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Thermal structure of the Alboran Domain in the Rif (northern Morocco) and the Western Betics (southern Spain). Constraints from Raman spectroscopy of carbonaceous material

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ABSTRACT In the Rif (northern Morocco) and the Western Betics (southern Spain), the Alboran Domain forms a complex stack of metamorphic nappes including mantle peridotites (Beni Bousera and Ronda). We present in this paper new temperature data obtained in the Alboran Domain based on Raman spectroscopy of carbonaceous material (RSCM thermometry). In the lower metamorphic nappes of the Alboran Domain (lower Sebtides–Alpujárrides) temperature ranges from $>$ 640 °C at the base of the metapelitic sequence to 500 °C at the top. The relationships between field isotherms and nappe structure show that peak temperatures were reached during strong ductile thinning of these nappes whereas they partly postdate this main episode in the Rif. In the upper nappes of the Alboran Domain (Ghomarides–Maláguides), generally supposed to be only weakly metamorphosed, temperatures range from $\sim$500 °C at their base down to $<$ 330 °C at the top. This temperature gradient is consistent with progressive Cenozoic resetting of K–Ar and ^{40}Ar–^{39}Ar ages. These nappes were thus affected by a significant thermal metamorphism, and the available age data in the underlying Sebtides–Alpujárrides show that this metamorphism is related to the metamorphic evolution of the whole Alboran Domain during the Late Oligocene–Early Miocene. Such thermal structure and metamorphic evolution can be explained by generalized extension in the whole Alboran Domain crustal sequence. At a larger scale, the present thermal structure of the Alboran Domain is roughly spatially consistent around the Beni Bousera peridotites in the Rif, but much more affected by late brittle tectonics around the Ronda peridotites in the Western Betics. Therefore, on the basis of the observed thermal structure, the metamorphic evolution of the Alboran Domain can be interpreted as the result of the ascent of hot mantle units contemporaneous with thinning of the whole lithosphere during an Oligo-Miocene extensional event. The resulting structure has however been dismembered by late brittle tectonics in the Western Betics.

Key words: Alboran Domain; Betics; exhumation; Rif; RSCM thermometry.

INTRODUCTION

The Betic (southern Spain) and Rif (northern Morocco) chains represent the western termination of the Alpine Mediterranean orogen and are the result of the convergence between the African and Eurasian plates since late Mesozoic times. From western Morocco to southern Spain, these moderately high topographic features form an arc-shaped mountain belt underlining the Gibraltar arc. Present on both sides and within the Alboran Sea, the Alboran crustal domain is the internal part of the Betico-Rifan orogen and is now a segment of thinned continental crust. This domain has recorded a complex metamorphic history associated with the uplift of large subcontinental mantle bodies, now represented by the Ronda and Beni Bousera peridotites, in southern Spain and northern Morocco, respectively. Several hypotheses have been proposed to explain the formation of the Betico-Rifan arc and the structure of the Alboran Domain including: (1) convective removal of subcontinental lithosphere (Platt & Vissers, 1989; Platt *et al.*, 2003a), (2) lithospheric delamination (Seber *et al.*, 1996; Calvert *et al.*, 2000; Tubía *et al.*, 2004), (3) slab break-off (Blanco & Spakman, 1993; Zeck, 1996) or (4) roll-back of an east dipping subduction zone (Frizon de Lamotte *et al.*, 1991; Royden, 1993; Lonergan & White, 1997).

Both the peridotites and surrounding crustal rocks have generated a considerable research effort in terms of petrology, structural geology and geochronology, especially in Spain. These studies reveal a strong thermal event associated with the thinning of the whole crustal sequence during the Late Oligocene–Early Miocene (e.g. Zeck *et al.*, 1992; Platt & Whitehouse, 1999; Platt *et al.*, 2003a and references therein). Petrological studies provide local *P–T* constraints on the evolution of these rocks (García-Casco *et al.*, 1993; García-Casco & Torres-Roldán, 1996; Balanyá *et al.*, 1997; Michard *et al.*, 1997; Tubía *et al.*, 1997; Argles *et al.*, 1999; El Maz & Guiraud, 2001), but the spatial extension of this thermal event is unknown as the metamorphic index minerals progressively disappear in the upper crustal levels. As the quantitative temperature field in the crustal rocks is scarcely known at a large scale, the link between the thermal event and the observed deformation in these rocks still remains largely unclear.

