

Redefinition of the deformation scheme of the Mulhacén Complex and implications for the relative timing of the overthrusting of the Alpujarride Complex in the Betic Zone (SE Spain)

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Abstract

A new deformation scheme is presented for the Mulhacén Complex of the Betic Zone in southern Spain. This deformation scheme, which consists of six phases of superimposed penetrative deformation, is based on structural investigations in the contact zone with the overlying Alpujarride Complex. The newly obtained data imply that overthrusting by the Alpujarride Complex was the last major event in the deformational history of the Mulhacén Complex.

Introduction

The Mulhacén Complex of the Betic Cordilleras, the Alpine belt in southern Spain, consists of three tectonic units (Bakker et al. 1989, De Jong & Bakker 1991; Fig. 1), from top to bottom:

- 1) Huertecicas Altas-Almocaizar Unit
- 2) Macael-Chive Unit
- 3) Nevado-Lubrin Unit

These three nappes are defined by superposition of Paleozoic rocks on Triassic metasedimentary series in conjunction with truncation of layering in the underlying tectonic units (De Jong & Bakker 1991). The Mulhacén Complex in turn is overlain by the Alpujarride Complex (Egeler & Simon 1969). Figure 1 demonstrates that the Alpujarride Complex truncates the internal nappe structure of the Mulhacén Complex: along the northern margin of the Sierra de los Filabres the Alpujarride Complex rests on the Huertecicas Altas-Almocaizar Unit, eastwards the contact cuts down into rocks of the

Macael-Chive Unit, still further to the east the foot-wall rocks are formed by the Nevado-Lubrin Unit.

The tectonic evolution and plurifacial metamorphism of the Mulhacén Complex in the eastern Sierra de los Filabres are well established (Langenberg 1972, Kampschuur 1975, Vissers 1981, Bakker et al. 1989, De Jong 1990). Recent investigations (De Jong 1991, De Jong 1993), however, show a number of important differences with respect to the deformation scheme for the Mulhacén Complex formerly established by Bakker et al. (1989). They were briefly discussed earlier (De Jong 1992a); a more thorough treatment is the subject of the present paper.

In the Sierra de los Filabres the contact between the Mulhacén Complex and the overlying Alpujarride Complex is well exposed. The newly established deformation scheme for the Mulhacén Complex (Table 1) has important bearing on the timing of the overthrusting by the Alpujarride Complex with respect to the deformational history of the Mulhacén

Complex in particular and to the tectonic evolution of the Betic Zone in general.

Polyphase deformation in the Mulhacen Complex

The deformation of Bakker et al. (1989) consists of five phases of penetrative deformation D_{x-1} , D_x , D_{x+1} , D_{x+2} and D_{x+3} . The D_x phase resulted in the most penetrative structures at all scales throughout the complex. These structures were formed during medium-grade metamorphism. The principal tectonic foliation, S_x , runs parallel to the sedimentary layering; this transposition foliation is continuous over at least 25 km along strike (De Jong & Bakker 1991). In contrast, D_{x+1} structures, mainly extensional crenulation cleavages, are confined to the contact with the Alpujarride Complex along the northern margin of the Sierra de los Filabres and to a number of zones within the Mulhacen Complex (Bakker et al. 1989). The authors, therefore, concluded that during D_{x+1} the Mulhacen Complex was overthrust by the Alpujarride Complex. The subsequent phase of penetrative deformation D_{x+2} consists of S to SW vergent folds associated with S to SW-ward thrusting. D_{x+2} evolved under retrograde conditions shown by widespread chlorite and albite growth. In

contrast, D_{x+3} took place at the climax of subsequent reheating, which resulted amongst others in oligoclase growth and local formation of staurolite. D_{x+3} deformation was concentrated in the higher levels of the Nevado-Lubrin Unit due to reactivation of the floor thrust of the D_{x+2} imbricate system (Bakker et al. 1989).

