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23. CORRELATION BETWEEN METAMORPHIC ROCKS RECOVERED FROM SITE 976 AND THE ALPUJÁRRIDE ROCKS OF THE WESTERN BETICS[1]

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ABSTRACT

The metamorphic basement of the Alboran Basin at Site 976 yields high-grade schists, gneiss, migmatitic gneiss, marble, calc-silicate rocks, and granites. In the Alboran Domain, lithologic sequences composed mainly of this set of high-grade metamorphic rocks only occur in the Jubrique and Blanca Group units belonging to the Alpujárride Complex (Sebtide in the Rif). These rocks show a complex tectonometamorphic evolution in which different events accompanied by different stages of mineral growth with variable pressure-temperature conditions can be noted. Studies of the lithologic and metamorphic characteristics of the samples from Site 976 and comparison with the western Alpujárride rocks have allowed us to propose a position for the drilled basement sequence within the Alpujárride Complex. We conclude that the basement sampled at Site 976 corresponds to rocks belonging to the Blanca Group, cropping out onshore below the peridotite bodies and/or in an imbricate zone between two peridotite slices (Montemayor slices). The tectonic exhumation of the Blanca Group units, partially contemporary with Upper Serravallian–Tortonian sediments, was produced during the rifting (northeast-southwest extension direction) of the Alboran Basin.

INTRODUCTION

Most western Mediterranean Neogene basins overlie attenuated continental crust belonging to an Alpine collisional orogen (Late Cretaceous–Paleogene) formed by several tectonometamorphic complexes. Significant segments of this orogen crop out onshore: the Betic and Rif internal zones (Alboran Domain), surrounding the Alboran Basin; the Kabylies, to the south of the Balearic-Algerian Basin; and some massifs of Sicily and Calabria, around the Tyrrhenian Basin (Boullin et al., 1986). The above-mentioned crustal segments overthrust peripheral arcuate thrust sheets of detached covers; the nappe stacking is concomitant with the rifting processes in the western Mediterranean basins.

Drilling in the Alboran Sea at Ocean Drilling Program Leg 161 Site 976 has confirmed the existence of continental crust beneath the western Alboran basin (Fig. 1). In fact, Holes 976B and 976E at Site 976 recovered 259 m and 84 m of high-grade metamorphic rocks, respectively (Shipboard Scientific Party, 1996). These rocks are similar to others on land that form part of one of the three main tectonometamorphic complexes comprising the Alboran Domain (Fig. 1): the Nevado-Filabride, Alpujárride, and Malaguide, from bottom to top. Only the Alpujárride Complex contains high-grade metamorphic rocks; thus, the Shipboard Scientific Party (1996) proposed that the basement rocks drilled at Site 976 belong to this complex.

Nevertheless, the Alpujárride Complex is formed of many crustal tectonic units; several mantle slabs (Ronda peridotites) are emplaced between them. Generally, the former thrust-nappe boundaries of the Alpujárride units are not preserved, having been reused or obliterated by brittle, low-angle, normal faults and extensional detachments related to the Miocene Alboran rifting. Structural position, pressure-temperature (PT) metamorphic conditions, and lithology are used to differentiate, correlate, and assemble the Alpujárride units over extended areas of the Alboran Domain (Tubía et al., 1992; Azañón et al., 1994; Balanyá et al., 1997).

Preliminary estimates of PT conditions from the high-grade metamorphic basement rocks at Site 976 (Shipboard Scientific Party, 1996) justify their being attributed to the Alpujárride units surrounding the Ronda peridotite massifs (west of Málaga; Fig. 1) described by Torres-Roldán (1979), Tubía et al. (1992), Balanyá et al. (1993), and Balanyá et al. (1997), among others.

The metamorphic evolution and the downward increase in metamorphic grade of basement at Site 976 is similar to the high-grade metamorphic rocks overlying the peridotite massifs; however, the lithologic assemblage is rather different because of the presence of marble, calc-silicate rocks, and granitic rocks (Shipboard Scientific Party, 1996). In fact, all these lithologies, together with high-grade schist, are characteristic of the units underlying the Ronda peridotite slabs.

We compared selected lithologic, metamorphic, and structural features common to both the basement rocks beneath Site 976 and to the onshore Alpujárride lithologic sequences surrounding the Ronda peridotite massifs. Our aim was to establish a more accurate structural position for the basement segment recovered at Site 976. Finally, we discuss some implications of our proposal for the correlation of these rocks.

REGIONAL SETTING

Data from holes drilled during Leg 161 (Comas, Zahn, Klaus, et al., 1996) confirmed the geologic assumption that the Alboran Sea basement is continental, consisting primarily of rocks belonging to the Alboran Domain (Balanyá and García-Dueñas, 1987; Comas et al., 1992; García-Dueñas et al., 1992; Vissers et al., 1995). This crustal domain includes the Internal Zones of the Betic and Rif Cordilleras.

The Alboran Crustal Domain, hinterland of the Gibraltar Arc, consists of several tectonic complexes that extend on land, thrusting over the detached covers of the Iberian and Maghrebian Margins. The seismostratigraphic sedimentary units identified in the Alboran Sea basin (Comas et al., 1992) also continue onshore, unconformably overlying the Alboran Domain.

The three main nappe complexes of the Alboran Domain can be differentiated by their tectonometamorphic record (Fig. 1). The Alpujárride Complex, tectonically placed over the Nevado-Filabride

