, the D2 prograde shear criteria are almost completely overprinted whereas away from the shear zones they are better preserved. In the Cuatro Amigos shear zone, the E-W trending retrograde stretching lineations (e.g green amphibole, chlorite) are observed next to NW-SE stretched black amphiboles. In the Jauro & Pocico shear zone, large chlorite grains in the foliation planes are stretched (BTJ-I193, figure 15 C-D and BTJ-16, figure 16) and a top-to-W retrograde sense of shear is dominant. Also small-scale brittle extensional structures formed in this shear zone (figure 25.I).

At the same time, a new shear zone (El Torcal shear zone) formed north of the Jauro & Pocico shear zone. It is an E-W striking, shallow north-dipping shear zone. It cuts through the Mafic Unit and separates the calcite marbles, amphibolites and slivers of garnet-micaschists in the north from the calc-schists in the south. The shear zone is localized in the calc-schists and garnet-schists. The minerals that are stretched are white mica's and chlorite. In the east, the sense of shear the shear zone is top-to-E, the opposite of the dominant top-to-W sense of shear elsewhere in the dome. Garnet-mica-schists are found just above the shear zone, with top-to-E sense of shear indicators (figure 28.I). Within the shear zone, small-scale brittle extensional features such as cataclasites and normal faults are observed, indicating a transition from ductile to brittle behaviour. Towards the west (figure 28.II and 28.III) the dip of the shear zone with lenses of quartz. A top-to-E sense of shear is found within the mylonites.

The Cuatro Amigos, Jauro & Pocico and Torcal shear zones accommodate a decrease in metamorphism form amphibolite to greenschist to locally even brittle conditions. However, there is no major tectonic omission observed across these shear zones, so these shear zones did not accommodate the main displacement during extension. This occurred along the main Zurgena detachment. This detachment defines the lower boundary of the Low Grade Unit and has emplaced it on top of the Bedar Unit and Mafic Unit. It is affected by D3-folding, just like the Cuatro Amigo and Jauro & Pocico shear zones and crops out at the northern and southern margins of the dome. In the north, it separates the

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Low Grade Unit in the hangingwall from the Mafic Unit in the footwall. In the south, it separates the dolomites of the Low Grade Unit in the hangingwall from dolomite marbles of the Bedar Unit in the footwall. The shear zone created a tectonic omission between the hanging-wall (greenschist facies to non-metamorphic) and the footwall (amphibolite facies).

In the north, a roughly 2-metre thick cataclasite cross-cuts a calc-schist mylonite (figure 29.I). The cataclasite contains large blocks of foliated amphibolite and garnet-micaschists that float in a thinly foliated black, fine grained matrix. Normal faults cut through the blocks of the cataclasite. Kinematic indicators in the calc-schist mylonite show a top-to-SW sense of shear. Riedel shears on the fault planes show an apparent normal movement where the top block also moved towards the southwest. Above the mylonite and cataclasite, a lense of dolomite is observed. Below the shear zone, a coarse-grained garnet-micaschist and foliated amphibolites of the Mafic Unit are found. West of de Bedar town (figure 29.II), the dolomites of the Low Grade Unit are separated from the amphibolites and calcite marbles of the Bedar Unit by a shallowly north dipping cataclasite. Blocks in the cataclasite have preserved an ultramylonitic fabric. Riedel shears in the cataclasite indicate a normal movement with a top-to-NW sense of shear. On the other side of the Sierra de Bedar, along the main road (figure 29.III), again the dolomites of the Low Grade Unit are separated from amphibolites of the Bedar Unit by a cataclasite. Here, the cataclasite dips towards the southwest. Riedel shears in the cataclasite indicate a normal movement with motion of the top block towards the SW. The sense of shear in the amphibolite below the cataclasite is top-to-W. The cataclasite itself is again cross-cut by a steeper normal fault with a motion of the hanging wall towards the SW.



**Figure 21** All S1, S2, S3 and S4 plotted as poles to plane on a lower hemisphere. For S1 and S2 the contour fit is plotted. S3 and S4 do not have enough measurements for statistical analysis.



Figure 22 All F1, F2, F3, F4 plotted on a lower hemisphere.



Figure 23 All stretching lineations plotted on a lower hemisphere. Open dots: sense of shear of top to between 0-179. Closed dots: sense of shear of top to between 180-359.



Figure 24 Distribution of the (a) pro- or retrograde related sense of shear and (b) the retrograde sense of shear.