D_{x+2} folds have a wavelength up to several hundreds of metres and amplitudes of the same order (De Jong & Bakker 1991, encl. II). D_{x+2} thrusting resulted in repetition of the D_x transposition stratigraphy in the Nevado-Lubrin Unit and substantially modified the original configuration of the three tectonic units within the Mulhacen Complex, bringing the Nevado-Lubrin Unit locally on top of the Macael-Chive Unit (De Jong & Bakker 1991, encl. I and II). Although the contact between the Mulhacen and Alpujarride Complexes is a D_{x+1} contact in the scheme of Bakker et al. (1989), the nappe contact is never affected by D_{x+2} folds and thrusts. Instead, cleavages and thrusts equivalent to D_{x+2} are systematically truncated by the basal thrust plane of the Alpujarride Complex (Fig. 2; De Jong 1991, 1993). Consequently, the present-day contact between the Alpujarride and Mulhacen Complexes in the northern Sierra de los Filabres was formed after D_{x+2} , rather than before this deformation phase as was

Table 1. Characteristics of the tectono-metamorphic phases of the Mulhacen Complex compared to the deformation scheme of Bakker et al. (1989)

Deformation phases	P-T conditions	Characteristics	Comparison with Bakker et al. 1989
D_1^{mulh}	475–525°C; 0.9–1.1 GPa	In glaucophane schists and gneisses; ESE-WNW stretching	D_{x-1}
D_2^{mulh}	525–575°C; decompression: 1.1 to 0.7 GPa	Main tectono-metamorphic phase; transposition foliation; ESE-WNW stretching; upwards increasing rotational component	D_x
D_3^{mulh}	400–450°C; 0.35–0.45 GPa retrogression	Local S to SW-vergent folding associated with S to SW-ward thrusting	D_{x+2}
D_4^{mulh}	425–525°C; 0.2–0.3 GPa reheating climax	Km-scale folds, local small scale structures; N-S shortening	D_{x+3}
D_5^{mulh}	Retrogression of 500 to 400°C	Mylonitization at the contact with the Alpujarride Complex	D_{x+1}
D_6^{mulh}	≤400°C	Folds associated with and cut by brittle-ductile shear zones at contact with Alpujarride Complex and at internal detachments	D_{x+3}

