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The tectono-metamorphic evolution of the Veleta Complex and the development of the contact with the Mulhacen Complex (Betic Zone, SE Spain)

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Abstract

Four phases of penetrative deformation (D_1^{vel} to D_4^{vel}) have been distinguished in the uppermost 0.5 km of the Veleta Complex, the lowest in the stack of four nappe complexes of the Betic Zone. The contact of the Veleta Complex with the overlying Mulhacen Complex is parallel to S_2, which is the main tectonic foliation in both complexes. The rotation sense of synkinematically grown D_2^{vel} garnets and the asymmetry of preferred orientations of quartz c-axes in mylonites in the highest part of the Veleta Complex demonstrate top-to-the-west shear, pointing to a westward movement of the Mulhacen Complex. The nappe contact was folded and locally overturned during D_3^{vel}, demonstrating that the tectonic contact was formed during D_2^{vel}. During D_4^{vel} the nappe contact was reactivated as shown by concentration of extensional structures in the uppermost 20 m of the Veleta Complex. It is argued that reactivation occurred during overthrusting of the Alpujarride Complex at higher structural level.

Although metamorphism of the graphite-rich pelites has not resulted in characteristic mineral assemblages, the relationship between mineral growth and deformation shows that, during the early tectonic evolution, both pressure and temperature in the Veleta Complex were *lower* than in the overlying Mulhacen Complex.

Introduction

The Internal Zone of the Betic Cordilleras (Betic Zone) consists of a stack of nappe complexes, which overrode the External Zone, equivalents of which crop out in windows as the (very) low-grade metamorphic Almagride Complex (Simon 1987, De Jong 1991). The structurally deepest rocks of the Betic Zone are exposed in the Sierra Nevada and in the western Sierra de los Filabres. They are often garnet-bearing, graphite-rich mica schists and quartzites, reaching a thickness of 7–8 kilometres, which were incorporated by Egeler & Simon (1969) into one major nappe complex, the Nevado-Filabride Complex, which underlies the Alpujarride Complex. These authors considered the graphite-rich metasediments as the pre-Alpine basement of the lowermost Nevado-Filabride tectonic unit, the Nevado-Lubrin Unit. Diaz de Federico et al. (1979) demonstrated, however, that a fundamental two-fold subdivision can be made within the monotonous graphite-rich metasedimentary sequence of the lower part of the Nevado-Filabride Complex into a Veleta Complex and an overlying Mulhacen Complex. They based their conclusions on the basal spacing of the crystal lattice of colourless mica, which is pressure-dependent (Sassi & Scolari 1974). It appeared that the rocks of the Veleta Complex experienced lower metamorphic pressures than the Mulhacen Complex. The contact between both nappe complexes is a shear zone (Gonzalez-Lodeiro et al. 1984, Martínez Martínez 1986, Orozco 1986, García Dueñas et al. 1987, De Jong 1991). However, major controversies exist on the sense of shear in the mylonite zone in the top of the Veleta Complex, which is interpreted as either top-to-the-east (Gonzalez-Lodeiro et al. 1984, Orozco 1986) or top-to-the-west (García Dueñas et al. 1987, De Jong 1991). Deformation in the Veleta Complex was polyphase and three (Gonzalez-Lodeiro et al. 1984) or four (Martínez Martínez 1986, Gomez-Pugnaire & Franz 1988, De Jong 1991) phases of penetrative deformation have been recognized. Gomez-Pugnaire & Franz (1988) argued that the earliest and most important deformation structures were formed during a pre-Alpine tectonic phase. Their conclusion was based on the composition of garnet in the Veleta Complex, which is similar to garnet included in presumed pre-Alpine chloritoid in the Mulhacen Complex.

Until now little attention has been paid to the timing of the establishment of the contact with the overlying Mulhacen Complex, relative to the superimposed phases of deformation in the Veleta Complex. Overturning of mylonites by younger folding phases, or overprinting of crystallographic fabrics due to renewed shear have important bearing on the interpretation of the kinematics of this contact. Furthermore, establishment of the relationship between superimposed deformation phases and mineral growth sheds light on the importance of Alpine versus pre-Alpine mineral growth in the Veleta Complex. In order to solve these problems, selected areas in the easternmost Sierra Nevada and in the western Sierra de los Filabres (Fig. 1) were studied in detail (De Jong 1991), the results of which are reported in this article.

The contact between the Veleta and Mulhacen Complexes

The Veleta Complex and the lowermost kilometres of the Mulhacen Complex are predominantly made up of graphite-rich, often garnet-bearing mica schists with intercalations of quartzites. In the eastern Betic Zone (Lomo de Bas) intercalated carbonates of the Veleta Complex yielded Eifelian (middle Devonian) fossils (Lafuste & Pavillon 1976). Puga & Diaz de Federico (1978) argued that a lighter colour of the rocks in the uppermost 200 m of the Veleta Complex and their albite content, may point to the presence, at least locally, of (Permo-)Triassic rocks at that structural level. This would imply that the nappe contact may be characterized by the superposition of older on younger rocks, as the metasediments of the basel part of the Mulhacen Complex were argued to be of pre-Permian age (Egeler & Simon 1969, De Jong & Bakker 1991).

