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Structural and kinematic constraints to the exhumation of the Alpujarride Complex (Central Betic Cordillera, Spain)

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Abstract

The polymetamorphic Alpujarride nappe Complex is one of the main constituents of the internal zones of the Alpine Betic–Rif chain. Still under debate are the tectonic processes involved in exhumation of its deep-seated portions, metamorphosed under high-pressure conditions during the Alpine crustal thickening. A systematic study of the exhumation-related ductile and brittle fabric observed in the different Alpujarride units reveals, independently from the metamorphic grade and age of the protoliths, a common sequence of deformation events. It involves early progressive top-to-the-N/NE ductile shearing, followed by a major top-to-the-N post-metamorphic extensional faulting event, which produced a complex re-organisation of the whole nappe pile. We propose that ductile exhumation of the deep-seated Alpujarride nappe piles was mainly completed before the onset of the post-orogenic extensional processes associated with the Early Miocene Alboran rifting. A switch from an early ductile underthrusting regime (Paleogene in age) to semibrittle-to-brittle extension (Early Miocene onward) is here proposed as responsible for the exhumation history of the Alpujarride Complex.

Keywords: Structural fabric; Exhumation; Orogenic wedges; Betic Cordillera

1. Introduction

High-pressure rocks are generally confined to metamorphic terranes exposed in the hinterland of orogenic belts and argue for subduction zone metamorphism at active convergent margins. A remarkable feature shown by many occurrences of high-pressure rocks is that they appear to have been exhumed during convergence, in the early stages of orogenic evolution (e.g. Platt, 1993; Jolivet et al., 1998a). Interpretation of the mechanisms (tectonic vs. erosional denudation) that controlled exhumation and preservation of the high-pressure rocks is a source of continuous debate in geological literature. This is mostly due to the fact that polyphase structural overprints inhibit the complete recognition of the tectono-metamorphic evolution of these units and, in particular, how the transition from the syn- to the post-orogenic stage occurred in orogens. Unravelling the complete structural history in polymetamorphic exhumed high-pressure units may thus help to provide insights into the processes operating during subduction and orogenic complex formation.

In the Mediterranean region, the reworking produced by Neogene back-arc extension on the Alpine, Late Cretaceous–Paleogene orogenic system allowed unroofing of the deeper portions of the orogenic complexes (e.g. Dewey, 1988; Jolivet and Faccenna, 2000) (Fig. 1A). Consequently, the deep-seated units are now exposed in areas dominated by extensional structures, such as in the Aegean, Tyrrhenian and Alboran regions, and post-orogenic extensional process have been commonly advocated as an efficient mechanism leading to their exhumation (e.g. Lister et al., 1984; Platt and Vissers, 1989; Carmignani and Kligfield, 1990; Gautier and Brun, 1994). Nevertheless, studies on the occurrence and mode of exhumation of the high-pressure units (eclogitic and blueschist facies rock sequences) exposed in these regions indicate that most of their exhumation predated whole-crustal back-arc extension (e.g. Jolivet et al., 1996, 1998b; Avigad et al., 1997; Balanyá et al., 1997; Rossetti et al., 1999).

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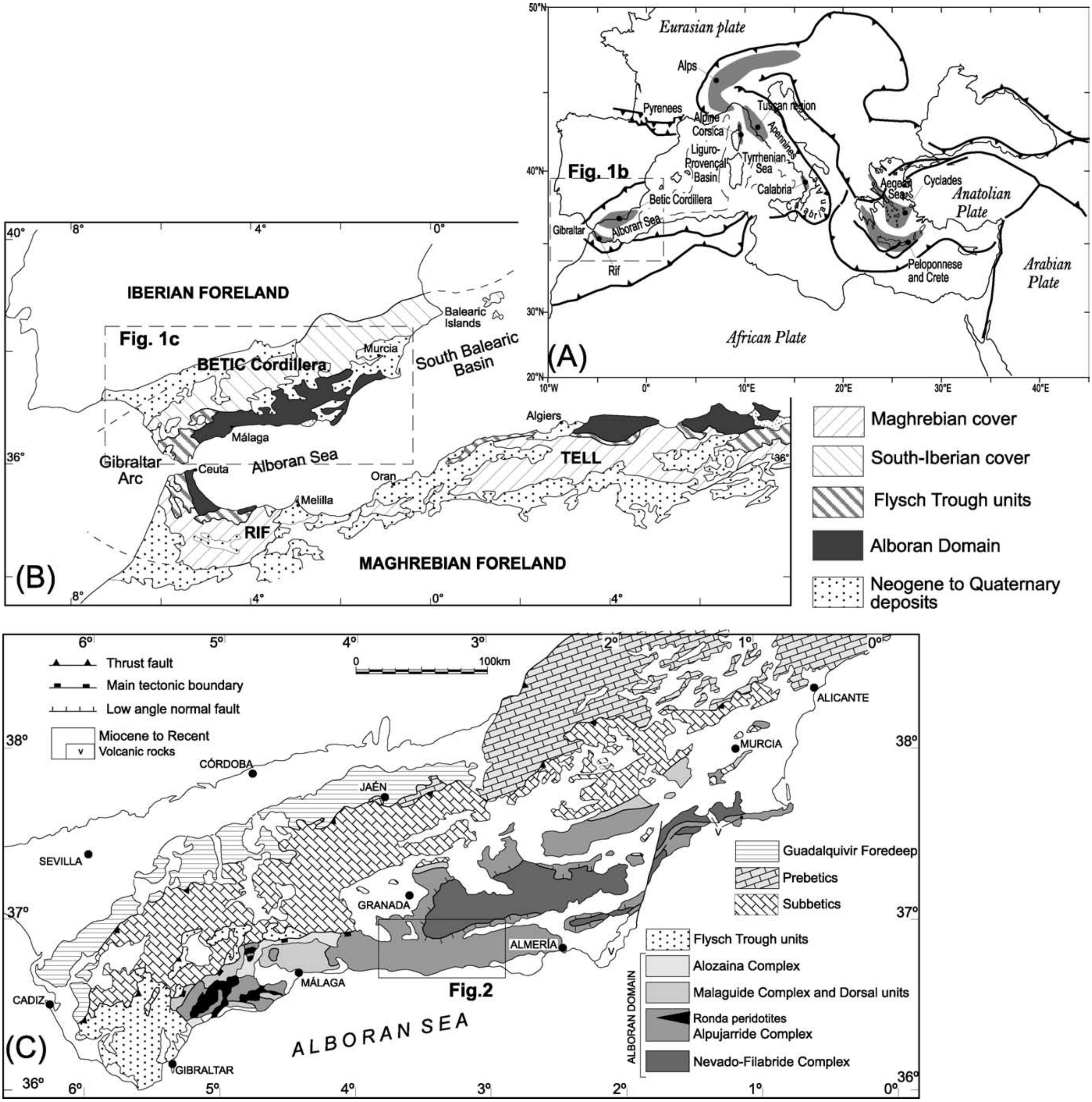

Fig. 1. (A) Simplified tectonic map of the Mediterranean region. The inset shows the exhumed high-pressure roots of the Alpine orogen, together with the study area (modified after Faccenna et al., 2004). (B) Composite tectonic map of the western Mediterranean region (modified after García-Dueñas et al., 1992). (C) Tectonic map of the Betic chain with location of the studied area (modified after Balanyá et al., 1997; Azañón et al., 1998; Azañón and Crespo-Blanc, 2000).

In the Betic–Rif mountain chain, the westernmost segment of the Alpine Mediterranean belt (Fig. 1B), interpretation of the processes involved in the exhumation of the metamorphic units exposed in the interior of the chain (the Alboran Domain; Fig. 1B), has been a long source of controversy. Indeed, there is no general agreement about the tectonic regime and the timing during which exhumation occurred, and very different tectonic and geodynamic models have been proposed. These include contractional (e.g. Tubía et al., 1992; Simancas and Campos, 1993), extensional (e.g. Platt and Vissers, 1989; Vissers et al., 1995; Platt et al., 1996, 2003a) or alternation of both regimes (e.g. Bakker et al., 1989; Azañón et al., 1997; Balanyá et al., 1997). In addition, there is still no agreement on the tectonic attribution, Alpine or pre-Alpine, of the metamorphic and structural fabric observed in the Paleozoic protolithic rocks of the Alpujarride Complex, one of the main constituents of the Alboran Domain (e.g. Balanyá et al., 1997; Michard et al., 1997; Zeck and Whitehouse, 1999, 2002; Azañón and Crespo-Blanc, 2000).

In this paper, we present a systematic study of the exhumation-related, structural fabric of the Alpujarride Complex. This analysis is based on new field investigations carried out in a selected area situated in the central Betic Cordillera, southwest of Sierra Nevada (Figs. 1C and 2). The results of this study, integrated with published petrographical and geochronological data, are used to show that much of the exhumation of the Alpujarride Complex was achieved during the build-up of the Betic Internal Zone, predating the Early Miocene post-orogenic extensional process associated with the Alboran rifting.

