Journal of the Virtual Explorer, 2002
Volume 08
Paper 2
http://virtualexplorer.com.au/

Intracrustal tectonic evolution of large lithosphere mantle slabs in the western end of the Mediterranean orogen (Gibraltar arc)

M. Sanchez-Gomez

Departamento de Geología, Universidad de Jaén, 23071, Jaén, Spain.
http://geologia.ujaen.es/usr/msgomez/

J. Carlos Balanya

Departamento de Ciencias Ambientales, Universidad Pablo de Olavide, Carretera de Utrera km 1, Sevilla, Spain.

V. Gracia-Duenas

Dpto. Geodinámica-Inst. Andaluz de Ciencias de la Tierra, Universidad de Granada, Campus Fuentenueva, 18002, Granada, Spain

J.M. Azañón

Dpto. Geodinámica-Inst. Andaluz de Ciencias de la Tierra, Universidad de Granada, Campus Fuentenueva, 18002, Granada, Spain

Keywords: western Mediterranean, Ronda peridotites, Alboran domain, extensional tectonics, mantle thrust, high-pressure metamorphism

Abstract: The Ronda and Rif peridotites interlayered with crustal rocks in the western Alboran Domain are a good example of a large volume of very deep rocks exhumed in an unlikely tectonic context. We have studied the western Alboran Domain on both sides of the Gibraltar arc, where a large number of peridotite bodies and high-pressure crustal rocks crop out. We have attempted to correlate microstructures, PT history and large-scale structures of nearby units (from the Alpujarride Complex) from the analysis of different tectonic levels, rock ages and geographic positions with respect to the Gibraltar arc. In this sense, the peridotite bodies, which have a definite structural position, have been taken as an important marker layer.

We propose four main tectonic events in the region related with the exhumation of the deep crustal and mantle rocks. The first event is a pre-Miocene collision that produced a similar high-pressure metamorphic record in both Alpujarride units, above and below the peridotites. It is therefore not considered to be directly related with the peridotite emplacement. The second event is the thinning and uplift of the former Alpujarride rocks, which produced a penetrative subhorizontal foliation and the rise of the top of the peridotites up to 6 kbar (ca. 18 km). A steep isothermal decompression is observed associated with the foliation development. The third event involves the peridotite emplacement on the crust. Large kilometric recumbent folds occur below the peridotite slab coupled with the development of crenulation cleavage. No clear metamorphic record of this event is observed, except diffuse heating in the unit beneath the peridotites. The fourth event corresponds to the Miocene collapse of the Alboran Domain, which resulted in the dismembering of the former peridotite slab. A N-S early extensional stage of this event is associated with ductile shearing and granite generation at 22-18 Ma. The N-S extension broke off the peridotite slab, individualizing the current bodies. Serpentinized peridotites flowed plastically between the main bodies. Throughout the Miocene, the peridotite bodies were dispersed and exhumed as passive elements of the Alboran Domain during its collision with the south-Iberian and Magrebian margins.

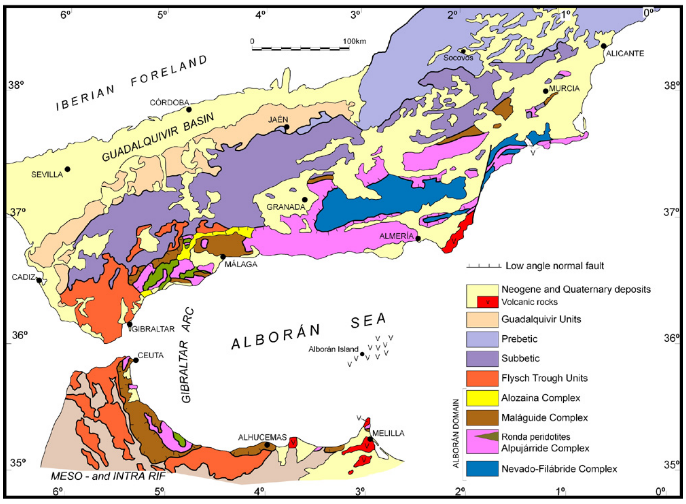
Several models for the western Mediterranean have implied radial emplacement or dispersion of the peridotite bodies, which disagrees with our observations. We propose that all the Alboran peridotite bodies were emplaced as a single slab, probably farther east from their present position. Afterwards, displacement to the west of the Alboran terrain was concomitant with N-S extension. A total cumulative N-S extension has been estimated based on the reconstruction of the former peridotite slab, of at least 1.4 to 2. Thus paradoxically, N-S extension is one of the most patent features of the Alboran orogen in a N-S plate convergence setting.

Table of Contents

Introduction

Most peridotite outcrops, such as mantle tectonically exhumed rocks, constitute major markers in the orogenic edifices where they are found. Peridotites are relatively common in considerably thinned continental margins (Beslier et al., 1990) or associated to ophiolite sequences derived from oceanic lithosphere (see, for instance, Kusky et al., 2001). Peridotite bodies among high temperature and pressure rocks, such as Ronda (Balanyá et al., 1997; Tubía et al., 1997) and Beni Bousera (Bouybaouene et al., 1998) (Figs. 1 and 2) are less common, and represent continental collision involving deep thrusts through the mantle (Tubía and Cuevas, 1986; Tubía, 1990). The Ronda and Beni Bousera peridotites, which constitute the largest outcrops of subcontinental mantle worldwide (Dickey et al., 1979), are intercalated in the Alpujarride complex, a group of tectonic units with a common record of high-pressure metamorphism (Azañón et al., 1998).