Garnets in the Veleta Complex are generally small (<1 mm) compared to garnets of the Mulhacen Complex, which are at least a few millimetres in diameter; however, the size of garnets in the top of the Veleta Complex tends to increase upwards. In contrast to the work of Diaz de Federico et al. (1979) in the central Sierra Nevada, the basal spacing of colourless mica in both the Mulhacen and Veleta Complexes failed as pressure indicator for early Alpine metamorphic conditions in the eastern Sierra Nevada, where part of the present study was performed. This is clearly shown by the data of Martínez Martínez (1986), which indicate similarly low pressures for both nappe complexes.

This review shows that distinction between both nappes purely on lithological and petrological criteria is not conclusive. Therefore, the contact between the Veleta and Mulhacen Complexes was defined in the present study on structural criteria: the uppermost 200–300 m of the Veleta Complex are characterized by a conspicuously upwards increasing strain, culminating in a zone of white-coloured quartz mylonites. They are overlain by a homogeneous series of garnet-bearing quartzitic mica schists of the Mulhacen Complex. This structural and lithological contact has been mapped out (Fig. 1).

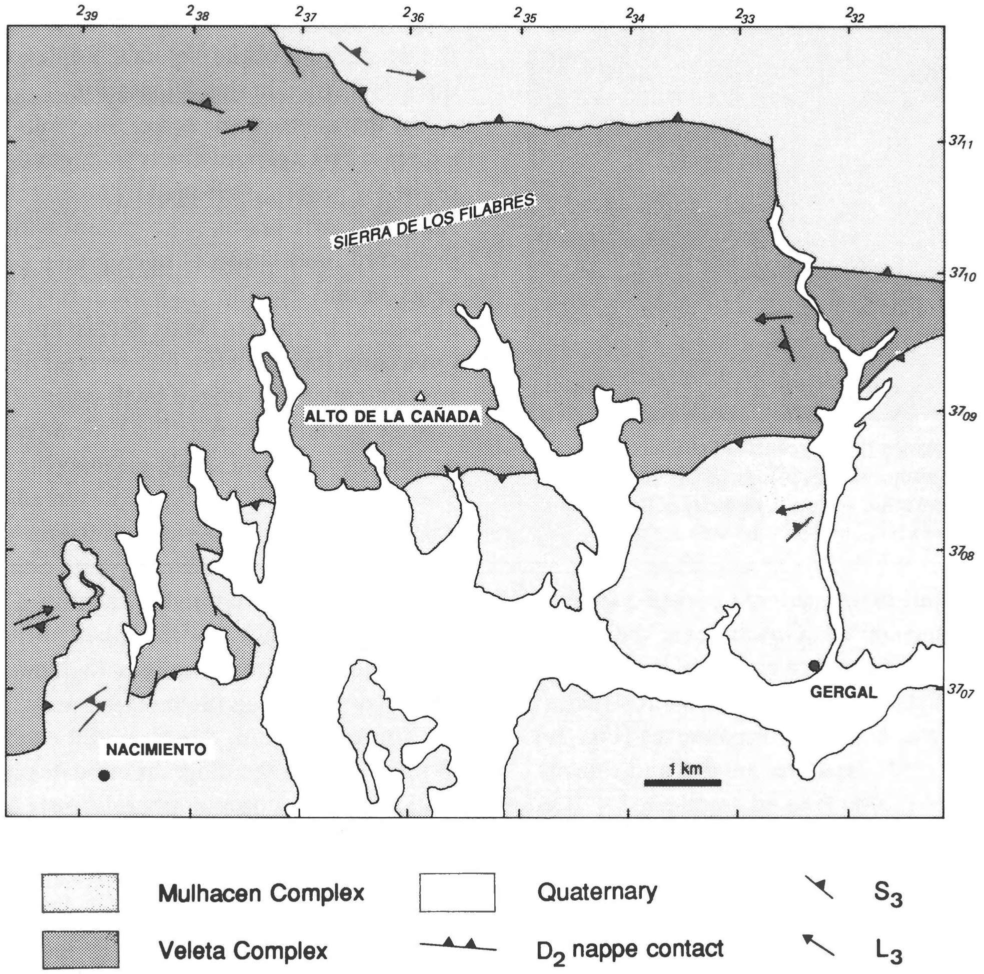

Fig. 1. Tectonic map of area between the eastern Sierra Nevada and the Sierra de los Filabres, displaying the contact between the Veleta Complex and the overlying Mulhacen Complex. Orientations of D_3 structures (S: foliation, L: lineation) in both nappes are indicated.

Polyphase deformation

On the basis of overprinting criteria, four phases of superimposed penetrative deformation have been identified in the uppermost 0.5 km of the Veleta Complex. This enables to date the establishment of the nappe contact with the overlying Mulhacen Complex relative to the sequence of deformation phases.

First generation structures (D_1^{vel})

The earliest deformation structures comprise a microscopically folded S_1 foliation, consisting of mica, chloritoid and epidote, within S_2 micro-lithons and sigmoidal inclusion patterns of graphite and occasionally quartz in pre- to syn-D_2^{vel} garnets (Fig. 2). The preferred orientation of metamorphic minerals indicates a tectonic nature of S_1.