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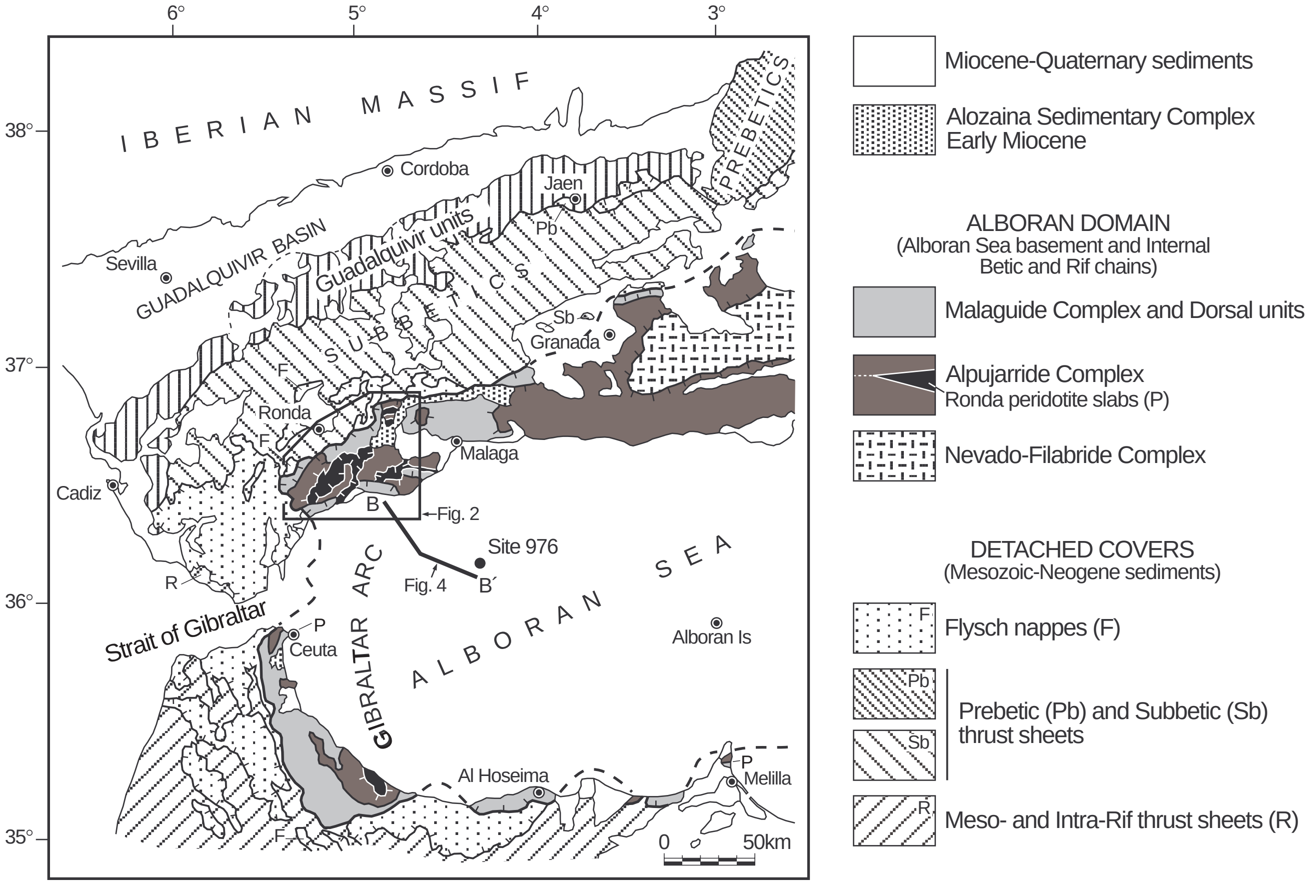

Figure 1. Main tectonic units of the Alboran Domain around the Gibraltar Arc. Cross section B-B′ is detailed in Figure 4.

Complex and below the Malaguide Complex, characteristically includes in its highest tectonic units rocks that reached temperatures of 550°–700°C under conditions of low-pressure, high-temperature metamorphism; that is, the same values as the basement rocks at Site 976 (Shipboard Scientific Party, 1996; Platt et al., 1996).

Summarizing Tubía et al. (1992), Azañón et al. (1994), and Balanyá et al. (1997), four groups of Alpujárride tectonic units have been distinguished in the Betics according to structural and metamorphic criteria, particularly taking into account conditions reached by the rocks from each unit in high-pressure, low-temperature, and low-pressure, high-temperature metamorphic events. From top to bottom, these groups of units are termed the following:

1. Jubrique Group. This group is typified by the Jubrique Unit in the western Betics (Fig. 2). The lithologic sequence of this unit formed from Triassic and Permian–Triassic protoliths in low-grade metamorphic conditions and from Paleozoic protoliths that reached medium- and high-grade metamorphic conditions in their upper and lower levels respectively (Torres-Roldán, 1979). Relict mineral assemblages preserved in Triassic and Permian–Triassic levels evidence an Alpine high-pressure metamorphic event; the overprinted metamorphic record displays progressive evolution up to low-pressure/high-temperature conditions (Azañón et al., 1994; Balanyá et al., 1997).
2. Blanca Group. Typified by the Ojen Unit in the western Betics (Fig. 2). It also includes Triassic, Permian–Triassic, and Paleozoic protoliths, but in the upper part of the lithologic sequence (Triassic and Permian–Triassic protoliths), high-grade metamorphic conditions can be recognized (Westerhof, 1975). Alpine eclogites have been found in the lower part of the Ojen lithologic sequence (Tubía and Gil Ibarguchi, 1991). The Ronda peridotite massifs and other minor-scale ultramafic slabs are intercalated between the units of the Jubrique and Blanca Groups (Sánchez-Gómez et al., 1995).
3. Escalate Group. This group only crops out in the central and eastern Betics. The units contain Triassic carbonate rocks and Permian–Triassic metapelites with high-pressure, low-temperature metamorphism evolving to low-pressure, low-temperature metamorphism.
4. Lujar-Gador Group. This group only crops out in the central and eastern Betics. The lithologic sequences are similar to those of the Escalate Group, although the metapelites record only low-pressure/low-temperature metamorphism.

The high-pressure event detected in Triassic, Permian–Triassic, and Paleozoic rocks belonging to the Jubrique, Blanca, and Escalate groups of units represents the former Alpine record of the Alpujárride Complex (Azañón et al., 1994). The present-day relative structural position of these groups of units implies extensive modification of the initial Alpujárride nappe stack, because high-grade metamorphic rocks from the Jubrique and Blanca Groups now systematically overlie the low-grade metamorphic rocks from the Escalate and Lujar-Gador Groups.

The tectonometamorphic evolution of the Alpujárride Complex was established on the basis of the metamorphic events and related structures observed in the Jubrique-Group tectonic units of the eastern and western Betics (Azañón et al., 1997; Balanyá et al., 1997). The proposed succession of events was contrasted with available