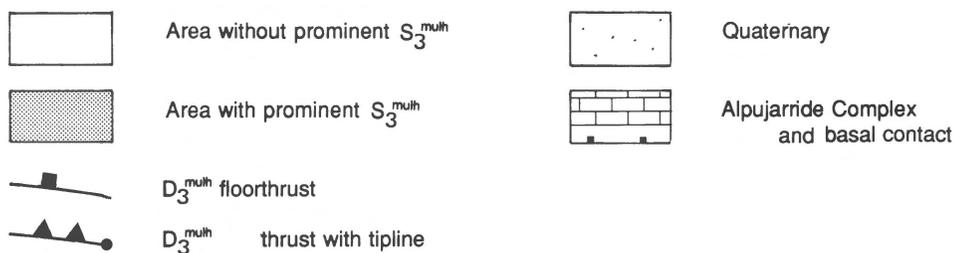
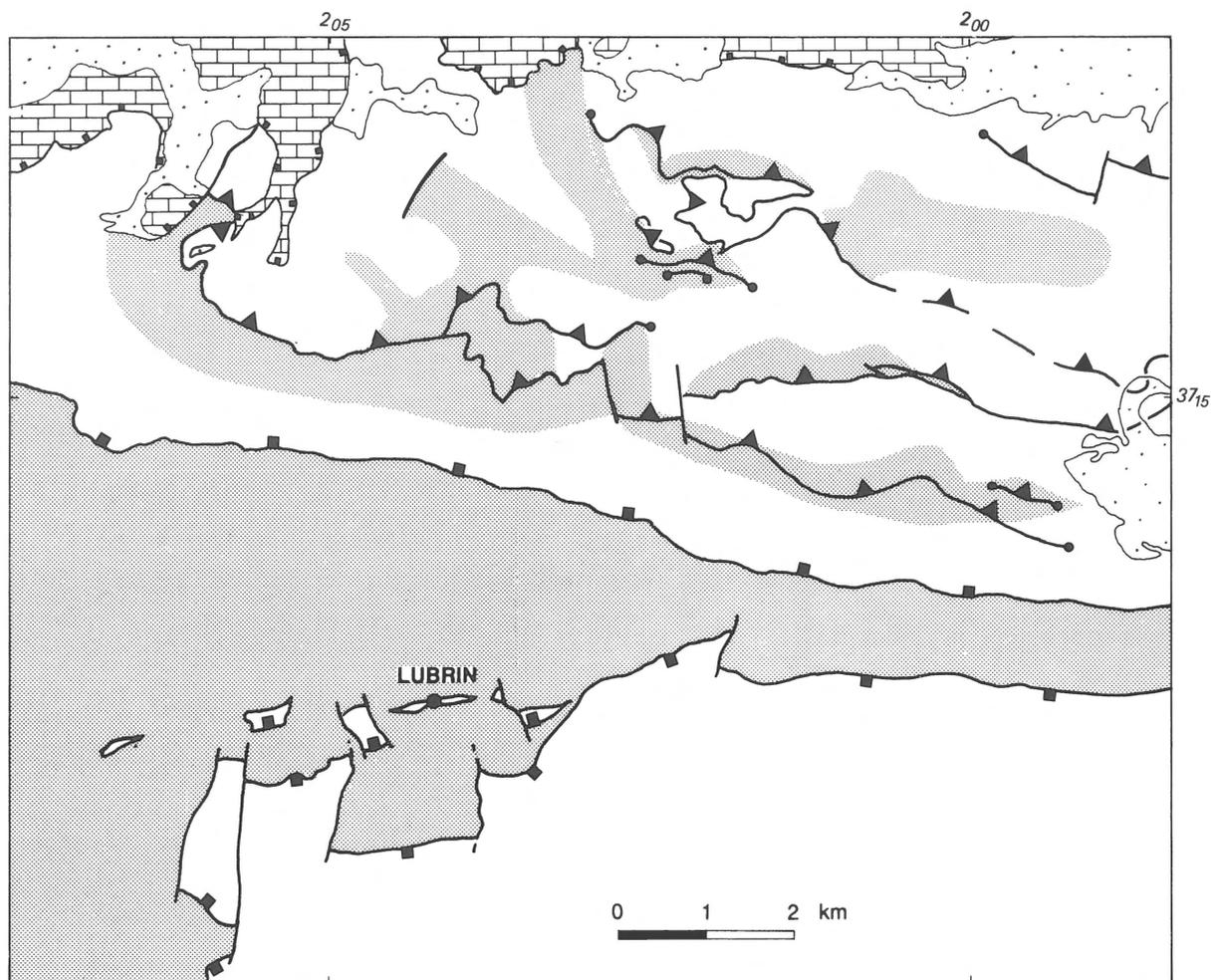


Fig. 2. Relationship between penetrative D_3^{mulh} folding and cleavage development and D_3^{mulh} thrusting in the eastern Sierra de los Filabres. The most penetrative D_3^{mulh} structures are developed in the vicinity of imbricate thrusts and below the floor thrust. Note the truncation of zones of penetrative D_3^{mulh} structures by the basal thrust plane of the Alpujarride Complex.

concluded by Bakker et al. (1989) and Bakker (1991). To test this working model, small-scale structures in the top of the Mulhacen Complex in the contact zone with the Alpujarride Complex were

reinvestigated and compared with the microstructural evolution of the Alpujarride-Mulhacen contact in the central and southern Sierra de los Filabres.