Second generation structures (D_2^{vel})

D_2^{vel} folds are tight to isoclinal, inclined to recumbent structures with an axial plane S_2, which refracts on tightly folded thick quartzite beds and forms a bedding-parallel foliation in isoclinally folded thin-bedded quartzite-mica schist sequences. S_2 in mica schists is characterized by an almost perfect quartz-

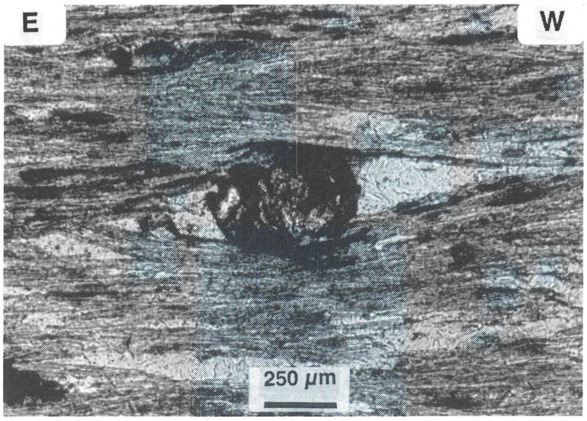

Fig. 2. Photomicrograph (plane polarized light, section parallel to L_2) of a D_2^{vel} synkinematically grown garnet wrapped by S_2. The dextral rotation sense and the asymmetry of the quartz-filled pressure shadows point to top to-the-west shear.

mica differentiation, indicating operation of solution transfer mechanisms. Quartzites in the highest part of the Veleta Complex are platy and strongly lineated mylonites with an annealed microstructure of grains of a few hundred micrometres (Fig. 3c). Elongated minerals (epidote, apatite and tourmaline) are preferentially oriented parallel to D_2^{vel} fold axes and stretching lineations, which have an approximate E–W trend (Fig. 4).

The tectonites at the Veleta-Mulhacen contact are the most intensely deformed rocks in an upwards increasing D_2^{vel} strain gradient in the top of the Veleta Complex, which is best expressed in the Sierra de los Filabres, about 5 km west of Gergal (Fig. 1; Alto de la Cañada), where the contact is not influenced by subsequent deformation phases D_3^{vel} and D_4^{vel}. A few hundred metres below the contact, the bedding-parallel S_2 in mica schists refracts through quartzite beds. The refraction angle decreases irregularly upwards in comparable lithologies. In the uppermost part of the section, S_2 forms the most penetrative planar fabric in quartzites as well; in the quartz mylonites in the top of the Veleta Complex S_2 has become bedding-parallel. The mylonitic fabric is parallel to S_2 in mica schists of the overlying Mulhacen Complex. Along the upwards increasing strain gradient, no reorientation of D_2^{vel} fold axes into parallelism with the mylonite lineation occurred; all lineations have a similar trend (Fig. 4). Tight, generally south-vergent D_2^{vel} folds in the deeper part of the Veleta Complex were consequently formed in this orientation.

On the microscopic scale, the strain gradient is expressed by a progressively stronger development of the D_2^{vel} fabric, indicated by an increasing aspect ratio of quartz grains concomitant with a stronger preferred orientation of mica grains parallel to S_2 (Figs 3a and b). The gradient is furthermore well expressed by quartz c-axis preferred orientations. Quartzites located a few hundred metres below the contact are characterized by ill-defined, symmetric crossed girdles, whereas the mylonites show well-defined asymmetric single girdles (Figs 5a and b). The asymmetry of the c-axis preferred orientation pattern (Fig. 5b) and the secondary grain shape fabric (Fig. 3c) in the same sample both point to top-to-the-west shear in the mylonite zone. The well-developed central girdle with kinked peripheral parts of the fabric diagram implies a high degree of non-coaxial deformation (Schmid & Casey 1986) during D_2^{vel} mylonitization. Absence of a clear maximum at the Y-axis of the diagram indicates limited prismatic slip and consequently relatively low temperatures (Lister & Hobbs 1980), consistent with temperatures of 425–500° C during D_2^{vel}, as discussed below. The top-to-the-west shear shear sense in the mylonites is consistent with the rotation sense of paracrystalline D_2^{vel} garnet porphyroblasts and the asymmetry of their quartz pressure shadows (Fig. 2). Consequently, the consistent rotational component of D_2^{vel} in the top of the Veleta Complex and the mylonite zone below the Mulhacen Complex are explained as the result of the westward movement of the latter with respect to the Veleta Complex during D_2^{vel}.

The structural characteristics of D_2^{vel} imply that the contact with the overlying Mulhacen Complex was formed during this phase, which is consistent with folding of the contact during D_3^{vel}.