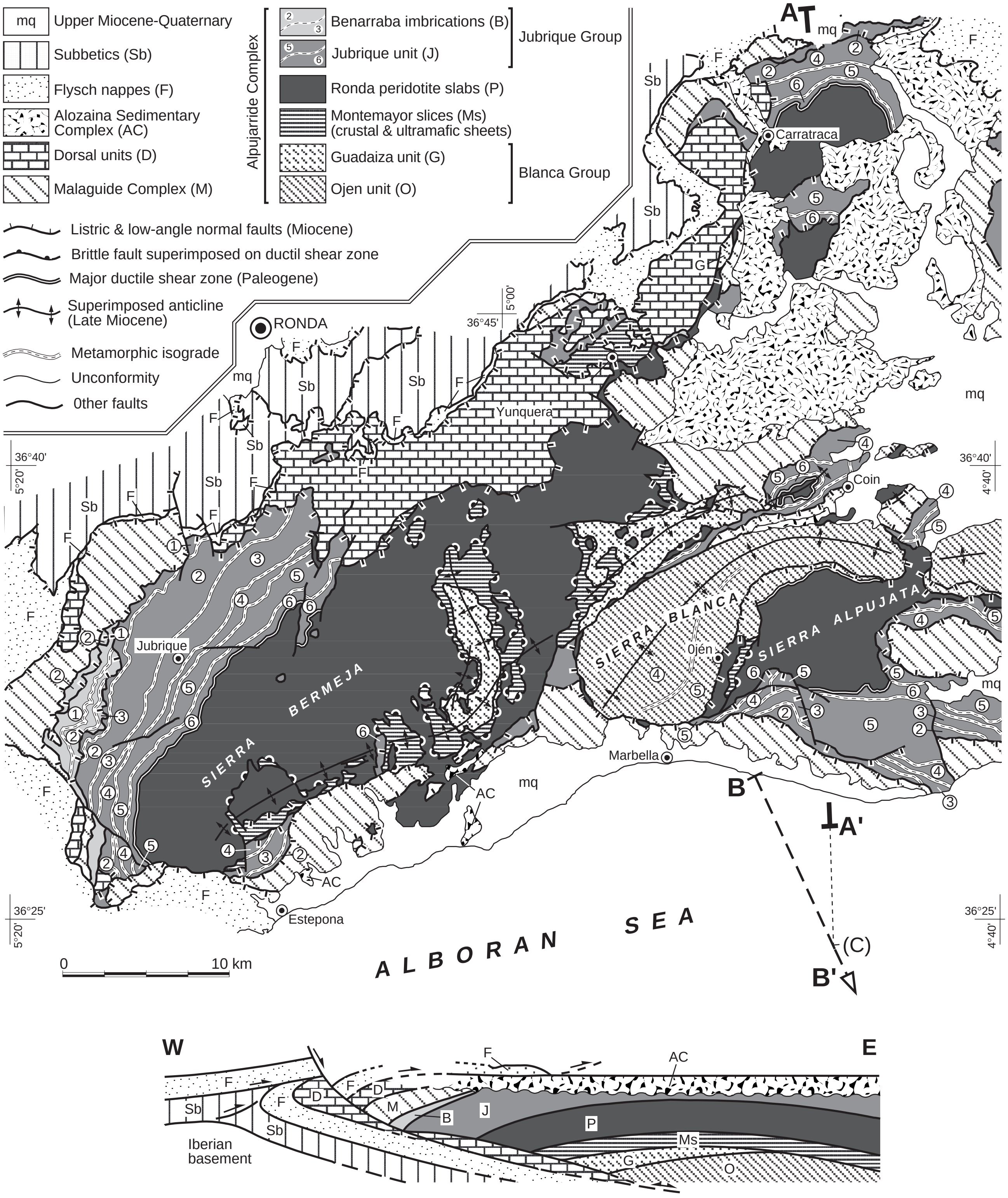

Figure 2. Groups of Alpujárride units in the Ronda region, western Betics. The schematic west-east cross section at the bottom of the figure shows the general structural position of the tectonic elements cropping out in the region. A-A′ and B-B′ are cross sections detailed in Figure 4; C is the intersection of the cross sections A-A′ and B-B′.

structural and metamorphic data for the remaining groups of Alpujárride units, and reflects the main orogenic events in the Alboran Domain.

Throughout event 1, crustal thickening occurred in a collisional setting, as suggested by the presence of high-pressure mineral assemblage relics and incipient foliation. Event 2 is related to the pervasive flattening foliation (Sp) that formed in nearly isothermal decompression conditions; significant crustal thinning is obvious in this event, as indicated by the PT paths and the approximation of metamorphic isograds. Event 3 coincides with the development of major north-vergent overturned and large-scale recumbent folds that deformed the Sp foliation and metamorphic-isograde geometries. These folds and associated thrusts contributed to the general reorganization of the former nappe stack; development of crenulation foliation (Sc) during this event was accompanied by low-pressure mineral growth. The Alpujárride units were once again heavily attenuated during the Miocene rifting (event 4) that culminated in the development of the Alboran basin over the continental crust collisional belt (e.g., Galindo et al., 1989; García-Dueñas et al., 1992; Crespo-Blanc et al., 1994); outward migration of the Gibraltar Arc mountain front was concomitant with the Alboran rifting (Platt and Vissers, 1989; García-Dueñas et al., 1992). Ductile and brittle extensional detachments and listric normal faults associated with tectonic event 4 altered the boundaries of the Alpujárride units. Finally, folds and faults that developed during a late contraction event 5 (Weijermars et al., 1985; de Larouzière et al., 1988) modified the regional physiography and reduced the Miocene Alboran basin to the boundaries of the present Alboran Sea.

In short, the orogenic evolution of the Alpujárride Complex, and therefore of the Alboran Domain, is characterized by alternating contractional and extensional events (Balanyá et al., 1997). The evolution started with continental collision around the Upper Cretaceous or Paleocene (DeJong, 1991; Azañón et al., 1994) and ended in the Miocene with crustal thinning (Alboran rifting), finally dominated by roughly isobaric cooling (Zeck et al., 1992; Monié et al., 1994).

ALPUJÁRRIDE UNITS IN THE RONDA REGION

The best exposure of the higher Alpujárride units is found in this region, corresponding to the Jubrique and Blanca Groups (Balanyá et al., 1997; Tubía et al., 1992), located respectively above and below the peridotite massifs (Figs. 1, 2).

The Jubrique Group (Fig. 2) consists of the Jubrique Unit and the overlying Benarraba imbrications (Balanyá et al., 1997). The metamorphic isograds display parallel to Sp foliation in all these units. This general parallelism was produced during the above-mentioned extensional event 2 (Loomis, 1972; Torres-Roldán et al., 1979; Balanyá et al., 1993); at the same time, the Jubrique Unit thinned to probably one-third its original thickness and the lower crust disappeared entirely (Balanyá et al., 1997).

Specifically, the Jubrique Unit (Balanyá, 1991; Balanyá and García-Dueñas, 1991) contains a 5-km-thick metamorphic succession of, from bottom to top (Fig. 3), garnet gneiss, migmatite gneiss, staurolite-bearing schists, chloritoid-bearing schists, fine-grained schists, quartzites, calc-silicate, and carbonate rocks. It has upward-decreasing metamorphic zoning, with isograds subparallel to the lithologic contacts. The surprisingly complete lithologic sequence of the Jubrique Unit roughly corresponds to a segment of condensed middle-upper crust (Balanyá et al., 1993; Balanyá et al., 1997). It grades from metapelitic granulites at the bottom to Triassic carbonate formations at the top, with little or no evidence of recrystallization. Each of the Benarraba imbrications (Figs. 2, 3) consists of lithologic sequences similar to the upper third of the Jubrique Unit, normally comprising chloritoid-bearing schists up to the formation of carbonates and, more locally, staurolite-bearing schists in a lowermost position.

The Blanca Group consists of, in ascending order, the Ojen and Guadaiza Units (Figs. 2, 3, 4), both predominated by high-grade metamorphic rocks intruded by variably sized granitic bodies (Navarro-Vilá and Tubía, 1983; Tubía, 1985).

The Ojen Unit, which underlies the Alpujata peridotite massif, is a large-scale recumbent syncline whose reverse limb crops out at the Sierra Blanca in the core of a late superimposed Miocene anticline (Fig. 2). The recumbent synclinal core contains thick marbles (Triassic protoliths) and the limbs contain high-grade schists, amphibolites, and gneissic rocks. Minor folds (Fig. 5C) and a penetrative axial-plane cleavage (Sc) overprint the Sp foliation. The Ojen lithologic sequence consists of the following members in ascending stratigraphic order (Fig. 3): migmatite and garnet gneiss (Fig. 5A), high-grade schist and gneiss with intercalated metabasites, and marbles, the latter attributed to the Triassic (Mollat, 1968; Westerhof, 1975). An abundance of metabasite intercalations, with eclogite relics in the lowest ones, is a characteristic feature of the Ojen Unit (Tubía and Gil Ibarguchi, 1991; Sánchez-Gómez, 1997).

