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Large-scale polyphase deformation of a coherent HP/LT metamorphic unit: the Mulhacen Complex in the eastern Sierra de los Filabres (Betic Zone, SE Spain)

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Abstract

This paper elucidates the large-scale polyphase deformation history of the Mulhacen Complex, the partially overprinted HP/LT metamorphic nappe complex in the Betic Zone of southeastern Spain, by tying zones of concentrated small-scale and mesoscopic deformation to large-scale structures, which could be mapped out due to excellent exposure. Small-scale structures show that progressively younger deformation was increasingly less homogeneous and became progressively more concentrated in zones.

The original D_1^{mulh}-D_2^{mulh} distribution of lithologic units and main tectonic units was disrupted during subsequent polyphase deformation. During a third phase of penetrative deformation (D_3^{mulh}), S-SW vergent folding and associated S-SW ward thrusting occurred; the most intense folding and cleavage development took place in the vicinity of these thrusts. During D_3^{mulh}, a level in the top of the lowest nappe of the Mulhacen Complex acted as floor thrust of the imbrications. Mapping and structural analysis showed that during subsequent deformation this zone was reactivated and that deformation was concentrated below the detachment. The last phase of deformation (D_7^{mulh}) did not result in penetrative deformation but in approximately N-S trending subvertical faults and associated similarly oriented flexures and large-scale open folds. Tortonian sediments show that D_6^{mulh} occurred before, and D_7^{mulh}, at least partly, after their deposition.

Introduction

The small-scale and mesoscopic polyphase deformation history of the Mulhacen Complex in the Sierra de los Filabres in the Betic Zone of southeastern Spain is well established (Langenberg 1972, Kampschuur 1975, Martínez Martínez 1980, Vissers 1981, Bakker et al. 1989, Zevenhuizen 1989, De Jong 1990, 1991, 1993a-this issue). The timing of phases of superimposed deformation with respect to mineral growth gave insight into evolving P-T conditions during the tectonic evolution (Vissers 1981, Bakker et al. 1989, De Jong 1990, 1991). In addition, excellent exposure enabled tracing of mesoscopic structures in relation to mapping of lithologic units, which resolved the large-scale polyphase structural evolution. This type of analysis of the Mulhacen Complex in the eastern Sierra de los Filabres, in relation to the cartography published earlier (De Jong & Bakker 1991, encl. I) is the topic of the present paper. The polyphase deformation of the Mulhacen Complex will be discussed in the context of a redefined deformation scheme (De Jong 1991); the differences between this scheme and the scheme of