Figure 25 Cross sections through the Jauro shear zone. See for localities of the cross section the geological map (figure 5). Thin sections of BTJ-437, BTJ-1185, BTJ-1193 are in figure 15. See for legend of lithology symbols figure 27.1





Figure 26 Cross sections through the Pocico shear zone. See for localities of the cross section the geological map (figuer 5). Thin sections of BTJ-16 are in figure 16, BTJ-212 in figure 8. See for legend of lithology symbols figure 27.1



Figure 27.1: Cross sections through Cuatro Amigo shear zone. See for localities of the cross section the geological map (figure5).

symbols figure 27. Figure 27 II, III and IV: Cross sections through Cuatro Amigo shear zone. See for localities of the cross section the geological map (figure 5). See for legend of lithology





Figure 28 Cross sections through Torcal shear zone. See for localities of the cross section the geological map (figure 5). See for legend of lithology symbols figure 27.1

Figure 29 Cross sections through the Zurgena Detachment that creates the main tectonic omission. See for localities of the cross section the geological map (figure 5). See for legend of lithology symbols figure 27.1



#### Interpretations

#### Pre-D1 events

During deposition of the protolith of the Permo-Triassic Tahal and Metallic schists, the Calar Alto and Bedar Unit were part of the same paleo-geographical continental or transitional environment. Based on the mineralogical composition, the black and purple phyllite of the Low Grade Unit are a metamorphic low-grade equivalent of the same protolith and therefore were part of the same environment. The alternation between quartz-rich and clay-rich layers suggests that deposition was close to a continental sediment source. Extension caused flooding of the continental to transitional environment. Carbonate rocks are deposited on top of the quartz and clay rich rocks in a shallow marine environment and the breccia at the base of the Dolomite Marbles of the Calar Alto marks the transgressive surface. The small mafic lenses often observed close to the Dolomite Marbles in the Calar Alto are possibly intrusions related to the extension.

The protoliths of the Mafic Unit have a very different provenance. The calcite marbles at the bottom are typically shallow marine deposits, in contrast to this, the amphibolites are part of an ophiolite complex (Bodinier et al. 1997, Puga et al. 1999) and thus belong to a former oceanic lithosphere. The protolith of the calc-schist on top of the meta-mafic rocks are deep marine pelagic and hemipelagic depositions and are overlain by turbidite sequences that are now the coarser garnet-mica-schist. To find deep marine sediments and part of an ophiolite-complex on top of shallow marine carbonates, a tectonic contact between them is required. Since the calcite marbles and amphibolites are folded isoclinally together, this tectonic contact must pre-date D1.

#### D1

The isoclinal folds of D1 show that burial of the rocks was accompanied by severe flattening. There are no shear zones or kinematic indicators related to D1 observed, but the E-W trend of indicates that the burial and flattening occurred in a N-S oriented compressional setting. The strong flattening together with the relicts of HPLT-metamorphism indicate that the D1-event is related to initial burial during subduction or thrusting processes. The main difference between D1 and D2 is the asymmetry of the D2 folds and the HTLP-metamorphism in contrast to the HPLT-conditions of D1. The asymmetry of the folds indicates that during D2 the rocks are not only flattened, but also severely sheared during burial. Strain localized in the contractional Jauro & Pocico and the Cuatro Amigo contractional shear zones generating three different nappes: the Calar Alto, the Mafic Unit and the Bedar Unit. The structurally lowest nappe is the Calar Alto and it is separated from the overlying Mafic Unit by the Jauro & Pocico shear zone. The Cuatro Amigo shear zone emplaced the Bedar Unit on top of the Mafic Unit. The top-to-NW prograde sense of shear indicators in the two shear zones and the E-W trend of F2 indicates that compression direction was roughly the same as during D1. The HTLP-metamorphism during nappe-stacking is typical for a continental collision setting.