The Guadaiza Unit contains a monotonous sequence of quartzites, high- and medium-grade schists, gneiss, and minor amounts of metabasites. Marble bodies are included within a thick fault zone overlying the unit; however, it is impossible to determine whether or not they form part of the unit.

The Montemayor tectonic slices lie beneath the Bermeja and Alpujata major peridotite bodies, but overlie the Guadaiza and Ojen Units (Figs. 2, 3). They are formed from alternating slices of peridotites or Blanca Group-type rocks, associated with abundant granitic rocks (Lundeen, 1978; Sánchez-Gómez et al., 1995). The Montemayor peridotite slices are generally undifferentiated in Figure 2 because of their extreme thinness (<10 m at times). Nevertheless, some Montemayor ultramafic slices are laterally continuous with the thick slabs forming the Ronda peridotite massifs, as is the case of the northeastern thinning of the lower of the two outcropping peridotite slabs 7 km north of Estepona (Fig. 2). The boudinlike structure of the Alpujata peridotite massif, emplaced between the overlying Jubrique Unit and the underlying Ojen Unit (Fig. 2), is an illustrative example of lateral thinning produced by northeast-southwest stretching. Nearly northwest-southeast extension can be seen throughout cross section A-A′ in Figure 4.

Migmatitic and intrusive granitic rocks (granite and granodiorite), normally rich in cordierite and xenoliths, commonly appear in the Blanca Group units and in the Montemayor slices and less commonly in the Jubrique Unit. Relationships with the other lithologies are varied and complex. These rocks occur as large sheetlike bodies associated with a wide shear zone that includes the lower peridotite boundary; they occur also as variably sized dikes cutting across most of the ductile structures (Fig. 5F).

The granitic rocks are subdivided in turn into three main lithologic sets according to their petrologic characteristics: diatexitic granitoids, porphyritic granitoids, and leucogranites, from oldest to youngest (Sánchez-Gómez, 1997). The radiometric ages of these rocks varies from 19 to 22 Ma (Priem et al., 1979; Zeck et al., 1989, 1992; Monié et al., 1994).

The superposition of extensional fault systems with transverse stretching during the Alboran Miocene rifting (event 4) gave rise to mega-chocolate tablet structures, a well-known regional feature in the tectonic units of the Alboran Domain Complexes (García-Dueñas et al., 1992; Comas et al., 1992; Crespo-Blanc et al., 1994; Crespo-Blanc, 1995). The extensional fault systems of this interference pattern dismembered the Alpujárride units and separated the peridotite massifs from the mantle lithosphere slabs that had presumably been emplaced during nappe-forming event 3. After extension, the main

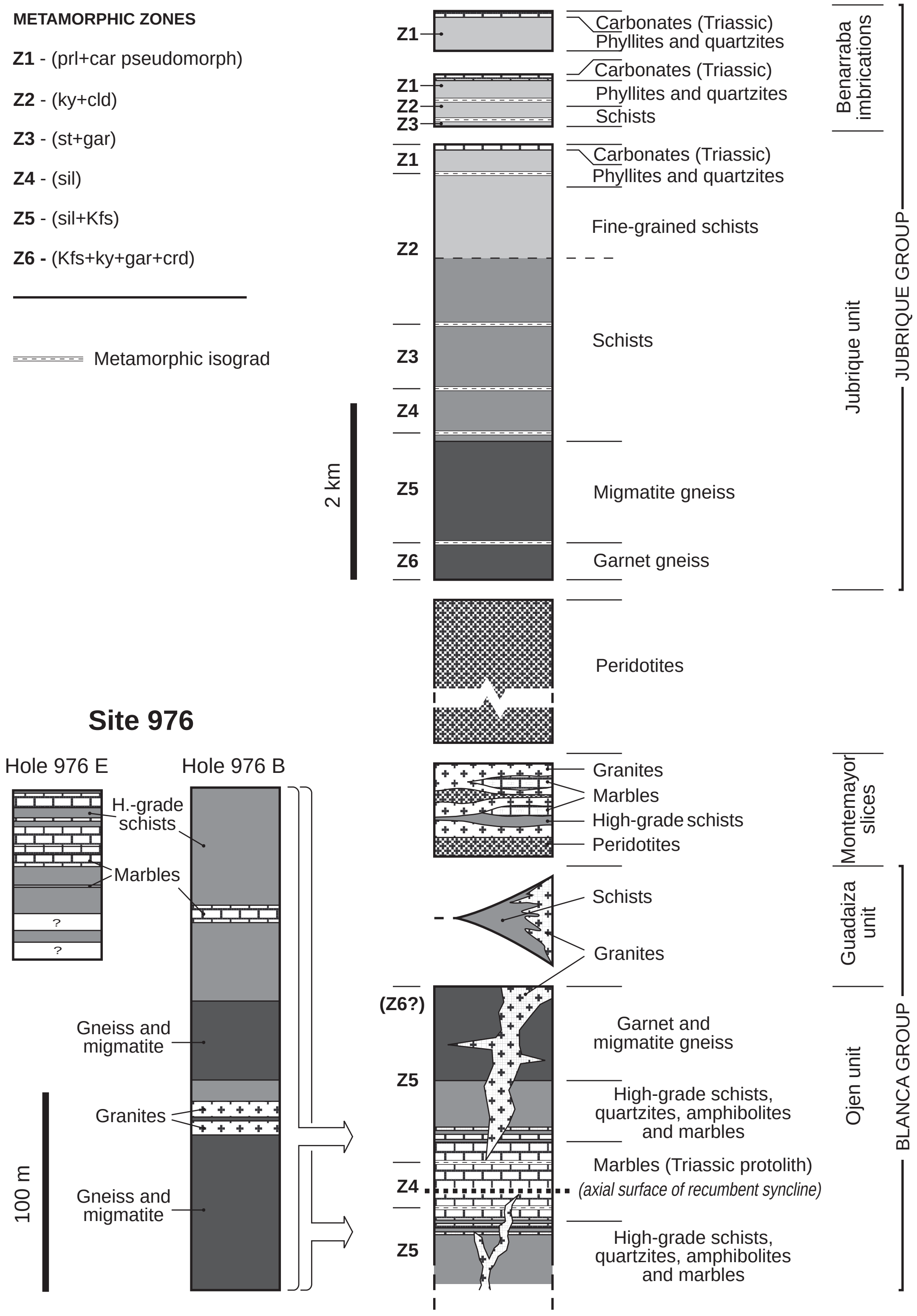

Figure 3. Basement rocks recovered from Site 976 (Shipboard Scientific Party, 1996) vs. representative lithologic sequences of the Alpujárride units belonging to the Jubrique and Blanca Groups (Ronda region, western Betics). Holes 976B and 976E were only 20 m apart. Arrows above and below the axial surface of the Ojen recumbent syncline indicate two tentative correlation proposals for the basement lithotypes cored at Site 976. Mineral abbreviations are as follows: car = carpholite, cd = cordierite, cld = chloritoid, gar = garnet, Kfs = K-feldspar, ky = kyanite, prl = pyrophyllite, sil = sillimanite.