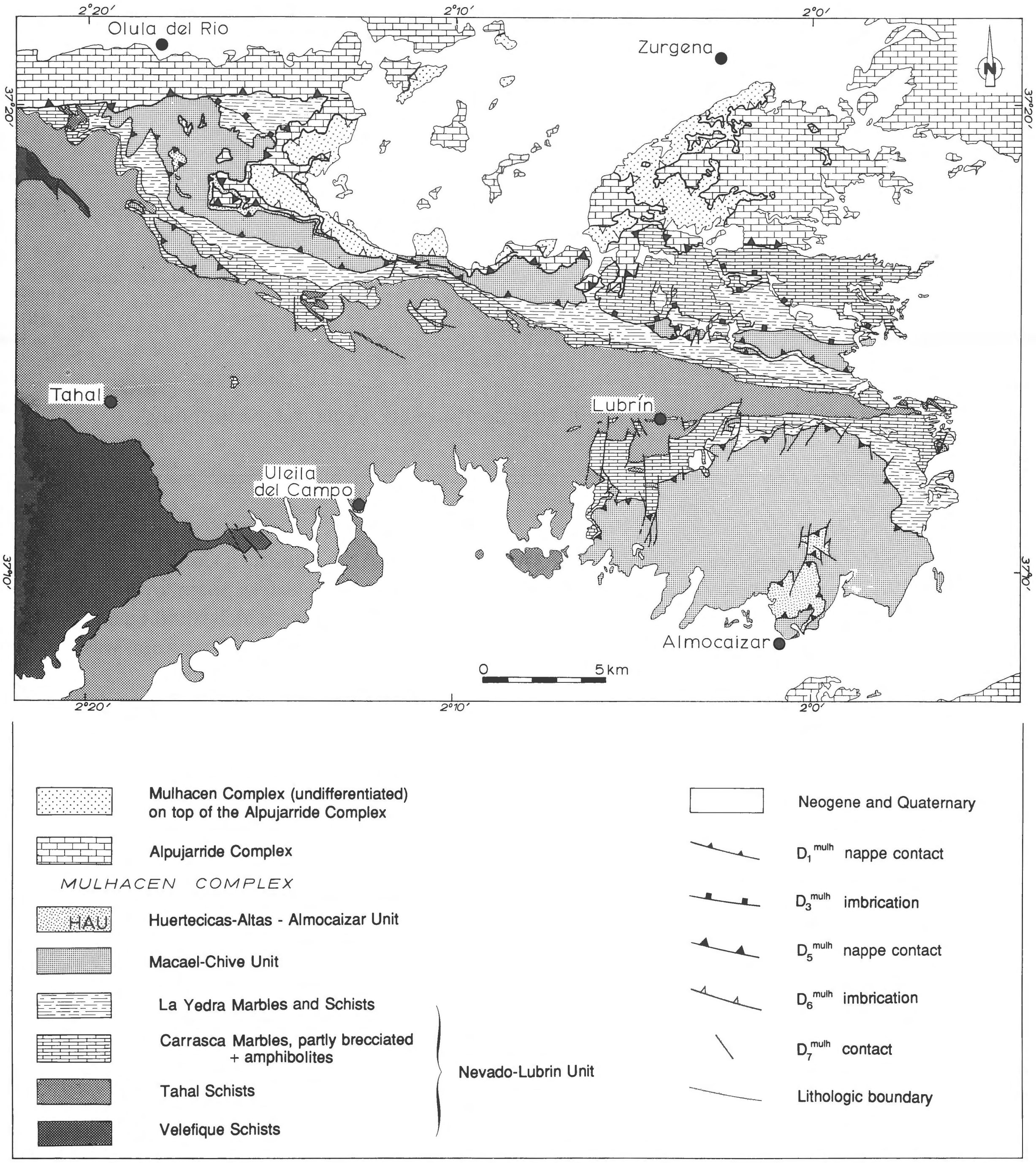

Fig. 1. Tectonic map of the eastern Sierra de los Filabres, compiled after Helmers & Voet (1967), Kampschuur (1975), Bakker et al. (1989) and De Jong & Bakker (1991).