In order to constrain the thermal structure of the Alboran Domain units over the Ronda and Beni Bousera peridotites, thermal metamorphism has been investigated using Raman spectroscopy of carbonaceous material (RSCM thermometry). This method has been recently calibrated (Beyssac *et al.*, 2002a) and has been shown to provide a reliable estimate of the peak metamorphic temperature in the range 330–640 °C (Beyssac *et al.*, 2004). This method allows us (1) to estimate the peak metamorphic temperature with an uncertainty of ± 50 °C, (2) to detect intersample variations as small as 10–15 °C providing a precise idea of the 'field thermal gradients' and (3) to map temperatures from local to regional scales. In the Alboran Domain, the RSCM method provides an interesting alternative to conventional petrology because carbonaceous material (CM) is almost ubiquitous in the metasedimentary crustal envelope. This method enables us to build an homogeneous data set with a constant methodology, as opposed to mineral- and therefore tool-dependent estimates of conventional petrology.

This study presents the results of 110 RSCM estimates of temperature through the whole Alboran Domain in both Morocco and Spain. Because the Alboran Domain in the Betics has been much more studied than in the Rif, denser sampling and more attention has been given to the relations between the deformation pattern and the temperature for the Rif region. The distribution of peak temperatures is described in the Rif and Western Betics from local to regional scale and compared with the deformation field and the nappe structure in order to decipher the exhumation history of the Alboran Domain. The regional geodynamic implications are then discussed for the evolution of the Betico-Rifan orogen.

GEOLOGICAL SETTING

The Betico-Rifan orogen

The Betico-Rifan orogen represents the western termination of the Alpine system. This active mountain belt is the consequence of the convergence between Africa and Iberia since late Mesozoic times. As attested by its unique arc-shaped profile and the presence of the world-largest peridotite bodies (Ronda–Beni Bousera) in its internal zone, this orogen results from complex and unusual mountain building processes. The Betic and Rif belts are commonly divided into several tectonic domains (Fig. 1): (1) The South-Iberian and Maghrebian domains represent the palaeomargins of the Iberian and African plates, (2) The Flysch units are made of Cretaceous to Miocene sedimentary rocks deposited in a deep basin on a highly thinned continental crust (Durand-Delga, 1980), (3) The Alboran Domain represents the Internal Zones of the Betics and Rif (Balanyá & García-Dueñas, 1987). This domain consists of a complex stacking of crustal metamorphic rocks, including locally mantle-derived bodies. In the Betics, it is divided from bottom to top into the Nevado-Filábride, Alpujárride and Maláguide complexes. The latter two have their equivalents in the Rif: the Sebtide and Ghomaride complexes, respectively. The supposedly non-metamorphosed Dorsale units also belong to the Alboran Domain. The following section synthesizes and compares the available data on the metamorphic history of the Alboran Domain in the Rif and the Betics. This history is complex, with a compressional high pressure–low temperature (HP–LT) metamorphic event locally followed by a high temperature–low pressure (HT–LP) metamorphic overprint during exhumation.

The Alboran Domain in the Rif

The Alboran Domain in the Rif is composed of two main stratigraphic ensembles from bottom to top: the Sebtide complex and the Ghomaride complex associated with the overlying 'Dorsale calcaire'. These complexes overlie the Beni Bousera peridotites and kinzigites (Fig. 2). The Sebtide complex is divided into the lower Sebtides (Filali unit) and upper Sebtides (Federico units) mainly on stratigraphic criteria.

The Filali unit is formed by Palaeozoic blackschists (Filali schists) and greywackes grading to migmatitic gneiss towards the base (Filali gneiss). The lower Sebtides are characterized by medium pressure–high temperature (MP–HT) to HT–LP metamorphism with maximum conditions of ∼7–8 kbar and ∼750 °C at the base of the schists and 8 kbar and ∼800 °C in the gneisses (Kornprobst & Vielzeuf, 1984; El Maz & Guiraud, 2001) (Fig. 3).