2. Geological background

2.1. Crustal domains and tectonic complexes in the Gibraltar Arc

The Gibraltar Arc has two arms represented by the Betic Cordillera of southern Spain and the Rif chain of northern Morocco, which land-locked the Alboran Basin situated in the internal part of the Arc (Fig. 1B). The mountain front of the Gibraltar Arc originated from the Early Miocene collision of the Alboran Domain with the South-Iberian and Maghrebian paleomargins, involving Mesozoic to Cenozoic platform and basinal sedimentary sequences (e.g. Balanyá and García-Dueñas, 1988). This collision lead to the obliteration of the Flysch Trough, a basin with

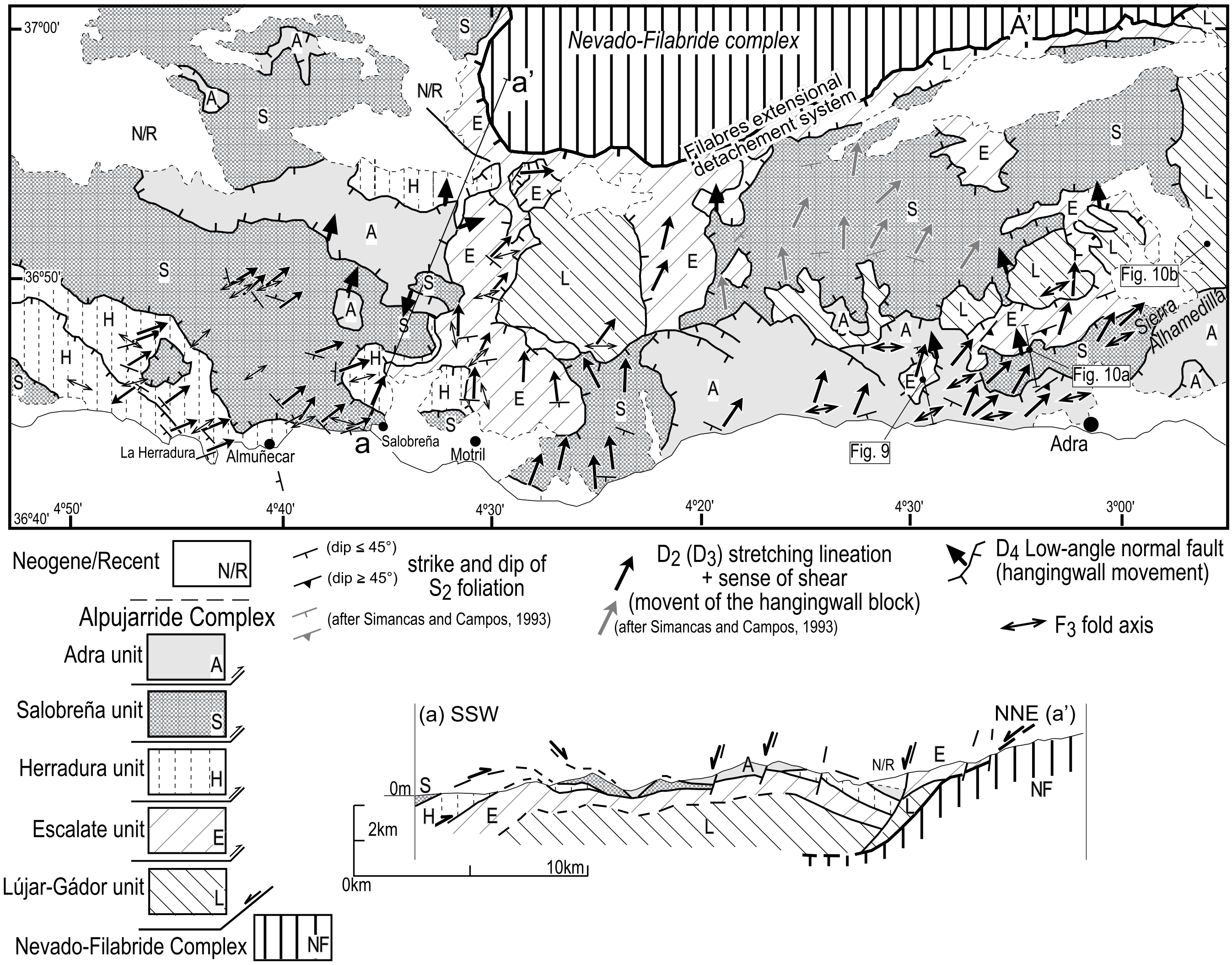

Fig. 2. Composite structural map of the Alpujarride Complex in the Central Betic Cordillera (modified after Azañón and Crespo-Blanc, 2000). Orientations of the main structural features presented and discussed in this study are also indicated. Names of Alpujarride units are after Azañón et al. (1994). Hanging-wall movement along D_4 faults according to García-Dueñas et al. (1992), Crespo-Blanc et al. (1994), Azañón and Crespo-Blanc (2000) and this work. The geological cross-section, modified after Azañón and Crespo-Blanc (2000), illustrates the tectonic setting of the Betic Cordillera in the study area and the control operated by the D_4 faulting episode on the present structural architecture of the Alpujarride Complex.

attenuated continental or possibly oceanic crust filled by Cretaceous to Miocene deep-water sediments. Due to the outward migration of the convergent front, an arcuate thin-skinned fold-and-thrust belt developed, formed by rocks derived from both paleomargins. Simultaneously, extension occurred in the inner part of the Gibraltar Arc and the Alboran Basin was formed (e.g. Balanyá and García-Dueñas, 1988; García-Dueñas et al., 1992).

The Alboran Domain represents the inner portion of the Betic orogen and consists, in ascending order, of the Nevado–Filabride, the Alpujarride and the Malaguide complexes (Fig. 1B and C). These complexes have been defined on the basis of their lithostratigraphic characteristics and metamorphic signature. The Nevado–Filabride complex consists of the superimposition of two main tectonic units (Martínez-Martínez et al., 2002, and references therein): the lower unit consists of a monotonous series of Palaeozoic graphitic rocks, while the upper ones are formed by metasediments and marbles developed from Palaeozoic to Cretaceous protoliths. The lower unit was metamorphosed for the most part to greenschist facies during the Alpine orogeny. By contrast, the upper ones show a metamorphic evolution similar to that of the intermediate Alpujarride Complex (see below), starting from eclogitic metamorphic conditions, followed by an amphibolite facies decompressional re-equilibration (e.g. Bakker et al., 1989; Puga et al., 2002 and references therein).

The Malaguide Complex retains Variscan orogenic features in the Palaeozoic rocks, and its Mesozoic to Paleogene cover did not suffer pervasive deformation and/or metamorphism (Chalouan and Michard, 1990). The sedimentary rocks belonging to the Dorsal units, Triassic to lower Neogene in age, are only rarely represented in the Betics (included in the Malaguide Complex in Fig. 1C) and outcrop structurally between the Flysch Trough units and the Malaguide Complex.

2.2. The Alpujarride Complex in the central Betics

At a regional scale, the Alpujarride Complex shows the superposition of rocks of different metamorphic grade belonging to various tectonic units; from bottom to top and in general order of increasing metamorphic grade (Azañón et al., 1994): Lújár-Gádor, Escalate, Salobreña, Herradura and Adra units (Fig. 2). The lithostratigraphic sequence of the Alpujarride units is similar for the whole Alpujarride Complex. Where complete, it includes a metapelitic sequence formed by migmatite gneisses, dark- and light-coloured schists attributed to Palaeozoic protoliths, overlain by fine-grained schists and carbonate rocks, attributed to Permo-Triassic and middle and upper Triassic (Braga and Martín, 1987) protoliths. The peridotite slabs of the Ronda region and its enveloping high-grade metamorphic cover (150 km west of the studied area) consist of independent tectonic slices included in the upper part of the Alpujarride nappe-stack (e.g. Balanyá et al., 1997, 1998; Tubía, 1997).

The Alpujarride rocks reveal a polyphased metamorphic history. The metamorphic climax corresponds to a high-pressure/low-temperature metamorphic ratio, followed by nearly isothermal decompression during which the main, second phase S–L fabric developed (e.g. Westerhoff, 1977; Bakker et al., 1989; Goffé et al., 1989; Tubía and Gil-Ibarguchi, 1991; García-Casco and Torres-Roldán, 1996; Balanyá et al., 1997; Azañón et al., 1998; Azañón and Crespo-Blanc, 2000). An increase in temperature during the last stages of the exhumation of these rock types, indicating heating during decompression, has been described in rocks drilled in the Alboran Sea (Platt et al., 1998). The pressure–temperature (P–T) paths for selected lithologies of different Alpujarride units cropping out in the study area are shown in Fig. 3. A complete description of the lithological sequence, metamorphic mineral assemblages and mineral zones of the Alpujarride units can be found in Azañón et al. (1998) and Azañón and Crespo-Blanc (2000). Here, we remark: (i) within the column of metapelitic rocks, the position of a given metamorphic zone varies from one unit to the next and so does the metamorphic grade of each unit; (ii) within each unit, the metamorphic grade increases systematically

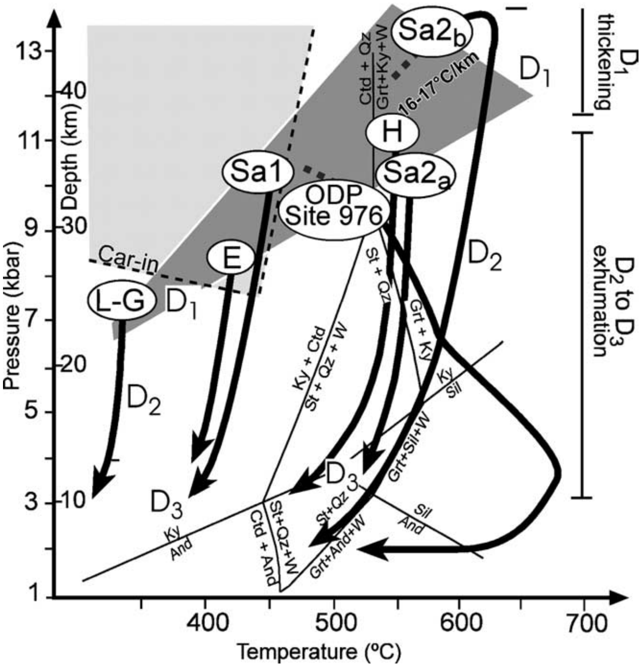

Fig. 3. P–T evolution of metapelitic levels from selected Alpujarride units exposed in the study area: L-G and E, fine-grained schists from the Lújar-Gador and Escalate units, respectively (after Azañón and Crespo-Blanc, 2000); H, light-coloured schists from the Herradura unit (after Azañón and Crespo-Blanc, 2000); Sa1 and $Sa2_{a,b}$, fine-grained (after Azañón and Crespo-Blanc, 2000), and dark-coloured ($Sa2_a$ after Azañón et al., 1996; $Sa2_b$ after Azañón et al., 1998) schists from the Salobreña unit, respectively ($Sa2_b$ constitutes the stratigraphic lower level of the unit); ODP Site 976, metamorphic rocks cored at site 976 of the Ocean Drilling Program Leg 161 (after Platt et al., 1998). Mineral abbreviations: And = andalusite; Car = carpholite; Ctd = cloritoid; Grt = garnet; Ky = Kyanite; Qz = quartz, St = staurolite, Sil = sillimanite; W = water. (Fe–Mg)–Carpholite stability field (Car-in) after Jolivet et al. (1998a).

downwards, and (iii) the metamorphic zones are closely spaced (Azañón et al., 1998). These points are well documented in the Salobreña unit, where metapelites with typical high-pressure/low-temperature parageneses (Sa_1 in Fig. 3: Mg–carpholite–kyanite-bearing; average P–T conditions of 10 kbar and 425 °C) overlay sequences with higher-grade metamorphic assemblages (Sa_2 in Fig. 3: garnet–kyanite–plagioclase-bearing; average P–T conditions of 13 kbar and 625 °C), but the assemblages are separated by only a 3-km-thick rock section subperpendicular to the main foliation attitude (Azañón et al., 1998).