Third generation structures (D_3^{vel})

D_3^{vel} has resulted in open to tight, inclined folds on the scale of a few decimetres to about 100 m, which

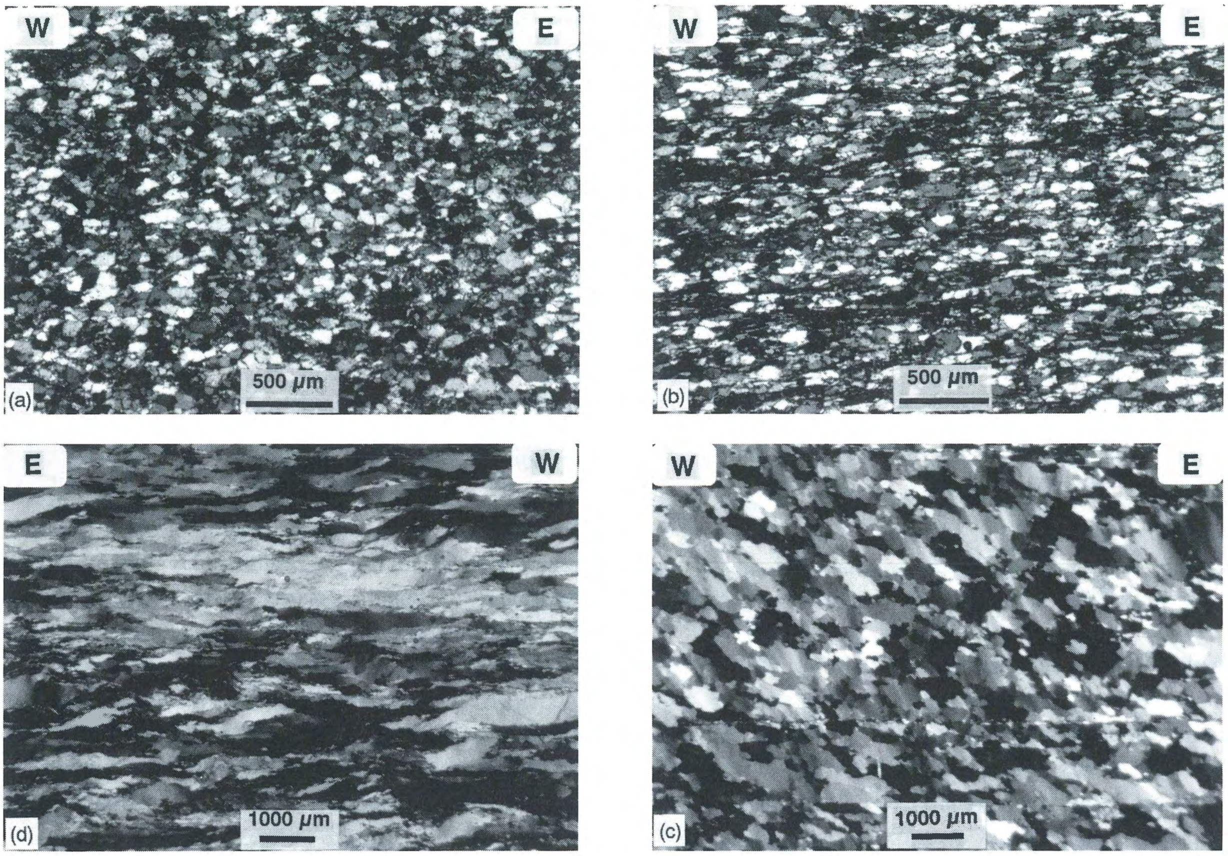

Fig. 3. Photomicrographs (crossed nicols, sections parallel to stretching lineations) of the structural development of the uppermost part of the Veleta Complex. a and b) D_2^{vel} strain gradient expressed by increasing aspect ratio of quartz grains and a stronger preferred orientation of mica crystals; a) low strain part and b) intermediate strain part (sample 87 JK 41), respectively 350 and 100 m below the Mulhacen Complex (Alto de la Cañada). c and d) Microstructure of quartz mylonites at the contact with the Mulhacen Complex. c) D_2^{vel} quartz blastomylonite (sample 87 JK 22, Alto de la Cañada) with an equidimensional asymmetrical grain shape fabric demonstrating (sinistral) top-to-the-west shear. d) D_4^{vel} quartz ribbon mylonite from a reactivated part of the nappe contact near Nacimiento.

cause repetitions and local overturning of the Mulhacen-Veleta contact (Fig. 6). L_2 stretching lineations in contact mylonites are locally folded over D_3^{vel} fold hinges. Fold axes trend WNW-ESE to ENE-WSW (Fig. 1), but deviations are common (Fig. 6). The axial plane cleavage, S_3, dips generally to the north, but dips moderately to the southeast in the investigated part of the Sierra Nevada (Figs. 1 and 6), as a result of later deformation. The generally south vergent folds have thickened hinges and thinned limbs. Quartz-mica differentiation of the S_3 crenulation cleavage indicates a predominant role of solution transfer mechanisms during D_3^{vel} in quartz-rich mica schists. On the other hand, S_3^{vel} axial planar shape fabrics of oriented, flattened quartz grains of 100–150 µm with mantles of dynamically recrystallized grains of 40–50 µm imply dominant crystal-plastic deformation in quartzites.