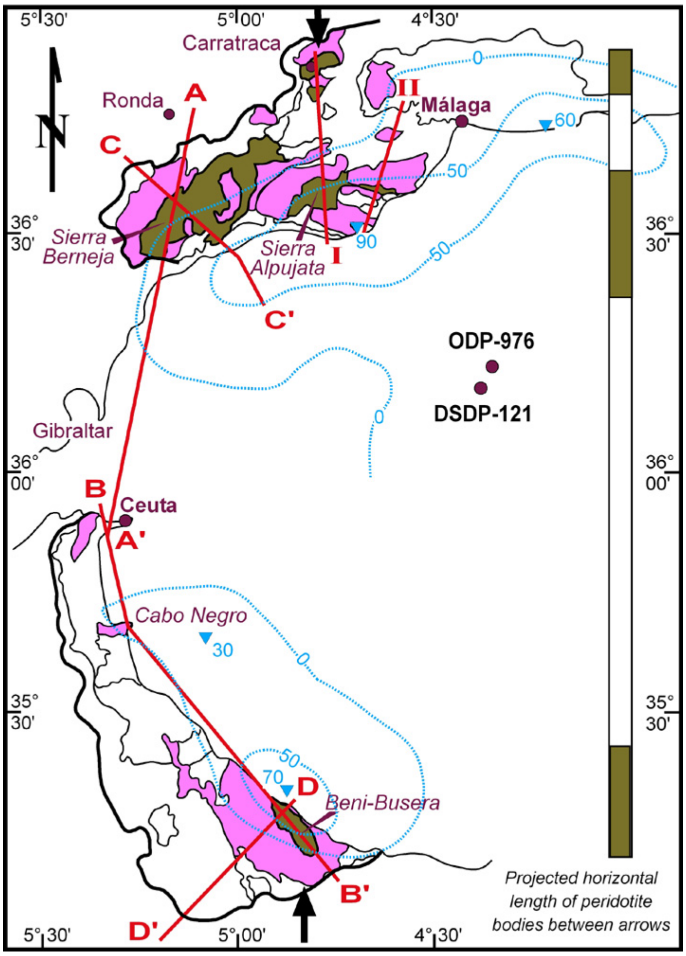
Figure 1. Main tectonic elements of the Gibraltar arc



Main tectonic elements of the Gibraltar arc: deformed foreland areas (Subbetic, Prebetic and Intra-Rif), Flysch Trough Complex, and the Alboran Domain (hinterland) Complexes. Peridotite units (green) belong to the Alpujarride Complex, which occupies an intermediate position within the Alboran Domain stack.

The Alpujarride peridotites are mostly concentrated around the Gibraltar arc, in the westernmost Mediterranean (Fig. 1). In addition to the outcropping bodies, several elliptical gravity highs (Fig. 2) displaced from the major peridotite outcrops suggest the existence of buried ultramafic slabs in the basement of the Alboran basin (Torné et al., 1992). The current geographic Gibraltar Arc and the rest of the Betic and Rif mountain chains were formed during the Miocene by the superposition of a crustal terrane called the Alboran Domain (made up, in ascending order, of the Nevado-Filabride, Alpujarride and Malaguide complexes) on the South Iberian and Maghrebian margins. During the collisional process, the mountain front migrated outward, imbricating the margin cover, while the Alboran domain underwent considerable tectonic thinning (García-Dueñas et al., 1992; Martínez-Martínez and Azañón, 1997). Several tectonic models have been proposed for the Alpujarride Peridotite evolution (Tubía and Cuevas, 1986; Van der Wal and Wissers, 1993; Tubía et al., 1994; Zeck, 1997), the Alboran Domain evolution (Platt and Vissers, 1989; Vissers et al., 1995; Martínez-Martínez and Azañón, 1997), and the entire Gibraltar Arc/western Mediterranean evolution (e.g. Lonergan and White, 1997; Doglioni et al., 1997; Gelabert et al., 2002). However, no consensus has been reached and relevant questions, such as the timing, kinetic vectors or number of tectonic events, remain a subject of discussion.

Figure 2. Main peridotite bodies and western Alpujarride outcrops in the Gibraltar arc.



Main peridotite bodies (green) and western Alpujarride (pink) outcrops in the Gibraltar arc. At the ODP-976 and DSDP-121 Sites marked on the figure, basement rocks attributed to the Alpujarride have been also recovered (Sánchez-Gómez et al., 1999). Geological sections of Figure 5 are indicated in red. Blue dashed lines and triangles are respectively Bouguer anomaly contours and maximums in mgal. Note the good correlation of some of the gravity anomaly highs with the Alpujata and Beni-Bousera massifs. The displacement of the gravity highs with the outcropping peridotites has been interpreted as due to the main part of the peridotite slabs remaining buried (Torné et al., 1992). Thus, gravity highs east of Málaga or Cabo Negro could correspond to hidden bodies of an intermediate size. The right bar roughly represents the projected horizontal length of the peridotite bodies, including the buried part, in a section from Carratraca to Beni-Bousera massifs (green lined bars). Supposing a single former peridotite slab, total N-S calculated extension is 2, but a more conservative value in the same section, considering the loss of undetectable serpentinized material, could be 1.4.

Alpujarride peridotite bodies constitute, due to their large volume and outcrop context, a key piece of the western Mediterranean puzzle, and their tectonic evolution should be carefully taken into account for the general models. Most peridote emplacement models include a former diapiric uplift through the mantle lithosphere (e.g. Dickey et al., 1979, Obata, 1980). Field geology evidence (e.g. Westerhof, 1977; Tubía and Cuevas 1987; Sánchez-Gómez et al., 1995) and geophysical data (Barranco et al., 1990, Torné et al., 1992) nevertheless show that peridotites form thick slabs among crustal rocks, which can only be tectonically emplaced, in opposition to the initial proposition that the mantle intruded diapirically through the crust (Loomis, 1972; Loomis, 1975).

In this paper we focus on the intracrustal evolution of the ultramafic rocks, discussing the emplacement into the middle-lower crust up to the final mechanism of exhumation, when average highs of more than one thousand metres were reached in the Sierra de Ronda. We will attempt to fit the structural evolution of the peridotite bodies in the tectonometamorphic history recorded by the surrounding crustal rocks and propose a coherent model for both crustal and mantle rocks.

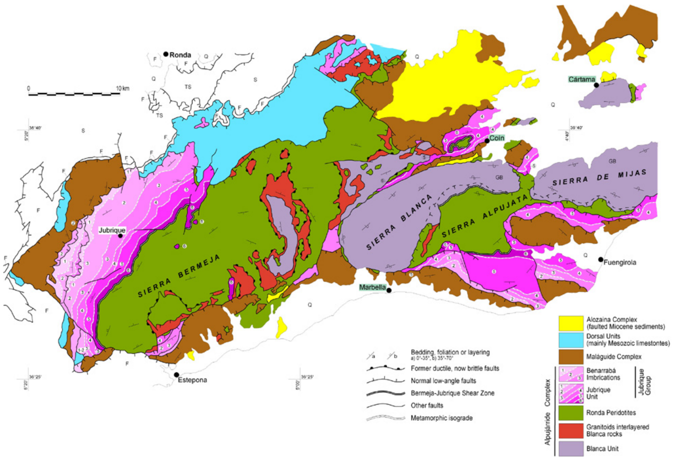
Peridotite bodies in the Alpujarride complex

The Ronda peridotite bodies (including in this term the ultramafic bodies on both sides of the Gibraltar arc) are systematically situated between the upper two tectonic units of the Alpujarride complex Jubrique Unit (top) and Blanca Unit (bottom). These Alpujarride units have similar lithologies and metamorphic records from the western end of the Alboran domain to the south of Granada (Fig.1, Azañón and Alonso-Chaves, 1995, Azañón et al., 1998).