#### D3 & D4

The relative timing between the D3 and D4 events is not straight forward. The D3-folds clearly affect the D4 structures, but at the same time the brittle structures related to D4 post-date the D3 folding under greenschist conditions. Therefore, the two events must have taken place roughly simultaneously. In comparison to D2, there is a decrease in metamorphic conditions during D3 and D4. The retrograde stretching lineations indicate that this drop is caused by tectonic exhumation. The dominant top-to-W sense of shear related to D4 implies a simple-shear extensional setting. The D4 folds are collapse-folds caused by vertical flattening of an inherited sub-vertical foliation during lateral extension (Froitzheim 1992). At the same time, the E-W oriented F3 folds show that N-S compression occurred simultaneously with the E-W extension. At the onset of exhumation, strain localized in the older nappe-stack shear zones and almost completely overprinted the D2 shear indicators with greenschist top-to-W sense of shear indicators. Part of the Torcal shear zone accommodated antithetic shearing in a top-to-E direction. As the N-S shortening folded and locally overturned the nappe stack shear zones, strain localization migrated to the Zurgena Detachment. This is the main detachment that created the tectonic omission during exhumation that is observed between the greenschist-facies to non-metamorphic Low Grade Unit in the hanging-wall and the rocks previously buried to amphibolite conditions of the Mafic Unit and Bedar Unit in the footwall. Continuous exhumation by the detachment transported the rocks from deeper ductile deformation into shallower brittle regime. The fact that also the detachment is affected by E-W trending D3-folds shows that N-S compression was still active even after the migration of strain localization, forming an a-type metamorphic dome characterized by N-S oriented shortening and E-W oriented extension.

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# Discussion

Based on the results of this study, we propose a revision of the meaning of the terms Nevado-Filabrides and Alpujarride. We consider the Nevado-Filabrides and Alpujarride as two tectonic units defined by the plate tectonic setting during the Alpine Orogeny. The Nevado-Filabrides was part of the lower, downgoing plate and the Alpujarride belonged to the overriding upper plate. The two plates are separated by a suture zone which contains oceanic material derived from oceanic lithosphere and overlying pelagic and turbidite sediments.

As a consequence of this view, we have re-defined the boundary between the Nevado-Filabrides and the Alpujarride on local scale in the eastern Sierra de los Filabres (figure 30). In this area, the rocks of the Mafic Unit represent the suture zone and are grouped in the Nevado-Filabrides. The Calar Alto is structurally below the suture zone and thus is also part of the Nevado-Filabrides. The Bedar Unit lies on top of the suture and may therefore be part of the overriding Alpujarride Unit. The Low Grade Unit is defined by the Zurgena detachment at its base. The Zurgena detachment does not exactly follow the suture zone and therefore the Low Grade Unit may contain both Nevado-Filabrides and Alpujarride derived rocks.

#### Redefining the Nevado Filabrides-Alpujarride boundary on a local scale

The results of this study show that on a local scale the nappe-stack related shear zones do not coincide with the major detachment. There is an ~45 degree angle between the initial direction of convergence (top-to-NW) and the direction of the simple shear extension (top-to-W). Because of this difference, the detachment did not exactly follow the nappe contacts. This shows that in contrast to previous studies the detachment cannot be used as the boundary between the Nevado-Filabrides and Alpujarride (Platt et al. 1984, Vissers et al. 1995).

Alternative to this, it is the suture that contains oceanic mantle rocks that should be used as the boundary. The suture is characterized by meta-ophiolite rocks derived from an ocean that opened in the Jurassic, separating the Nevado-Filabrides from the Alpujarride. Before the opening of the intervening Jurassic ocean, the two units were part of the same continental plate. The oceanic lithosphere and/or exhumed continental mantle adjacent to an oceanic domain (sensu Manatschal & Müntener 2009) as the origin of the meta-mafic rocks in the suture zone is supported by the geochemical MORB-signature observed in previous studies (Bodinier et al. 1987, Hebeda et al. 1980, Puga, et al. 1999). The Jurassic age of this ocean is supported by radiometric dating of the mafic rocks (148 Ma to 183-187 Ma, Hebeda et al. 1980, Puga et al. 2011). The hypothesis that the oceanic-derived material separates the Nevado-

Filabrides from the Alpujarride is in partial contrast to the reconstruction of Puga et al. (2017), where the suture zone is recognized, but only interpreted as just one of the contractional shear zones within the Nevado-Filabrides.

