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High-temperature emplacement of the Los Reales peridotite nappe (Betic Cordillera, Spain)

JOSE M. TUBIA and JULIA CUEVAS

Departamento de Geomorfología y Geotectónica, Facultad de Ciencias, Universidad del País Vasco,
Apartado 644, Bilbao, Spain

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Abstract—West of Malaga (Southern Spain), the Sierra Alpujata belongs to the Alpujarride Complex in the Internal Zone of the Betic Cordillera, and is composed of migmatites underlying alpine-type peridotites. The migmatite–peridotite contact zone is a ductile zone of shear with highly strained rocks. This is demonstrated using field structural data and systematic analysis of the microstructures and the preferred orientations of enstatite and olivine. We establish that the peridotites were thrust over continental crust from the WSW to the ENE, in relatively low temperature conditions for the olivine deformation (porphyroclastic and mylonitic textures; $T \simeq$ 900°C) but high enough to lead to syntectonic migmatization in crustal rocks, with identical kinematic signatures on both sides of the contact.

Résumé—A l'Ouest de Malaga, la Sierra Alpujata appartient au Complexe Alpujarride des Zones Internes des Cordillères Bétiques. Elle est constituée par des migmatites surmontées par des péridotites alpinotypes. Une zone mylonitique apparaît au contact migmatites–péridotites. Les données structurales de terrain montrent qu'un chevauchement ductile sépare les péridotites de la série migmatitique. L'analyse systématique des structures et des orientations préférentielles de réseau dans l'enstatite et l'olivine permet d'établir que les péridotites ont été charriées de l'Ouest-Sudouest vers l'Est-Nordest, dans des conditions de relativement base température pour la déformation de l'olivine (facies porphyroclastique à mylonitique; $T \simeq$ 900°C). Par contre, ces conditions thermiques, de haute température pour le matériel de composition crustale, conduisent à la migmatisation. Ces migmatites sont elles-mêmes déformées à proximité de leur contact avec les péridotites, suivant un régime cinématique analogue.

INTRODUCTION

THE RONDA ultrabasic massifs, in the westernmost part of the Betic Chain, are formed by alpine-type peridotites located in a continental crustal setting (Nicolas & Jackson 1972). Unlike other similar massifs (Lanzo, Lherz, Beni Bousera) of the European alpine belt, highly metamorphic rocks outcrop extensively under the Ronda peridotites (Lundeen 1978; Navarro-Vila & Tubia 1983). These metamorphic materials display structural characters comparable to those existing in the dynamothermal aureoles underlying the basal tectonites of many ophiolitic series (Williams & Smyth 1973, Coleman 1977, Nicolas & Le Pichon 1980, Boudier & Coleman 1981, Jamieson 1981). According to Boudier *et al.* (1982), the formation of these aureoles is caused by the overthrusting of an oceanic slab of lithosphere in an oceanic environment near a subduction zone.

The Ronda peridotite massifs appear in the Betic zone, where large N-directed nappes have been recognized for a long time (Westerveld 1929, Blumenthal 1949). In short, two important questions arise in connection with the Ronda peridotites. (1) Can the deformation of the basal peridotites and underlying metamorphic rocks be regarded as produced by the peridotite slab emplacement? (2) Is this deformation related to the classically proposed northward sense of thrusting in the Betic zone? In order to clear up these questions this paper describes the contact zone between the peridotite massif and the underlying metamorphic rocks of Sierra Alpujata. A systematic study of fabrics, microstructures and field structures of both the peridotites and the metamorphic rocks is used to derive the kinematics of the peridotite emplacement.

GEOLOGICAL SETTING

In the Internal zone of the Betic chain, three tectonic complexes have been distinguished, which are, from bottom to top: the Nevado–Filabride, the Alpujarride and the Malaguide (Julivert *et al.* 1972). In Sierra Alpujata, the metamorphic rocks and the overlying peridotites belong respectively to the recently defined (Navarro-Vila & Tubia 1983) Ojen and Los Reales nappes, attributed to the Alpujarride Complex.

The Ojen nappe is composed of a metapelitic sequence overlain by a thick series (~400 m) of mainly dolomitic marble (cross-section, Fig. 1). This nappe is affected by a metamorphism producing, in the metapelitic sequence, mineral associations with biotite, garnet and sillimanite. In the vicinity of the contact with the overlying Los Reales peridotite nappe and down to a maximum thickness of 500 m under it coarse-grained migmatites crop out. They present mineral associations with K-feldspar, plagioclase, cordierite and quartz. Within 100 m of the contact with the peridotites these rocks display an intense plastic deformation, and the mineral association is complemented by biotite, sillimanite and garnet. Besides the existence of this inverse metamorphic zonation, the Ojen nappe material is characterized, all along the contact with the upper unit,