Presently, no precise constraint exists for the timing of the early high-P metamorphic climax in the Alpujarride units and in the whole Alboran Domain. Tentatively, a Paleogene age for the main underthrusting event in the Betic Internal zone has been proposed on the base of different argumentations (e.g. Balanyá et al., 1997; Zeck, 1996; Platt et al., 1998, 2003a). Nevertheless, an Early Miocene cluster of radiometric ages is recorded in most of the rocks of the Alboran Domain on the basis of the simultaneous application of thermochronometers with different closure temperatures (Platt and Whitehouse, 1999; Sánchez-Rodríguez and Gebauer, 2000; López-Sánchez-Vizcaíno et al., 2001; Platt et al., 2003a; Whitehouse and Platt, 2003). This age cluster has been interpreted as evidence for Early Miocene high-grade metamorphism in the Alboran Domain (Zeck et al., 1992; Platt et al., 1998, 2003a; Platt and Whitehouse, 1999). The final cooling at near surficial conditions occurred at around 18–16 Ma, as constrained by fission track thermochronology (Andriessen and Zeck, 1996; Platt et al., 1998; Sosson et al., 1998). Accordingly, these radiometric age data have been used to propose very high rates of cooling and exhumation for the deep-seated portions of the Alboran Domain.

The present-day geometry of the Alpujarride Complex consists of a post-metamorphic stack of units, bounded by extensional low-angle normal faults (e.g. García-Dueñas et al., 1992). An overall inverted metamorphic sequence is recorded from the stacking order of these units, with higher-grade units lying on top of lower grade ones (Azañón et al., 1994; Balanyá et al., 1998) (Fig. 2). In the central Betics, two main systems of extensional faults were active during the Neogene rifting of the Alboran Basin (e.g. Comas et al., 1992; García-Dueñas et al., 1992; Martínez-Martínez and Azañón, 1997). The first, associated with a NNW–SSE-trending extension direction, corresponds to the Early Miocene in age Contraviesa fault system of Crespo-Blanc et al. (1994), and the second corresponds to the Middle Miocene top-to-the-WSW Filabres extensional detachment system, whose sole detachment marks the Alpujarride/Nevado–Filabride tectonic boundary (García-Dueñas et al., 1986; Platt and Vissers, 1989; García-Dueñas et al., 1992; Johnson et al., 1997; Martínez-Martínez et al., 2002). The final uplift of part of the Alboran Basin and its basement is due to a post-Tortonian to Present N–S to NW–SE compression, which produced folds (mainly kilometre-scale E–W-striking folds) and faults (high-angle normal and reverse faults and conjugate systems of strike-slip faults) (e.g. Comas et al., 1992; Rodríguez-Fernández and Martín-Penela, 1993).

3. Structural evolution of the Alpujarride units

Coupled structural and petrographical investigations were carried out in an area located in the central Betic Cordillera, southward of Sierra Nevada. Our study was based on analyses carried out along different structural transects traversing the whole nappe pile constituting the Alpujarride Complex (Fig. 2). This study reveals, independently from the metamorphic grade of the units, a common sequence of deformation events (D_1–D_4), evolving in time from ductile to semibrittle and brittle conditions. The superimposition of these deformation fabrics records the transition from an early deep burial stage when the peak metamorphic conditions were reached (D_1) to subsequent metamorphic retrogression and exhumation, from ductile (D_2–D_3) to brittle (D_4) conditions. The intense overprinting associated with the exhumation stage (D_2–D_3 composite fabric) resulted in widespread transposition of the early D_1 fabric. The previous S_1 foliation is in fact recognizable only in small lens-shaped microlithons enclosed within the D_2 crenulation cleavage (low-grade rocks), or as inclusions in porphyroblasts such as plagioclase or garnet (high-grade rocks). Consequently, no conclusive data are available for the characterisation of the early D_1 thickening history (see also Tubía et al., 1992; Azañón et al., 1997; Balanyá et al., 1997).

3.1. D_2 deformation: main fabric development

In all the investigated Alpujarride units the main (regional) fabric is associated with a penetrative second-phase S_2–L_2 deformation fabric. This fabric was acquired during the main exhumation stage of the Alpujarride complex and is synkinematic relative to the crystallisation of retrograde parageneses consisting of white mica, chlorite, chloritoid and pyrophillite in the low-grade domains (Permo-Triassic protoliths) and of biotite + white micas + sillimanite/andalusite ± K-feldspar in the high-grade ones (Palaeozoic protoliths), respectively (Balanyá et al., 1997; Azañón et al., 1998). The D_2 fabric is pervasive throughout the whole nappe complex and shows different characteristics (morphology and intensity) according to metamorphic grade (variable from unit to unit and within each unit). The S_2 schistosity is usually a transposing foliation and subparallel to the primary compositional banding (Fig. 4A). The L_2 lineation is outlined by the preferred orientation and stretching of syn-kinematic mineral associations on the S_2 surfaces (Fig. 4B). Syn-D_2 stretching is also associated with extensional veins, filled by the same retrogressive mineral assemblages. These veins are steeply dipping and occur as

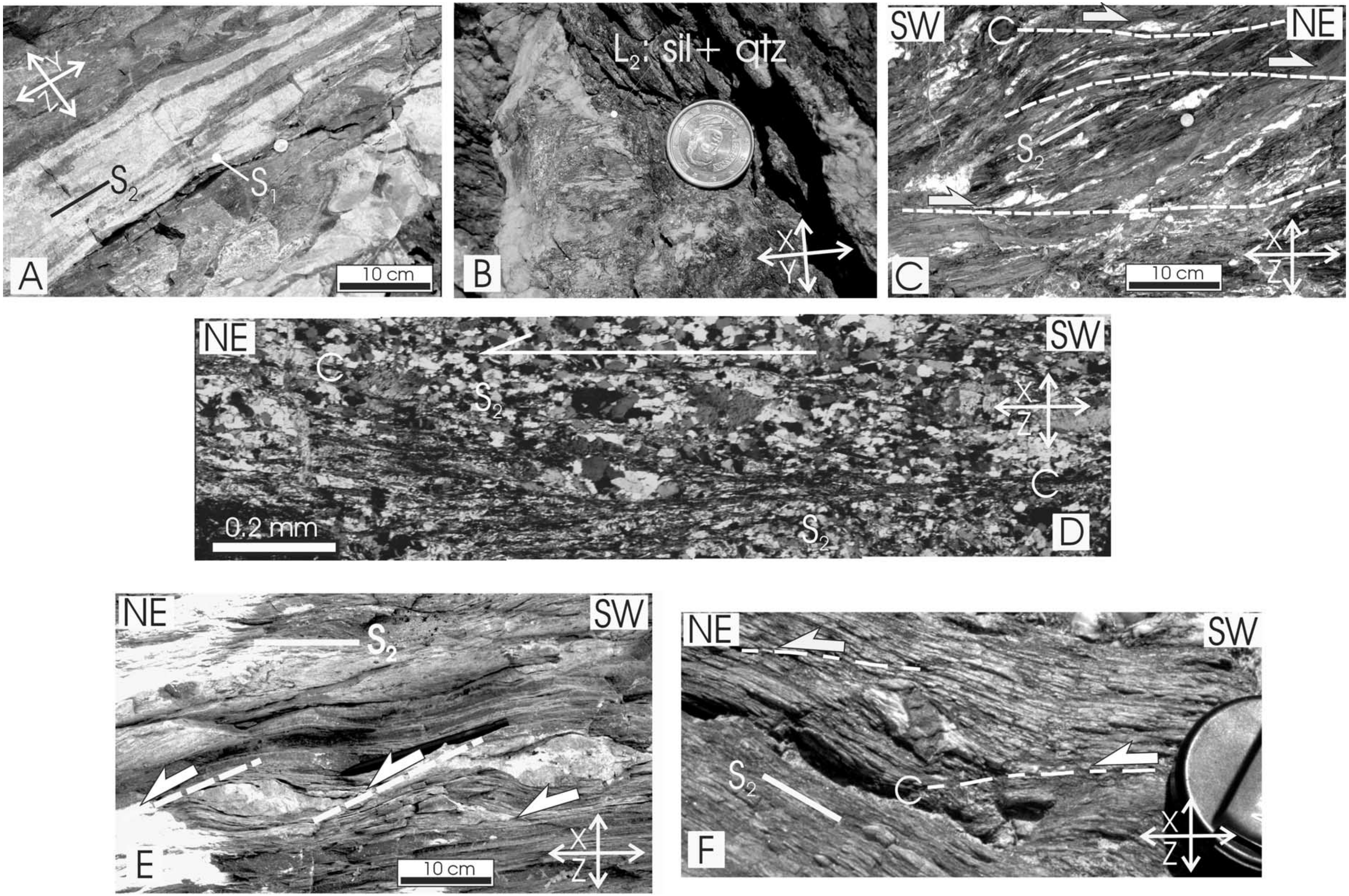

Fig. 4. Field examples of the ductile structural fabric associated with the D_2 deformation. (A) Transposing S_2 foliation in the high-grade schists of the Salobreña unit. (B) L_2 stretching lineations provided by sillimimanite (sil)–quartz (qtz) segregations on the S_2 foliation in the high-grade schists of the Salobreña unit. (C) S–C shear fabric and asymmetric boudinage in the Escalate unit. Dextral shear sense (exposure normal to S_2 and parallel to L_2; coin for scale in the centre of the photograph). (D) Thin section showing D_2 mylonitic shear bands in the Salobreña unit. The oblique foliation and the S–C fabric indicate sinistral shear sense. Quartz in the matrix is dynamically recrystallised and defines an oblique foliation (crossed polars; section normal to S_2 and parallel to L_2). (E) C′-type shear bands indicating sinistral shear in the low-grade schists of the Salobreña unit (exposure normal to S_2 and parallel to L_2). (F) Detail of the S–C fabric in mylonite from the Escalate unit. Quartz-bearing σ-type pressure shadows and the S–C fabric indicate sinistral shear sense (exposure normal to S_2 and parallel to L_2).

single sets oriented roughly perpendicular to the finite L_2 stretching direction.