Locally, Malaguide Complex rocks directly overlie thin peridotite slices in the areas subjected to late Miocene extension, such as that evidenced northeast of the Sierra Bermeja (Fig. 3). However, when primary top boundaries are well preserved, as in the Alpujata, Bermeja and Carratraca massifs (Figs. 2 and 3), garnet lherzolites of the peridotite top underlie garnet gneiss in the footwall of the Jubrique Unit. In this case, the contact between the mantle and crustal rocks is included in the so-called Bermeja-Jubrique shear zone (Balanyá et al., 1997), which can be considered to have been a tectonic paleo-Moho at some time in the pre-Miocene times (Balanyá et al., 1997; Reuber et al., 1982).

The Jubrique Unit contains a 5-km-thick metamorphic succession of, from bottom to top (Figs. 3 and 4), garnet gneiss, migmatite gneiss, staurolite-bearing schist, chloritoid-bearing schist, phyllites, quartzites, calc-silicates and carbonate rocks. It has upward-decreasing metamorphic zoning, with isogrades subparallel to the lithologic contact and to the main foliation (Sp). The complete lithologic sequence of the Jubrique Unit roughly corresponds to a segment of condensed middle-upper crust (Balanyá et al., 1997), from metapelitic granulites at the bottom to scarcely recrystallized Triassic carbonates at the top.

Figure 3. Western Alboran Domain in the Betic chain

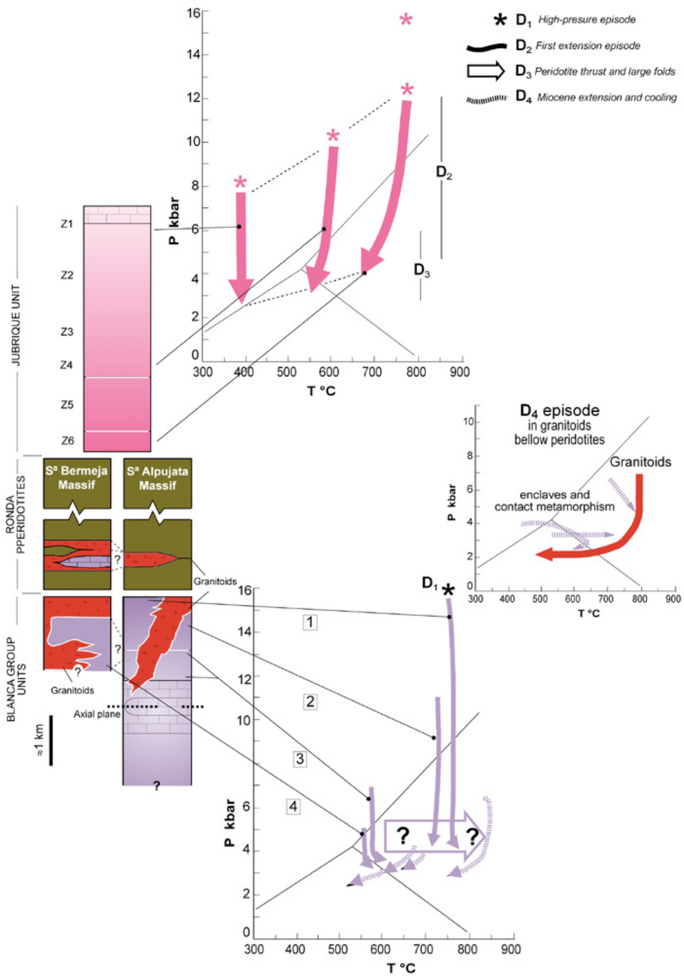


Geological map of the western Alboran Domain in the Betic chain. Note the thin slices of peridotites (mainly serpentinites) that connect the main massifs, generally associated with large omissions of the units above. F: Flysch Trough Units; S: Subbetic; TS: tertiary sediments; Q: Quaternary. Numbers on the Jubrique unit represent metamorphic zones as in Figure 4.

Where the bottom of the Ronda peridotite crops out, the Blanca unit underlies the ultramafic bodies. The Blanca Unit group comprises a set of rocks showing high-temperature, medium-pressure metamorphism, ranging from granites to high-grade schist and marbles. Under the Bermeja body (Fig. 3) and Ceuta slice (Fig. 1), directly below the peridotites, there is a peculiar rock that consists of cordierite granitoid rich in heterogeneous fragments of lithologies characteristic of Alpujarride units, including peridotites and serpentinites. This fragment-bearing granitoid has features of both tectonic (Sánchez-Gómez et al., 1995) and "magmatic" (Lundeen, 1978) breccia. The Alpujarride fragments vary considerable in size: although most of them are centimetric, some reach a few hundred meters long. These fragments reveal the main Alpujarride penetrative foliation (Sp) and a superposed crenulation cleavage (Sánchez-Gómez et al., 1995). Late leucocratic dykes intrude fragment-bearing granitoids, peridotites and lower levels of the Jubrique unit.

In the Alpujata massif (Fig. 3), the peridotites overlie an inverse, condensed, but complete Alpujarride sequence, from garnet gneiss to marble (Fig. 4). The main difference with the Jubrique and other Alpujarride units is that sillimanite is ubiquitous in all the metapelite levels and marbles have high-temperature minerals such as diopside and forsterite (Westerhof, 1977).

Figure 4. Lithologic columns and PT trajectories



Lithologic columns and PT trajectories of different rock levels within the units overlying (Jubrique Unit) and underlying (Blanca Group Units) the two main peridotite massifs in the western Betics. Granitoid bodies, over 22 my in age, mostly intruding the lower units. D1 to D4, tectonometamorphic events (see text for further explanation). Z1 to Z6 metamorphic mineral zones: Z1= pyrophyllite+ carpholite; Z2= kyanite+ chloritoid; Z3= staurolite+ garnet; Z4= Sillimanite; Z5= Sillimanite+ K feldspar; Z6= K feldspar+ kyanite+ garnet+ cordierite.