Fourth generation structures (D_4^{vel})

D_4^{vel} structures comprise cm-dm spaced extensional crenulation cleavages (ECCs) in mica schists and asymmetric pull-aparts of layering in more quartz-rich rocks. Movement on the ECCs took place at a high angle to the intersection of shear bands and S_2 or of conjugate sets (Fig. 7a). ECCs are developed

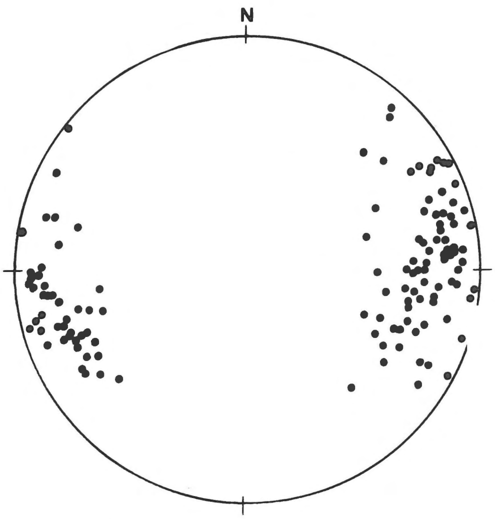

Fig. 4. D_2^{vel} fold axes and stretching lineations in the uppermost 0.5 km of the Veleta Complex (Lower hemispere projection).

in alternating zones with an opposite sense of shear, either top-to-the-east or top-to-the-west. The extensional structures are superimposed on S_3, disrupt D_3^{vel} folds and strongly modify D_3^{vel} microstructures. They occur exclusively in the uppermost 10–20 m of the Veleta Complex, which is characterized by a conspicuous increase of D_4^{vel} strain towards the contact with the Mulhacen Complex. In zones with penetrative D_4^{vel} deformation, mylonitic quartzites and quartz lenses are made up of type I monocrystalline ribbons of Boullier & Bouchez (1978), with lengths in the order of 1000 μm (Fig. 3d). Development of the extensional structures after D_3^{vel} folding of the contact with the Mulhacen Complex implies that D_4^{vel} is related to reactivation of this nappe contact. The non-unique sense of shear shown by both D_4^{vel} quartz mylonites and ECCs (De Jong 1991) indicates that movements during reactivation were not uni-directional.

Timing of the nappe contact and relationship with deformation phases in the Mulhacen Complex

The observed local overturning of the Veleta-Mulhacen contact during D_3^{vel} and the D_4^{vel} reactivation leading to extension parallel to L_2^{vel} are probably the cause of the already mentioned controversy on the movement direction on the nappe contact. As the top-to-the-west shear in the mylonite zone and rotation of garnets in the Veleta Complex are observed in a section through the contact devoid of D_3^{vel} and D_4^{vel} structures, D_2^{vel} shear in the top of the Veleta Complex implies a westward movement of the overlying Mulhacen Complex during this phase.

Although there is no gradient of downward increasing D_2^{mulh} strain (De Jong 1991), it is argued

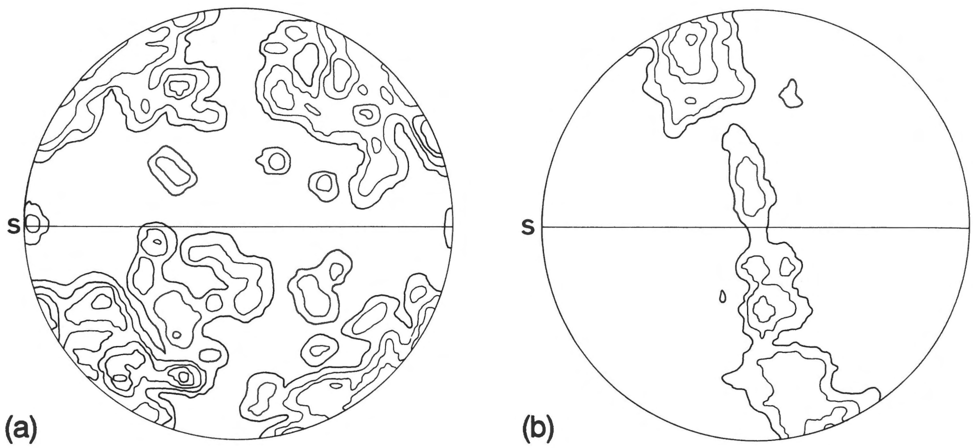

Fig. 5. D_2^{vel} lattice-preferred orientation diagrams of quartz c-axes (Alto de la Cañada). a) Sample 87 JK 41 (see Fig. 3b) shows an ill-defined symmetrical crossed girdle; b) sample 87 JK 22 (see Fig. 3c) shows a well-developed asymmetrical single girdle, indicating top-to-the-west shear; a) and b) are respectively from 100 m and a few decimetres below the Mulhacen Complex. Number of measurements: 150; contours drawn at 0, 2, 4, 6 and 8%; S is the trace of foliation S_2; sections parallel to L_2.