#### Mechanism creating the tectonic omission

A consequence of the new boundary between the Nevado-Filabrides and Alpujarride is that the rocks in the hanging-wall of the detachment are not by definition part of the Alpujarride Unit, but could also contain low-grade rocks derived from the Nevado-Filabrides by cross-cutting of the extensional detachment through the nappe contacts. The mechanism that preserves low-grade parts of both units is related to the difference in angle between contraction and subsequent extension. At the end of D2, the Alpujarride is emplaced on top of the Nevado-Filabrides by nappe stacking by the Cuatro Amigos shear zone. The thickening of the crust caused amphibolite facies (HTLP) metamorphism at the base of both tectonic units. During D4, the younger detachment cuts the nappe-stack. The detachment does not exactly follow the older Nevado-Filabrides/Alpujarride boundary, but sometimes localizes in the Nevado-Filabrides, sometimes in the Alpujarride. In this way, the detachment crosses the Nevado-Filabrides-Alpujarride boundary several times and creates slivers of low-grade Nevado-Filabrides in the hanging-wall and high-grade Alpujarride in the footwall (figure 31a). The depth at which the detachment cuts the nappe-stack controls the metamorphic grade of these slivers. Moreover, detachment migration due to synchronous doming may create stepwise smaller tectonic omissions in terms of metamorphic degree instead of one large metamorphic jump. Post-detachment doming and subsequent erosion exposes the nappe-stack related shear zones in the core of the dome and the detachment at the boundaries of the dome (figure 31b).

#### Composition of the Mafic Unit: obduction vs. subduction channel

Based on the results of this study, the best explanation for the pre-D1 tectonic contact between the marbles and amphibolites with completely different origin in the Mafic Unit is an obduction contact. Since the amphibolites and marbles are folded and metamorphosed together during the subduction of D1, obduction must have occurred prior to the HPLT-event, which contrasts with the interpretation of timing of Puga et al. (2017). The slow-spreading ridge (Vissers et al. 2013) and the presumably many transform faults (Schettino & Turco 2009) of the Western Tethys at Jurassic times which separated the Nevado-Filabrides from the Alpujarride are favorable boundary conditions for oceanic obduction.

This interpretation is in contrast to the hypothesis that the mafic rocks and the shallow carbonates are brought together in a subduction channel on top of the westwards retreating slab (Behr

et al. 2012, Booth-Rhea et al. 2015). This model predicts rotation in sense of shear from top-to-W at the bottom of the channel to top-to-E at the top. However, this has not been observed in the Sierra de los Filabres. The Cuatro Amigo shear zone marks the boundary between the Nevado-Filabrides and Alpujarride and should therefore be the roofing shear zone of the subduction channel. The dominant sense of shear in this shear zone is top-to-W instead of the predicted top-to-E. The only shear zone with a partly top-to-E sense of shear is the Torcal shear zone, but this sense of shear is not consistent along strike of the shear zone. Moreover, the Nevado-Filabrides-Alpujarride boundary has not been observed close to the Torcal shear zone; it is thus unlikely that this shear zone is related to the roof of a subduction channel. Nevertheless, it is possible that part of the subduction channel geometry is omitted by the detachment during extension. Therefore, the results of this study cannot fully exclude the possibility that part of the mafic rocks and marbles are brought together in a subduction channel.

#### Regional metamorphism in the Sierra de los Filabres

This study shows that there are two distinct peaks in metamorphism in the Nevado-Filabrides. The first is associated with HPLT-metamorphism during subduction, the second peak is under amphibolite facies related to continental collision and almost completely overprints the first peak. The fact that the second peak of metamorphism is related to burial due to nappe stacking supports the interpretation that the Nevado-Filabrides underwent two PT-loops with distinct peak conditions (Puga et al. 2000, Aerden et al. 2013, Li & Massone 2018).

These findings are in line with the subdivision of the ages for peak metamorphism in two different groups: the first that is related to subduction in the Eocene to early Oligocene and the second related to continental collision in the late-Oligocene-middle Miocene (Monie et al. 1991, Augier et al. 2005b, Li & Massone 2018). This is in contradiction with the studies that, based on isotope dating of garnets, suggest subduction during the middle Miocene (Platt et al. 2006, Behr et al. 2012, Kirchner et al. 2016). Our findings support the explanation of Aerden et al. (2013) that garnet overgrowth of the HProcks during the second peak in metamorphism has mislead a better supported interpretation in terms of timing of events.

#### Strain localization during extension in the suture

The high-grade Nevado-Filabrides and Alpujarride are exhumed by a west-dipping detachment in a simple shear extensional setting in the Middle to Late Miocene. A west-dipping detachment is in line with previous structural analysis of Internal Betics and the Sierra de los Filabres in particular (Jabaloy et

al. 1993, Martinez-Martinez et al. 2002, Augier et al. 2005a) and the progressively younging of exhumation towards the west (Johnson et al. 1997, Vazquez et al. 2011).