Granitoid generation and granitoid-related paths are restricted to the D4 event. Aluminosilicate triple junction according to Bohlen et al. (1991). Together with stability phase fields, temperature determinations were principally based on garnet-biotite (metapelites) and garnet-clinopyroxene geotermometers (pyroxenite lenses). GASP barometer, silica content of phengites, and MgCrd=Py+Si+Qz, and Qz+MCtd=Chl+ky+W equilibria were mainly employed for pressure determinations. PT-paths from Balanyá et al. (1997), Tubía y Gil Ibarguchi (1991) and Sánchez-Gómez (1997).

Beyond the main peridotite massifs, thin, discontinuous layers of serpentinite and small, elongated, serpentinized peridotite bodies frequently mark the boundary between the Blanca-group units and the units above it (the Jubrique and, in some instances, a Malaguide unit)(Fig. 3). The nearly uninterrupted rosaries of serpentinite slices suggest an initial continuity of the main peridotite bodies (Navarro-Vilá and Tubía, 1983; Sánchez-Gómez, 1997).

The connection between the distinct massifs can be seen in the geologic map of Figure 3. Here, the succession of serpentinite bodies implies that roughly NE-SW extension separated the components of a continuous peridotite slab, as illustrated by the lateral thinning toward the NE and SW of the Alpujata body. On the other hand, the separation of the main bodies of Bermeja and Alpujata point to a different, E-W extension system. Thus, the north metamorphic branch of the Gibraltar arc outlines a roughly orthogonal pattern of total extension.

Similar superimposed extension has been reported in other areas of the Betic chain (Crespo-Blanc et al., 1995, García-Dueñas et al., 1992). The general boudin-like shape of most Alpujarride units, among them the Ronda peridotite bodies, can be explained as the effect of Miocene extension related to a rifting process that culminated in the formation of the Alboran basin.

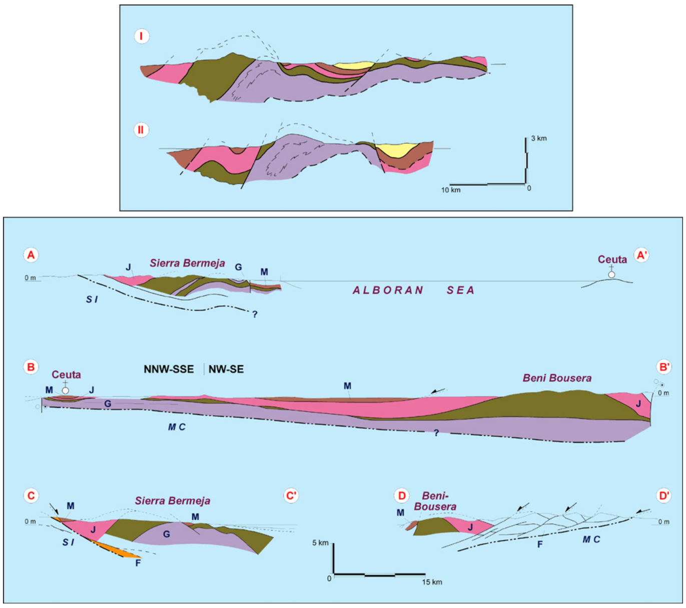
Structures and metamorphic effects of peridotite emplacement.

Different structures contribute to the emplacement and exhumation of the peridotite bodies. Many are extensional shear zones and normal faults that were superposed on previous contacts with an originally contractive nature. Because this type of structure cannot be distinguished on the basis of geometric criteria alone, the metamorphic record becomes a necessary reference for establishing its character and deformation conditions.

As mentioned above, the upper boundary of the Ronda peridotites is located in a thick shear zone that represents the paleo-Moho. This shear zone developed in extensional conditions before the Miocene (Balanyá et al., 1993, Tubía, 1994), although previous works associated it with the thrusting of peridotites (Tubía and Cuevas, 1986, 1987). During this extensional event, the main Alpujarride foliation (Sp) was generated after a high pressure – low gradient event (Fig. 4, Azañón et al., 1997, 1998). The P-T paths of garnet gneiss and lherzolite in the Bermeja-Jubrique shear zone indicate that general flattening, local simple shear and the omission of crustal rocks took place at the same time as the uplift of the peridotites through the mantle, to the base of the crust (Fig. 4). Whereas the pressure in garnet gneiss drops from >14 kbar at syn-kinematic conditions to ca. 6 kbar at post-kinematic conditions (T=850-700°C; Balanyá et al., 1993), in the garnet lherzolite pressure ranges around 20 kbar (Van der Wal and Vissers, 1993) to 4-8 kbar (Obata, 1994) for a comparable temperature range.

The lower part of the peridotite massifs contains two structural devices. In the Bermeja massif, peridotite layers of varying thickness are intercalated among layers of fragment-bearing granitoids (Figs. 3 and 4). These can be interpreted as mantle imbrications overthrusting crustal rocks that were later strongly modified by superimposed faulting. On the other hand, under the peridotites of the Alpujata massif, a large overturned limb of the Blanca Unit (Fig.5) exhibits crenulation cleavage and microfolding. Moreover, the lithostratigraphic sequence and metamorphic zones are inverted (Figs. 3 and 5). This would appear to confirm that the emplacement of the peridotite slabs is related to tectonic inversion, crenulation cleavage and large folds, as previous authors have suggested (Buntfuss, 1970, Westerhof, 1975, Navarro-Vilá and Tubía, 1983). The presence of microfolds and crenulation cleavage in enclaves in the granitoids at the bottom of some peridotite bodies also support this hypothesis.

Figure 5. Shear zones beneath the peridotites



Shear zones beneath the peridotites that have traditionally been attributed to "cold emplacement" (Westerhof, 1977) or to a late emplacement stage (Tubía and Cuevas, 1986) correspond to ductile N-S extension described in greater detail below.