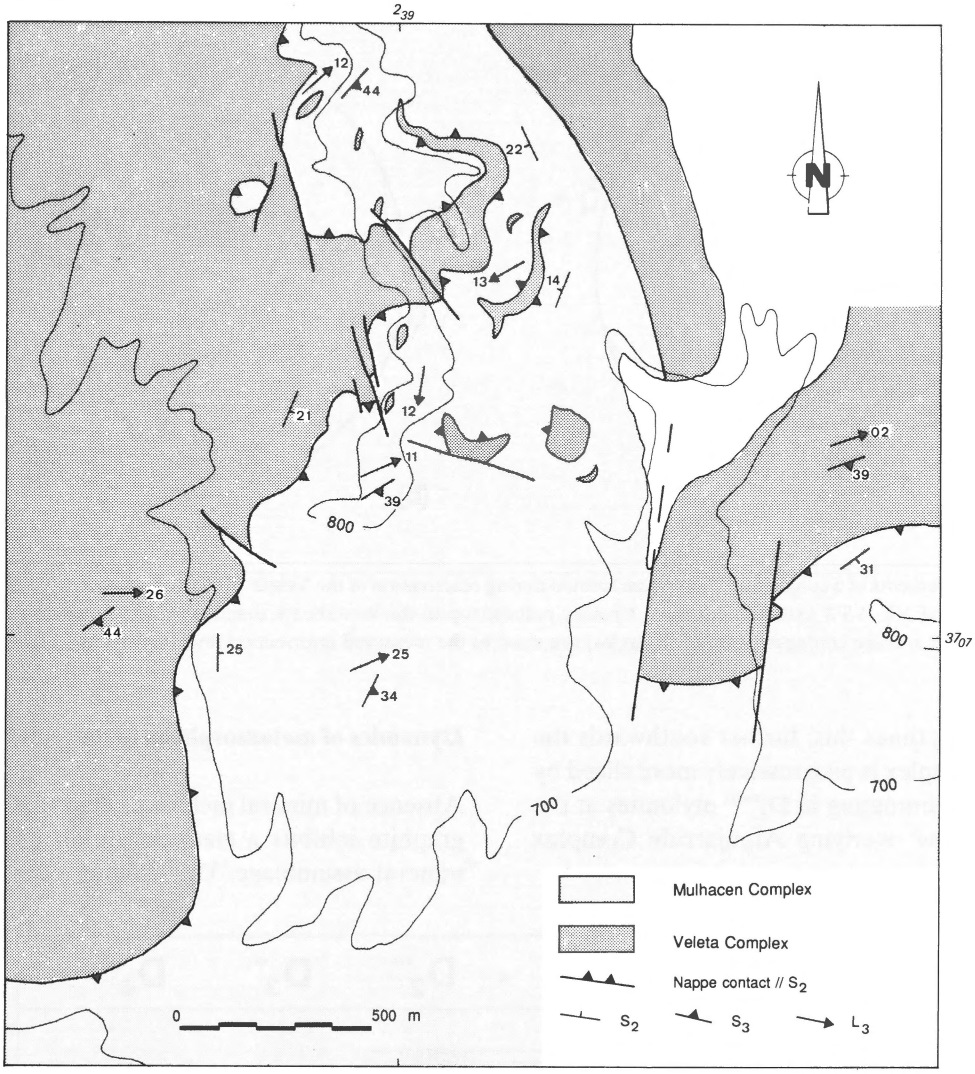

Fig. 6. Geological map of the Mulhacen-Veleta contact in the eastern Sierra Nevada, north of Nacimiento, detail of Fig. 1. The nappe contact, which is parallel to S_2 in both nappes, is folded and locally overturned by D_3^{vel} folds, which can be traced into D_3^{mulh} folds. White: Quaternary, topographic contours in metres; S: foliation, L: lineation.

that the second deformation phase in both nappe complexes was approximately coeval. This is based on the similar rotation sense of paracrystalline D_2^{mulh} and D_2^{vel} garnets (De Jong 1991) and by the parallelism of S_2 in both complexes. The observation that mesoscopic D_3^{vel} folds, which deform the nappe contact with the Mulhacen Complex (Fig. 6), can be traced into D_3^{mulh} folds supports this interpretation.

Prominent ECCs in the lowermost 100 m of the Mulhacen Complex point, like D_4^{vel} ECCs in the top of the underlying Veleta Complex, to ENE-WSW extension during reactivation of the nappe contact (Fig. 7b). Confinement of oxy-chlorite and biotite growth to the shear bands shows that they are D_5^{mulh} structures, which are characteristic for the Mulhacen Complex below the Alpujarride Complex (De Jong 1991). This implies that reactivation of the Veleta-Mulhacen contact was coeval with overthrusting of the Alpujarride Complex at a higher level in the stack of nappes. Stronger D_4^{vel} reactivation in the southern part of the study area, near Nacimien-