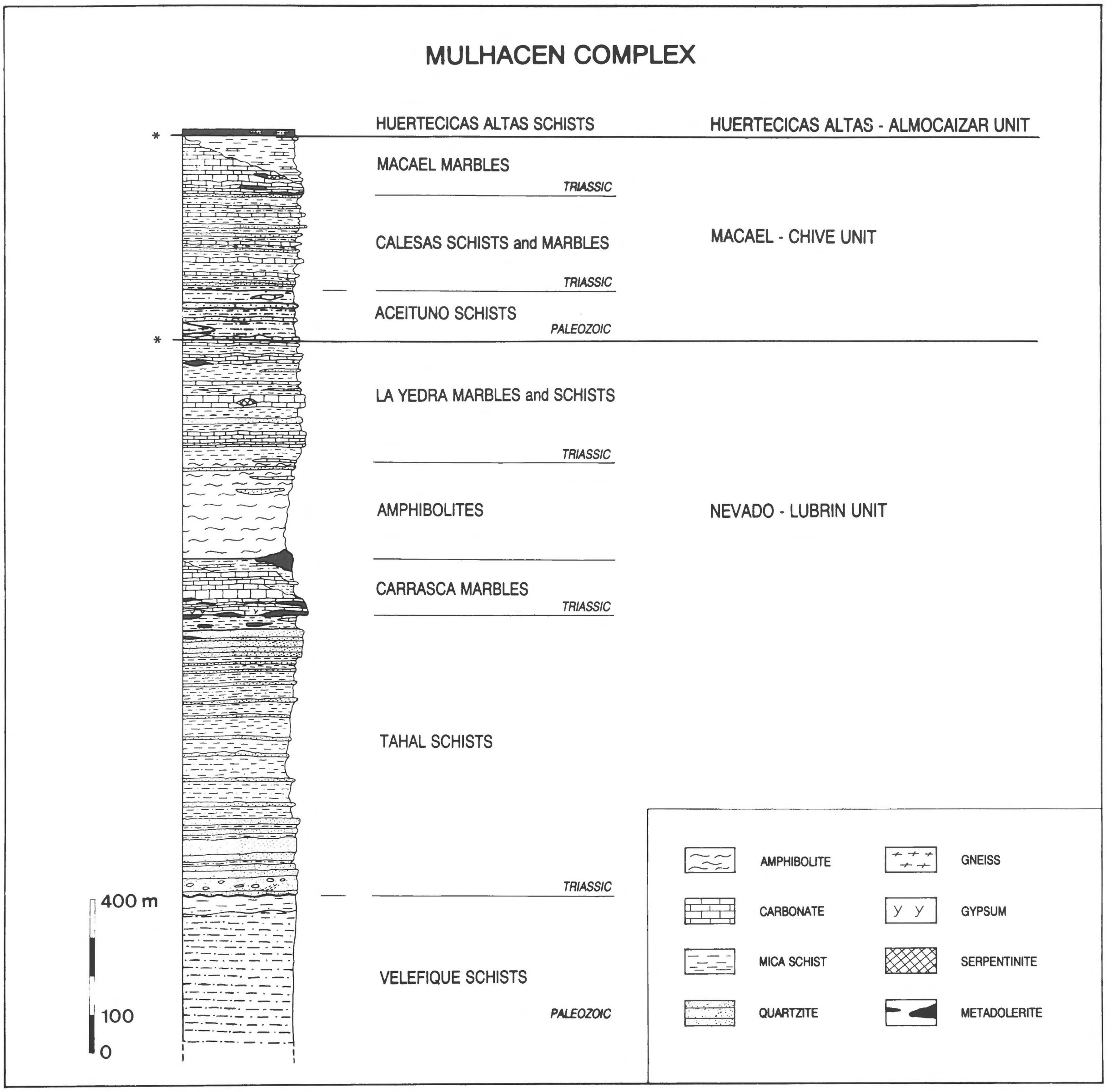

Fig. 2. Tectono-stratigraphic column of the upper part of the Mulhacen Complex in the eastern Sierra de los Filabres (modified after De Jong & Bakker 1991). Asterisks: location of D_1^{mulh}-D_2^{mulh} thrust planes.

Bakker et al. (1989) are outlined in an accompanying paper (De Jong 1993a).

Regional structure of the Mulhacen Complex

The Mulhacen Complex in the eastern Sierra de los Filabres consists of three tectonic units (Figs 1, 2; Bakker et al. 1989, De Jong & Bakker 1991, De Jong 1991), 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 top of Triassic series (Helmers & Voet 1967, Kampschuur 1975, De Jong & Bakker

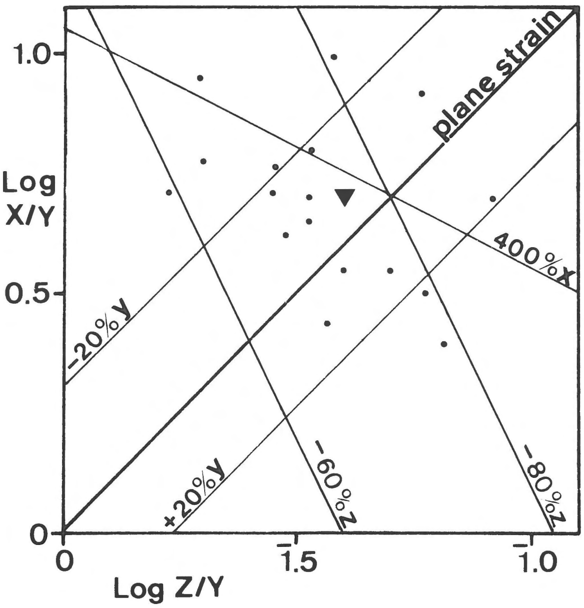

Fig. 3. Log-strain diagram for feldspar phenoclasts in amphibolites of the Nevado-Lubrin Unit near Lubrin. The average (triangle) indicates about 75% shortening perpendicular to the D_2^{mulh} transposition foliation and an extension of around 380%.

1991). The tectonic nature of the contact between the Macael-Chive Unit and the Nevado-Lubrin Unit is furthermore demonstrated by the regional truncation of its layered Triassic series, the La Yedra Marbles and Schists, by the basal thrust plane of the Macael-Chive Unit (De Jong & Bakker 1991, encl. I). Similarity in early Alpine metamorphic HP/LT evolution in all three tectonic units implies that their stacking occurred during the first tectonometamorphic phase, here called D_1^{mulh} (Bakker et al. 1989, De Jong 1990, 1991).

On outcrop scale the thrust planes of the three nappes in the Mulhacen Complex run parallel to S_2, the main phase transposition foliation. D_2^{mulh} was the most prominent deformation phase and resulted in penetrative structures at all scales. Strain analysis showed that rocks of the Mulhacen Complex experienced considerable strain (Borradaile 1976, De Jong 1990, 1991). Shortening values of 60–80% perpendicular to this foliation (Fig. 3) agree with the regional transposition of bedding and S_2, forming the main foliation in the Nevado-Lubrin Unit, which is continuous over at least 25 km along strike (De Jong & Bakker 1991, encl. I). The average extension parallel to the WNW-ESE strike of the transposition foliation amounts to about 380% (Fig. 3). These strain values account for the low-angle truncation of the layering in the Nevado-Lubrin Unit by the Macael-Chive Unit.