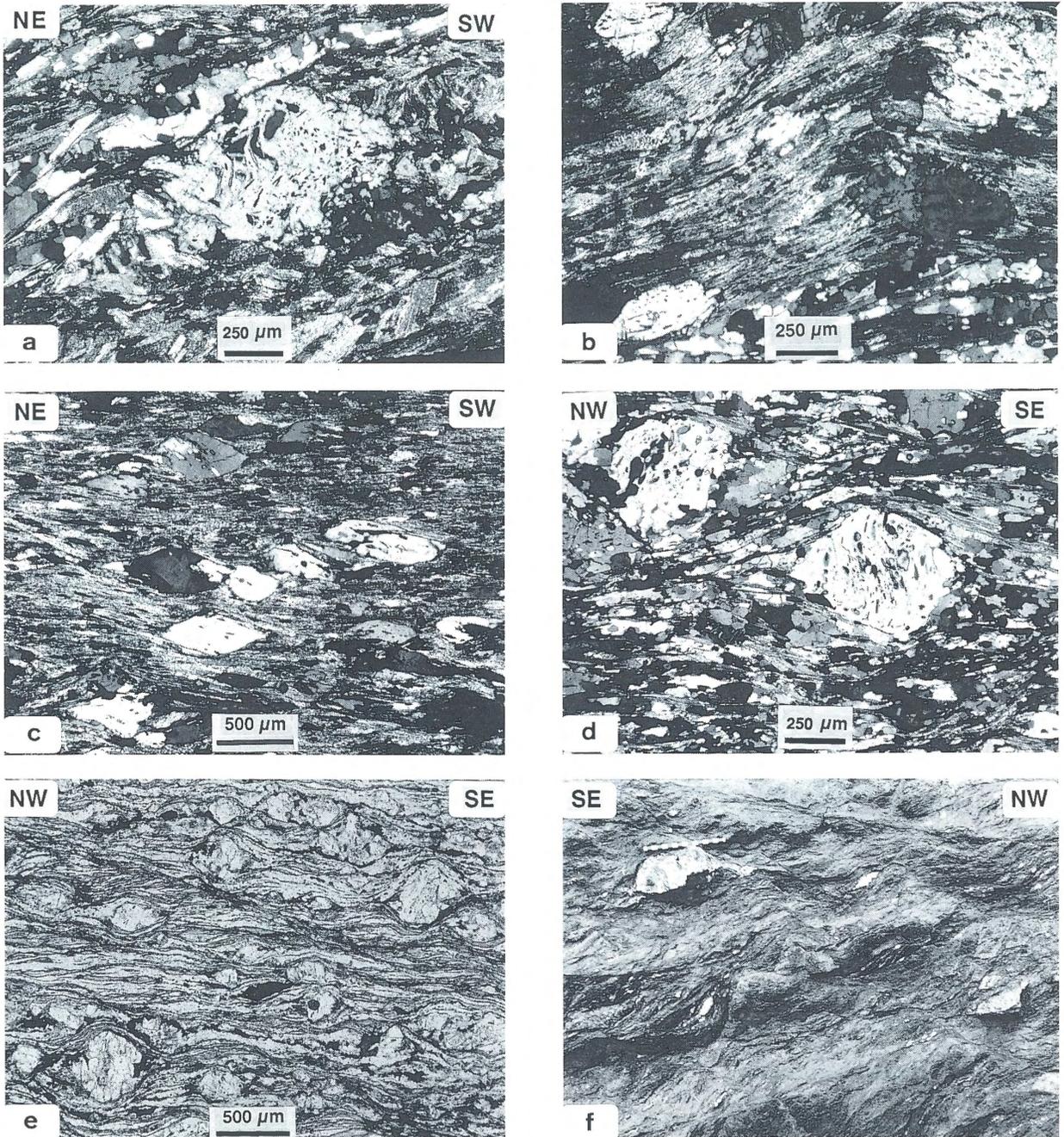


Fig. 3. Photomicrographs of the relation between syn- D_3^{mulh} albite and D_5^{mulh} mylonitic deformation. a) An albite crystal with a typical syn- D_3^{mulh} internal inclusion fabric; NE Sierra de los Filabres, about 50m below the Alpujarride Complex, loc. a, Fig. 4. b) Albite displaying lattice bending in the margin of a D_5^{mulh} shear band; the external foliation does not curve around the albite crystals indicating relatively low- D_5^{mulh} strain; same location as a). c) Lozenge-shaped albites locally with asymmetrical rims of oligoclase; the main foliation gently curves around the plagioclase crystals; central Sierra de los Filabres, loc. b, Fig. 4. d) Syn- D_3^{mulh} inclusion pattern in an albite porphyroclast; same location as c). e) Albite porphyroclasts in a D_5^{mulh} mylonite; the totally dynamically recrystallized mylonite foliation curves around the plagioclases; southern margin Sierra de los Filabres, loc. c, Fig. 4. f) D_6^{mulh} brittle-ductile shears in garnet mica schists of the Nevado-Lubrin Unit, indicating dextral, i.e. top-to-the-NW movement; southern margin Sierra de los Filabres, loc. c, Fig. 4. Scale bar in centimetres.