At the mesoscale, D_2 deformation is variably partitioned between nearly vertical coaxial shortening and SW/NE- to N/S-directed stretching. Fig. 2 shows the attitude of the S_2–L_2 fabric in the study area, whereas Fig. 5 shows the related structural data relative to the different units exposed along the transects. The S_2 foliation is usually shallow dipping (towards the SW for the Escalate, Herradura and Salobreña units and towards the SSE for the Adra unit, respectively) and the L_2 attitude is generally down-dip. A systematic study of L_2 orientation shows, in particular, that its mean orientation is SW–NE in the Herradura, Salobreña and Adra units, whereas it is roughly N–S-trending in the Escalate unit (Figs. 2 and 5). Deviations from this general orientation pattern are locally observed. In particular, in the central part of the study area (around meridian of Motril in Fig. 2), L_2 lineations in the Salobreña unit show a N-S orientation, similar to the one detected in the underlying Escalate unit.

Sections parallel to L_2 stretching directions and normal to S_2 foliation (corresponding to the *X–Z* section of the D_2 finite strain ellipse) systematically show pervasive ductile non-coaxial shear features. Kinematic criteria (e.g. Passchier and Trouw, 1996) such as shear band cleavage (C- and C′-type; Fig. 4C–E), σ-type asymmetric pressure shadows (Fig. 4F), systematically indicate top-to-the-NE/N shearing. In the highest strained domain, intrafoliar oblique to sheath F_2 folds were commonly observed, with fold hinges stretched apart parallel to the L_2 stretching direction.

3.2. D_3 deformation: folding and localised shearing

The D_2 fabric is reworked by D_3 deformation In most cases, a clear distinction between D_2 and D_3 fabrics can be made, but structures showing progressive deformation from D_2 to D_3 have been locally observed. The main fabric associated with D_3 deformation consists of a small-scale crenulation cleavage, axial planar to F_3 folds refolding the main S_2 schistosity. Shear strain localisation also occurs during D_3 and ductile mylonites to semibrittle shear bands are locally present. Syn-D_3 mineral growth consists of low-P mineral assemblages, such as quartz + chlorite ± white mica ± albite in low-grade rocks and biotite + andalusite + white micas ± staurolite in high-grade ones, respectively (e.g. Azañón et al., 1998).

F_3 folds show variable styles moving within each unit, as their morphology is intimately related to the D_3 shearing localisation and intensity. In zones of low D_3 strain

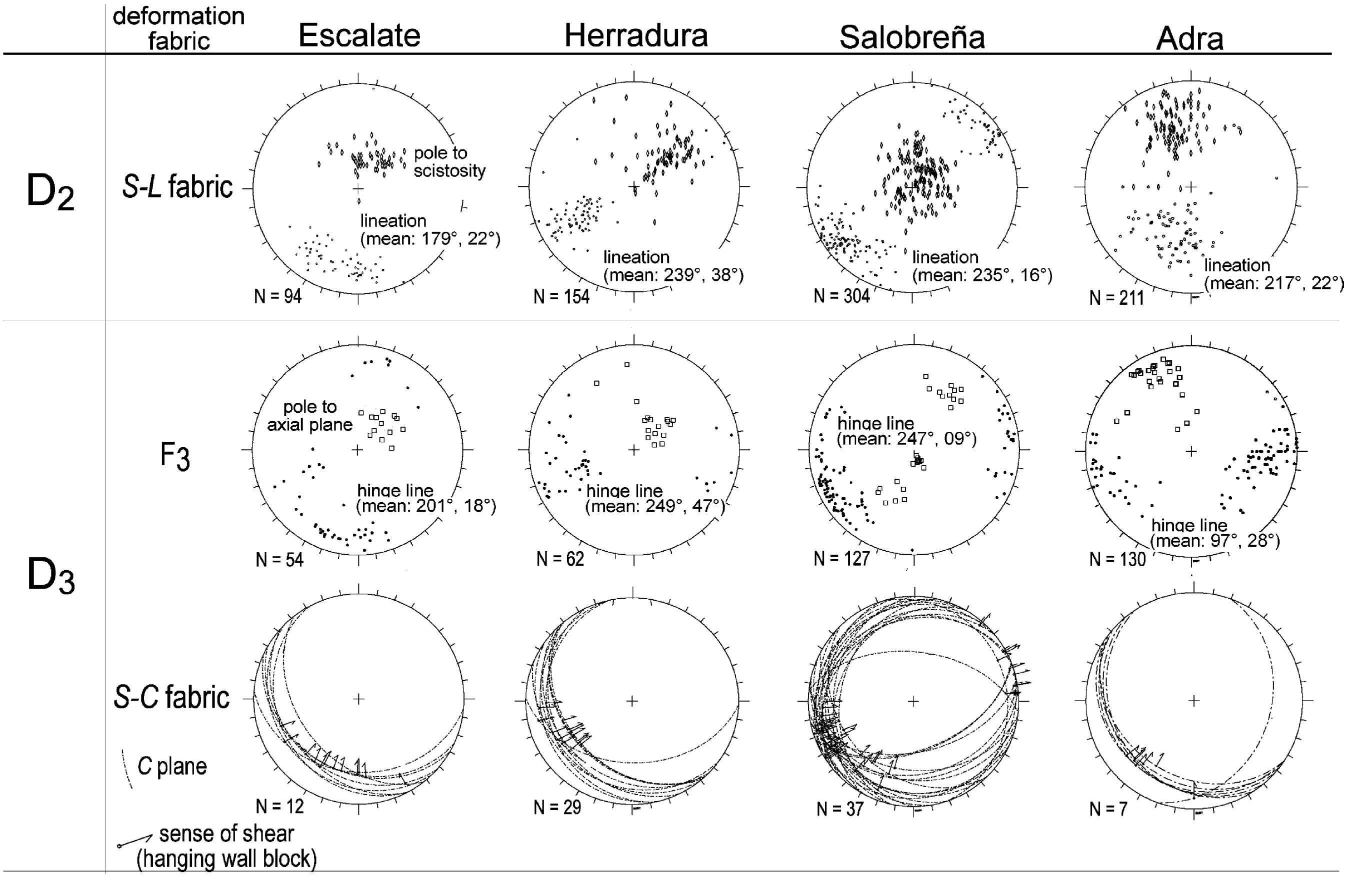

Fig. 5. Stereoplots (lower hemisphere equal-area projection) showing the attitude of the D_2–D_3 composite fabric in different tectonic units of the Alpujarride Complex. See text for further details.