Tight to isoclinal D_2^{mulh} folds have resulted in repetitions of lithologies at the scale of 10–15 metres, which are too small to be revealed by mapping at the scale of enclosure I of De Jong & Bakker (1991); see also Zevenhuizen (1989). Mesoscopic D_2^{mulh} folds are systematically south-vergent. Major reversals of vergence, required for the presence of a foldnappe proposed by García-Dueñas et al. (1988) to explain the regional structure of the Mulhacen Complex in the eastern Sierra de los Filabres, are lacking. These authors proposed that the core of the envisaged foldnappe is formed by tourmaline gneisses of the Aceituno Schists (Macael-Chive Unit), and that the upper and lower limbs of the structure are represented by the Calesas Schists and Marbles and Macael Marbles (Macael–Chive Unit) and by the Carrasca Marbles and the La Yedra Marbles and Schists (Nevado-Lubrin Unit), respectively. Detailed lithological sections (Fig. 2; De Jong & Bakker 1991), however, show that lithologies on both limbs of the foldnappe envisaged by García-Dueñas et al. (1988) are not comparable, pointing to the absence of such a structure.

The regional D_2^{mulh} structure of the Mulhacen Complex was strongly modified during subsequent deformation phases. The continuity along strike of the Macael-Chive and Huertecicas Altas-Almocaizar units and the layering in the Triassic series of the Nevado-Lubrin Unit have been disrupted. Moreover, the stack of tectonic units was folded into an E-W trending antiform in the core of which the deepest lithologic unit, the Velefique Schists, forming the Paleozoic basal series of the Nevado-Lubrin Unit (Fig. 2), is exposed. Due to the eastward plunge of the hinge line, progressively higher lithologic and tectonic units are exposed going eastwards (Fig. 1). In contrast to D_2^{mulh}, the younger phases are not penetrative throughout the Mulhacen Complex but concentrated in zones (Figs 5, 6), enabling to relate the mesoscopic structural development to structures at the map scale. It will be shown that the regional distribution of tectonic and