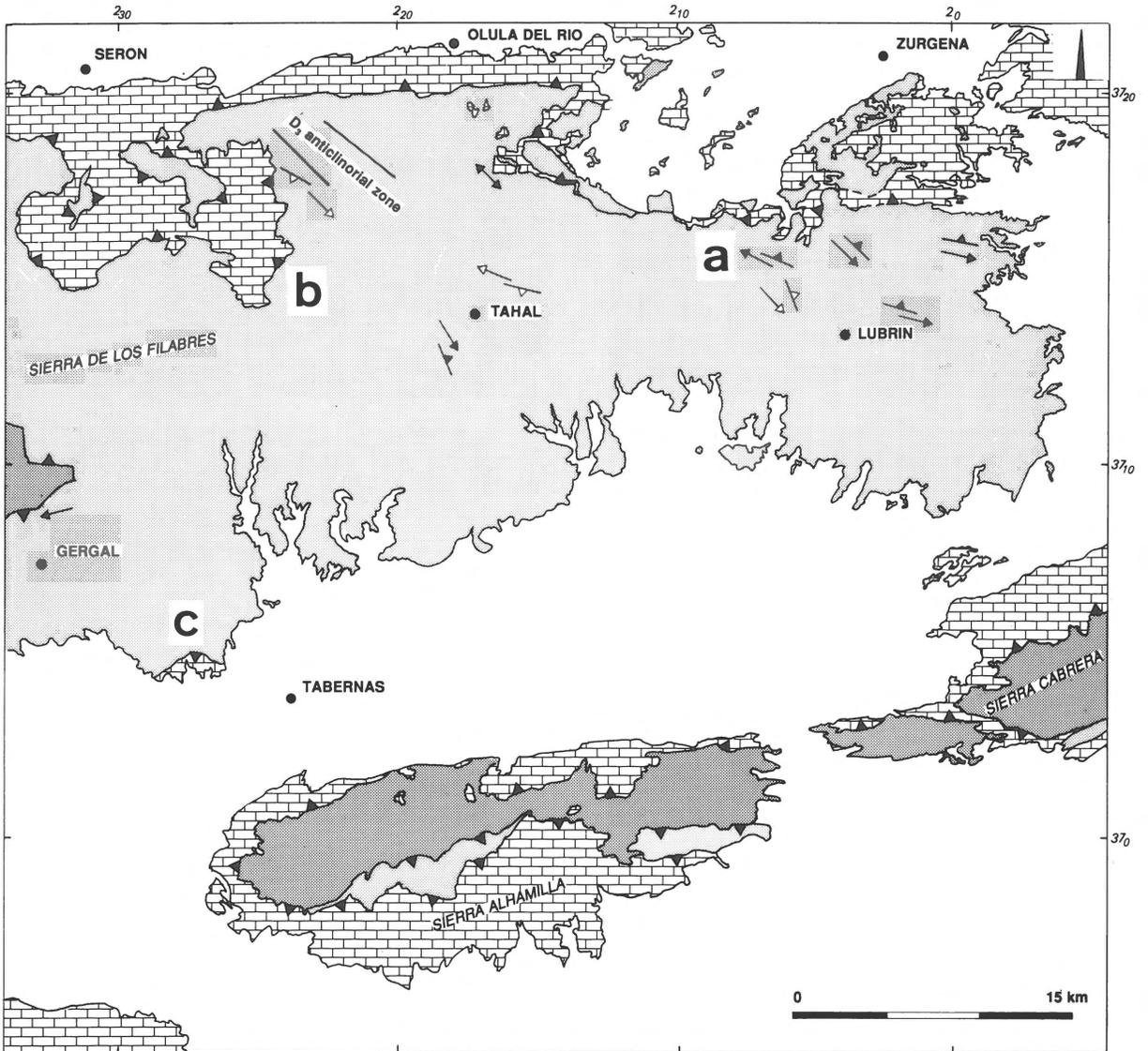


Fig. 4. Trend of macroscopic D_3^{mulh} and D_4^{mulh} structures in the Mulhacen Complex of the Sierra de los Filabres. Regional distribution of the nappe complexes based on interpretation of maps by Vissers (1981), Platt et al. (1983), Weijermars et al. (1985) and De Jong & Bakker (1991) and on mapping by the author. Locations discussed indicated by a, b and c.