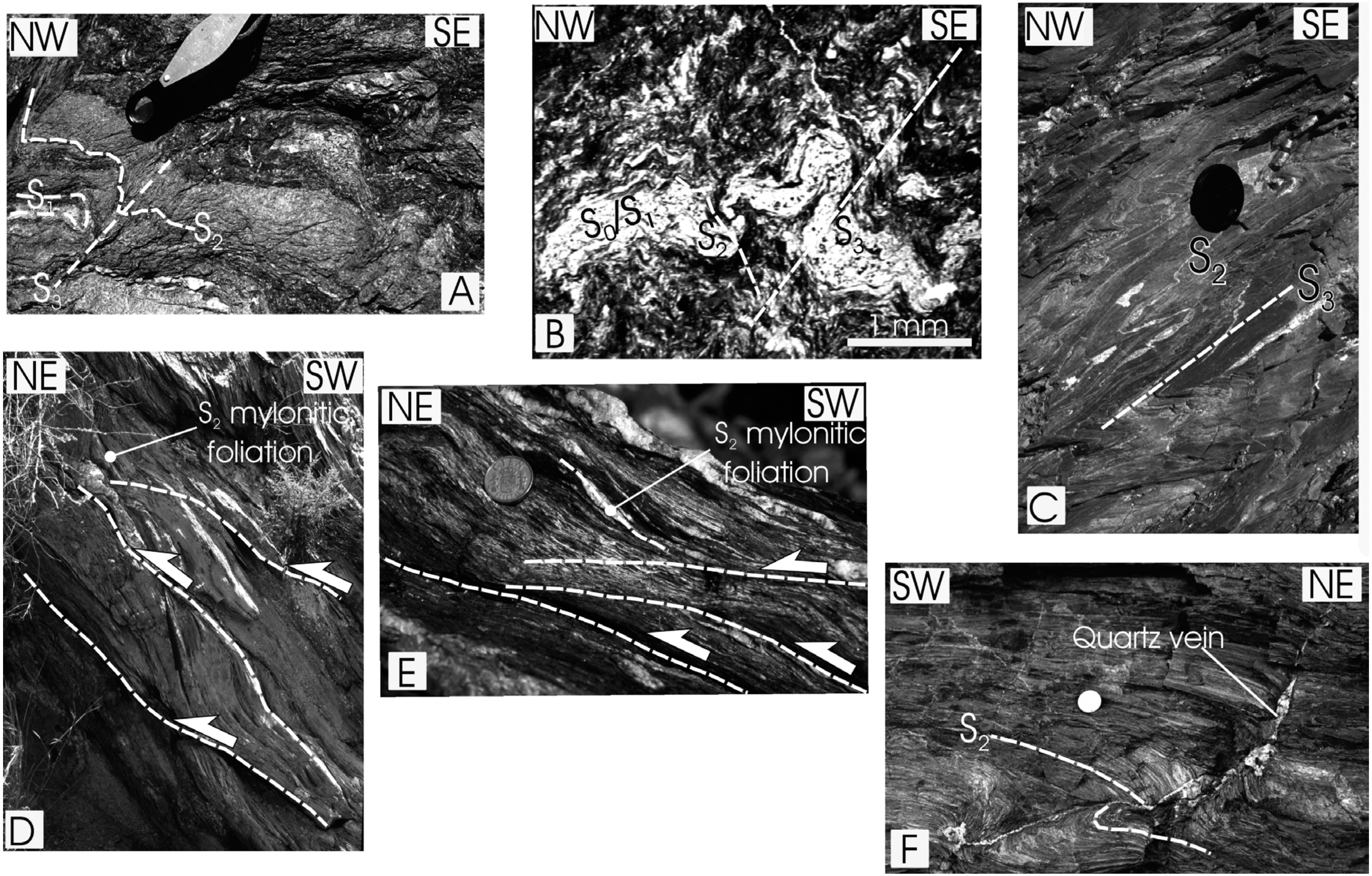

Fig. 6. Field examples of the structural fabric associated with the D_3 deformation. (A) D_3 crenulation cleavage preserved in the hinge zone of the F_3 folds in low-grade schists of the Salobreña unit. (B) Thin section (plane polarised light) showing the overprinting relations among D_1, D_2 and D_3 fabrics in the low-grade Lújar-Gádor unit. (C) Transposing S_3 schistosity axial planar to F_3 folds in high-grade schists of the Adra unit. (D) D_3 low-grade S–C tectonites in the Escalate unit. Sinistral shear sense. (E) D_3 S–C fabric overprinting the D_2 mylonitic foliation in the Adra unit. Sinistral shear sense. (F) n-Type flanking fold around a rotated quartz vein in the low-grade schists of the Salobreña unit. The deflection of the foliation indicates a dextral shear sense.

and in the low-grade domains, F_3 folds consist of a millimetre- to decimetre-scale crenulation, associated with a discontinuous S_3 cleavage (Fig. 6A and B). Intermediate zones of D_2–D_3 superposition show a more pronounced folding (open to chevron-type folds) of the previously developed D_2 fabric and S_3 crenulation cleavage, which is pervasive only in the hinge zones. In the highly strained zones, F_3 folds are mostly isoclinal and the S_3 axial planar schistosity becomes the main planar rock fabric (Fig. 6C). In that case, the S_3 crenulation cleavage is associated with a L_{2-3} intersection lineation on the S_2 surfaces, which trend roughly parallel to the F_3 fold axes.

A S_3–L_3 fabric is observed to have developed in the D_3 highly strained domains, where it corresponds to shear strain localisation. L_3 lineations trend NE–SW (Lújar-Gador, Adra, Herradura, and Salobreña units) to NS (Escalate unit), roughly parallel to the L_2 stretching direction (Fig. 3). Kinematic indicators within the D_3 shear zones, mostly provided by S–C structures, indicate a general top-to-the-ENE shearing in the Herradura and Salobreña units, whereas dominant top-to-the-NNE shear senses have been detected in the Escalate unit (Figs. 2, 5 and 6C–E). D_3 shearing progressed under semibrittle conditions, overprinting early D_2 vein arrays and producing trains of n- and s-type flanking folds (Passchier, 2001, and references therein). The deflection of foliation and fold vergence (e.g. Grasemann and Stüwe, 2001) attests local reactivation of the vein walls compatible with drag produced by the overall top-to-the-N/NE sense of shear (Fig. 6F). Systematic measurements of the F_3 fold elements (axial planes and hinge lines) show a great variability of their azimuthal distribution (Figs. 2 and 5). In particular, the main F_3 fold axes orientation trend is NNE–SSW in the Escalate unit, NE–SW in the Herradura and Salobreña units, and roughly E–W in the Adra unit (Fig. 2). At mesoscale, F_3 hinge line orientations are strongly controlled by D_3 shear strain localisation. The F_3 folds, in fact, commonly show curved hinge lines, from highly oblique (in the low-strain domains) to near parallelism with the L_2–L_3 stretching direction (in the high-strain shear domains) (Figs. 2 and 7). In the high-strained domains, where shear localisation occurs, F_3 fold limbs are sheared out consistently with the overall NE- to N-directed asymmetry of the D_3 deformation and rootless folds are usually observed in the high strained domains.

As a last point, it is worthwhile to note that in the higher-grade rock successions of the Adra, Salobreña and Herradura units, the post-kinematic crystallisation of low-P index minerals, such as andalusite and/or staurolite porphyroblasts, systematically overprints the previous ductile D_2/D_3 composite fabric (Fig. 8A–B; see also Azañón et al., 1997; Simancas and Campos, 1993). This post-D_3 mineral crystallisation coincides with pressure–temperature conditions at the end of the decompression path (Fig. 3; Azañón et al., 1997, 1998; Balanyá et al., 1997; Azañón and Crespo-Blanc, 2000), and marks the end of the ductile-dominated deformation history.

3.3. D_4 deformation: brittle top-to-the-N shearing and late regional-scale folding

The D_4 deformation consists of a composite fabric evolving from semibrittle to brittle deformation conditions. The main D_4 structural features are represented by meso-to-regional-scale anastomosing flat-lying extensional fault zones, which trend roughly E–W to WNW–ESE and accommodate a general top-to-the-N sense of shear (Fig. 2). These D_4 faults are the main boundaries between the different tectonic units that form the Alpujarride Complex, and are responsible for the large-scale omission of parts of the lithological sequence and for the metamorphic breaks detected across the main

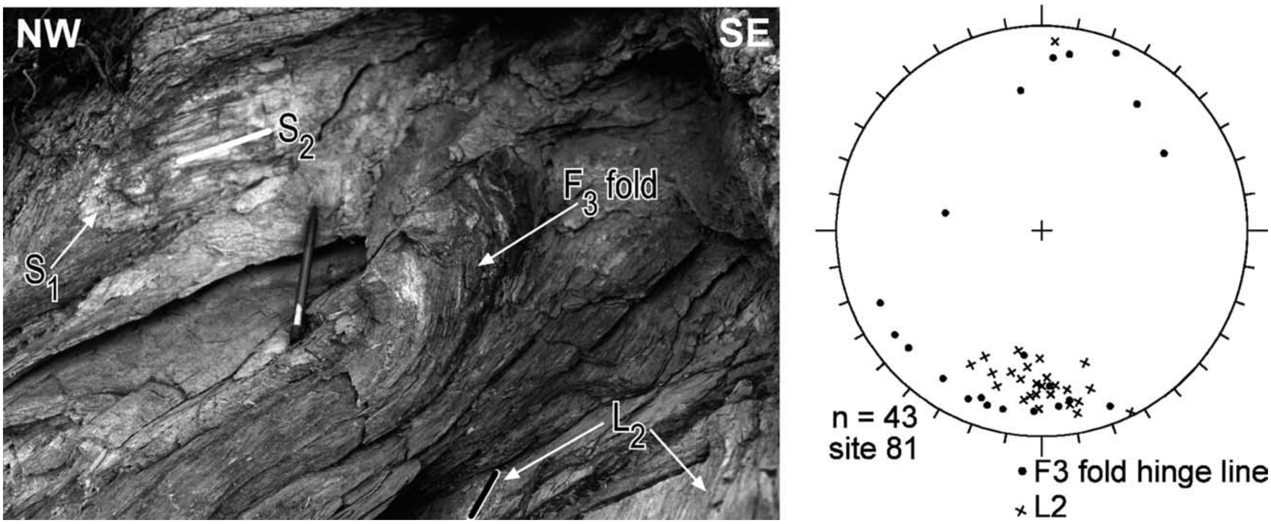

Fig. 7. Field example from the Escalate unit illustrating the F_3 hinge line rotation to parallelism with L_2/L_3 composite linear fabric in the highly sheared D_3 domains. The stereoplot (lower hemisphere equal-area projection) document such geometric relations.

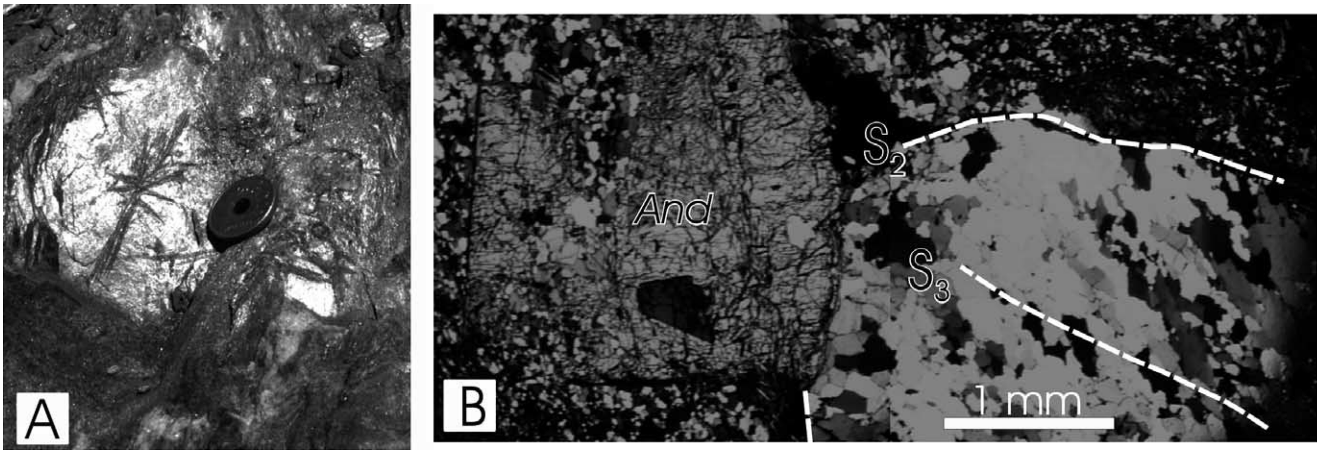

Fig. 8. Examples documenting the post-kinematic crystallisation of low-pressure assemblages relative to the D_3 deformation event in the high-grade rock sequences of the Alpujarride units. (A) Andalusite porphyroblasts suturing the D_2–D_3 composite fabric in the Salobreña unit. (B) Thin section showing post-tectonic andalusite porphyroblasts overprinting F_3 folds in the Salobreña unit.

contacts among the different units (Fig. 2) (see also Crespo-Blanc et al., 1994; Azañón et al., 1997). It must be stressed that the present geometry of the D_4 faults, dipping slightly towards the SW in the Adra region (Fig. 2), is due to the late, Tortonian–Messinian, shortening episode (Rodríguez-Fernández and Martín-Penela, 1993).