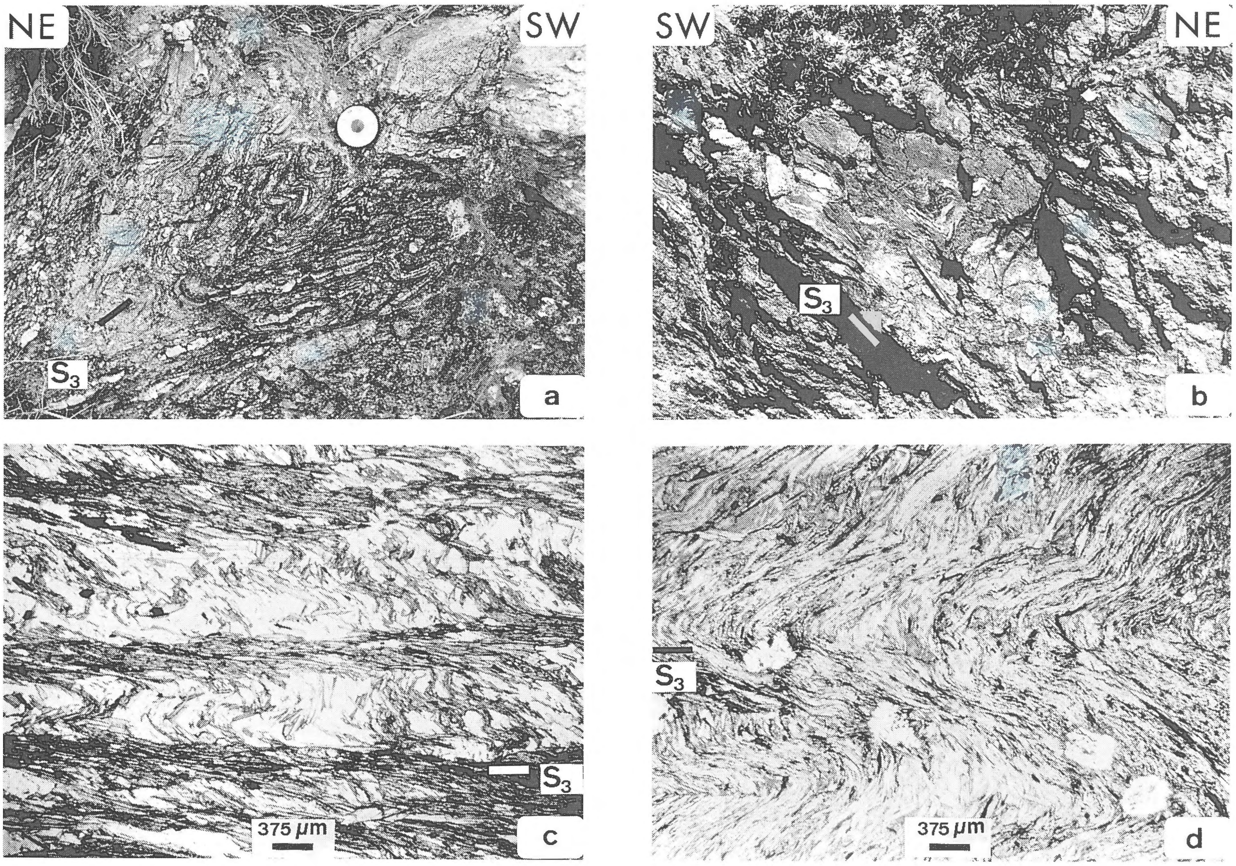

Fig. 4. Photographs (a and b) and photomicrographs (c and d plane polarized light, sections perpendicular to L_3^{mulh}) demonstrating the relation between the intensity of D_3^{mulh} folds and cleavages and D_3^{mulh} thrusting in the La Yedra Marbles and Schists (Nevado-Lubrin Unit). a) Tight S-vergent folds in quartz mica schists directly below a D_3^{mulh} imbrication. b) Open S-vergent folds with an ill-developed dm-spaced axial planar cleavage 400 m below a D_3^{mulh} imbrication. c) Tight crenulation of S_2^{mulh} resulting in a differentiated S_3^{mulh} cleavage with quartz-rich microlithons and mica-rich septa, 150 m below a D_3^{mulh} imbrication. d) Open to tight crenulation of S_2^{mulh} without quartz-mica differentiation, intermediate D_3^{mulh} strain, 300 m below a D_3^{mulh} imbrication.

lithologic units is the result of several phases of superimposed deformation.

Mesoscopic structures and large-scale polyphase deformation

D_3^{mulh} structure

The continuity of exposure of the Macael-Chive Unit in the northern margin of the Sierra de los Filabres is disrupted by thrusts which bring rocks of the Nevado-Lubrin Unit on the Macael-Chive Unit (Fig. 1; De Jong & Bakker 1991, encl. I and II). Mapping revealed the presence of imbrications of deeper parts of the Nevado-Lubrin Unit (Carrasca Marbles and associated amphibolites) on top of higher parts (La Yedra Marbles and Schists) in the north-eastern part of the range. These thrusts are incorporated into D_3^{mulh} because the intensity of D_3^{mulh} folds and cleavages increases towards the thrusts (Figs 4, 5). Close to the thrusts, folds are tight and subsimilar with a differentiated axial plane crenulation cleavage (Fig. 4a, c). Away from the thrusts, low-strain D_3^{mulh} folds are open with rounded or angular hinges with an ill-developed, widely spaced axial plane cleavage, which does not show important quartz-mica differentiation (Fig. 4b, d). The south-vergent fold asymmetry agrees with the southward imbrication by the thrusts.