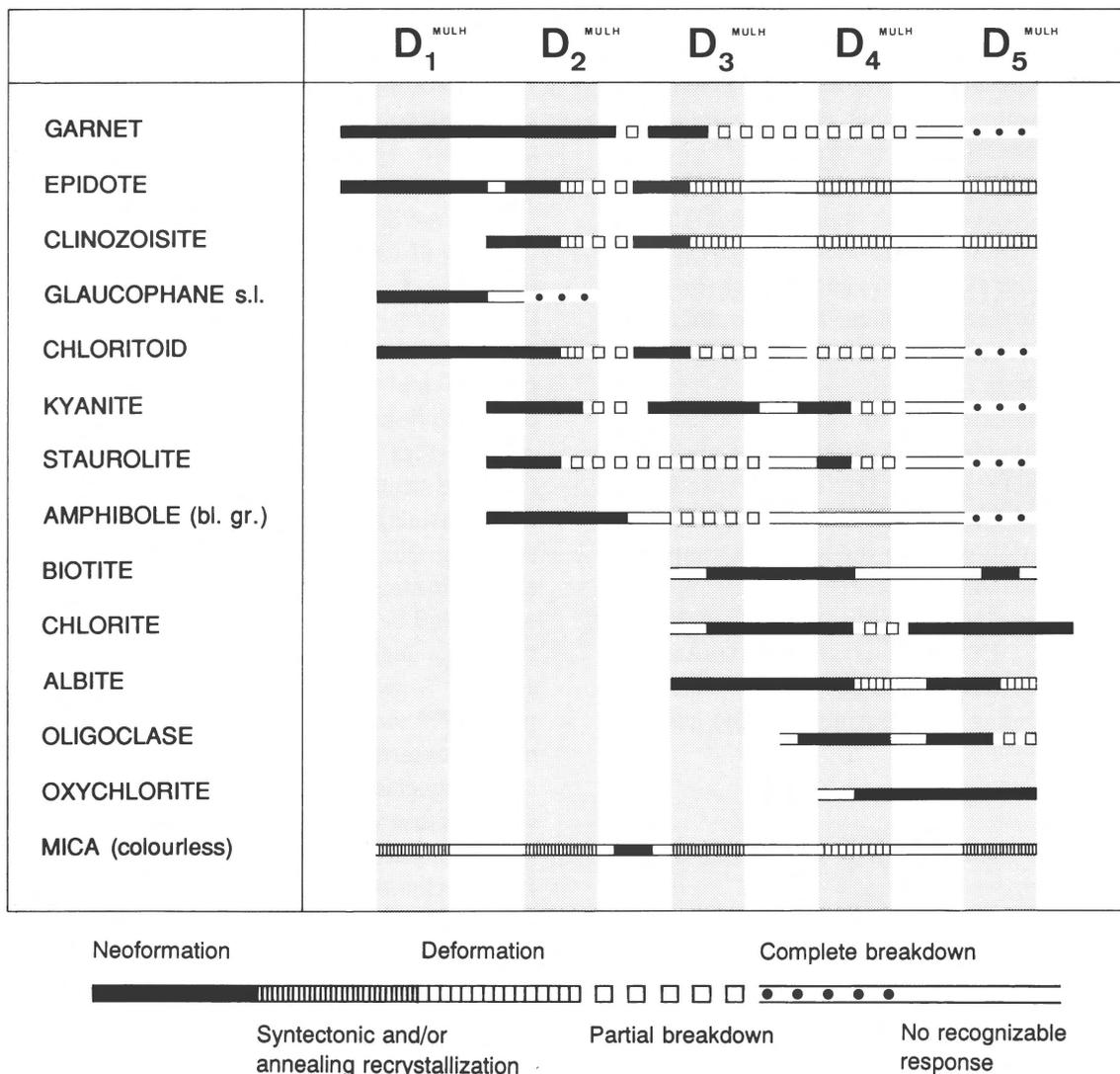


Fig. 5. Relationship between mineral growth and deformation phases in mica schists of the Mulhacen Complex in the Sierra de los Filabres, easternmost Sierra Nevada and Sierra Alhamilla.