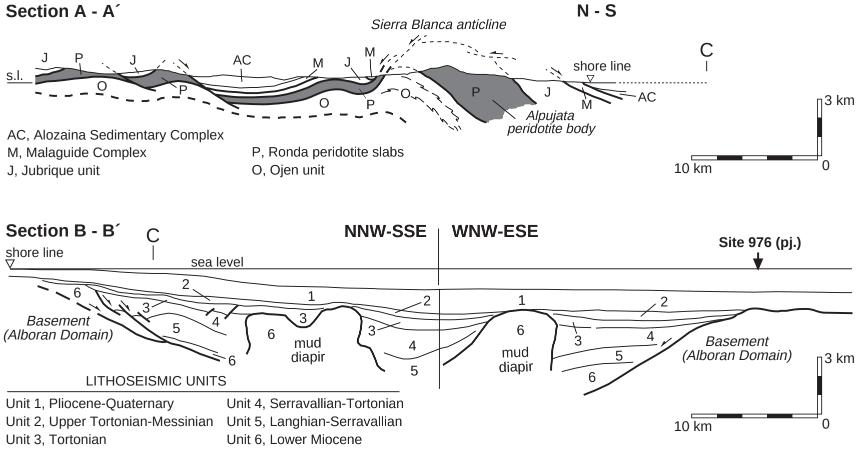

Figure 4. Cross sections showing the structural relationships between the Site 976 high and the Alpujárride units in the Ronda region. Cross section A-A′ (see Fig. 2 for location) exhibits the extensional thinning and dismembering of the Alpujata peridotite body (stretching nearly northwest-southeast). Cross section B-B′ (see Fig. 1 for location) shows the main low-angle normal faults bounding a northeast-southwest Miocene graben beneath the northwest Alboran Sea and mud diapirs related to the extension (simplified from two MCS profiles across the northwestern Alboran Basin, from Comas et al., 1992); lithoseismic units after Comas et al. (1992). The Alozaina Sedimentary Complex (AC) is the equivalent on land of lithoseismic unit 6.

peridotite bodies were connected only by thin discontinuous sheets of serpentinized peridotites.

METAMORPHIC PT CONDITIONS

Jubrique Unit

The Jubrique Unit consists of a segment of severely thinned middle and upper crust at the end of event 2 (Balanyá et al., 1997), where each metamorphic zone formed an approximately horizontal level whose PT conditions were determined by the geothermal gradient. The metamorphic evolution of four sections was analyzed: the phyllites, the fine-grained schists, the sillimanite-bearing schists, and the garnet gneiss (Figs. 3, 6A).

The presence of pre-Sp carpholite pseudomorphs in quartz veins from the phyllite, quartzite, and calc-schist sections indicates that event 1 reached high-pressure, low-temperature conditions (Balanyá et al., 1997). The stability field for carpholite depends on the end-member of the solid solution between Fe-carpholite and Mg-carpholite (Vidal et al., 1992). The X_{Mg} ratio is 0.75, indicating $P > 7$ kbar, whereas the absence of kyanite implies a temperature limit of 400°C. The association between chloritoid ($X_{Mg} = 0.34$), kyanite, and chlorite ($X_{Mg} = 0.75$) appears in the fine-grained schists, indicating $P = 8$ kbar and $T \approx 425$°C, according to the reaction calculated by the GEO-CALC program (Brown et al., 1988).

During Sp development, pyrophyllite, chloritoid, and carpholite were replaced by white mica and chlorite. The white mica, associated with biotite, K-feldspar, and quartz (Massonne and Schreyer, 1987), contains 3.15 atoms per formula (apf) Si, which is indicative of a minimum pressure of ~4 kbar at 400°C (Balanyá et al., 1997).

Syn- and post-Sp sillimanite is the index mineral for the lower part of the metapelites (Fig. 6A; sillimanite-bearing schists). The metamorphic peak in this mineral zone gives temperatures of 600° ± 40°C using the garnet-biotite geothermometer (Perchuk and Larent'eva, 1983; Ganguly and Saxena, 1985) in garnet cores and biotites. A garnet-aluminosilicate-plagioclase (GASP) geobarometer was used at different calibrations (Koziol and Newton, 1988; Powell and Holland, 1988) on garnet cores and pre-Sp plagioclase, yielding a pre-Sp episode pressure of 11 ± 1 kbar for an assumed temperature of 600°C. These results, however, must be considered approximate, because diffusion may have altered core compositions at such high temperatures. The first post-Sp growth of sillimanite in these schists and its subsequent transformation to andalusite indicate that a temperature of >550°C was maintained below a pressure of 3 kbar (Fig. 6A). Andalusite commonly encloses post-Sp staurolite in Z4. Several reactions occurred in the garnet gneisses during event 2 (formation of main foliation): the transformation of rutile to ilmenite (although it is preserved as inclusions in the garnet); the transformation of kyanite to sillimanite; and a late-phase progressive substitution of garnet by cordierite. All these reactions indicate substantial decompression.

The retrograde profiles of the nuclei of large garnets were used to determine the PT conditions for the beginning of event 2 or the end of event 1 (Fig. 6A; garnet gneiss). Temperature was established using the geothermometer mineral pair garnet-clinopyroxene (Ellis and Green, 1979; Powell, 1985) at 770°–790°C. GASP equilibrium (garnet-aluminosilicate-plagioclase) at different calibrations (Koziol and Newton, 1988; Powell and Holland, 1988) was used to determine pressures of 11.5 and 13.5 kbar, in the nuclei of both plagioclase porphyroblasts and plagioclase included in garnet (assuming $T = 780$°C). These pressures are in accordance with the presence of rutile included in the garnet.

Pressures of 5–7 kbar were determined by applying the same geobarometer to the garnet rims and to post-Sp mylonitic plagioclase (Fig. 6A; garnet gneiss). The temperature for the same episode of mineral growth was estimated at 725°–795°C using the garnet-biotite geothermometer (Perchuk and Larent'eva, 1983; Ganguly and Saxena, 1985). Nevertheless, the presence of post-Sp cordierite and the composition of the adjacent garnet rims indicate that the end of event 2 saw lower-pressure conditions of around 3–4.5 kbar (Fig. 6A; garnet gneiss) at temperatures that were still relatively high (650°–700°C). These pressures and temperatures were obtained assuming a water activity of 0.3 using Phillips' method (1980) and applying the graph geothermobarometers of Martignole and Sisi (1981) and the numerical ones of Bhattacharya (1986). The garnet gneiss, therefore, indicates a practically isothermal decompression trajectory for event 2. No mineral textures provide information on the evolution of event 3 metamorphic conditions. Circumstances were similar for event 4, which saw no significant mineral growth in the garnet gneisses. Final cooling at low pressure, characterized by the substitution of K-feldspar and cordierite by sericite and pinnite, is attributed to events 4 and 5.