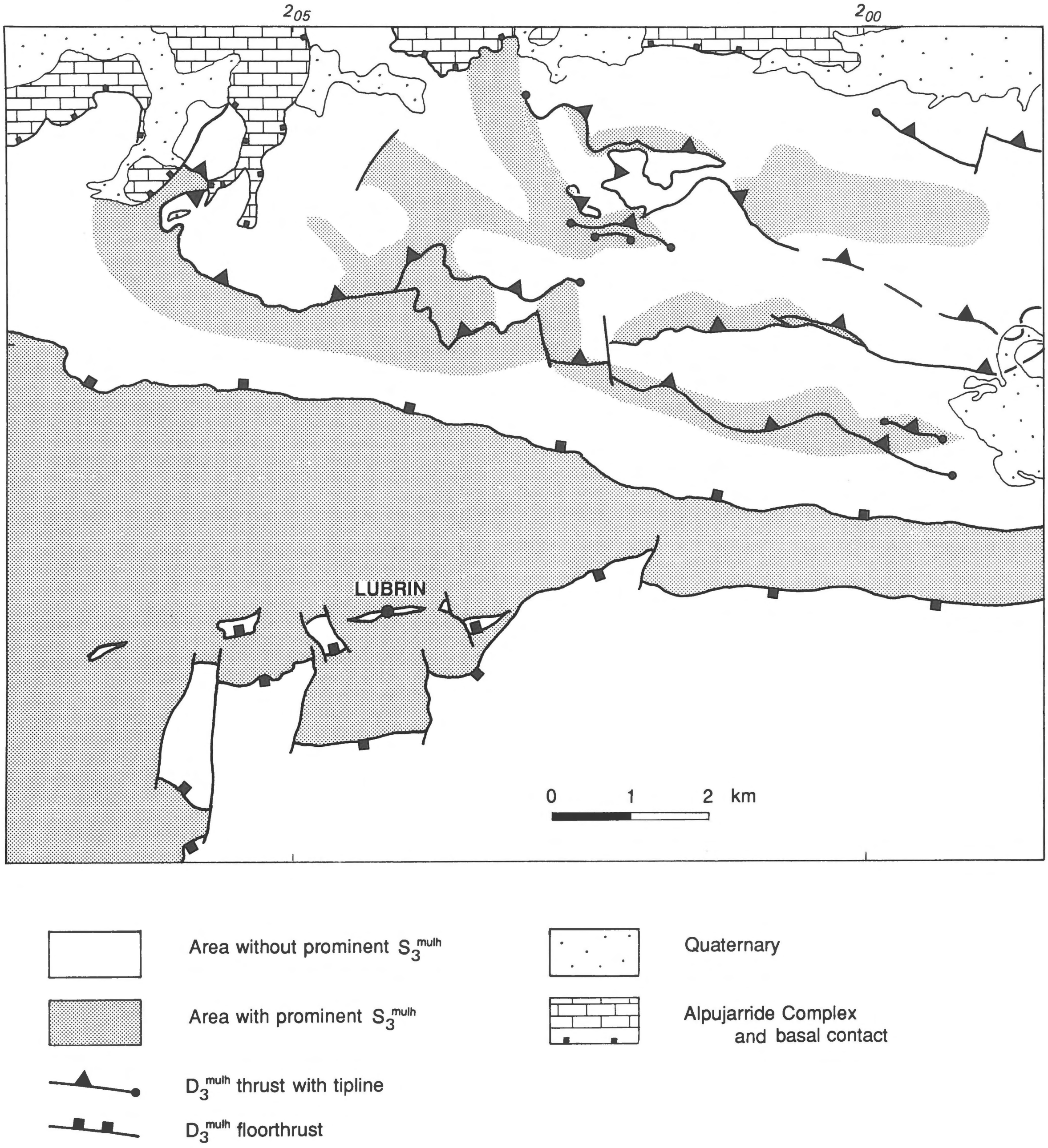

Fig. 5. Relationship between penetrative D_3^{mulh} folding and cleavage development and D_3^{mulh} thrusting in the eastern Sierra de los Filabres. The most penetrative D_3^{mulh} structures are developed in the vicinity of imbricate thrusts and below the floor thrust.

In the Nevado-Lubrin Unit, D_3^{mulh} imbrications involve rocks of the upper part of the unit only; rocks of the Tahal Schists are excluded (Fig. 1; De Jong & Bakker 1991; encl. I and II). This points to the presence of a floor thrust between the Tahal Schists and the Carrasca Marbles and associated amphibolites, in agreement with an observed break in the intensity of D_3^{mulh} structures at this level: D_3^{mulh} structures in the top of the Tahal Schists are the most penetrative ones at this level (Fig. 6),

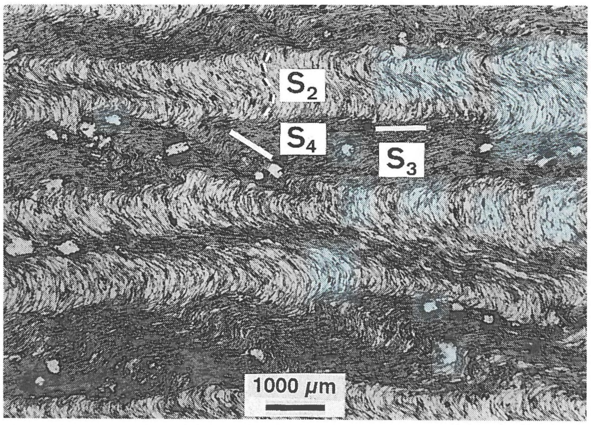

Fig. 6. Photomicrograph (plane polarized light, section perpendicular to L_4^{mulh}) of S_2^{mulh}, crenulated by D_3^{mulh} and D_4^{mulh}, demonstrating that later cleavages become progressively less penetrative; S_4^{mulh} is developed selectively in the mica-rich septa of S_3^{mulh} only. Upper part of the Tahal Schists.

whereas the intensity of D_3^{mulh} is much lower in rocks immediately above the Tahal Schists (Fig. 5). The difference in accomodation of D_3^{mulh} strain in the Tahal Schists and the imbricated higher rocks might be due to the presence of thick marble intercalations above the Tahal Schists, forming a bending resistance and allowing stress build-up, which was released by failure.

D_4^{mulh} structure

Penetrative small-scale D_4^{mulh} deformation is exclusively developed in the uppermost few hundred metres of the Tahal Schists. Folds are open to close with a parallel geometry. Axial plane cleavages are typically formed in the most micaceous rock types of folded multilayered sequences or in mica-rich septa of older cleavages (Fig. 6). Redistribution of S_3 as a great circle around L_4 (Fig. 7) and opposite vergence of mesoscopic D_4^{mulh} folds on either side of the E-W trending antiform with Tahal Schists in the core demonstrate that this major structure is essentially a D_4^{mulh} feature (Fig. 1). This also shows that during this deformation phase the afore-mentioned D_3^{mulh} floor thrust was folded. Preferent development of a penetrative S_4^{mulh} cleavage and D_4^{mulh} folds in the top of the Tahal Schists indicates reactivation of the D_3^{mulh} floorthrust during the development of the large antiformal structure, reflecting flexural slip or translations along this zone during D_4^{mulh}.