The D_4 shearing is spectacularly exposed in the eastern sector of the study area, where contacts between the high-grade rocks of the Adra unit and the underlying units are systematically controlled by top-to-the-N fault system. Extensive omission of the complete nappe sequence also occurs, being the high-grade Adra unit directly juxtaposed onto the low-grade rocks of the Escalate and Lújar-Gádor tectonic units (Fig. 2 and cross-section in Fig. 9A). At meso-scale, the N-verging fault systems systematically show an arcuate geometry, resulting in an overall ramp-flat geometry (Fig. 9B–D). Subsidiary structures are associated with the fault movement. They consist of F_4 folds and contractional kink bands and small-scale extensional joints and veins (Fig. 9C). Both types of fabrics, contractional and extensional, strike roughly perpendicular to D_4 fault transport direction and occur in correspondence with contractional and extensional bends along the dip of the D_4 arcuate faults. The F_4 axial schistosity is weakly developed and there is no metamorphic crystallisation.

Pervasive regional-scale folding of the metamorphic isograds and of the linked D_2–D_3 composite fabric of the Alpujarride Complex is systematically observed (e.g. Azañón et al., 1997; Balanyá et al., 1997; Orozco et al., 1998, 2004). In the study area, this folding episode consists of F_4, E–W-trending north-verging synclines. These F_4 synclines show a short southern flank, generally vertical or highly-dipping and are situated at the footwall of main D_4 fault-controlled boundaries. The relationships between the D_4 faulting and F_4 footwall synclines are clearly exposed in the Adra region (easternmost part of the study area in Fig. 2) and documented in the geological cross-section shown in Figs. 9A and 10A. The cross-sections clearly illustrate how the D_4 faults systematically cut down-section through the footwall rocks. It is also worth noting that these F_4 synclines trend subperpendicular to the D_4 slickenlines and are north-verging, which is coherent with the slip direction along the D_4 faults. The D_4 fault systems also induced extensive folding and tectonic repetition of the lithological layering (carbonate and pelitic protoliths) in the Lújar-Gádor unit, northward of the Sierra Alhamedilla area (Figs. 2 and 10B).

4. Discussion

4.1. Structural summary: constraints to an exhumation model

Based on the superposition of structures from small-to-medium scale described above, the following points should be emphasised: (i) a sequence of deformation episodes from a ductile (D_2–D_3) to a brittle (D_4) regime was reconstructed, which culminates in a post-metamorphic re-organisation of the Alpujarride Complex; (ii) such a sequence of deformation events was observed in all Alpujarride rock types, independently from the protolith ages (Palaeozoic–Triassic rocks), metamorphic grade and/or structural position within the nappe pile; (iii) the ductile deformation field (D_2–D_3) records the progressive exhumation of the Alpujarride complex from deep to shallow crustal conditions, during progressive top-to-the-N/NE shearing; (iv) the end of D_3 deformation took place at shallow crustal levels, as attested by the post-kinematic crystallisation of low-P mineral associations, suturing the D_2–D_3 composite fabric in the higher grade rocks (confining pressure below ca. 4 kbar as deduced by the stability of andalusite in the high grade domains; Fig. 3); (v) this post-kinematic blastesis suggests a

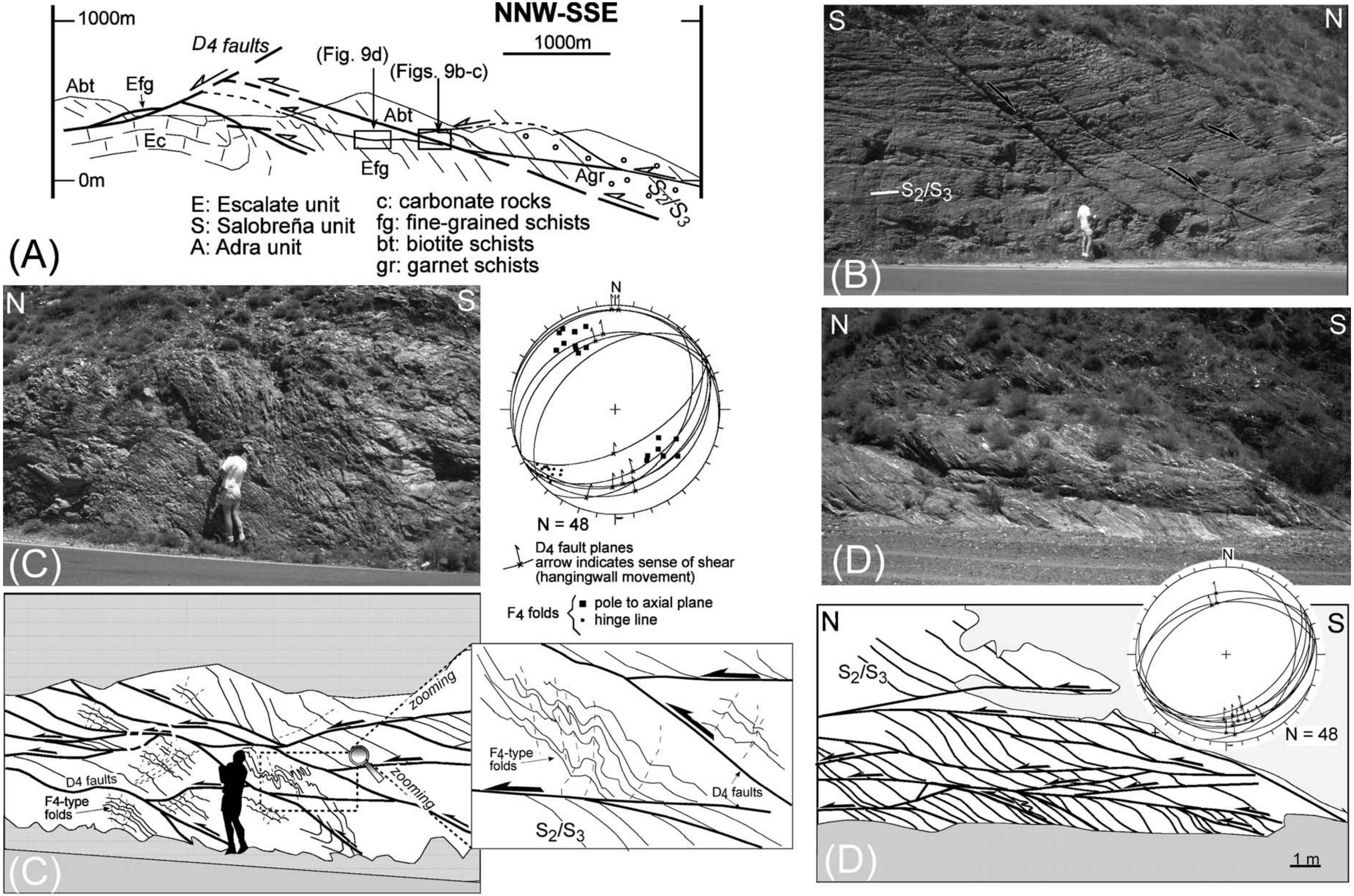

Fig. 9. (A) Cross-section showing the attitude of D_4 faulting at the tectonic contact between the Adra and Escalate units (Rambla de Huarca area; see Fig. 2 for cross-section location). (B) D_4 faulting in the Adra unit (hanging wall of the contact). (C) Field example, interpretative line-drawings and stereoplots (lower hemisphere equal area projection) illustrating the subsidiary structures (F_4 kink-type folding) associated with the D_4 top-to-the-N brittle shearing at the outcrop-scale. (D) Attitude of the D_4 low-angle faulting in the Escalate unit (footwall of the contact).

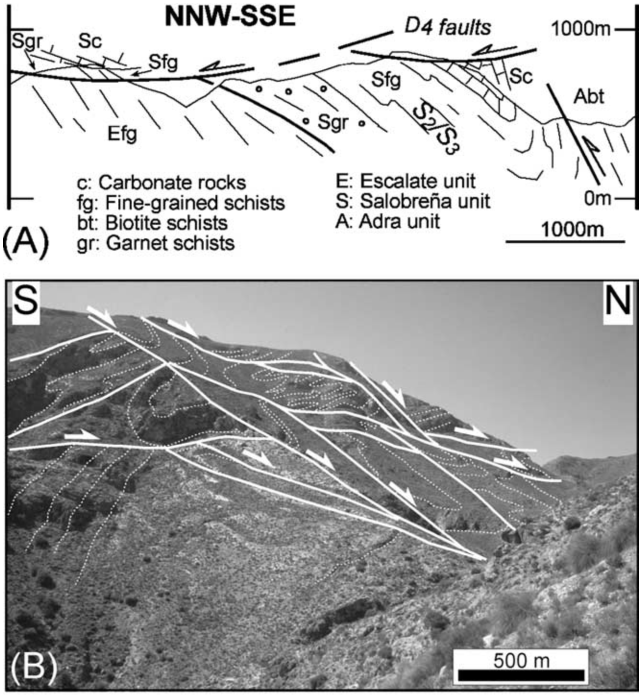

Fig. 10. (A) Cross-section showing the relationships between F_4 folding and top-to-the-N brittle faulting in the Adra region (see Fig. 2 for cross-section location). (B) View (looking north-westward) and interpretative line drawing of the northern portion of the Sierra Alamedilla area (see Fig. 2 for location), showing relationships between D_4 faulting and F_4 folding in the Escalate unit.