The Federico units are mainly composed by Permo-Triassic phyllitic schists and quartzites, overlain by Triassic limestone and dolomite. These units crop out either directly over the Filali unit and the Beni Bousera peridotites–kinzigites in the southern Rif, or in the northern part of the Rif near the Gibraltar Strait (Fig. 2). These units recorded HP–LT metamorphism with maximum conditions of ∼16 kbar and 550 °C (Bouybaouène *et al.*, 1995). However, the southern units located on top of the Beni Bousera peridotites recorded higher temperature conditions at lower pressure as attested by late andalusite and cordierite

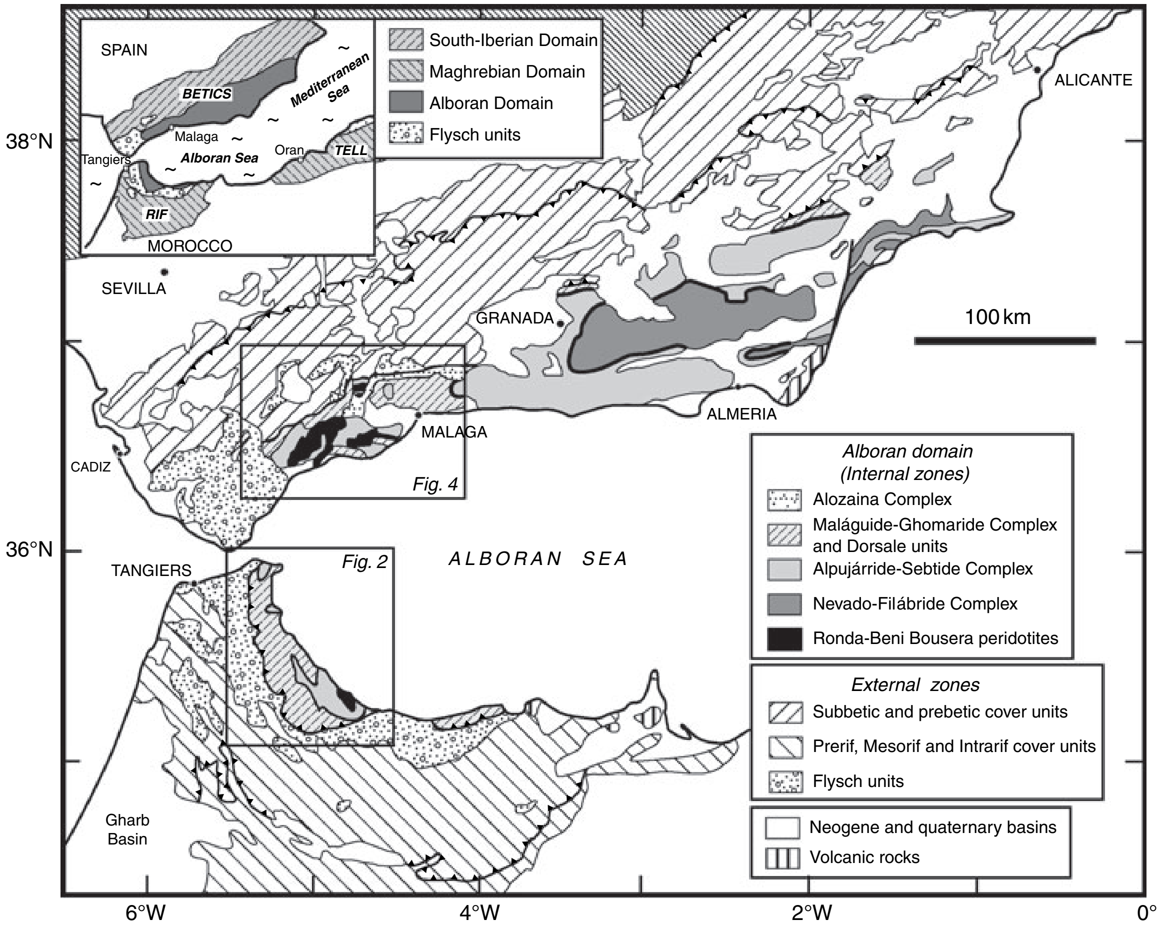

Fig. 1. Geological map of the Betico-Rifan Cordilleras. Note the similarity of the structural organization in the Alboran Domain between the Rif (northern Morocco) and the Western Betics (southern Spain). Locations of studied areas are depicted.