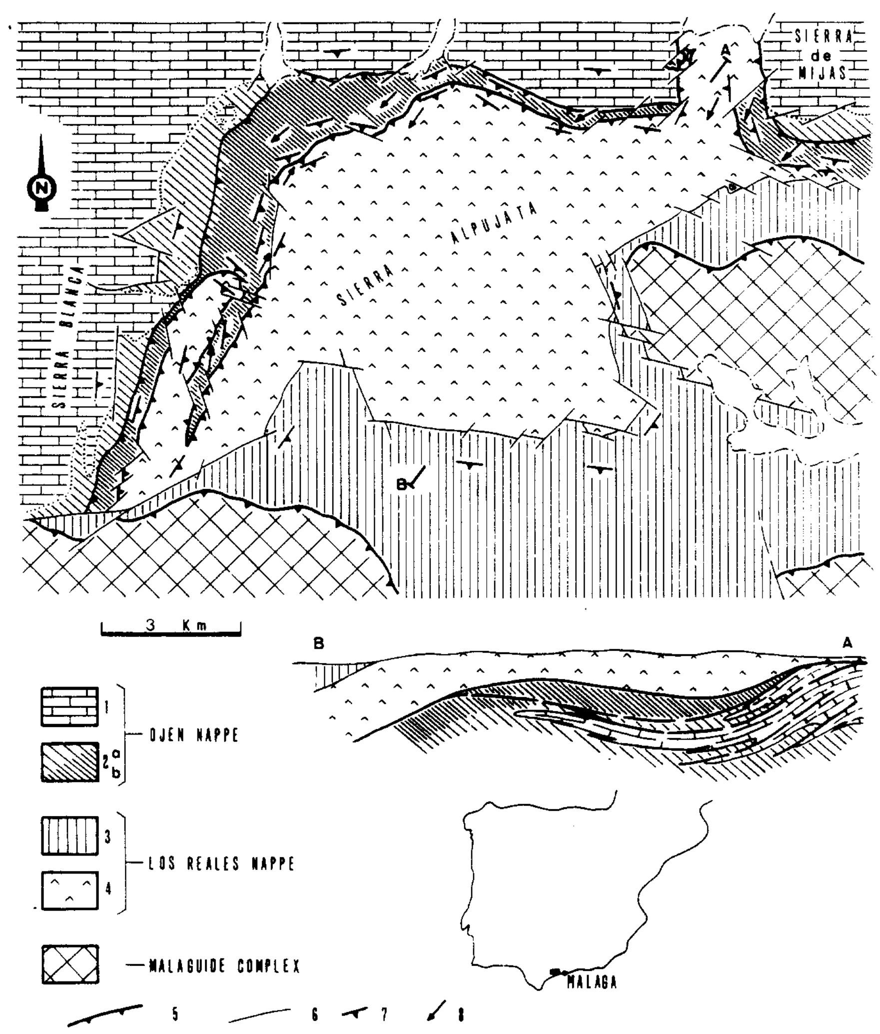

Fig. 1. Map and schematic geological profile across the Sierra Alpujata, after Tubia (unpublished). 1, marbles; 2a, metapelitic sequence; 2b, migmatites and mylonites; 3, metamorphic series of Los Reales nappe; 4, peridotites; 5, thrust contact; 6, other tectonic boundaries; 7, foliation dips; 8, stretching lineations; unornamented, post-nappe deposits.

between Sierra Blanca to the west and Sierra de Mijas to the east (Fig. 1), by (1) the systematic presence of intensely deformed migmatites and mylonitic rocks up to 100 m thick, and (2) the presence of isoclinal folds, hectometric to metric in amplitude, with axes trending towards N 105°E on average, and with vergence towards the NNE. The overturned limbs of these folds place the normally underlying metapelitic sequence over the marbles.

The base of Los Reales nappe is made of peridotites 1.5 km in maximum thickness, composed mainly of lherzolites, with minor dunites and harzburgites (Hernandez-Pacheco 1967, Obata 1977 & 1979). These peridotites are occasionally cross-cut by acidic dykes, as described by Hernandez-Pacheco (1967) in Sierra Alpujata and by Dickey & Obata (1974) in Sierra Bermeja. Their mineralogical composition is similar to that of the coarse-grained migmatites of the underlying Ojen nappe. It is convenient to remark that harzburgite and dunite, as well as the acid dykes, are particularly abundant in the basal zone of the Sierra Alpujata peridotites, whereas lherzolite is predominant in the core. Above the peridotites there is a metasedimentary unit composed of kinzigites, migmatites, gneiss and graphitic schists. These rocks are affected by prograde metamorphism which, in this region, presents associations varying from high grade, with K-feldspar, kyanite and garnet in the kinzigites, to low to medium grade, represented by biotite-bearing schists.

FIELD STRUCTURES

The mylonitic foliation and lineation related to the emplacement of the Los Reales nappe over the Ojen nappe are best imprinted in the proximity of the contact. In the Ojen nappe, these structures affect mainly the quartz–feldspar migmatites; in the Los Reales nappe only peridotites are affected (Fig. 2). Folds formed synchronously with the mylonitic foliation and the shearing structures are also described. Later deformations are not considered here.