hiatus between the ductile- and brittle-dominated deformation evolution; and (vi) the D_4 top-to-the-N brittle faulting episode is responsible for the final exhumation of the Alpujarride Complex nappe edifice. Such a faulting episode is associated with mesoscale features such as folds and kink bands oriented roughly parallel to the regionally-distributed F_4 folds. Based on the kinematic compatibility that exists among the orientation and vergence of such folds and the sense of shear of the D_4 faults system, the F_4 folds can be tentatively interpreted as drag folds associated with the D_4 fault movement. Systematic preservation of F_4, N-verging synforms at the footwall of the main D_4 fault-bounded contacts is here interpreted as a consequence of the incremental deformation linked to D_4 shearing. This constitutes an important point in our structural reconstruction, as in previous papers, independently from their tectonic interpretation (compressional or extensional), the small-scale F_3 folds were considered to be second- or higher-order folds associated with the regional-scale north-facing folding episode (see e.g. Simancas and Campos, 1993; Azañón et al., 1997; Orozco et al., 1998, 2004; Azañón and Crespo-Blanc, 2000). Our structural data rule out a possible connection between the F_3 fold system and the F_4 large-scale one, for the following reasons: (i) F_3 hinge lines trend roughly parallel to the N/NE-directed L_2–L_3 composite fabric, whereas F_4 folds are E–W-trending and, systematically, N-verging; and (ii) the azimuthal distribution of F_3 axes are controlled by intensity and localisation of the retrogressive D_2–D_3 top-to-the N/NE non-coaxial shearing. Based on these arguments, we exclude a continuum of deformation from D_3 to D_4 and, consequently, the interpretations considering the large-scale N-facing folds as produced during progressive (ductile-to-brittle) top-to-the-N shearing (Orozco et al., 2004)

In summary, all the arguments discussed above show that any model for the exhumation of the Alpujarride Complex has to account for the following points: (1) there is a hiatus, documented in terms of both structural and metamorphic record, between the ductile (D_2–D_3)- and the brittle (D_4)-dominated exhumation-related deformation history, although there is an apparent correspondence of the present-day stretching direction (probably accidental in the light of the large-scale block rotations detected in the area; e.g. Platt et al., 2003b, and references therein); (2) within the ductile-dominated evolution, a continuum from D_2 to D_3 deformation has been reconstructed and associated with a progressive top-to-the-N/NE non coaxial shear; and (3) the D_4 top-to-the-N faulting event is responsible for the final structural architecture of the Alpujarride Complex.

4.2. Age of exhumation

In order to elucidate the tectonic context leading to the superimposition of structures deduced from our study, it is crucial to discuss first the chronological constraints to the ductile (D_2–D_3) and brittle (D_4) exhumation-related deformation stages recognised in the Alpujarride Complex.

Ages of metamorphic episodes associated with ductile deformation in the Alpujarride Complex have been extensively investigated by means of both high- (SHRIMP U/Pb dating on zircons) and low- ($^{40}Ar/^{39}Ar$ dating on white micas) T isotopic closure systems. As previously reported, the large amount of radiometric data clustering at the Early Miocene times (19–23 Ma) has had a major impact on the interpretation of the tectonic environment controlling the exhumation of the Alpujarride Complex. However, interpretation of this radiometric cluster is not straightforward. In particular, it has been interpreted either as the evidence for a thermal pulse followed by rapid exhumation in a post-orogenic extensional regime coeval with the Alboran rifting and the collapse of the Betic chain (e.g. Zeck et al., 1992; Vissers et al., 1995; Platt et al., 1996, 1998, 2003a; Zeck, 1996; Platt and Whitehouse, 1999; Whitehouse and Platt, 2003) or as the evidence for a metamorphic climax during thickening and subduction of the Alboran Domain (Sánchez-Rodríguez and Gebauer, 2000; López-Sánchez-Vizcaíno et al., 2001). However, the latter interpretations are at odds with the fact that: (i) rare-earth elements in zircon and garnet point to a decompressional signature rather than to the peak of metamorphism for the U/Pb ages obtained from the zircon rims (Whitehouse and Platt, 2003), (ii) metamorphic Alpujarride clasts were included in sedimentary rocks lying over the internal zone of the Betics since Burdigalian times (20.5–16.4 Ma; Lonergan and Mange-Rajetzky, 1994); and (iii) Early Miocene (21 ± 2 Ma) granitic dykes cut across the D_2–D_3 ductile-structured rocks of the Alpujarride Complex in the western Betics (Zeck et al., 1989; Sánchez-Gómez et al., 1995). Based on the above, we may conclude that the Alpujarride units were almost completely exhumed prior to the Burdigalian.

The Miocene extension linked to the Alboran rifting (e.g. Comas et al., 1992; García-Dueñas et al., 1992) provides key issues for the timing and tectonic context of the brittle faulting affecting the Alpujarride Complex. In particular, Crespo-Blanc et al. (1994) and Crespo-Blanc (1995) showed that extension liked to the Contraviesa fault system was active during Burdigalian–Langhian times (approximately 20.5–15 Ma, according to Berggren et al. (1985)). Moreover, the lower Burdigalian generalised marine transgression in the inner part of the Gibraltar Arc suggests that the onset of extension in that region took place possibly at the Oligocene–Miocene boundary (Rodríguez-Fernández et al., 1999).

Our structural study documented that high- and low-grade units (Palaeozoic and Triassic protoliths, respectively) record the same ductile deformational pattern (D_2–D_3), attesting that this exhumation-related fabric was acquired during the same Alpine deformation history, although in different P–T environments. The end of this early part of the exhumation path is marked by the post-kinematic crystallisation relative to the D_3 deformation phase of low-pressure metamorphic assemblages, indicating that the growth of these late-stage porphyroblasts outlasted D_3 deformation. The hiatus associated with the post-D_3 static crystallisation of low-pressure mineral assemblages also indicates that the Alpujarride metamorphic pile was almost completely exhumed and resided at shallow crustal conditions before low-P metamorphic conditions were achieved in the exhumed metamorphic pile. Consequently, we infer that the Early Miocene radiometric age cluster corresponded to a regional thermal pulse that affected the Alboran Domain (Platt et al., 1998, 2003a), but taking place at the end of the ductile D_2–D_3 exhumation of the Alpujarride Complex, when it had almost completed its way back to shallow crustal conditions. It is thus suggested, as already proposed by Lonergan and Mange-Rajetzky (1994), that the Early Miocene thermal pulse produced a widespread resetting of the isotopic systems in the tectonic units of the Alpujarride Complex. This is confirmed by the overlapping of ages derived by both high- (SHRIMP U/Pb dating on zircons) and low- (^{40}Ar/^{39}Ar dating on white micas) temperature isotopic closure systems.

The D_4 top-to-the-N faulting then re-organised the previously exhumed, ductile-deformed Alpujarride Complex metamorphic pile at shallower crustal conditions (confining pressure below ca. 4 kbar in the high-grade rocks). This faulting event is also responsible for the tectonic elision and thinning of the nappe sequences and can be thus referred to as the Early Miocene phases of the Alboran rifting. In particular, it can be tentatively ascribed to the Contraviesa extensional fault system of Crespo-Blanc et al. (1994) for the style of deformation and the associated extension direction.

We conclude: (i) the early ductile-dominated exhumation stage recorded by the D_2-to-D_3 composite fabric can be assumed as pre-Miocene in age and (2) the D_4 top-to-the-N faulting corresponds to an extensional event linked to the early phases of the Alboran rifting (Early to Middle Miocene in age) and is responsible for the final exhumation of the Alpujarride Complex nappe edifice and its final tectonic organisation.

4.3. Tectonic interpretation: framing the exhumation of the Alpujarride Complex within the western Mediterranean scenario

The Betic–Rif orogen represents the westernmost segment of the peri-Mediterranean orogenic system, whose inner domains, stretched and drifted apart during the Neogene rifting processes, are now represented by boudins of the Alpine metamorphic belt exposed in northern Apennines, Calabria, Kabylides and in the Alboran Domain. These boudins constitute the remnants of an active margin linked to the western Mediterranean subduction zone (WMSZ), presently documented by the Calabrian subduction zone (Fig. 1A; Faccenna et al., 2004). The evolution of the WMSZ is marked by a first phase of crustal thickening during orogenic complex formation (attested by the D_1 fabric in the Alpujarride Complex), followed by trench retreat and back-arc extension (Faccenna et al., 2001, 2004). Although geological and radiometric evidence indicates that crustal thickening in the Mediterranean region is bracketed between the Paleogene and the Early Miocene (Faccenna et al., 2004, and references therein), in the Betic Cordillera pre-Miocene radiometric ages are poorly preserved. Nevertheless, ages derived from both high-T (U/Pb SHRIMP dating on zircons from the Adra tectonic unit, indicating an age of ∼37 Ma; Sánchez-Rodríguez, 1998) and low-T (^{40}Ar/^{39}Ar dating on single barroisitic amphibole from the Nevado–Filabride Complex indicating an age of ∼44 Ma; Monié et al., 1991) closure isotope systems, can be tentatively used to constrain the timing for the underthrusting of the Alboran Domain to Paleogene times. This is coherent with the compressive regime, which produced large-scale folding in the Malaguide Complex, which took place during the NP23 zone time interval (Martín-Martín et al., 1997), i.e. between 31.5 and 31 Ma (Berggren et al., 1985).

Thickening in the internal zone of the WMSZ was closely followed by the extensional collapse of the orogenic system, in conjunction with the inception of back-arc extension at about 30 Ma (Jolivet and Faccenna, 2000; Faccenna et al., 2004). Back-arc extension caused first the opening of the Liguro–Provençal basin, and then shifted southwestward with the opening of the Alboran (since 27 Ma according to the thermal modelling of Platt et al. (1998)) and Valencia (since 26 Ma according to Vergés and Sàbat (1999)) basins.