crystallization (Bouybaouène, 1993; Michard *et al.*, 1997). The Ghomaride complex overlies the Sebtide complex in the whole inner Rif. This complex is formed by a sequence of Palaeozoic metapelites, Triassic reddish beds and thin Liassic and Palaeocene–Eocene limestones (Chalouan & Michard, 1990). The Ghomarides show no evidence for significant Alpine metamorphism and their supposedly low-grade metamorphism is thought to represent remnants of the Hercynian orogeny (Chalouan & Michard, 1990).

The Alboran Domain in Western Betics

In the Western Betics as in the Rif, the Alboran Domain consists of the Alpujárride and Maláguide complexes. Both these present very similar stratigraphic and metamorphic characteristics to those described in the Rif, and are therefore considered to be the equivalent of the Sebtides and Ghomarides respectively (Didon *et al.*, 1973). A major difference between the Rif and the Betics is the presence of several peridotite massifs in the Western Betics, among which the two major massifs crop out in Sierra Bermeja and Sierra Alpujata and form the so-called Ronda peridotites (Fig. 4).

The Alpujárrides are divided into several tectonometamorphic units: the Jubrique and the Blanca Groups (Tubía *et al.*, 1993, 1997; Balanyá *et al.*, 1997). The Jubrique Group structurally overlies the peridotites and is the strict equivalent of the Sebtides units observed in the Rif. The most complete Alpujárride sequence crops out over the Sierra Bermeja peridotites and is formed from bottom to top by: granulitic gneisses, migmatitic gneisses, sillimanite- to kyanite–chloritoid-bearing Palaeozoic metapelitic schists (Genal schists), Permo-Triassic fine-grained metapelitic schist with alternation of quartzites, and Triassic carbonates (Balanyá *et al.*, 1997) (Fig. 4). The so-called granulitic gneisses are the equivalent of the Beni Bousera kinzigites; the Palaeozoic schists and the migmatitic gneisses are the equivalent of the Filali unit, and the Permo-Triassic schist and the overlying Triassic carbonates are the equivalent of the Federico units. The following *P–T* conditions have been estimated in the Jubrique units over the Sierra Bermeja peridotite (Balanyá *et al.*, 1997): 8–11 kbar, 590–