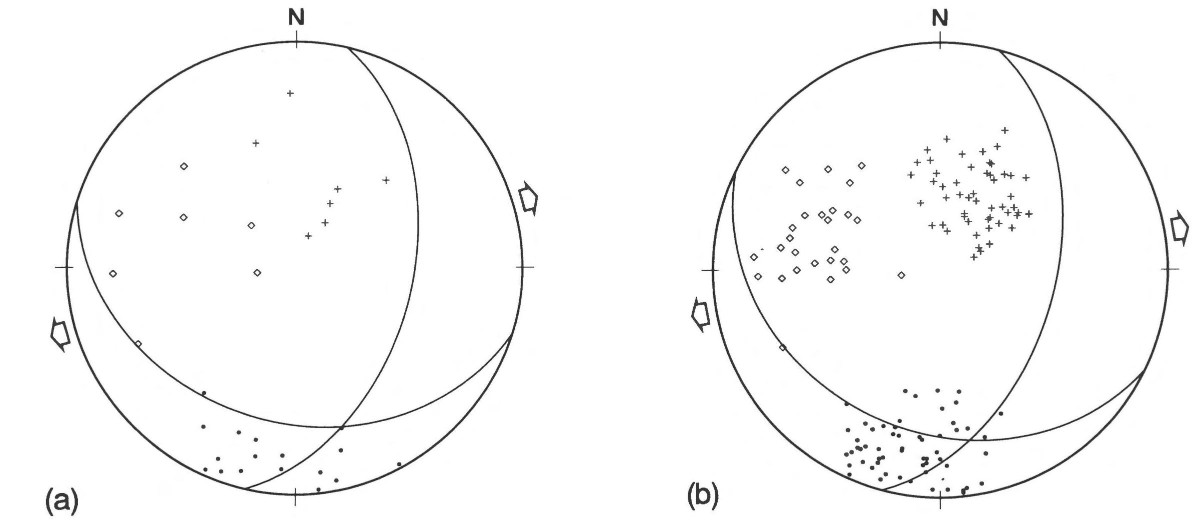

Fig. 7. Structural elements of a conjugate ECC system formed during reactivation of the Veleta-Mulhacen contact. a) D_4^{vel} and b) D_5^{mulh} ECCs both point to ENE-WSW extension (arrows). Crosses: poles to top-to-the-west shears, diamonds: poles to top-to-the-east shears. Intersections of the average conjugate sets (great circles) are close to the measured intersection lineations (dots). Lower hemisphere projection.

to (Fig. 1) underlines this; further southwards the Mulhacen Complex is progressively more sliced by D_5^{mulh} ECCs culminating in D_5^{mulh} mylonites at the contact with the overlying Alpujarride Complex (De Jong 1991).

Dynamics of metamorphism in the Veleta Complex

Absence of mineral inclusions in garnet other than graphite inhibits a clear definition of a pre-D_2^{vel} mineral assemblage. D_2^{vel} folding of a chloritoid-

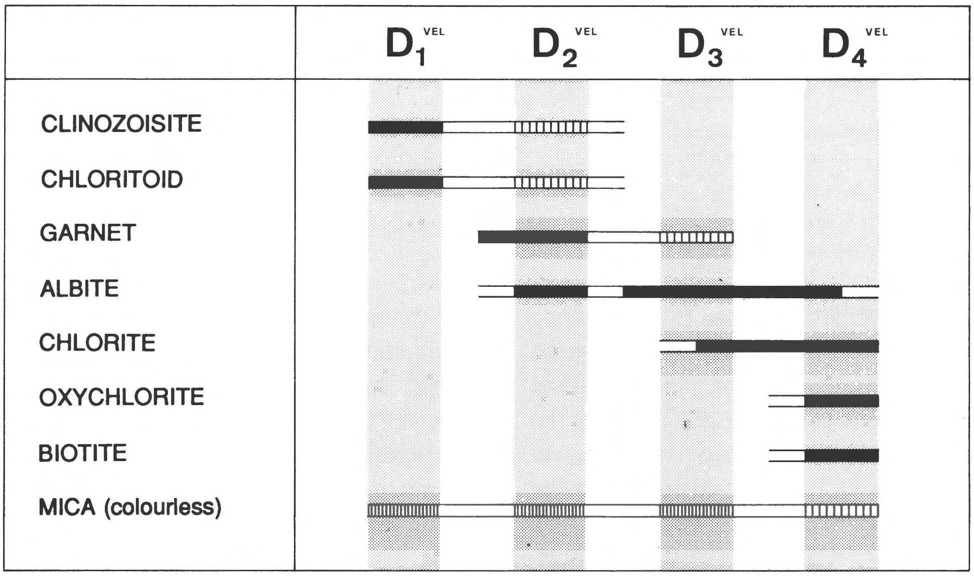

Fig. 8. Relationship between mineral growth and deformation phases in mica schists in the top of the Veleta Complex. Mineral growth: black bar, syntectonic recrystallization: fine hatching, deformation: broad hatching.

epidote-mica fabric, however, implies pre-D_2^{vel} and probably syn-D_1^{vel} growth of these minerals (Fig. 8).

Paracrystalline rotation of garnet (Fig. 2) and occurrence of chloritoid parallel to S_2 imply their stability during D_2^{vel} (Fig. 8). Temperatures during D_2^{vel} can be estimated roughly between 425 and 500°C (Fig. 9) based on this assemblage (Puga & Diaz de Federico 1978, Martínez Martínez 1986, De Jong 1991) and the relatively Ca- and Mn-rich composition of garnet (Gomez-Pugnaire & Franz 1988). The Fe-rich composition of chloritoid implies relatively low pressures (Martínez Martínez 1986, Gomez-Pugnaire & Franz 1988). The locally observed stability of clinozoisite, albite and S_2 colourless mica, which is a solid solution of phengite and paragonite (Martínez Martínez 1986), and absence of zoisite may point to pressures below 0.6 to 0.7 GPa during D_2^{vel} (Fig. 9, curve 2). Puga & Diaz de Federico (1978) made a similar estimate on the basis of early Alpine growth of actinolite in stead of glaucophane in metadolerites in the Sierra Nevada.