The P-T conditions of the contractive emplacement of the peridotites must have been similar to those reached at the end of the uplift through the mantle peridotites, that is, <800°C and 6 kbar (Obata, 1994). These conditions comprise the stability field of the porphyroclastic plagioclase-bearing peridotites (recrystallized granular peridotites, Lenoir et al., 2001). There is no evidence of a significant pressure increase in the rocks of the Blanca Unit. However, the ubiquitous presence of sillimanite, which developed simultaneously to the crenulation cleavage, indicates T>500°C and P<9 kbar in all the pelitic formations of the Blanca Unit (Fig. 4), later resulting in extensive migmatization and generation of granitoids. The main consequences of the emplacement of the peridotites would therefore be the tectonic inversion of part of the Ojén unit, and the nearly complete thermal homogenization of the unit. Eclogite remnants near the bottom of the Alpujata peridotites (stratigraphic bottom of the Blanca Unit) have been attributed to the emplacement of the peridotite slab (Tubía and Gil Ibarguchi, 1991), but similar eclogites and HP granulites have been found above the peridotite bodies, at the bottom of the Jubrique Unit (Balanyá et al., 1997; Michard et al., 1997). Moreover, assemblages of HP-LT metamorphism have been preserved at the top of the Jubrique Unit (Michard et al., 1993; Azañon et al., 1995; Bouybaouene, 1995), at conditions in agreement with the gradient suggested by the eclogites (Fig. 4). In this context, eclogites and granulites below the peridotite slab represent the P-T conditions reached during a contractive episode prior to its emplacement; thus, peridotites were contractively emplaced after they reached extensionally mid-crustal levels after the previous HP event.

In short, the emplacement of the mantle slab was the result of a composite thrust after lithosphere-wide extension. It is possible that several peridotite imbrications originated in a complex suture, while at the same time the overthrust crustal units were intensely folded. Recumbent folds (Simancas and Campos, 1993) and crenulation foliation (Tubía et al., 1992, Azañón et al., 1996) are common in all the units of the Alpujarride complex, and together with the peridotite emplacement, they mark a major organizational episode in the Alpujarride complex.

Extensional dismembering of the peridotite slab

At present, the peridotite bodies are severely thinned, ranging from kilometric thickness in the most important massifs to decametric or even metric thickness in the nearby serpentinite sheets (Figs. 3 and 5). Several brittle and ductile fault systems are responsible for this thinning. The oldest fault system recognized is contemporaneous with the formation of the granitoids (Sánchez-Gómez et al., 1995), which is 20-22 M.a. in age (Priem et al., 1979, Zeck et al., 1992, Monié et al., 1994). Later fault systems completed the exhumation of the peridotites during the middle Miocene (García-Dueñas and Balanyá, 1991, García-Dueñas et al., 1992).

The first Miocene extensional episode is characterized by a distinctive N-S to NNE-SSW directed stretching lineation that developed in shear zones preferentially situated close to the lower boundary of the peridotite massifs. A comparable stretching lineation is more weakly represented at some points in the Jubrique sequence. The shear zones are retrograde, and developed over the granite simultaneously with or just after its intrusion (Sánchez-Gómez, 1997). Broken feldspars, elongated in the direction of the lineation, are transformed to white micas, and chlorites grow at the expense of ferromagnesian minerals where the deformation is most intense. Quartz, however, sustains its ductile behaviour, showing ribbons and cross-hatched mosaic microstructures. Therefore, a great deal of the observed structures developed in brittle-ductile conditions. Likewise, vertical penetrative E-W joints, occasionally with quartz filling, are frequent even when the stretching lineation is not well developed.

The transformation of peridotite into serpentinite (now chrysotile) occurs when the shear zones affect the peridotite slab; S-C structures and stretching lineation (Hoogerduijn Strating and Vissers, 1994) develop in these shear zones. Marbles and dark schists, close to or surrounded by the granite, include similar shear zones, their lineation respectively marked by large calcite crystals (1-5mm) and andalusite porphyroblasts that grow over chlorite and biotite aggregates.

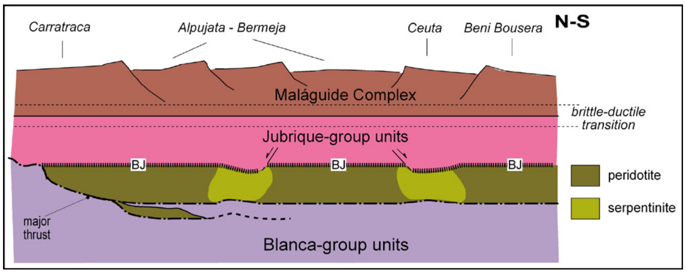
The transport sense of the hanging-wall is variable, and conjugate senses within a single outcrop are frequent, but N to NNE transport directions are constant, even on both sides of the Gibraltar strait. In Ceuta (Figs.1 and 2), an extensional shear zone that encloses a 50m-thick layer of serpentinite and peridotite has a predominant southward sense of transport. In the northern part of the Gibraltar arc, transport senses to the north are more common.

The brittle-ductile shear zones of the first extensional episode dismembered the former peridotite slab. Much of the present N-S separation is likely due to this episode. Nonetheless, the fault systems developing later throughout the Miocene accentuated the initial separation or fragmented the first longitudinal extensional bodies, depending on the superimposed extensional direction. This would have caused the layers of serpentinite to be stretched and become locally discontinuous. The distribution of the peridotite bodies (Figs. 2, 3 and 5) is congruent with the superposition of the almost transverse extensional systems, as mentioned earlier. The shape of the peridotite bodies, probably all connected by thin serpentinite sheets, would conform well with the Miocene extensional patterns, as has been shown in the western Betics (García-Dueñas et al., 1992). The distribution of the highest gravity anomalies (Fig. 2) is also compatible with the established directions of extension.

The serpentinite layer in Ceuta represents a link between the Ronda peridotites (~90mGal anomaly) and the Beni Bousera massif (~70mGal anomaly) through a hypothetical peridotite body near Cabo Negro that would correspond to a minor gravity anomaly (~30mGa anomaly) (Figs. 2 and 5).

In order to illustrate the first extensional episode described above, Figure 6 shows the initial effects of N-S extension on a major peridotite slab during the primary stages of its dismemberment. Throughout the extensional event, the peridotites exhibit brittle behaviour, though serpentinization would result from the circulation of fluids promoted by fracturing. As serpentinite minerals remain ductile until much shallower conditions, above 1.5 kbar and 350°C (Raleigh and Paterson, 1965, Wicks, 1984), it is reasonable to postulate that the brittle individualization of the bodies was followed by their separation under ductile conditions from the serpentinite sheets and crustal rocks. Later, the thin serpentinite layers would have undergone widespread extension while the behaviour of the quartz-feldspathic crustal rocks evolved from ductile to brittle.