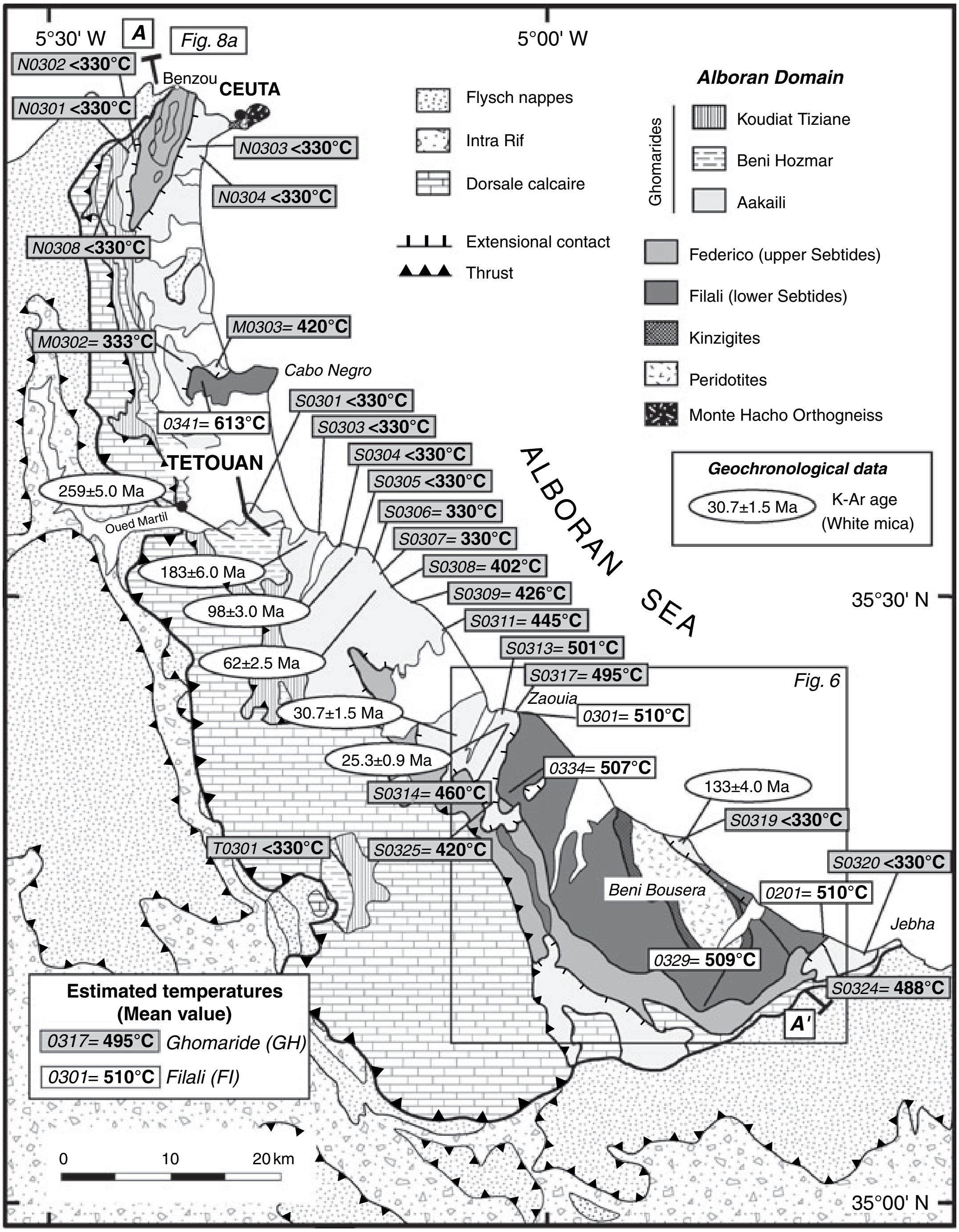

Fig. 2. Geological map of the inner Rif (modified after Rif 1/500 000 geological map, Geological Survey of Morocco; Suter, 1980) showing mean temperatures estimated by the RSCM method in the Ghomaride and lower Sebtide complexes (see location on the map in Fig. 1). K–Ar ages in the Ghomarides are after Chalouan & Michard (1990) and Michard *et al.* (1991). The absolute uncertainty on RSCM temperatures is ± 50 °C.

640 °C at the base of the Genal schists (sillimanite-bearing metapelites) and 7–9 kbar, 400–480 °C in the Permo-Triassic phyllites (Mg–chloritoid–kyanite assemblages) (Fig. 3).

The Maláguide complex overlies the Jubrique unit in the Western Betics (Fig. 4). As in the Ghomarides, the bulk of this complex does not show any evidence for significant metamorphism. However, andalusite and biotite occurrences have been reported in the lowermost levels (i.e. Early Palaeozoic) of the Maláguide complex north of Malaga (Tubía *et al.*, 1993; Platt *et al.*, 2003b).