The detachment localized in the suture zone that formed the weakest part of the crust at the time of extension. On the regional scale of the Internal Betics, the (meta-)ophiolites are always observed close to the detachment (figure 32). Despite the difference in direction of movement between contraction and subsequent extension, the planes along which the movement occurred are roughly similar. This means that the rheological properties of the suture that formed during convergence control the strain localization during later extension.

#### Overview of the major events in the Sierra de los Filabres

During the Triassic, the Nevado-Filabrides and Alpujarride were both part of the extended southern passive margin of Iberia (figure 33a). During the Jurassic, rifting resulted in the opening of an ocean that separated the two units (figure 33b). The Alpujarride formed a micro-continent in the Western Tethys whereas the Nevado-Filabrides was still part of the Iberian passive margin. During inversion at the end of the Cretaceous, part of the oceanic mantle and crust is obducted on top of the Iberian passive margin (figure 33c). After this, the oceanic derived material together with the passive margin were buried and flattened by subduction beneath the Alpujarride under HPLT-metamorphic conditions (D1). The closure of the Tethys ocean was followed by continental collision. Nappe stacking emplaced the base of the Alpujarride on top of the Nevado-Filabrides, separated by a suture containing the obducted oceanic material (figure 33d). The burial due to the collision flattened and sheared both the Nevado-Filabrides and Alpujarride and caused a second peak in metamorphism under amphibolite facies (D2). Postorogenic collapse caused simple shear extension accommodated by a major detachment and the highgrade rocks are exhumed from greenschist to brittle conditions (D3 and D4) (figure 33e). Locally, the detachment cuts the suture zone that marks the boundary between the Nevado-Filabrides and Alpujarride with an angle. Low-grade Nevado-Filabrides and Alpujarride rocks in the hangingwall are emplaced on top of their high-grade equivalents in the footwall. On a regional scale, the detachment reused the suture zone, despite the difference in orientation of tectonic movement between contraction and extension. Continuous orthogonal N-S shortening during the E-W post-orogenic extension gave rise to the present-day exposed a-type metamorphic dome.



**Figure 30** Subdivision of the studied area in Nevado-Filabrides and Alpujarride complexes. **A:** Subdivision proposed by Martínez-Martínez et al. (2002) and used by most studies thereafter (e.g. Augier et al. 2005a, Booth-Rhea et al. 2015, Kirchner et al. 2016). The boundary between the two complexes is the detachment. **B**: Improved subdivision of this study. The boundary between the two units is the suture zone. In the north, the detachment emplaced low-grade Nevado-Filabrides on top of highgrade Nevado-Filabrides. In the south, the same detachment has emplaced low-grade Alpujarride on top of high-grade Alpujarride.



**Figure 31** Mechanism creating the metamorphic jump in the NF and Alp. During D2, the Alpujarride (green symbols) is emplaced on top of the Nevado-Filabrides (purple symbols) by nappe stacking (black line). The metamorphic gradient (highgrade at the base (+), low-grade at the top (-)) is caused by the burial due to the nappe stacking. At the onset of D3 (a), the younger detachment cuts the NF-Alp contact. Slivers of low-grade Nevado-Filabrides and high-grade Alpujarride are preserved in respectively the hanging-wall/footwall of the detachment. After the doming of D3 and subsequent erosion (b), high-grade rocks of both the Nevado-Filabrides and Alpujarride separated by the suture are exhumed in the core of the dome, whereas the low-grade rocks of both the Nevado-Filabrides and Alpujarride crop out at the margins of the dome.



**Figure 32** Geological map of the Internal Betics after Puga et al. (2017) displaying the locations of the (meta-)ophiolites that are located in the suture zone. The detachment is used as the boundary between the Nevado-Filabrides (Mulhacen Complex) and the Alpujarride. On the regional scale of the Internal Betics, the detachment and the suture zone coincide. The suture formed a weakness in the lithosphere in which the strain localized during simple shear extension.



**Figure 33** Simplified reconstruction explaining the genetical origin of the NF and Alp tectonic units. Rifting during Triassic resulted in the opening of an ocean in the Jurassic. This ocean marks the boundary between the NF in the northwest and the Alpujarride in the southeast. In the Late Cretaceous, inversion initiated subduction below the Alp and part of the ocean to obduct on top of the NF. Closure of the ocean during caused continental collision. The Alp is emplaced on top of the NF, separated by a suture. In the Middle Miocene, E-W extension accommodated by the detachment localizes on a regional scale in the suture zone. Coeval N-S shortening forms the E-W trending metamorphic domes.