Figure 6. Initial effects of N-S extension on a major peridotite slab



Initial effects of N-S extension on a major peridotite slab during the primary stages of its dismemberment.

Discussion: the role of the lithospheric mantle in the evolution of the Alborán orogen

The Ronda peridotites, the small Ceuta body, the Beni Bousera massif, and the deep-seated peridotite bodies inferred from the Bouguer gravity anomalies would have formed part of a large allochthonous mantle slab imbricated in the units of the Alpujarride complex, as supported by the petrological and geochemical similarities of the peridotite massifs (Gervilla et al., 1988, Targuisti, 1994). The abundance of major and minor peridotite bodies in the Gibraltar arc is a consequence of the large-scale fragmentation of the former slab. The individualization and dispersion of these peridotite bodies is congruent with the Miocene extensional directions that are well established in the Betic and Rif chain (García-Dueñas et al., 1992; Martínez-Martínez and Azañón, 1997).

The presence of HP above and below the peridotite slab and the relationship of the PT conditions with the relative position in the Apujarride sequence, not with the relative position with respect to the peridotite slab, indicate that the intracrustal emplacement was later than the HP metamorphism. Thus, HP metamorphism has no direct relationship with the peridotite emplacement as suggested Tubía et al. (1997), but probably with a very high-pressure record in the peridotites (Davies et al. 1993). This fact disagrees with tectonic models that suppose a single and continuous extensional episode after a collisional event until the present-day Alborán basin (see, for example, Platt and Vissers, 1989, Van der Wal and Vissers, 1993;Vissers et al., 1995; Zeck, 1997). These models generally propose radial dispersion and/or emplacement of the peridotite bodies from a central source to explain the present-day distribution around the Gibraltar arc, but they do not take into account the N-S predominant direction of the shear zones that fragment the former slab. In accordance with these models, for example, the Ceuta peridotite slice would be related with top-to-west detachments, not with the N-S (N 190°E) lineated ductile shear zone that encloses the thin relics of peridotites (Kornprobst, 1962; Sánchez-Gómez et al, 1995).

Other models, focused on the peridotite emplacement, consider a tarnspressive main fault (Tubía and Cuevas, 1986), or oblique subduction (Tubía, 1994; Tubía et al., 1997). These models, which are based mainly on detailed observations in the Alpujata massif (Fig. 3), better reflect the structural relationship of an early orogenic configuration, but contemplate different emplacement faults for the Betic and Rif peridotites in a geographic position not far from their present location. Late extension and, more crucially, lower Miocene vertical axis rotations (Saddiqi et al., 1995; Feinberg et al., 1996) invalidate most of their regional implications, such as the meaning of the thrust lineations.

A more reliable general setting has been proposed by Lonergan and White (1997), who suggest a former collision at 35 Ma around the present Balear Islands, far from the current position of the Alboran domain, and then a subduction roll-back process up to the present. The space and timing constraints of this model agree with structural reconstructions (García-Dueñas et al., 1993), although it does not explain in detail the tectonometamorphic history of the Alboran domain.

Conclusions

Alboran peridotites have been emplaced in the crust by means of a complex process that comprised at least two main contractional events: the first one recorded by HP mineral assemblages on crustal and mantle rocks, and a second one expressed by the superposition of units (incuding the peridotite slab) and large recumbent folds. Between the main contractional events there was vertical lithospheric thinning contemporary with the rise of the peridotites through the mantle to the bottom of a thin crust (4-6 kbar, ca. 15-20 km).

All the Alboran peridotite bodies were emplaced as a single slab, probably farther east from the present position, forming an intra-Alpujarride suture during the early Miocene-Oligocene. Destabilisation of this second contractive event, or roll-back of a subducting lithosphere slab, generated considerable extension that affected the former peridotite slab. Initial fragmentation in the early Miocene was caused by ductile N-S lineated shear zones that individualized the main peridotite bodies and produced nearly continuous serpentinite slices between them. Middle to late Miocene brittle fault systems finalized the separation of the bodies to the current location.

Total accumulative N-S extension can be estimated from the reconstruction of the former peridotite slab (Fig. 6), of at least 1.4 to 2 (Fig. 2). Thus, paradoxically, N-S extension is one of the most patent features of the Alboran orogen in an N-S plate convergence setting.

Acknowledgements

This study was supported by the project REN2001-3868-C03-01 and REN2001-3378 /RIES of the Spanish Ministerio de Ciencia y Tecnología.

References

Azañón, J.M. and Alonso-Chaves, F. 1996. Alpine tectono-metamorphic evolution of the Tejeda unit, an extensionally dismembered Alpujarride Nappe. Comptes Rendus de l'Académie des Sciences de Paris, 322, Série II, 47-54.

Azañón, J.M., Balanyá, J.C. and García-Dueñas, V. 1995. Registro metamórfico de alta presión-baja temperatura en la unidad de Jubrique e Imbricaciones de Benarrabá (Cordillera Bético-Rifeña). Geogaceta, 17, 133-134.

Azañón, J.M., Crespo-Blanc, A. and García-Dueñas, V. 1997. Continental collision, crustal thinning and nappe forming during the pre-Miocene evolution of the Alpujarride Complex (Alboran Domain, Betics). Journal of Structural Geology, 19, 1055-1071.

Azañón, J.M., Crespo-Blanc, A., García-Dueñas, V. and Sánchez-Gómez, M. 1996. Folding of metamorphic isogrades in the Adra extensional unit (Alpujarride complex, Central Betics). Comptes Rendus de l'Académie des Sciences de Paris, 323, série II, 949-956.

Azañón, J.M., García-Dueñas, V. and Goffé, B. 1998. Exhumation of high-pressure metapelites and coeval crustal extension in the Alpujarride Complex (Betic Cordillera). Tectonophysics, 258, 231-252.

Balanyá, J.C., Azañón, J.M., Sánchez-Gómez, M. and García-Dueñas, V. 1993. Pervasive ductile extension, isothermal decompression and thinning of the Jubrique unit in the Paleogene (Alpujárride Complex, western Betics Spain). Comptes Rendus de l'Académie des Sciences de Paris, 316, Série II, 1595-1601.

Balanyá, J.C., García-Dueñas, V., Azañón, J.M. and Sánchez-Gómez, M. 1997. Alternating contractional and extensional events in the Alpujarride nappes of the Alboran Domain (Betics, Gibraltar Arc). Tectonics, 16, 226-238.