Mylonitic foliation

The rock foliation has the same orientation in both nappes, parallel to the contact surface, striking N 110°E on average and dipping moderately S. Minor variations

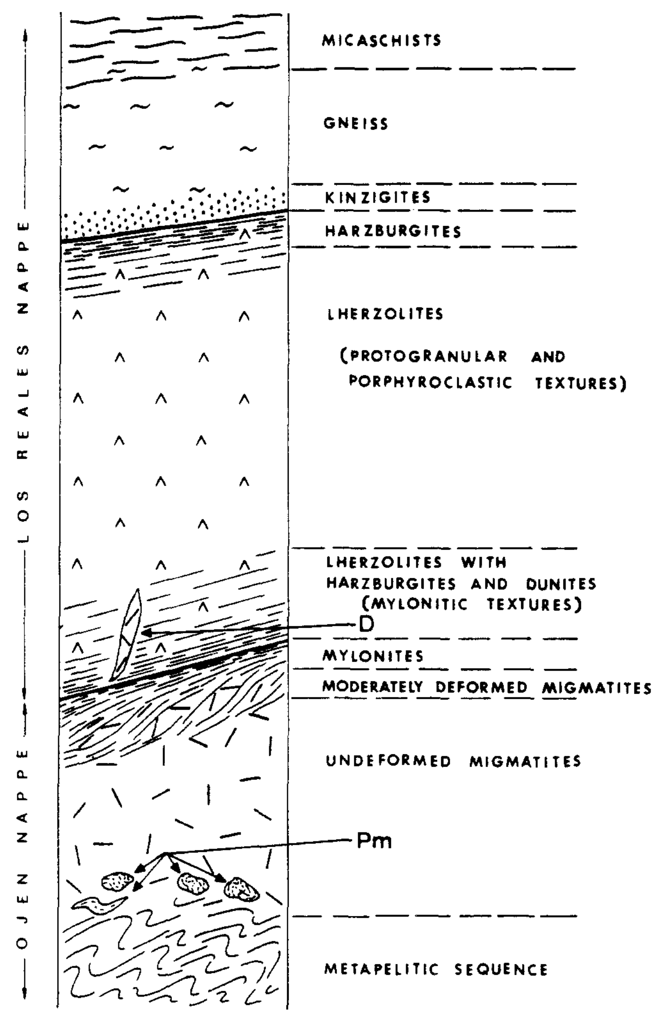

Fig. 2. Synthetic cross section through the Sierra Alpujata with the lithological and structural variation near to the contact between Ojen and Los Reales nappes. Discontinuous lines represent the mylonitic foliation which increases toward the nappe contact. Undeformed rootless acid dykes (D) cross-cut the peridotite. Patches of metapelitic sequence (Pm) in the basal undeformed migmatites indicate the gradual decrease of migmatization going away from the peridotite contact. The thickness of the peridotite slab is approximately 1.5 km.

along the contact are due to late open folds (Fig. 3a). The foliation is defined by the shape orientation of quartz and K-feldspar in the Ojen nappe, and by olivine and enstatite grains in the Los Reales nappe. The foliation, parallel to the mean mineral flattening surface, can be considered as parallel, or nearly so, to the *XY* principal plane of finite strain (Nicolas & Poirier 1976). It is locally reinforced by a tectonic banding, with alternating layers of different grain size. Within 100 m of the contact the rocks of the Ojen nappe are always strongly foliated; further away the foliation only appears in anastomosing bands which delimit plurimetric lozenge-shaped bodies of coarse grained migmatite; and finally, at a distance greater than 500 m, only sporadic and narrow (5 cm) mylonitic bands appear in otherwise nearly unstrained migmatite. Locally, on both sides of the contact zone itself, the mylonitic foliation is obliquely cross-cut by shear zones millimetres to decimetres in thickness. The core of these shear zones is made up of much smaller and flattened grains than on their periphery, and in some cases these form a dark-coloured ultramylonite band.

Mylonitic lineation

A penetrative and strongly defined stretching lineation appears in the mylonites on both sides of the contact, N 70°E in average azimuth (Fig. 3b). In the migmatites of the Ojen nappe it is marked by the elongation of biotite and sillimanite aggregates, and K-feldspar porphyroclasts. In the peridotites, the enstatite porphyroclasts, with *X*/*Z* axial ratios in the range of 10/1, define a lineation, similar to the 'lamellar enstatite lineation' described by Darot & Boudier (1975).

Folds

Rare folds affect the mylonitic foliation in the rocks of the Ojen nappe; they are strongly flattened, asymmetric, and have amplitudes ranging from one millimeter to ten centimeters. Their axes, usually subparallel to the stretching lineation, may vary in orientation up to 90° to

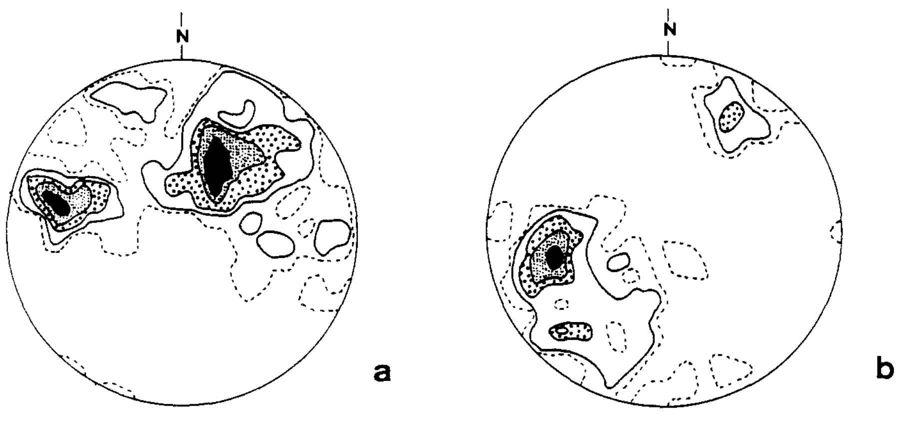

Fig. 3. Orientation of field structures in the contact zone between Ojen and Los Reales nappes (lower-hemisphere equal-area projections). (a) Poles to mylonitic foliation, 105 measurements; contours: 0.5, 1.5, 3.5, 5.5, >7.5%. (b) Stretching lineations, 60 measurements; contours: 0.5, 1.5, 5.5, 8.5, >11.5%.

the lineation. These features resemble those of sheath folds, as described by Carreras *et al.* (1977) in the quartz mylonites of the Cape Creus. These folds affect the foliation, but develop a new mylonitic foliation parallel to their axial planes. Consequently, the planar structures of the Ojen nappe, acquired in the course of successive stages of mylonitization related to the emplacement of the Los Reales nappe, have probably been transposed several times.