# Conclusions

The improved tectono-stratigraphy together with the (micro-)structural kinematic analysis of this study provides new insights in the understanding of the relationship between the nappe-stacking and the subsequent exhumation of the metamorphic rocks in the eastern Sierra de los Filabres. On a local scale, the detachment cannot be used as the boundary between the Nevado-Filabrides and Alpujarride. Instead, the oceanic mantle derived (ultra-)mafic rocks at the top of the Nevado-Filabrides that represent a suture zone and should therefore be used as the boundary between the two tectonic units. The quantitative kinematic analysis of this study shows that there is a ~45 degrees difference in direction of tectonic transport between burial (top-to-NW) and exhumation (top-to-W). Initially the nappe-stack related shear zones were re-activated during exhumation, but due to N-S compression perpendicular to the E-W extension the strain localization migrated to the main detachment that makes an angle with respect to the nappe-stack shear zones. It is because of this angle that the younger detachment locally cross-cuts the boundary between the Nevado-Filabrides and Alpujarride. The tectonic omission created by the detachment does not only emplace low-grade Alpujarride on top of high-grade Nevado-Filabrides, but also slivers of high-grade Alpujarride and low-grade Nevado-Filabrides are preserved in the footwall and hanging-wall, respectively.

In the light of these findings future work in the Internal Betics may focus on two things. Firstly, it is highly possibly that the detachment cross-cuts the boundary between the Nevado-Filabrides and Alpujarride at more places within the Internal Betics than just in the area of interest of this study. Since in previous field studies the detachment is often used as the boundary, this cross-cutting relation has not been observed elsewhere yet. If more slivers of low-grade Nevado-Filabrides that are preserved in the hanging-wall can be identified, they can be used to get a better constraint on the pre-Alpine history of this unit, since a there is a smaller metamorphic overprint in these slivers. At the same time, high-grade Alpujarride slivers in the footwall of the detachment may be used to find better constraints on the burial history of this unit. This can add more details to the evolution of the Western-Tethys during the Alpine Orogeny. Secondly, future numerical and/or analogue models that describe continental collision followed by (post-)orogenic collapse may use the case of the Betics as a reference to study the rheological properties and their effects on the resulting geometry of a weak layer in the system such as a suture zone. Despite the ~45 degree obliquity between the contraction and subsequent extension in the Betics, on a regional scale strain localized in the suture zone during both events.

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# Appendix

# Coordinates of the samples of thin-sections

Sample	Latitude	longitude	Foliation		Lineation		Unit
			Dip	Dipdirection	Plunge	Orientation	
BTJ-15	37.21355	-2.02202	31	75	28	121	Mafic Unit
BTJ-16	37.2346	-2.04554	60	338	27	264	Pocico Shear Zone
BTJ-212	37.23379	-2.03904	37	358	30	310	Calar Alto
BTJ-328	37.20464	-2.09984	34	155	12	89	Calar Alto
BTJ-437	37.21577	-1.98188	38	8	5	86	Jauro Shear zone
BTJ-438	37.21524	-1.98331	50	24	30	108	Mafic Unit
BTJ-655	37.3086	-2.05234	22	104	10	80	Mafic Unit
BTJ-660A	37.307	-2.05149					Low Grade Unit
BTJ-C118	37.20465	-2.00451	16	291	11	259	Bedar Unit
BTJ-E148	37.19883	-1.98523	17	185	9	247	Bedar Unit
BTJ-G161	37.20346	-2.07496	52	35	51	21	Calar Alto
BTJ-H172	37.20998	-2.09361	80	170	53	95	Mafic Unit
BTJ-H175	37.20881	-2.10187	74	95	5	181	Calar Alto
BTJ-I185	37.21824	-2.00325					Calar Alto
BTJ-187	37.21832	-2.01522	193	103	57	197	Calar Alto
BTJ-I193	37.2187	-2.04123	64	150	30	75	Jauro Shear Zone
BTJ-K212	37.31615	-2.0294	15	215	8	287	Low Grade Unit
BTJ-L226	37.22189	-2.12924					Calar Alto
BTJ-L229	37.22064	-2.13189	5	191	12	98	Calar Alto
BTJ-N249	37.19041	-2.10532	48	76	48	81	Calar Alto
BT-74	37.18906	-1.97441					Bedar Unit