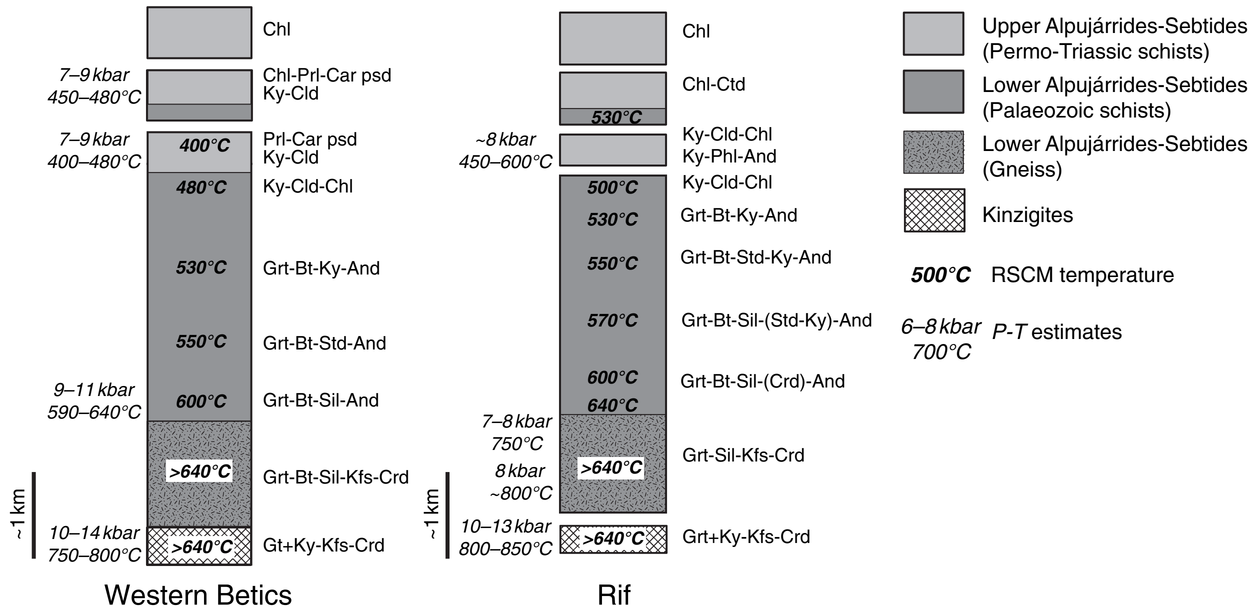

Fig. 3. Lithological and metamorphic sequence of the Alboran Domain units in the Rif and the Western Betics. The Western Betics sequence corresponds to the Alpujárride units cropping out over Sierra Bermeja peridotites (modified after Balanyá *et al*., 1997) and the Rif sequence to the Sebtide units cropping out over the Beni Bousera peridotites (modified after Michard *et al*., 1997). Metamorphic assemblages and *P–T* conditions in the Sebtide units are from Bouybaouène (1993), Bouybaouène *et al.* (1995), El Maz & Guiraud (2001) and this study. Metamorphic conditions and *P–T* estimates in the Alpujárride complex are taken from Balanyá *et al.* (1997). RSCM temperatures (this study) in both sequences are also reported. Mineral abbreviations are after Kretz (1983). Car psd: carpholite pseudomorphs.