Shear-band structures

In the west of Sierra Alpujata and south of Sierra de Mijas the K-feldspar-bearing rocks show C-S structures like those described by Berthé *et al.* (1979) in granitic orthogneiss. The dominant planar structure corresponds to the C shear-plane which cuts obliquely across the S foliation, or average mineral flattening plane (Fig. 4a). This suggests that deformation was produced under a regime close to simple shear (op. cit.). The angle (~30°) between C and S planes suggests a late deformation event along with moderate strain. In our opinion, the zones displaying these C-S structures correspond to stages of the emplacement of the Los Reales nappe after the mylonitization described in this paper, since they are accompanied by retrograde metamorphism in the rocks of the Ojen nappe and by serpentinization in the peridotites.

MICROSTRUCTURES

Both the peridotites and migmatites show a progressive reduction in grain-size and variation in grain-shape when approaching the contact. The core of the peridotite massif shows coarse-grained porphyroclastic and protogranular textures (Mercier & Nicolas 1975). All along the contact and within a sole of 300 m in thickness the textures are fine grained porphyroclastic and mylonitic with a usually fine-grained groundmass (0.1–0.3 mm) of olivine including large enstatite (~1 cm) and sometimes olivine porphyroclasts.

In the quartz–feldspar mylonites, the K-feldspar appears commonly as porphyroclasts up to 5 cm in size, with undulose extinction. They are enclosed in a groundmass made of small K-feldspar and quartz grains forming asymmetric pressure shadows (Fig. 4b); they are commonly affected by fractures (Fig. 4c) along which small and undeformed K-feldspar neoblasts appear. The quartz microstructures are variable, depending on whether this mineral dominates or not with respect to the brittle and/or phyllosilicate minerals. In the quartz-poor mylonites quartz-ribbons are observed whereas in quartz-rich ones (Qtz > 50%), elongate (Bouchez & Pêcher 1981) and cross-hatched mosaic microstructures (Lister & Dornsiepen 1982) are common (Fig. 4d).

The microstructures described above due to plastic deformation contrast with those of the underlying undeformed to slightly deformed migmatites. In these, the K-feldspar grains have no particular shape-preferred orientation. The quartz grains are coarse with rather straight boundaries suggesting a post-tectonic high-temperature coarsening. Slight undulose extinction zones mark the imprint of late minor strain pulses.

QUARTZ AND OLIVINE-ENSTATITE ORIENTATIONS

The quartz *c*-axis orientation in the quartz-rich (Qtz > 50%) migmatite tectonites of the Ojen nappe, and the olivine and enstatite total crystallographic orientations in the mylonitic peridotites have been studied optically using the U-stage. The sample descriptions are given in Table 1. The orientation diagrams have been plotted

Table 1. Distance to the nappe-contact, mineralogical assemblage, grain-measurements and quartz-microstructures of the samples selected for petrofabric analysis. qtz, quartz; gr, garnet; sl, sillimanite; biot, biotite; cord, cordierite; pl, plagioclase; k-fd, K-feldspar; ol, olivine; en, enstatite

Sample	Rock type	Distance to the contact (m)	Mineralogical assemblage	Quartz textures
Tb 415	Mylonitic quartzite Qtz%: 70%	50	qtz + gr + sl + biot + pl + cord	Ribbon and cross-hatched mosaic microstructures $X = 0.7$ mm; $Z = 0.1$ mm
Tb 388	Quartz–feldspar mylonite Qtz%: 35%	200	qtz + k-fd + pl + sl + biot	Ribbon $X = 1.2$ mm; $Z = 0.2$ mm
Tb 365	Quartz–feldspar mylonite Qtz%: 40%	20	qtz + gr + sl + biot + cord + k-fd + pl	Cross-hatched mosaic microstructures $X = Z = 0.3$ mm
Tb 379	Quartz–feldspar mylonite Qtz%: 45%	5	qtz + gr + biot + cord + k-fd + pl	Ribbon $X = 1.5$ mm; $Z = 0.2$ mm
Tb 410	Highly foliated mylonite Qtz%: 40%	10	qtz + gr + sl + biot + pl + k-fd	Ribbon $X = 0.3$ mm; $Z = 0.05$ mm
Tb 363	Quartz–feldspar mylonite Qtz%: 42%	15	qtz + gr + sl + biot + pl + k-fd	Ribbon and elongate mosaic $X = 0.9$ mm; $Z = 0.1$ mm
Tb 402	Highly deformed migmatite Qtz%: 50%	60	qtz + gr + biot + pl + k-fd	Elongate mosaic $X = 1$ mm; $Z = 0.3$ mm
Tb 573	Deformed vein of quartz Qtz%: 95%	750	qtz	Cross-hatched mosaic $X = Z = 0.7$ mm
Tb 357	Mylonitic to fine grain porphyroclastic harzburgite Ol: 70%; En: 30%	30	ol + en	—