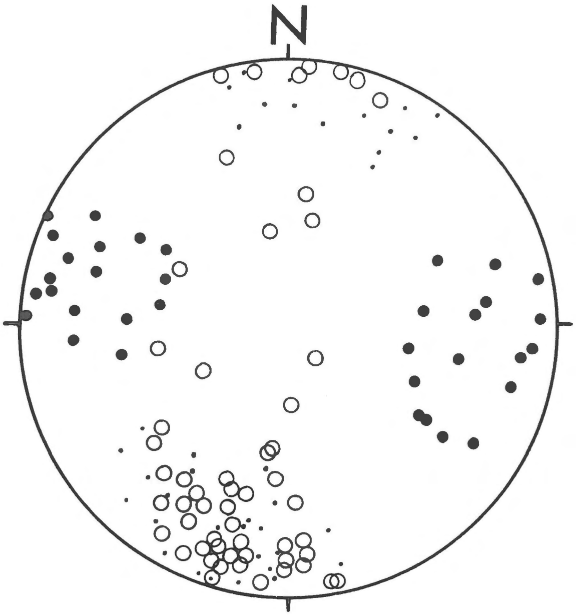

Fig. 7. Lower hemisphere projection of D_3^{mulh} and D_4^{mulh} structural elements in the Tahal Schists east of Lubrin (Fig. 1). Poles to S_3^{mulh} (circles) define a great circle around E-W trending D_4^{mulh} foldaxes (dots); poles to S_4^{mulh} (small dots) define the steeply dipping axial cleavage of the fold structure.

D_4^{mulh} structures are the youngest structures that are cut off by the basal thrust plane of the Alpujarride Complex. This is observed in slices of Tahal Schists occurring associated with the lowest Alpujarride unit, the Almanzora Unit, in the northern margin of the Sierra de los Filabres (coordinates 41_{26}-5_{82}, encl. I, De Jong & Bakker 1991) and elsewhere in the range (De Jong 1991, 1993a).

D_5^{mulh} structure

D_5^{mulh} structures are extensional crenulation cleavages, which characterize the contact with the overlying Alpujarride Complex (De Jong 1991, 1993). The presence of a zone of 15–20 metres thickness with a prominent extensional crenulation cleavage on either side of the nappe contact between the Macael-Chive Unit and the Nevado-Lubrin Unit indicates that this contact was reactivated during the

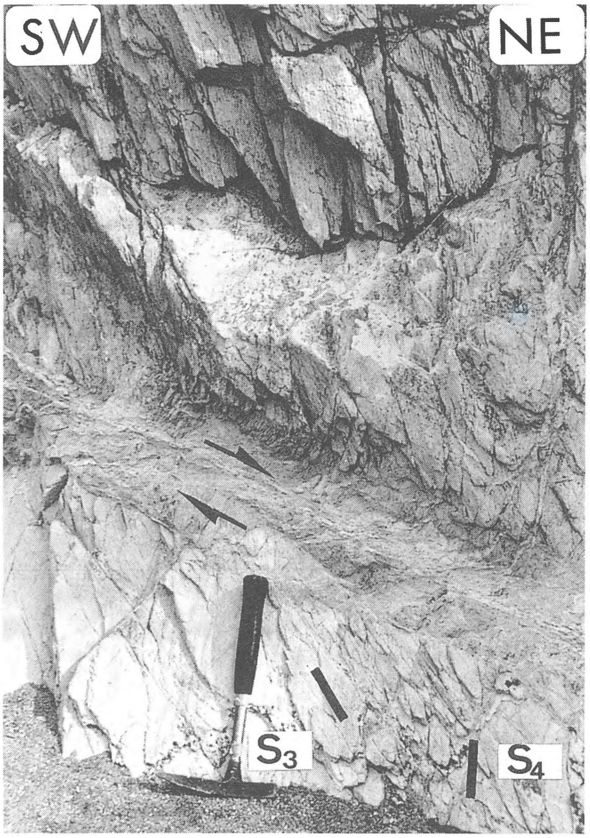

Fig. 8. D_6^{mulh} brittle-ductile shear zone in the uppermost part of the Tahal Schists cutting both S_3^{mulh} and S_4^{mulh}, which are deflected in the margin of the shear zone formed by an array of narrowly spaced faults.

overthrusting by the Alpujarride Complex. The scarce occurrence of this type of cleavage in mica schist intercalations in the Carrasca Marbles implies that the D_3^{mulh} floor thrust was also reactivated during D_5^{mulh}. However, this reactivation did not result in structural changes at the scale of the map; it will not be further considered. Outside the mapped area the contact between the Mulhacen Complex and the underlying Veleta Complex was locally strongly reactivated during D_5^{mulh}, as discussed elsewhere (De Jong 1993b).