New deformation scheme for the Mulhacen Complex

Northern Sierra de los Filabres

In the northern margin of the Sierra de los Filabres (Fig. 4, loc. a) the intensity of extensional crenulation cleavages (ECCs) increases upwards towards the basal thrust plane of the Alpujarride Complex, implying that cleavage development is related to overthrusting. About 150 metres below the Alpu-

jarride basal thrust, mica schists of the Mulhacen Complex contain a decimetre-spaced ECC-system; in mica schists directly below the contact these cleavages form the prominent tectonic foliation with a spacing of 0.5–1 cm. Dynamic recrystallization is concentrated within individual shear bands. Albite porphyroblasts may contain folded inclusion trails with D_{x+2} characteristics (Fig. 3a), in agreement with observations by Bakker et al. (1989) elsewhere. Such crystals are wrapped by the main foliation in the rocks (Fig. 3a). Albite crystals in the mar-

gins of shear bands display lattice bending (Fig. 3b) and may be pulled apart. ECCs disrupt D_{x+2} folds and occur superimposed on a locally penetrative S_{x+2} . This demonstrates that the development of overthrust-related ECCs occurred after D_{x+2} . Thus microstructural observations also show that the nappe contact between the Mulhacen and Alpujarride Complexes was not formed during D_{x+1} as argued by Bakker et al. (1989) and Bakker (1991) but after D_{x+2} . Furthermore, these relations imply that D_{x+2} is not a fourth but a third deformation phase, viz. D_3^{mulh} (Table 1).

Locally, where rocks of the Alpujarride Complex overlie the Tahal Schists of the Nevado-Lubrin Unit in the northern part of the range (coordinates 41₂₆-5₈₂, encl. I De Jong & Bakker 1991), a steeply dipping foliation plane in the footwall, equivalent to S_{x+3} in the scheme of Bakker et al. (1989), is cut off at the nappe contact, implying formation of the contact after D_{x+3} . Unfortunately, the relationship between ECCs and S_{x+3} could not be established here as no overprinting of both structure types has been observed.

Southern and central Sierra de los Filabres

In the southern and central Sierra de los Filabres the bedding-parallel main foliation S_2 , equivalent to S_x (Table 1), is folded by meso- and macroscopic WS-vergent D_3^{mulh} folds, which exhibit similar (micro)structural characteristics and relationships to mineral growth as D_{x+2} structures of Bakker et al. (1989) in the eastern Sierra de los Filabres (Table 1). S_3 is locally overprinted by a crenulation cleavage S_4 , which has the same features as S_{x+3} of Bakker et al. (1989), namely a typical confinement in the most mica-rich layers of pre-existing foliations (De Jong 1993: fig. 6) and synkinematic growth of oligoclase (Fig. 5). D_2^{mulh} to D_4^{mulh} are equivalent to D_1 to D_3 of Vissers (1981). Both D_3^{mulh} and D_4^{mulh} folds are cut off by the Alpujarride basal thrust plane (Fig. 4, loc. b) in agreement with observations in the eastern part of the range. In the contact zone with the Alpujarride Complex along the southern margin of the Sierra de los Filabres (Fig. 4, loc c), D_4^{mulh} folds are truncated by mylonite zones that are related to

overthrusting of the Alpujarride Complex. The contact between the Alpujarride and Mulhacen Complexes was thus established after D_4^{mulh} during a separate deformation phase D_5^{mulh} (Table 1), during which ECCs and related mylonites were formed.