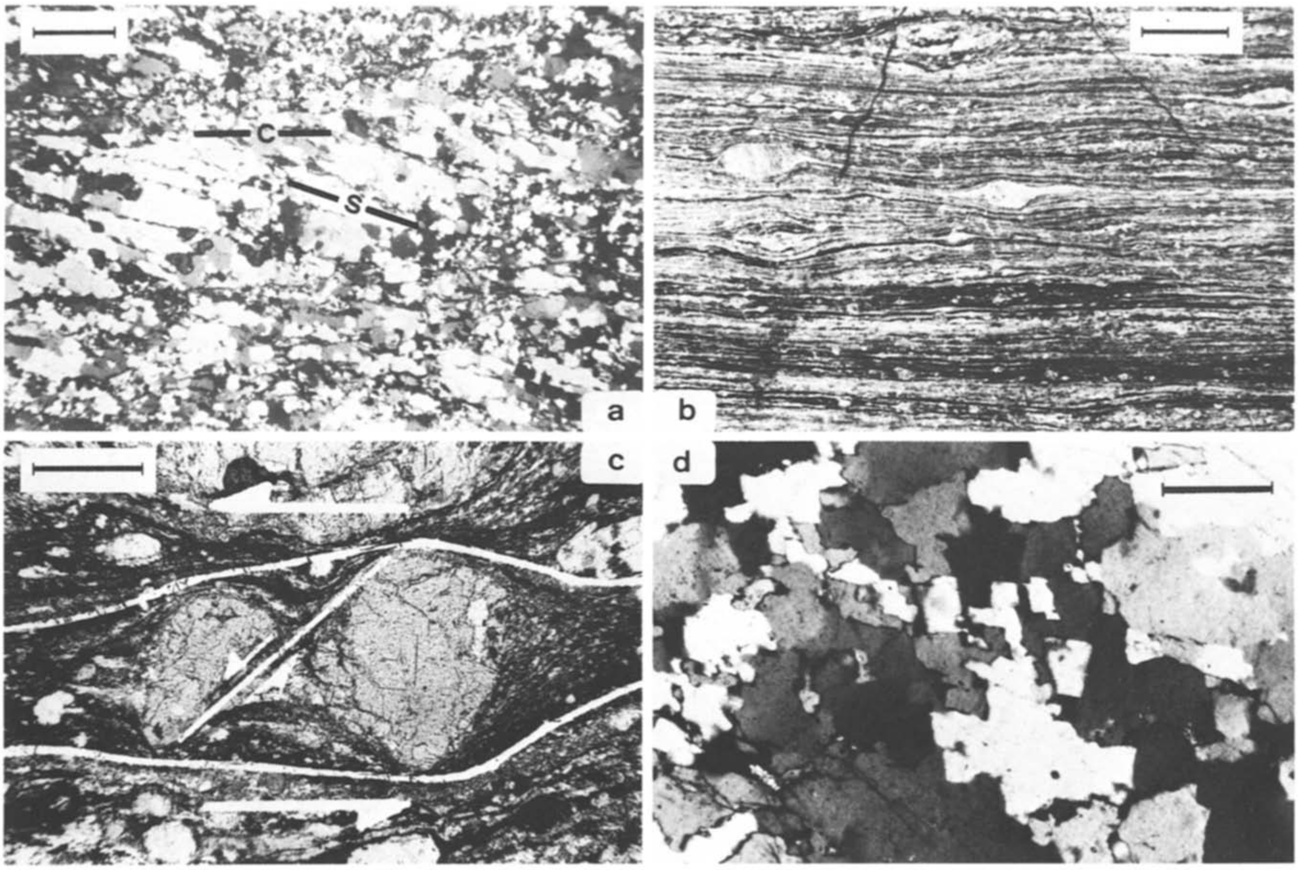

Fig. 4. Microstructures of the mylonites in the Ojen nappe. *XZ* sections. (a) C-S structures indicating sinistral shear. Scale bar = 1 mm, crossed nicols. (b) Asymmetric feldspar augen in a quartz–feldspar mylonite indicating dextral shear. Scale bar = 1 cm. (c) Fractured K-feldspar porphyroclast with asymmetric pressure shadows both indicating a dextral shear. Scale bar = 1 mm, crossed nicols. (d) Cross-hatched mosaic microstructures in quartz showing typical straight grain-boundaries at 90°. Crossed nicols. Scale bar = 1 mm.