Ojen Unit

The Ojen Unit, a recumbent syncline with abundant granitic intrusive rocks (Fig. 3), is characterized by minimum temperatures of >550°C, even in the higher lithostratigraphic levels (attributed to the Permian–Triassic); well-developed crenulation foliation (Sc) is related to folding. In contrast with the Jubrique Unit, the Ojen Permian–Triassic rocks yield no high-pressure, low-temperature traces. Some relics of the high-pressure metamorphism (eclogites) were found from metabasites located in the lower part of the lithostratigraphic sequence belonging to the reverse limb of the syncline (Tubía and Gil Ibarguchi, 1991; Sánchez-Gómez, 1997).

Two lithologic sections from the upper and lower parts of the lithostratigraphic sequence were selected to present the PT evolution

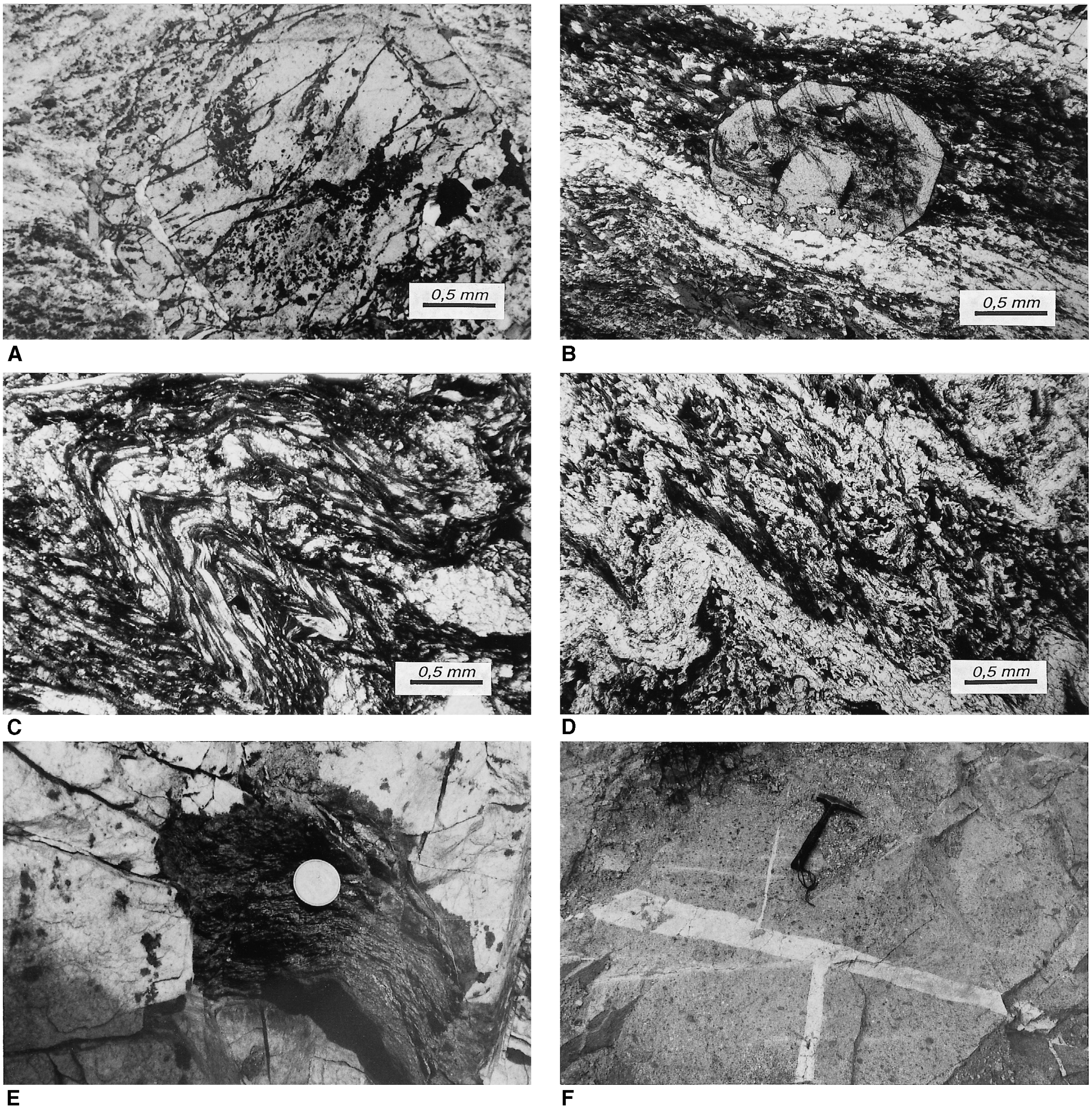

Figure 5. **A.** Garnet in Guadaiza high-grade metapelites (sample HB); the idioblastic garnet rim is synkinematic to the external foliation (Sp), and the core, with abundant inclusions, is also idioblastic. **B.** Garnet in the high-grade schists from Sample 976E-14R-1, 45–50 cm; similar textural features as in photograph in A. **C.** Sillimanite deformed by post-Sp folds in high-grade schists from the Ojen Unit (sample OJ-2571-C). Note the presence of sillimanite crystals in the axial planes of these folds. **D.** Sillimanite growth in the axial plane of post-Sp crenulation folds (Sample 976B-1, 119–124 cm). **E.** Porphyric granite intruded into the Guadaiza Unit including xenoliths of high-grade schists. **F.** Leucogranite dikes cutting across diatexites and granites with xenoliths of high-grade schists (Montemayor slices).

of the Ojen Unit (Figs. 3, 6B). The highest section stratigraphically consists of high-grade schists and impure marbles, whereas the lowest section stratigraphically consists of migmatite and garnet gneiss.