D_6^{mulh} *structure*

D_6^{mulh} structures comprise brittle-ductile shear zones and associated folds, which occur superimposed on S_3 and S_4 in the uppermost 100-200 metres of the Tahal Schists (Fig. 8; see also: De Jong 1993, fig. 3f). Superposition on D_5^{mulh} mylonites, outside the map area, shows that they are due to reactivation of the nappe contact between the Mulhacen and Alpujarride Complexes, during which the higher parts of the Nevado-Lubrin Unit and overlying tectonic units of the Mulhacen Complex were thrust on the Alpujarride Complex (De Jong 1991, 1993a). This configuration characterizes the northernmost margin of the Sierra de los Filabres (Fig. 1). Mapping revealed that the rocks of the Nevado-Lubrin Unit that are involved in thrusting and reactivation of the footwall, consist almost exclusively of rocks situated above the Tahal Schists. This shows that the contact zone between the Tahal Schists and the overlying rocks, which is formed by carbonate breccias containing mica schist fragments with S_4, again acted as detachment surface during D_6^{mulh}. Exclusive development of D_6^{mulh} structures in the uppermost part of the Tahal Schists agrees with this interpretation.

Mapping demonstrated excision of nearly the complete La Yedra Marbles and Schists above the detachment going from east to west, bringing the Macael-Chive Unit in direct contact with the Carrasca Marbles of the Nevado-Lubrin Unit (Fig. 1; De Jong & Bakker 1991, encl. I). This implies that during D_6^{mulh} besides imbrications also important extensional movements occurred. Mesoscopic scale, extensional, brittle-ductile shear zones are always superimposed on D_6^{mulh} folds, showing that regional extension marks the later stages of the D_6^{mulh} deformation phase, which implies an extension of the imbricate structure. The imbrications and extensional structures are covered by only slightly disturbed Tortonian conglomerates, both in the northern (De Jong & Bakker 1991, encl. I, II) and southern margin (De Jong 1991, fig. 2.30) of the Sierra de los Filabres.

D_7^{mulh} *structure*

During D_7^{mulh}, a group of non-penetrative structures were formed, consisting of NNE-SSW to NNW-SSE trending subvertical faults and associated similarly oriented megascopic flexures and open folds, which affect all older structures. N-S trending mesoscopic folds and kink-like crenulations, generally without an axial plane cleavage, occur very locally, partly associated with faults. The D_7^{mulh} fault system is characteristic for the entire Sierra de los Filabres. Locally D_7^{mulh} faults are covered by Tortonian sediments, but the majority cut deposits of this age (Weijermans et al. 1985, De Jong 1991, fig. 2.30) and even rocks as young as the Messinian (Kleverlaan 1989, Ott d'Estevou et al. 1990) at the contact with the metamorphic rocks. D_7^{mulh} is thus partly coeval with the structural evolution of the sedimentary basins adjacent to the metamorphic range.

Conclusions

Large-scale deformation of the Mulhacen Complex in the eastern Sierra de los Filabres was polyphase. Early deformation was penetrative at all scales and resulted in a regionally continuous transposition foliation of bedding and S_2; shortening values perpendicular to this foliation are in the order of 60–80%. Subsequent deformation was not homogeneous, but concentrated in a number of zones, and changed the D_2^{mulh} regional structure considerably.

D_3^{mulh} imbrication resulted in disruption of lithologic units and of the previously formed stack of three nappes within the Mulhacen Complex. The floor thrust of the imbricate system was located above the Tahal Schists in the top of the deepest nappe. The strongest folding during D_3^{mulh} and the most intensely developed crenulation cleavages were formed adjacent to the imbricate thrusts and below the floor thrust.

During D_4^{mulh}, the D_3^{mulh} basal thrust was reactivated in conjunction with the development of a large-scale antiformal structure, which is the most prominent structure in the Mulhacen Complex of the eastern Sierra de los Filabres. The floor thrust was again reactivated during D_6^{mulh}, when the D_5^{mulh} nappe contact between the Mulhacen Complex and overlying Alpujarride Complex was disrupted and parts of the Mulhacen Complex situated above the Tahal Schists were thrust on the Alpujarride Complex.

D_7^{mulh} resulted in subvertical, approximately NNE-SSW to NNW-SSE trending faults and associated similarly oriented flexures and open folds. In contrast to D_6^{mulh} these non-penetrative structures affect Tortonian deposits.

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