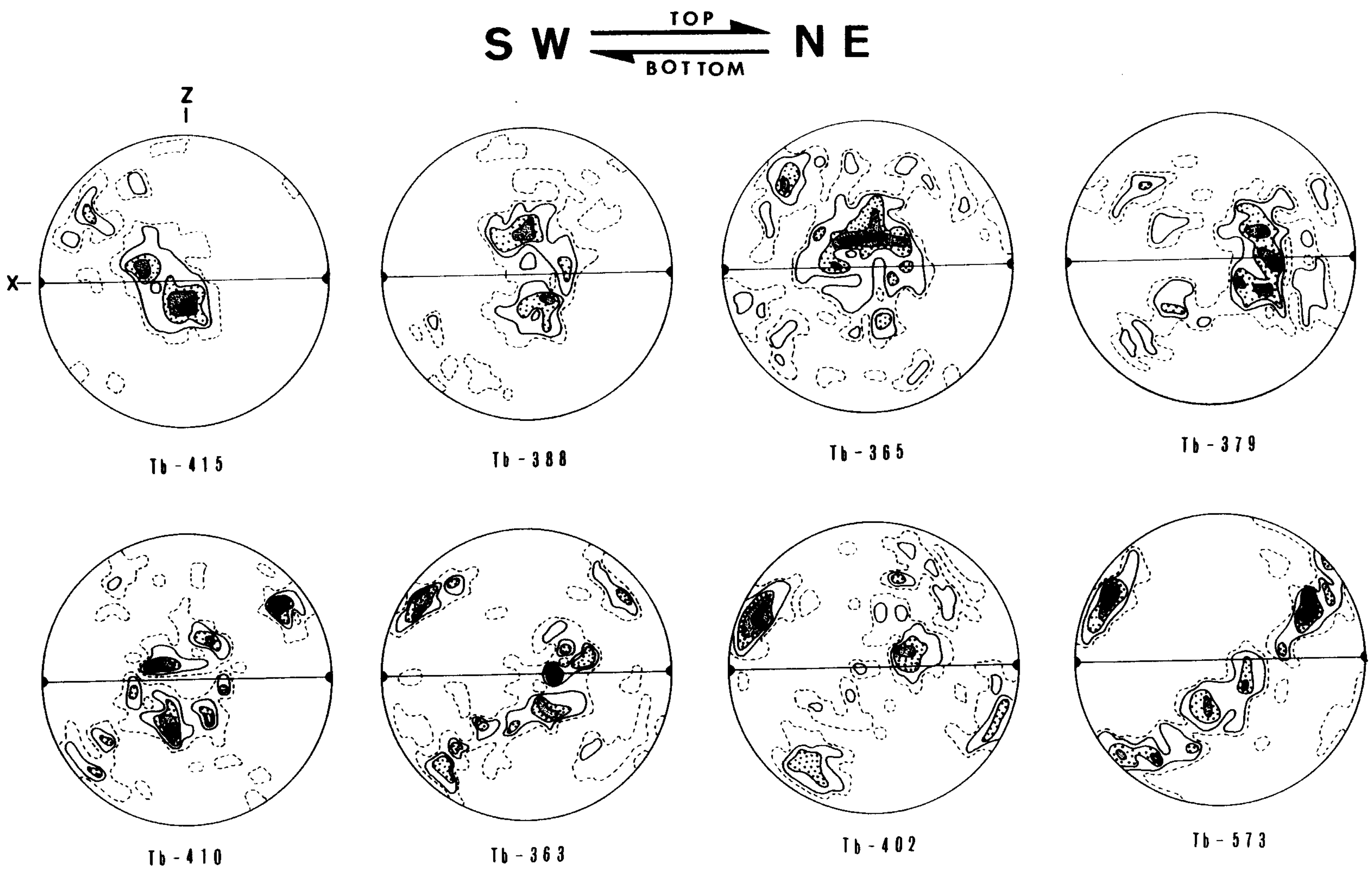

Fig. 5. Quartz *c*-axis orientation diagrams. *XZ* sections: *X* is the stretching lineation. 150 measurements per diagram: Contours: 1, 2, 4, 6, ≥ 8% per 0.45% area; lower-hemisphere equal-area projection. The *Y*-maximum concentrations and tendency for two girdles crossing at 90° point to high temperature deformation. See Table 1 for location.