Barranco, L., Ansorge, J. and Banda, E. 1990. Seismic refraction constraints on the geometry of the Ronda peridotitic massif (Betic Cordillera, Spain). Tectonophysics, 184, 379-392.

Beslier, M.O., Girardeau, J. and Boillot, G. 1990. Kinematics of peridotite emplacement during North Atlantic continental rifting, Galicia, northwest Spain. Tectonophysics, 184, 321-343.

Bohlen, S.R., Montana, A. and Kerrick, D.M. 1991. Precise determinations of the equilibria kyanite-sillimanite and kyanite-andalusite and a revised triple point for Al2SiO5 polymorphs. American Mineralogist, 76, 677-680.

Bouybaouene, M, Michard, A. and Goffé B 1998. High-pressure granulites on top of the Beni Bousera peridotites, Rif belt, Morocco: a record of an ancient thickened crust in the Alboran domain. Bulletin de la Societe Geologique de France, 169, 153-162.

Bouybaouene, M.L., Goffé, B. and Michard, A. 1995. Hig-presure, low-temperature metamorphism in the Sebtides nappes, nothern Rif, Morroco. Geogaceta, 17, 117-119.

Buntfuss, J.D. 1970. Die Geologie der Küstenkentten zwischen dem Rio Verde und dem Campo de Gibraltar (Westliche Betische Kordillere/Südspanien). Geol. Jb., 88, 373-420.

Crespo-Blanc, A. 1995. Interference pattern of extensional fault systems: a case study of the Miocene rifting of the Alboran basement (North of Sierra Nevada, Betic Chain). Journal of Structural Geology, 17, 1559-1569.

Davies, G.R., Nixon, P.H., Pearson, D.G. and Obata, M. 1993. Tectonic implications of graphitized diamonds from the Ronda peridotite massif southern Spain. Geology, 21, 471-474.

Dickey, J.S., Lundeen, M.T. and Obata, M. 1979. Geologic map of the ultramafic complex, southern Spain. Geological Society of America Map and Chart Series, MC-29, 1-4.

Doglioni, C., Gueguen, E., Sábat, F. and Fernández, M. 1997. The Western Mediterranean extensional basins and the Alpine Orogen. Terra Nova, 9, 109-112.

Feinberg, H., Saddiqi, O. and Michard, A., 1996. New constraints on the bending of the Gibraltar Arc from palaeomagnetism of the Ronda peridotites (Betic Cordilleras, Spain). In: A. Morris and D.H. Tarling (Editors), Palaeomagnetism and Tectonics of the Mediterranean Region. Special Publication Geological Society of London, London, 43-52.

García-Dueñas, V. and Balanyá, J.C. 1991. Fallas normales de bajo ángulo a gran escala en las Béticas Occidentales. Geogaceta, 9, 33-37.

García-Dueñas, V., Balanyá, J.C. and Martínez-Martínez, J.M. 1992. Miocene Extensional Detachments in the Outcropping Basement of the Northern Alboran Basin (Betics) and their Tectonic Implications. Geo-Marine Letters, 12, 88-95.

García-Dueñas, V. et al., 1993. Kinematics of the miocene extension detachment faults and shear zones in the Betics and Rif chains. In: M. Séranne and J. Malavieille (Editors), Late orogenic extension in Mountain belts. B.R.G.M., Fr., 76-77.

Gelabert, B., Sábat, F. and Rodríguez-Perea, A. 2002. A new proposal for the late Cenozoic geodynamic evolution of the western Mediterránean. Terra Nova, 14, 93-100.

Gervilla, F., Leblanc, M. and Torres-Ruiz, J. 1988. Relaciones entre la zonalidad petrológica y metalogénica de los macizos lherzolíticos de las cadenas alpinas de Mediterráneo occidental (Cordillera Bético-Rifeña y Kabylias). Estudios Geológicos, 44, 375-383.

Hoogerduijn Strating, E.H. and Vissers, R.L.M. 1994. Structures in natural serpentinites gouges. Journal of Structural Geology, 16, 1205-1215.

Kornprobst, J. 1962. Observations sur la série métamorphiquede la presqu'île de Ceuta (Rif septentrional, Maroc). Comptes Rendus de l'Académie des Sciences de Paris, 255, 2140-2142.

Kusky, T M; Li, J H; Tucker, R D, 2001. The Archean Dongwanzi ophiolite complex, North China craton: 2.505-billion-year-old oceanic crust and mantle, Science, 292, 5519, 1142-1145

Lenoir, X., Garrido, C.J., Bodinier, J.L., Dautria, J.M. and Gervilla, F. 2001. The recrystallization front of the Ronda peridotite: thermal erosion and melting of the subcontinental lithospheric mantle beneath the Alboran basin. Journal of Petrology, 42, 141-158.

Lonergan, L. and White, N. 1997. Origin of the Betic-Rif mountain belt. Tectonics, 16, 504-522.

Loomis, T.P. 1972. Diapiric emplacement of the Ronda Hig-Temperature Ultramafic Intrusion, Southern Spain. Geological Society of America bulletin, 83, 2475-2496.

Loomis, T.P. 1975. Tertiary mantle diapirism, orogeny and plate tectonics east of the Strait of Gibraltar. American Journal of Science, 275, 1-33.

Lundeen, M.T. 1978. Emplacement of the Ronda peridotite, Sierra Bermeja, Spain. Geological Society of America bulletin, 89, 172-180.

Martínez-Martínez, J.M. and Azañón, J.M. 1997. Mode of extensional tectonics in the southeastern Betics (SE Spain). Implications for the tectonic evolution of the peri-Alborán orogenic system. Tectonics, 16, 205-225.

Michard, A. et al., 1993. High-pressure, low-temperature metamorphic rocks and mantle peridotites in the Rif belt, Morocco: whith role for the late orogenic extension? In: M. Séranne and J. Malavieille (Editors), Late orogenic extension in Mountain belts. B.R.G.M., Fr., 144-145.

Michard, A., Goffé, B., Bouybaouene, M.L. and Saddiqi, O. 1997. Late Hercinian-Mesozoic thinning in the Alborán domain: metamorphic data from the northern Rif, Morocco. Terra Nova, 9, 171-174.