In the southern and central parts of the range the intensity of ECCs in the uppermost 500 metres of the Mulhacen Complex increases upwards towards the overlying Alpujarride Complex, culminating into D_5^{mulh} mylonites, which are present in the uppermost 100 metres (Vissers 1981, De Jong 1991). The main foliation curves around lozenge shaped albite crystals (Figs 3c and d), which are elongated parallel to the stretching lineation in mylonites. Tails of these crystals generally have an oligoclase composition (Fig. 3c; Vissers 1981, De Jong 1991). Albite crystals in mica schists in which the main foliation S_2 was folded before development of the ECC have type D_{x+2} inclusion trails (Fig. 3d), pointing to syn- D_3^{mulh} growth of albite (Fig. 5). Due to post- D_3^{mulh} shear the continuity between the internal and external foliation was lost (Fig. 3d). Stability of oligoclase in the tails of albite porphyroclasts suggests that initiation of ECCs took place under similar physical conditions as D_4^{mulh} . However, the D_5^{mulh} mylonite fabric curves around zoned porphyroclasts of albite and oligoclase (Fig. 3e), which are locally cut by albite extension veins, implying that mylonitization progressed under falling temperatures. This agrees with widespread retrograde reactions like chloritization of staurolite, garnet, chloritoid and kyanite in these tectonites (Fig. 5; De Jong 1991). Similar observations were made by Konert & Van den Eeckhout (1983) and Platt et al. (1983) in the contact zone exposed in the Sierra Alhamilla (Fig. 4) further southwards and in the southern margin of the easternmost Sierra Nevada (Martínez Martínez 1986, De Jong 1991).

The last phase of penetrative deformation in the Mulhacen Complex D_6^{mulh} (Table 1) is related to reactivation of the contact with the overlying Alpujarride Complex, locally resulting in thrusting of the higher parts of the Mulhacen Complex over the Alpujarride Complex (De Jong 1993). Mesoscopic structures related to this reactivation are brittle-ductile shear bands (Fig. 3f), which are partly asso-

ciated with angular folds. Folds are generally disrupted along the flat-lying limbs and axial plane. Similar brittle-ductile structures were also noted by Konert & Van den Eeckhout (1983) and Platt & Behrmann (1986) in the overthrust zone exposed in the Sierra Alhamilla and in the easternmost Sierra Nevada (Martínez Martínez 1986, De Jong 1991).

Absolute timing of the nappe contact

The establishment of the contact between the Mulhacén and Alpujarride Complexes occurred as the last major event in the deformational history of the Mulhacén Complex, viz. D_5^{mulh} and D_6^{mulh} . This explains the generally observed truncation of folds and the lithologic layering in the Mulhacén Complex by the basal thrust of the Alpujarride Complex, which characterizes the regional structure of the Sierra de los Filabres (Figs 1, 2). Two-dimensional modelling of the cooling branches of the P-T-t path of the Mulhacén and Alpujarride Complexes (Van Wees et al. 1992) implies that overthrusting occurred during the earliest Miocene. $^{40}\text{Ar}/^{39}\text{Ar}$ thermo-geochronology of the Mulhacén Complex (De Jong 1991, De Jong et al. 1992) and Alpujarride Complex (Zeck et al. 1992) and a N5 microfossil age for the oldest post-nappe deposits bordering the eastern Sierra de los Filabres (the Alamo Formation) and Early Burdigalian microfossil ages for equivalents of this formation elsewhere in the Betic Zone (Geel et al. 1992, Zeck et al. 1992) indicate that at least the ductile part of the thrusting, i.e. D_5^{mulh} , was completed before 19Ma. It is discussed elsewhere (Van Wees et al. 1992, De Jong 1991, 1992b, De Jong et al. 1992) that thrusting and concomitant cooling of the nappes complexes is due to inversion of the latest Oligocene to earliest Miocene extensional structure of the Betic Zone.

Conclusions

1) The tectonic evolution of the Mulhacén Complex is characterized by six phases of penetrative deformation, which become progressively con-

centrated into smaller zones, reflecting falling temperatures.

- 2) The nappe contact between the Mulhacén and Alpujarride Complexes was principally formed during D_5^{mulh} ; earlier formed structures in the footwall are cut off at the nappe contact or are progressively modified in mylonites associated with the overthrusting.
- 3) The Mulhacén-Alpujarride contact was reactivated during the last phase of penetrative deformation (D_6^{mulh}) during which thrusting of higher parts of the Mulhacén Complex over the Alpujarride Complex took place.
- 4) Ductile thrusting of the Alpujarride Complex over the Mulhacén Complex (D_5^{mulh}) was completed before 19Ma.

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