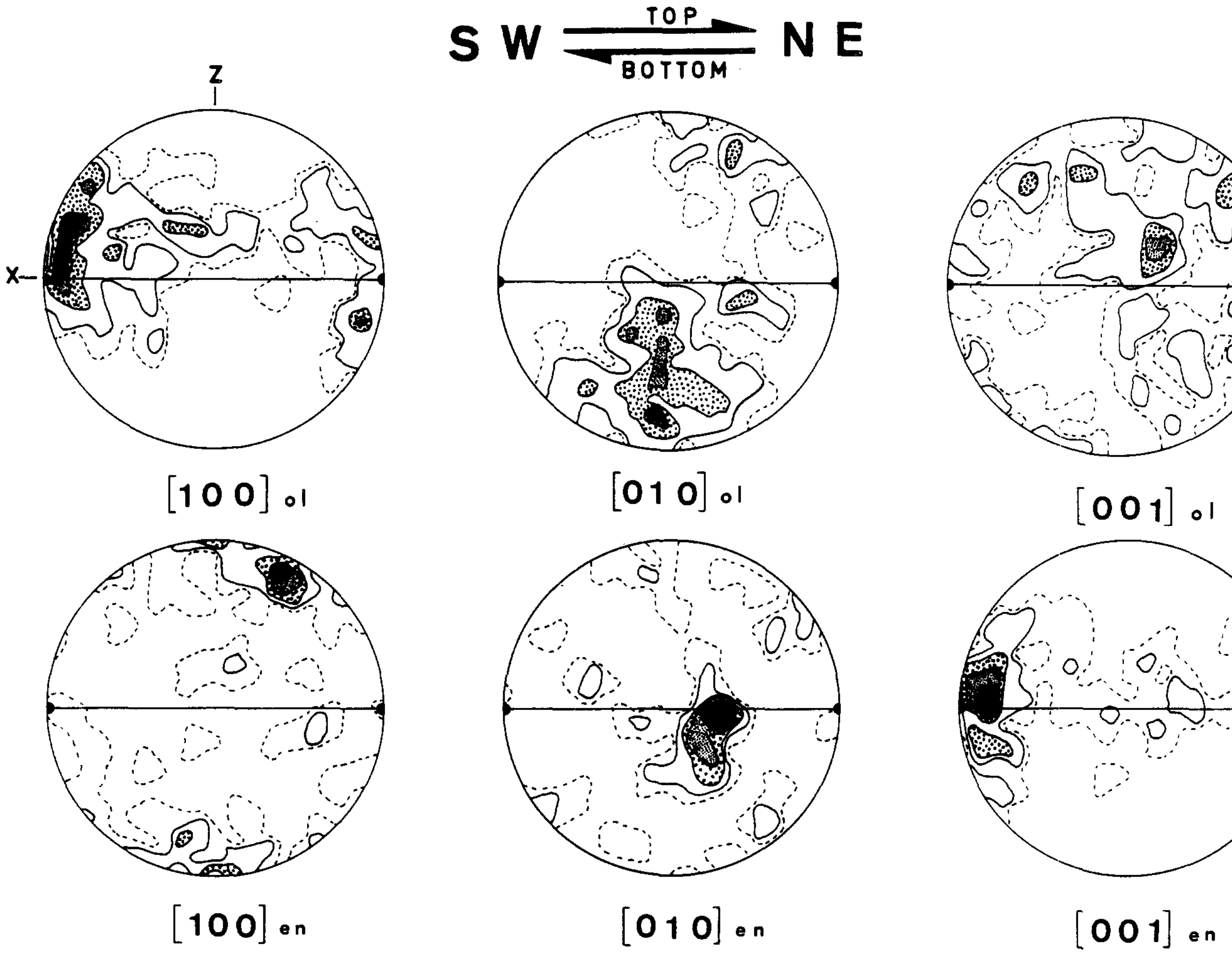

Fig. 6. Olivine (ol) and enstatite (en) preferred orientations in a basal harzburgite. *XZ* sections: *X* is the stretching lineation and the solid line is the foliation. 100 measurements. Contours: 1, 2, 4, 6, ≥8% per 0.45% area; lower-hemisphere equal-area projection. The obliquity of [100]ol, [001]en and [100]en axes relative to shape fabric indicates a dextral shear sense.

using oriented samples and *XZ* sections; that is, parallel to the stretching lineation and perpendicular to the foliation.

The quartz diagrams (Fig. 5) have in common important concentrations of the *c*-axes in the area of the *Y* axis of the finite strain ellipsoid. Such concentrations are frequently described in quartz tectonites, and are attributed to the activity of prismatic {*m*} slip planes along the ⟨*a*⟩ slip direction (Wilson 1975, Bouchez 1977). In addition to these *Y* concentrations the diagrams are unusual compared to the classically published ones, except those of Lister & Dornsiepen (1982) from the Saxony granulites, which show a tendency to a distribution along girdles making a rather low angle with the *XY* foliation plane. The diagrams Tb-402, 573 & 363 (Fig. 5) clearly show a pattern composed of a unique girdle and a strong maximum of *c*-axes perpendicular to the girdle. Such patterns can be considered as a particular case of the high-angle crossed-girdle pattern where one of the girdles is reduced to its peripheral maxima. Lister & Dornsiepen (1982) interpret the high-angle crossed girdles as due to the combination of prism ⟨*c*⟩ and basal ⟨*a*⟩ systems and possibly ⟨*c* + *a*⟩ slip directions, concentrations of *c*-axes close to *Y* being classically interpreted as due to the prism ⟨*a*⟩ contribution. In the case of diagrams such as Tb-402 and 573, the presence of basal subboundaries in quartz grains having their *c*-axes within these peripheral maxima making a low angle with the lineation is interpreted as due to predominant [*c*] slip for these grains (Bouchez & Tubia in press). Finally, some patterns found very close to the peridotite contact with *c*-axes mostly disposed along small circles around *Z* (Tb-379), are probably due to a strong flattening component.

In the peridotites at the base of Los Reales nappe, the enstatite crystallographic orientations have the [001] and [100] axes, respectively at a small and a large angle to the lineation, and [010] contained in the *XY* plane (Fig. 6). It confirms that plastic deformation occurred in enstatite according to the (100) [001] slip system (Nicolas & Poirier 1976).

For olivine the distribution of the [100] and [010] axes is clear and indicates the activity of the high to medium temperature {Okl} [100] slip system. The tendency of [100] to extend along the *XY* plane explains the rather diffuse but complementary distribution of [001]; this points to a deformation regime in the flattening domain or to the incipient activity of the [001] low-temperature slip direction of olivine (T° < 950°C) as suggested in Boudier & Coleman (1981).

DIRECTION AND SENSE OF THRUSTING

The structures and microstructures of the rocks on both sides to the Los Reales nappe basal contact resemble those that exist in numerous ductile shear zones. They characterize a thrust zone, with penetrative deformations having a geometry close to simple shear with local flattening (Tb-379, Fig. 5; olivine, Fig. 6). Accordingly the stretching and mineral lineations (N 70°E) in these tectonites approximately indicate the transport direction of the Los Reales nappe.