Navarro-Vilá, F. and Tubía, J.M. 1983. Essai d'une nouvelle différenciation des Nappes Alpujarrides dans le secteur occidental des Cordilleres Bétiques (Andalousie, Espagne). Comptes Rendus de l'Académie des Sciences de Paris, 296, Série II, 111-114.

Obata, M. 1980. The Ronda peridotite: garnet-, spinel and plagioclase-, lherzolite facies and the P-T trajectories of a high-temperature mantle intrusion. Journal of Petrology, 21, 533-572.

Obata, M. 1994. Material transfer and local equilibria in a zoned kelyphite from a garnet pyroxenite, Ronda, Spain. Journal of petrology, 35, 271-287.

Platt, J.P. and Vissers, R.L.M. 1989. Extensional collapse of thickened continental lithosphere: A working hipothesis for the Alboran Sea and Gibraltar Arc. Geology, 17, 540-543.

Raleigh, C.B. and Paterson, M.S. 1965. Experimental deformation of serpentinite and its tectonic implications. Journal of Geophysical Research, 70, 65-75.

Reuber, I., Michard, A., Chaulan, A., Juteau, T. and Jermoumi, B. 1982. Structure and emplazament of the Alpine type peridotites from Beni Bousera, Rif Morocco: a polyphase tectonic interpretation. Tectonophysics, 82, 231-251.

Saddiqi, O., Feinberg, H., El Azzab, D. and Michard, A. 1995. Paléomagnétisme des péridotites des Beni Bousera (Rif interne, Maroc): conséquences pour l'évolution miocène de l'Arc de Gibraltar. Comptes Rendus de l'Académie des Sciences de Paris, 321, Série II, 361-368.

Sánchez-Gómez, M. 1997. Intracrustal emplacement and extensional dismembering of the Ronda and Rif peridotite bodies (Gibraltar arc). Ph. D. Thesis, University of Granada, Granada, 237 pp.

Sánchez-Gómez, M., Azañón, J.M., García-Dueñas, V. and Soto, J.I. 1999. Correlation between metamorphic rocks recovered from Site 976 and the Alpujárride rocks of the western Betics. In: R. Zahn, M.C. Comas and A. Klaus (Editors), Proccedings of the Ocean Drilling Program, Scientific results, College Station, TX, 307-317.

Sánchez-Gómez, M., García-Dueñas, V. and Muñoz, M. 1995. Relations structurales entre les Péridotites de Sierra Bermeja et les unités alpujarrides sous-jacentes (Benahavís, Ronda, Espagne). Comptes Rendus de l'Académie des Sciences de Paris, 321, Série II, 885-892.

Simancas, J.F. and Campos, J. 1993. Compresión NNW-SSE tardi a postmetamórfica y extensión subordinada en el Complejo Alpujárride (Dominio de Alborán, Orógeno Bético). Revista de la Sociedad Geológica de España, 6, 23-35.

Targuisti, K. 1994. Petrología y Geoquímica de los Macizos Ultramáficos de Ojén (Andalucía) y de Beni-Bouzera (Rif septentrional, Marruecos). Ph. D. Thesis, University of Granada, 226 pp.

Torné, M., Banda, E., García-Dueñas, V. and Balanyá, J.C. 1992. Mantle-Litosphere bodies in the Alboran crustal domain (Ronda peridotites, Betic-Rif orogenic belt). Earth and Planetary Science Letters, 110, 163-171.

Tubía, J.M. 1990. Comment on "Mantle core complexes and Neogene extensional detachement tectonics in the western Betic Cordilleras, Spain: an alternative model for the emplacement of the Ronda peridotite" by Miguel Doblas and Roberto Oyarzum. Earth and Planetary Science Letters, 96, 499-500.

Tubía, J.M. 1994. The Ronda peridotites (los Reales nappe): an example of the relationship between lithospheric thickening by oblique tectonics and late extensional deformation within the Betic Cordillera (Spain). Tectonophysics, 238, 381-398.

Tubía, J.M. and Cuevas, J. 1986. High-temperature emplacement of the Los Reales peridotite nappe (Betic Cordillera, Spain). Journal of Structural Geology, 8, 473-482.

Tubía, J.M. and Cuevas, J. 1987. Structures et cinématique liées à la mise en place des péridotites de Ronda (cordillères Bétiques, Espagne). Geodinamica Acta, 1, 59-69.

Tubía, J.M., Cuevas, J. and Gil-Ibarguchi, J.I. 1997. Sequential development of the metamorphic aureole beneath the Ronda periodotites and its bearing on the tectonic evolution of the Betic Cordillera. Tectonophysics, 279, 227-252.

Tubía, J.M., Cuevas, J., Navarro-Vilá, F., Alvarez, F. and Aldaya, F. 1992. Tectonic evolution of the Alpujárride Complex (Betic Cordillera, Southern Spain). Journal of Structural Geology, 14, 193-203.

Tubía, J.M. and Gil Ibarguchi, J.I. 1991. Eclogites of the Ojén nappe: a record of subduction in the Alpujárride complex (Betic Cordilleras, southern Spain). Journal of the Geological Society of London, 148, 801-804.

Van der Wal, D. 1993. Deformation processes in Mantle Peridotites: with emphasis on the Ronda peridotite of SW Spain. Univ. Utretch, pp. 180.

Van der Wal, D. and Vissers, R.L.M. 1993. Uplift and emplacement of upper mantle rocks in the western Mediterranean. Geology, 21, 1119-1122.

Vissers, R.L.M., Platt, J.P. and van der Wal, D. 1995. Late orogenic extension of the Betic Cordillera and the Alboran Domain: A litospheric view. Tectonics, 14, 786-803.

Westerhof, A.B. 1975. Genesis of magnetite ore near Marbella, southern Spain: Formation by oxidation of silicates in polymetamorphic gedrite-bearing and other rocks. GUA Papers of Geology, Series 1, Amsterdam, 216 pp.

Westerhof, A.B. 1977. On the contact relations of high-temperature peridotites in the Serranía de Ronda, Southern Spain. Tectonophysics, 39, 579-591.

Wicks, F.J. 1984. Deformation histories as recorded by serpentinites. II. Deformation during and after serpentinization. Canadian Mineralogist, 22, 197-204.

Zeck, H.P. 1997. Mantle peridotites outlining the Gibraltar Arc-centrifugal extensional allochthons derived from the earlier Alpine, westward subducted nappe pile. Tectonophysics, 281, 195-207.