The relative chronology of structures and metamorphic events integrated with the arguments discussed above point to a main phase of ductile exhumation for the Alpujarride Complex, which occurred in pre-Miocene times, namely prior to the onset of the main phase of the Alboran rifting. The regional-scale structural organisation of the Alpujarride Complex as a post-metamorphic nappe stack with metamorphic-zone inversions and the similar structural signature of the rock types (independently from their structural position and/or metamorphic grade) attests that in the Alpujarride Complex there is no evidence for the abrupt transition in both metamorphic grade and deformation intensity from lower-plate to upper-plate rocks, which is the major diagnostic features of extensional metamorphic core complexes (e.g. Lister and Davis, 1989). Consequently, a post-orogenic extension-related exhumation process linked to the Alboran rifting may be ruled out. Accordingly, our preferred model for the ductile exhumation stage is a syn-orogenic tectonic scenario. On the basis of the structural data collected we cannot establish if the ductile deformation (D_2–D_3) accompanying the main phase of exhumation of the Alpujarride Complex is related to compressional deformation (as suggested by Tubía et al. (1992), Simancas and Campos (1993) and Azañón and Crespo-Blanc (2000)), or if it is related to extensional processes developed at the top of the accreting orogen (Balanyá et al., 1997). The first scenario, however, seems to fit better the pervasive distribution of the ductile non-coaxial shearing and the progression in the deformation intensity (from D_2 to D_3) systematically recorded in all the tectonic units constituting the Alpujarride Complex nappe edifice. In particular, erosion and coeval crustal thickening can efficiently exhume mid- to low-crustal sections buried to a depth of around 30–35 km (Stüwe and Barr, 1998), which indeed constitute the main rock type of the Alpujarride Complex in the study area. This hypothesis is also supported by the pre-Miocene apatite fission-track ages (from about 28 to 44 Ma) obtained from detrital zircons and apatites hosted in Oligo-Miocene synorogenic sediments deposited on the northern margin of the Betic Cordillera Internal Zone, which are interpreted as the record of the progressive erosive unroofing of the Alboran Domain thrust stack (Lonergan and Johnson, 1998).

At the onset of the Alboran rifting, the Alpujarride Complex was already exhumed at shallow crustal conditions, entering the brittle domain. Thinning by the anastomosing D_4 top-to-the-N brittle extensional shearing produced the final unroofing of the nappe edifice under anomalously high geothermal gradient conditions. The marked increase in cooling rate during the Burdigalian (from about 16 to 20 Ma) deduced from the fission track dating of the Alboran Domain units (Lonergan and Johnson, 1998; Platt et al., 1998; Sosson et al., 1998) is consistent with the Early Miocene switching from shortening to post-orogenic extension. We thus propose a two-stage tectonic model for the exhumation history of the Alpujarride Complex: an early syn-orogenic exhumation (D_2–D_3 in Fig. 11), Eocene–Oligocene in age, followed by the post-orogenic extensional collapse of the Betic chain during the Early Miocene opening of the Alboran Sea (D_4 in Fig. 11). Most of the exhumation path occurred during orogenic complex formation and active subduction of the WMSZ, and exhumation was mainly completed before the onset of the thermal relaxation processes connected to the post-orogenic Alboran rifting. It is then suggested that the tectonic evolution of the Alpujarride nappe Complex includes an early underthrusting regime, followed by the progressive exhumation of the deep-seated rocks during active convergence. This interpretation is supported by the preservation of highly temperature-sensitive high-P/low-T (Fe, Mg)-carpholite-bearing parageneses in the low-grade metapelites successions of the Alpujarride Complex (Goffé et al., 1989; Azañón et al., 1998; Both-Rea et al., 2002), which is indicative of exhumation processes attained during suppressed geothermal conditions typical of subduction zone metamorphism (see Jolivet et al., 1998a). In this framework, we suggest that the different thermal signatures recorded by the tectonic units of the Alpujarride Complex might have been related to the different positions occupied within the Betic orogenic wedge prior to the Alboran rifting: more external and shallowly located for the low-grade units (early exhumed), and more internal and deeper for the higher-grade ones. This may also explain why the 'cold' units apparently escaped heating during decompression, describing isothermal retrogressive paths, while others (the innermost and the deeper) experienced heating during the last stages of decompression, such as those flooring the Alboran Sea (Platt et al., 1996, 1998).

The switch from crustal thickening to crustal thinning is recorded in the Alpujarride Complex by a network of top-to-the-N extensional shear zones (D_4 event in our reconstruction), responsible for the final post-metamorphic reorganisation of the whole nappe complex. Orozco et al. (2004) have recently proposed a similar scenario, emphasizing the role of the post-orogenic top-to-the-N extensional phase in controlling the nappe architecture of the Alpujarride Complex. However, in our model, conversely to what is commonly assumed in extension-driven exhumation models (see also Platt and Vissers, 1989; Vissers et al., 1995), extensional deformation only contributes to the late-stage exhumation path of the deep-seated Alpujarride rocks. On the other hand, the post-orogenic extensional phase strongly influenced the final structural organisation of the nappe edifice.

The two-stage, syn- and post-orogenic, exhumation model presented here for the unroofing of the Alpujarride Nappe Complex is consistent with the idea that the major contribution to the exhumation history of the HP metamorphic rocks exposed in the Mediterranean region

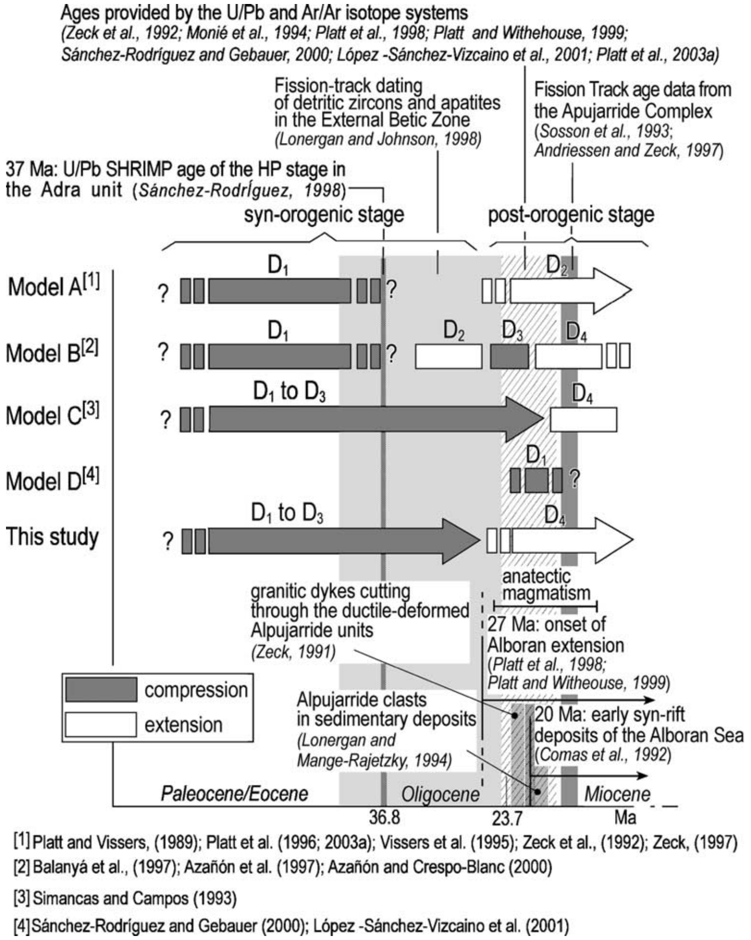

Fig. 11. Our model for the tectonic evolution of the Alpujarride Complex compared with the principal models previously proposed for the tectonic evolution of the Alboran Domain. D_1 event corresponds to the thickening and underthrusting stage; D_2 corresponds to the inception of the exhumation for the deep-seated units. (For ages provided by the U/Pb and Ar/Ar isotope systems see Monié et al. (1994) and others.)

occurred during orogenic complex formation, within an overall convergent plate setting (Jolivet et al., 1998a). The orogenic wedge dynamics, with or without the contribution of syn-orogenic extension, is thus here recognised as the main factor controlling modes exhumation and P–T evolution of the deep roots of the Alpine orogen in the Mediterranean region.

4.4. A cautionary note

The post-metamorphic D_4 nappe-forming event responsible for the present architecture of the Alpujarride Complex necessarily occurred after the Early Miocene thermal pulse was achieved, as it is responsible for the juxtaposition of high-grade, thermally reset units (i.e. Adra unit) onto the previously ductile-structured nappe pile. Nevertheless, the regional consistency of the sense of shear associated with the D_4 faulting episode apparently rules out the possibility that these nappes developed as a chaos-type structure induced by anastomosing extensional fault systems (Wernicke and Burchfiel, 1982). Also, the regular distribution of the nappes and the regional significance of metamorphic grade recurrences within the nappe edifice (Azañón et al., 1994; Balanyá et al., 1998; Azañón and Crespo-Blanc, 2000) are not coherent with a chaos-type extensional structure. Consequently, in the assumption made in this study that the post-metamorphic tectonic setting resulted from the tectonic transport along extensional fault systems associated with the Early Miocene rifting, the main question remains to be addressed concerns how an extensional event can produce a nappe architecture so well organised as that of the Alpujarride Complex.

5. Conclusions

From the structural data presented in this paper, the following key points must be considered in any tectonic model proposed in the future: (i) the ductile exhumation of the Alpujarride nappe complex from deep to shallow crustal conditions occurred during progressive top-to-the-N/NE shearing (present co-ordinates); (ii) brittle top-to-the-N extensional faulting is responsible for the final organisation of the Alpujarride complex into a complex stack of nappes where both normal and inverted metamorphic sequences are recorded; and (iii) no link exists between the ductile- and brittle-dominated tectonic evolution of the nappe edifice, being the two deformation stages separated by a deformation hiatus, which occurred under low-P metamorphic conditions. These points provide the evidence that the previously ductile-deformed Alpujarride nappe pile was already exhumed to near surficial conditions before the onset of the post-orogenic thermal relaxation processes connected to the Early Miocene Alboran rifting.

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