The NE sense of transport has been obtained, in the Ojen nappe, from the systematic sense of asymmetry of the pressure-shadows surrounding the porphyroclasts and from the fracture arrangement of the K-feldspar porphyroclasts (Etchecopar 1977). The sense of shear derived from the quartz diagrams is not straight forward but it is compatible with the other criteria if interpreted according to Bouchez & Tubia (in press), at least for Tb-363, 402 and 573 diagrams. In the peridotites, sense of shear is deduced from the obliquity between (100) cleavages of the elongated enstatite porphyroclasts and the foliation plane ([100]en, Fig. 6). The enstatite and olivine crystallographic fabrics in the fine-grained porphyroclastic to mylonitic peridotites show the same shear sense (Fig. 6). All these criteria point to a sense of transport such that the Los Reales nappe was emplaced over the Ojen nappe, from WSW to ENE.

This movement is clearly different to that accepted generally in the Betic chain (Aldaya 1969, Platt 1982) which are towards the north in the central part of the Chain and towards the northwest in the western one (Dürr 1967, Bourgeois 1978). This contradiction is only apparent as our results express an initial stage of emplacement in ductile conditions whereas the displacements toward the north and northwest correspond to late thrustings (Miocene age) in more superficial conditions (Paquet 1974).

DISCUSSION AND CONCLUSION

In the Sierra Alpujata the peridotites (Los Reales nappe) clearly overlie a dynamothermal aureole. Along with symmetric positive deformation gradients towards the nappe contact and the inverse metamorphic zonation in the Ojen formations, it points to the thrusting of a hot slab of peridotite over continental crust.

The thermal aureole of Ojen nappe shows a continuous adiabatic metamorphic evolution from a first high-pressure and high-temperature dynamic stage (9 kb, ~750°C) to a static stage at 3.5 kb and 750°C (Westerhof 1975 & 1977). The biotite–sillimanite and garnet association of the dynamothermal aureole is developed during an intermediate dynamic stage (7 kb, ~725°C). This dynamic stage is accompanied by partial melting giving acidic dykes cross-cutting the peridotites and subsequently deformed with them. The dynamic stage is also hinted at by the high-temperature plastic deformation of quartz with possible prism ⟨*c*⟩ systems (Lister & Dornsiepen 1982, Bouchez & Tubia in press) along with prism ⟨*a*⟩ and basal ⟨*a*⟩ systems. At the base of the peridotites, this dynamic stage is marked by the fine-grained porphyroclastic to mylonitic texture which developed during plastic deformation under relatively low-temperature conditions for olivine and enstatite. We estimate this temperature at around 900 ± 100°C by comparison with fabrics in the basal peridotites of ophiolites (Boudier & Coleman 1981). This conclusion is also consistent with the absence of serpentinization or of hydrated minerals such as amphibole or chlorite in the mylonitic peridotites.

According to Loomis (1972), Kornprobst (in Didon *et al.* 1973), Westerhof (1975, 1977) and Lundeen (1978), a late static metamorphism under conditions of low pressure and high temperature can be recognized in the dynamothermal aureole underlying these ultramafic rocks of the Betic Cordillera. The common presence of undeformed acidic dykes in the peridotites can be related to migmatization during this static metamorphism. The fact that deformation occurred at very high temperatures, close in time to the migmatization and the late static metamorphism, could explain the growth of a narrow mylonitic zone at the peridotite contact, according to the theoretical data of Fleitout & Froidevaux (1980).

Several models have been proposed for the emplacement of the peridotites in the Betic chain, generally referred to as the Ronda peridotites. In Sierra Bermeja in particular, similar peridotites have a similar structural position, lying above high-grade quartz–feldspar rocks (Lundeen 1978, Navarro-Vila & Tubia 1983). According to our data from the Sierra Alpujata reconstructions invoking an opposite structural position (peridotites underlying the quartz–feldspar rocks) (Loomis 1972, Torres-Roldán 1979), or invoking temperature conditions in the brittle field for the emplacement of the peridotites (Torres-Roldán 1979), are inadequate. Much more acceptable is the emplacement model proposed by Reuber *et al.* (1982) in the case of the Beni Bousera (Morocco) peridotite massif. In this model, mantle rocks rose up nearly to the surface in a rifting environment, and rift closure during a slightly later compressional event then thrust a hot slab of mantle onto continental crust. This latter episode is that described in this paper: in southern Spain, the thrusting direction is from WSW to ENE. The metamorphism of the Ojen nappe close to the contact, and particularly the migmatization, has to be attributed to heat conducted from the high-temperature Los Reales peridotite.

Isotopic dating of the metamorphic sequences underlying and overlying the peridotites, and of the acid dykes enclosed in them (Loomis 1975, Priem *et al.* 1979), provide radiometric ages close to 22 Ma. These are interpreted as cooling stages of metamorphism. They clearly show the relationship of the high-grade metamorphism with the Alpine orogeny. Similar conclusions arise from the study of the equivalent Beni Bousera peridotites (Polvé & Allegre 1980) and the overlying metamorphic complex (Michard *et al.* 1983).

The geodynamical episode which is the object of this paper has therefore to be considered as of Alpine age, in contrast to the pre-Alpine emplacement proposed by Kornprobst (1976) and Reuber *et al.* (1982).

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