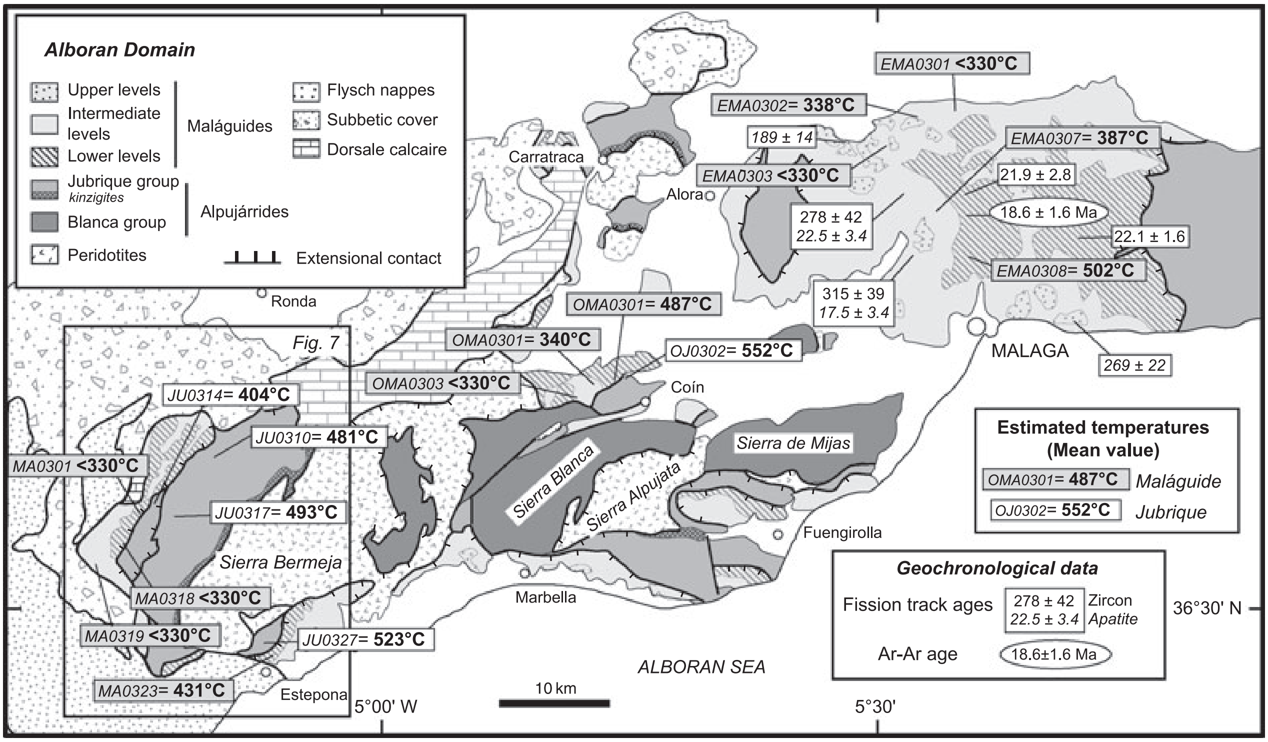

Fig. 4. Map of the Alboran Domain in Western Betics showing RSCM temperatures in the Maláguide complex and the Jubrique unit (see location on the map in Fig. 1). ^{40}Ar–^{39}Ar and fission-track ages on Maláguide rocks north of Malaga are after Platt *et al.* (2003b). The absolute uncertainty on RSCM temperatures is ± 50 °C.

Deciphering the metamorphic evolution and the exhumation of the Alboran Domain

Both the *P–T* conditions and available geochronological data suggest that the Alboran Domain was affected by a strong thermal event during the Late Oligocene–Early Miocene (e.g. Zeck *et al.*, 1992; Platt *et al.*, 2003a). A key question is the link between the thinning of the whole crustal sequence and this event. Some authors have pointed out that strong thermodynamic disequilibrium between minerals attributed to fast decompression could affect the metamorphic equilibria (García-Casco *et al.*, 1993; García-Casco & Torres-Roldán, 1996; Soto & Platt, 1999). Actually, temperatures derived from the widely used garnet–biotite geothermometer locally yielded very scattered or unrealistic temperatures, compared with the main metamorphic assemblage (García-Casco & Torres-Roldán, 1996; Soto & Platt, 1999).

The RSCM method offers an interesting alternative to that issue as CM is almost ubiquitous in the metapelitic rocks. In order to precisely constrain the thermal metamorphic gradient in the crustal rocks of the Alboran Domain, systematic sampling through the different units in both the Rif and the Betics has been undertaken. Particular attention was paid to measuring the geographical position and to making precise structural measurements at each site. Then, our samples have been referenced in a common structural framework with those from the literature whenever possible.