Syn- to post-D_3^{vel} growth of albite and of chlorite in a late stage of D_3^{vel} (Fig. 8) was probably controlled by dephengitization and unmixing of the paragonite component from D_2^{vel} colourless mica. Albite and chlorite are deformed in D_4^{vel} shear bands. Conspicuous oxy-chlorite and local biotite growth is confined to shear bands and the deflected adjoining S_2 or S_3 foliation. These minerals do not occur inside albite crystals, indicating their D_4^{vel} origin (Fig. 8). The late-stage mineral assemblages are unfortunately not P–T indicative. However, cogeneity of D_3^{vel} and D_4^{vel} with D_3^{mulh} and D_5^{mulh}, respectively, shows that the physical conditions in the Veleta Complex during the late stage of the Alpine evolution were essentially the same as in the Mulhacen Complex, which experienced pressures around 0.45–0.3 GPa and temperatures in the order of 400–500°C (Bakker et al. 1989) during these phases. Local late-stage growth of staurolite in the Sierra Nevada (Puga & Diaz de Federico 1978) might be related to a similar reheating as experienced by the Mulhacen Complex (Bakker et al. 1989, De Jong 1990, 1991, Fig. 9).

The failure of the basal spacing of colourless mica as pressure indicator for early Alpine metamorphic conditions in the investigated area shown by the data of Martínez Martínez (1986) is most probably due to pervasive structural and chemical recrystallization of phengite, shown by widespread (oxy)chloritization during the D_3^{vel} folding and D_4^{vel} reactivation of the nappe contact at low pressures. Progressive downward increase in decomposition of garnets (Vissers 1981) and important (oxy)chlorite growth (De Jong 1991) in the basal part of the Mulhacen Complex in the Sierra de los Filabres point to similar retrograde conditions in the overlying nappe during reactivation of the contact.

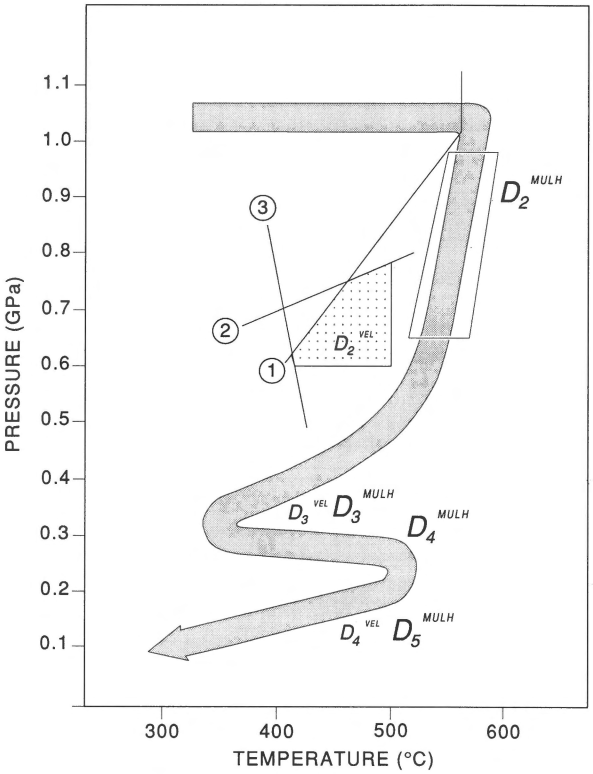

Fig. 9. P-T conditions during D_2^{vel} in the Veleta Complex (light shaded area) compared to the P–T path of the Mulhacen Complex. Folding of the nappe contact during D_3 in both complexes implies comparable P–T conditions during and after this phase. 1) glaucophane stability (Maresch 1977), 2) anorthite + albite + H_2O = paragonite + zoisite + quartz (Franz & Althaus 1977), 3) chloritoid-in (Frey 1972).

The P–T conditions during D_2^{vel} were lower than the early Alpine metamorphic conditions in the overlying Mulhacen Complex, which experienced pressures of about 1.1 GPa (Bakker et al. 1989, De Jong 1990, 1991, Fig. 9). Syn-D_2^{mulh} metamorphism is characterized by important pressure decrease from

1.1 to 0.7 GPa, concomitant with cooling to below 550° C (De Jong 1991). Part of the cooling in the Mulhacen Complex during its exhumation is likely to be due to its movement over the relatively cool Veleta Complex (De Jong 1990, 1991). Because D_2^{vel} is intimately associated with this movement, the early metamorphic conditions in the Veleta Complex clearly relate to the Alpine tectonic evolution. On the basis of analogy with the tectono-metamorphic evolution of the Mulhacen and Alpujarride Complexes, De Jong (1991) argued that D_1^{vel} structures were formed at the end of the subduction stage and are thus also of Alpine age.

Conclusions

The tectono-metamorphic evolution of the Veleta Complex is intimately related to Alpine nappe emplacement. D_2^{vel} strain in the top of the Veleta Complex increases upwards and culminates in mylonites immediately below the Mulhacen Complex. Top-to-the-west shear in the top of the Veleta Complex is related to translation of the Mulhacen Complex. During the early Alpine tectonic evolution of the Veleta Complex, pressures and temperatures in this complex were lower than those of the Mulhacen Complex. Movement of the Mulhacen Complex over the relatively cool Veleta Complex explains cooling of the former during its decompression.

D_3^{vel} folding, local overturning and D_4^{vel} reactivation of the Veleta-Mulhacen contact, leading to extension parallel to the L_2 stretching lineation, strongly modified the D_2^{vel} structural characteristics of the nappe contact, especially in the southern part. Reactivation resulted in dephengitization and unmixing of the paragonite component from D_2^{vel} colourless mica at low pressure conditions. D_4^{vel} is related to overthrusting of the Alpujarride Complex at higher structural level.

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