In the marbles (Triassic protoliths) the mineral association includes diopside + forsterite ± phlogopite ± spinel ± clinohumite ± rutile ± ilmenite, which indicates high-grade metamorphic conditions. In the schists, the structural and metamorphic features of event 1 were not preserved. Event 2 must also have developed in high-grade conditions because K-feldspar and muscovite grew during Sp development. The most interesting mineral association in the schists is quartz + biotite + plagioclase + sillimanite ± K-feldspar ± cordierite ± muscovite (Sánchez-Gómez, 1997), and when the whole chemical composition of the rocks is favorable, other metamorphic minerals such as clinopyroxene, spinel, corundum, tourmaline, and cum-

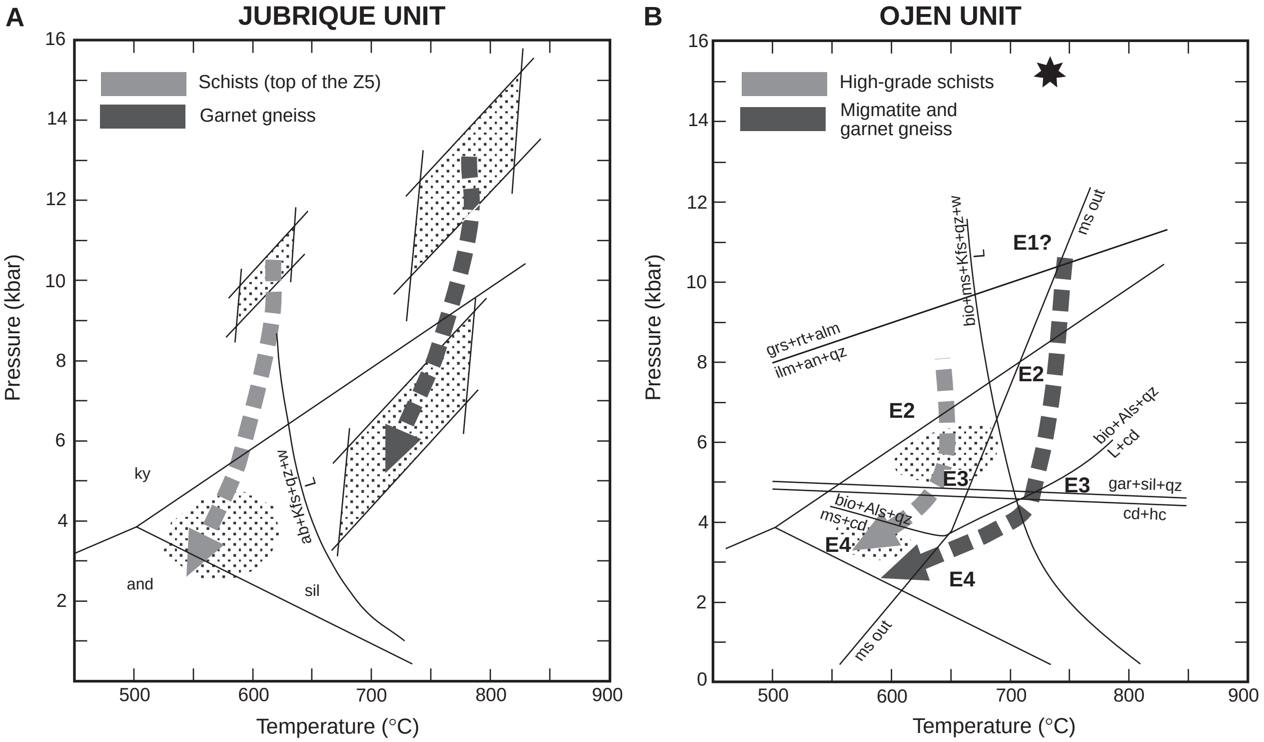

Figure 6. **A.** PT conditions reached during the metamorphic evolution of two rock levels in the Jubrique Unit (from Balanyá et al., 1997). Aluminosilicate stability fields from Holdaway (1971). **B.** PT diagram summarizing PT evolution of two rock levels in the Ojen Unit (from Sánchez-Gómez, 1997). E1, E2, E3, and E4 = tectonometamorphic events (see text for explanation). Star indicates the minimum PT conditions for the eclogites (Tubía and Gil Ibarguchi, 1991). Mineral abbreviations are as follows: ab = albite, alm = almandine, Als = aluminosilicate, an = anorthite, and = andalucite, bio = biotite, cd = cordierite, gar = garnet, grs = grossular, hc = hercynite, ilm = ilmenite, Kfs = K-feldspar, ky = kyanite, L = liquidus, ms = muscovite, qz = quartz, rt = rutile, sil = sillimanite, w = water.

mingtonite are observed (Westerhof, 1975). All these mineral associations indicate that high-grade conditions were reached in the schists. The presence of syn- to post-Sc K-feldspar, a product of the reaction muscovite + quartz = K-feldspar + biotite + sillimanite + water (ms-out reaction in Fig. 6B), indicates that the Ojen Unit schists reached temperatures of ≤700°C during event 3, although the preservation of syn-Sp muscovite may indicate that these reactions were not widely surpassed (Fig. 6B, high-grade schists).

Migmatite and garnet gneiss are similar to the Jubrique Unit ones and have the same mineral association (garnet-potassium feldspar-plagioclase-quartz-cordierite-sillimanite), except that no crystals or kyanite pseudomorphs can be seen. This does not mean, however, that they were never in kyanite conditions (i.e, metamorphic zone 6; see Fig. 3) because the presence of rutile as inclusions in the garnet indicates pressures of >8 kbar (calculated with the GRIPS reaction, grossularite + almandine + rutile = ilmenite + anorthite + quartz; Sánchez-Gómez, 1997). The complete disappearance of kyanite can be attributed to high temperatures during the intermediate-pressure event 3, as may be noted in the remaining levels in the Ojen lithologic sequence. Textural evidence of the reaction garnet + sillimanite + quartz = cordierite + hercynite unequivocally indicates a pressure drop below 5 kbar at high-temperature conditions during the metamorphic evolution of these rocks.

A decompression path has also been obtained from the gneiss using the garnet-biotite geothermometer (Perchuk and Larent'eva, 1983; Ganguly and Saxena, 1985) and the GASP geobarometer (equilibrium at different calibrations; Koziol and Newton, 1988; Powell and Holland, 1988); this path is in accordance with data from Westerhof (1977), Torres-Roldán (1981), and Tubía and Gil Ibarguchi, (1991). Minimum metamorphic conditions reached during event 1 are shown in Figure 6B (migmatite and garnet gneiss), although the pressure conditions must have been similar to those recorded for the eclogites (>14 kbar; Tubía and Gil Ibarguchi, 1991). The end of the Sp development must have taken place at P > 4–5 kbar and T ≈ 700°C, which are the conditions for the garnet to cordierite transformation, occurring during event 2 and later. Event 3, poorly defined in these rocks, probably occurred under the same PT conditions because K-feldspar and sillimanite grow along the axial plane foliation of the folds of this event (Fig. 5C). Subsequent decompression and associated cooling, corresponding to event 4, was most likely marked by reequilibrium of the garnet rims with biotite and plagioclase.

As can be seen in Figure 6B, at the end of event 2 the gneiss surpassed the PT conditions for generation of melts, which was more or less abundant depending on the amount of water available. These H_2O-poor rocks produced a limited amount of melt that gave rise to the migmatitic gneiss (metatexites) with S2-parallel differentiates. The gneiss show crenulation folding (event 3) and constitute xenoliths in the granites, granitoids, and diatexites that formed during event 4.

It can be assumed that the evolution of the granitic rocks intruding the Ojen Unit occurred during event 4, because they are not affected by the main Sp foliation (event 2) nor by the crenulation folds (event 3). Indeed, both of these structures are found inside xenoliths or are cut by dikes and granite bodies (Figs. 5E, 5F).

ALBORAN BASEMENT BENEATH SITE 976

Holes 976B and 976E at Site 976 penetrated into metamorphic basement of the Alboran Sea basin, where 259 m and 84 m of basement rocks, respectively, were drilled. Serravallian sediments of lithostratigraphic Unit IV directly overlie the basement. Figure 3 displays simplified lithologic columns from both holes (for detailed description see Shipboard Scientific Party, 1996).

The most abundant lithologies from Holes 976B and 976E are gneiss (including migmatite), high-grade schist, and marble; intervals of calc-silicate rocks occur in all these rocks. Dip of the main foliation ranges from 10° to 90° (maximum 10°–30°) from Hole 976B, and from 30° to 90° (maximum 30°–50°) from Hole 976E. Zones of cataclastic breccia and fault gouge are numerous and represent 18% and 29% of the total basement thickness recovered from Holes 976B and 976E, respectively.

The difference in depth (at least 11 m) to the sediment/basement boundary between Holes 976B and 976E (only 20 m apart) indicates considerable basement relief. This basement feature and the existence of breccias containing microfossils below the sediment/basement boundary suggest active faulting in a marine environment during the Serravallian. In addition, left-lateral oblique faulting was suggested based on the occurrence of striae on fault planes that developed in the basement (Shipboard Scientific Party, 1996).

Preliminary PT diagrams suggest that the metamorphic evolution of the high-grade schist and migmatitic gneiss from Site 976 followed an approximately isothermal path from 7 to 3 kbar at temperatures in the range between 580° and 630°C; granitic melts formed after decompression at <3 kbar and >670°C (Shipboard Scientific Party, 1996; Platt et al., 1996).

PT conditions for high-grade schist and gneiss from the basement recovered at Site 976 were established by Soto et al. (Chap. 19, this volume). According to these authors, the high-grade schist reached P ~ 4-5 kbar at temperatures in the range 650°–700°C at the end of the tectonic event that developed the main foliation (biotite + sillimanite + K-feldspar + quartz + plagioclase ± garnet assemblage). These PT conditions were estimated using thermobarometric studies and standard phase relations in pelitic systems. The mineral assemblage developed because of the completion of the staurolite-out and muscovite-dehydration melting reactions, determining both the final growth of biotite + sillimanite and local garnet as the main phases of the assemblage. In the gneissic rocks, melting probably occurred at $P < 7$ kbar and T between 700° and 750°C, with the formation of the main mineral assemblage (biotite + sillimanite + cordierite + K-feldspar + quartz + plagioclase). PT conditions for melting must be taken with caution because of considerable uncertainty in thermobarometric results and the variance of this assemblage. After decompression, accompanied by melting in the gneiss, a probable quick cooling PT path occurred up to the andalusite-stability field ($P < 3$ kbar, $T < 600$°C).

DISCUSSION AND CONCLUSIONS

As correctly pointed out by the Shipboard Scientific Party (1996), the basement beneath Site 976 comprises metamorphic rocks similar to those that compose some of the Alpujárride nappes in the Ronda region. The pelitic and carbonatic composition of the protoliths and the Alpine metamorphic record are the distinctive characteristics of all these rocks, which reached condition of high-grade metamorphism (≥600° across a variable range of pressures).

In the Alboran Domain, lithologic sequences formed mainly of high-grade schists, gneiss, and migmatites are found solely in the tectonic units belonging to the Jubrique and Blanca Groups of the Alpujárride Complex, located above and below the Ronda peridotite slabs, respectively (Figs. 2, 3). To the east of Málaga (Azañón et al., 1994; 1997), high-grade metamorphic rocks from the Jubrique Group units lie directly over Blanca Group units because of the absence of the Ronda peridotite slabs, which were thinned and moved southwest along extensional detachment faults (Balanyá et al., 1997).

Metamorphic and lithologic criteria are used to clarify whether the basement rocks recovered from Holes 976B and 976E formed part of any of the tectonic units belonging to the Blanca or Jubrique Groups. Partial PT conditions reached by the high-grade schists of the Alboran Sea basement are fairly similar to those of the high-grade schists from the Ojen Unit. In both cases, temperatures of 650°C were reached at ~4–5 kbar at the end of tectonometamorphic event 2 (see Fig. 6 and comments in text on the PT metamorphic conditions of the Alpujárride units and on the Alboran basement beneath Site 976). High-grade schists are found only adjacent to or near marble (probable Triassic protolith) in the Blanca Group units and in the cored basement from Holes 976B and 976E. In contrast, in the Jubrique Unit, phyllites and fine-grained schists stratigraphically close to Triassic carbonate rocks recorded a metamorphic evolution at temperatures of <500°C (Balanyá et al., 1997). The PT conditions of gneiss from the Jubrique and Ojen Units, and of the gneiss from the basement beneath Site 976, are similar.

The lithologic assemblages from the cored basement and the Ojen Unit are also similar. Alternating marble and high-grade schists appear in the Ojen Unit on both sides of the axial-plane of a major recumbent syncline formed during tectonometamorphic event 3 (see Fig. 3). Some of these alternations appear to of stratigraphic origin, but at least some of them are related to the second-order folds of the recumbent syncline.

The rocks recovered from Holes 976B and 976E are similar to those comprising the Ojen unit in the Ronda region. Nevertheless, structural considerations lead us to present the two tentative correlation proposals in Figure 3. It is possible that part of the rocks drilled at Site 976 were Guadaiza Unit schists or marbles and high-grade schists from one of the Montemayor slices. However, numerous fault rock zones were drilled, which suggests that the original thickness of the lithologic sequence was significantly reduced, with the consequent approximation of the lithologic boundaries.

The tectonic exhumation of rocks from the Blanca Group is partially contemporary with the deposition of lithoseismic unit 4 (Upper Serravallian-Tortonian; Comas et al., 1992) and this tectonic exhumation forms part of an extensional episode of the Alboran Basin rifting that had a direction of roughly northeast–southwest (García-Dueñas et al., 1992). Cross section B-B′ (Fig. 4) shows the structural relationship between the Alpujárride units of the Ronda region (cross section A-A′, Fig. 4) and the basement high beneath Site 976. Mud diapirs are related to the north-northwest–south-southeast extension episode that produced thinning and dismembering of the Alpujárride units located to the north of the Sierra Blanca (cross section A-A′). Superimposed northeast–southwest extension-generated faults, with a transport sense toward the southwest (García-Dueñas et al., 1992; Balanyá et al., 1997), probably reused the previous faults as ramps, with right-lateral slip (fault next to the shoreline) and left-lateral slip (fault north of the basement high).

Final positioning of the peridotite bodies around the Gibraltar Arc (Fig. 1) shows the result of the superposition of the two transverse extensional systems. The Ronda peridotite bodies could be connected to the Beni Bousera massifs of the Rif through a thin layer of serpentinized peridotites, visible at Ceuta (north-northwest–south-southeast extensional direction), in the same way that the Carratraca and Bermeja bodies are connected (northeast–southwest extensional direction; Fig. 2).

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