ESTIMATING PEAK TEMPERATURES BY RAMAN SPECTROSCOPY OF CARBONACEOUS MATERIAL

RSCM method

During diagenesis and metamorphism, the CM present in the initial sedimentary rock is progressively transformed into graphite (graphitization). The corresponding progressive evolution of the CM degree of organization is considered to be a reliable indicator of metamorphic grade, and more specifically of temperature (Wopenka & Pasteris, 1993 and references therein). Because of the irreversible character of graphitization (CM is tending towards the thermodynamic stable phase which is graphite), CM structure is not sensitive to retrograde metamorphism and therefore primarily depends on the maximum temperature reached during metamorphism, whatever the retrograde history of the sample (Wopenka & Pasteris, 1993; Beyssac *et al.*, 2002a). It also has been observed that samples collected from neighbouring outcrops with clearly different strain have the same degree of graphitization, indicating that deformation does not significantly affect the structural organization of the CM in metamorphic rocks (Beyssac *et al.*, 2002b).

Raman microspectroscopy is the most suitable technique to study metamorphic CM *in situ* within thin sections (Wopenka & Pasteris, 1993; Beyssac *et al.*, 2003). The first-order Raman spectrum of disordered CM exhibits a graphite G band at 1580 cm^{-1}, E2g2 mode corresponding to in-plane vibration of aromatic carbons, and several defect bands (D1, D2, D3), corresponding to 'physico-chemical defects' (e.g. Beyssac *et al.*, 2003 and references therein). The structural organization of CM can be quantified through the R2 parameter defined as the relative area of the main defect band D1 [$R2 = D1/(G + D1 + D2)$ peak area ratio]. A linear correlation between this R2 parameter and metamorphic temperature was calibrated using samples from different regional metamorphic belts with well-known *P–T* conditions in the range 330–640 °C (RSCM method; Beyssac *et al.*, 2002a). RSCM can be applied to metasediments of pelitic lithology in which CM precursor is mainly a kerogen. The uncertainty on temperature is ±50 °C because of uncertainties on petrological data used for the calibration. The relative uncertainties on temperature are much smaller, around 10–15 °C (Beyssac *et al.*, 2004), allowing an accurate estimate of 'field thermal gradients' (Bollinger *et al.*, 2004).

Analytical procedure

Raman microspectroscopy was performed by using three different instruments. Whatever the system, the 514.5 nm exciting line of an argon laser was used and the excitation laser beam was focused on the sample using a microscope. The instruments are a DILOR XY with a nitrogen cooled CCD detector and a 50× magnification objective (LST; ENS Lyon, Lyon, France), a Jobin Yvon T64000 (IPG, Paris, France) with a nitrogen cooled CCD detector and a 100× magnification objective (NA = 0.95), and a Renishaw RM1000 (GPS-Caltech, Pasadena, CA, USA) with a Peltier cooled CCD detector and a 100× magnification objective (NA = 0.90). With all configurations, the laser spot diameter is in the range 1–3 μm and the laser power is estimated at ~1 mW at the sample surface. Before each session the spectrometer was calibrated with a silicon standard. Because Raman spectroscopy of CM can be affected by several analytical mismatches, we followed closely the analytical and fitting procedures described by Beyssac *et al.* (2002a, 2003). For maximum reliability, measurements were made (1) on conventional petrological polished thin-sections cut along the stretching lineation and parallel to the main foliation and (2) below transparent minerals, quartz for instance, to avoid any effect of polishing on the structure of CM (Beyssac *et al.*, 2003). For each sample, six to 25 spectra were recorded in order to smooth out the within-sample structural heterogeneity and the spectra were processed using the Peakfit program following the procedure described by Beyssac *et al.* (2003).

In the original calibration, Beyssac *et al.* (2002a) used a DILOR XY system (ENS Lyon) with the configuration described above. In order to check any instrumental effect on the measurements in terms of spatial and/or spectral resolution, all the samples used for the original calibration were systematically re-measured using the Renishaw RM 1000 spectrometer. Furthermore, 10 samples from the Rif representative of various CM degrees of organization have been measured with both the T64000 and the Renishaw RM 1000 system. The difference of mean R2 value calculated for $\sim$10 spectra is systematically lower than the standard deviation calculated on each set of analyses, and it is thus assumed that the instrumental effect, if any, is negligible.

Applicability of the RSCM method to the Rif and Betics

For all the samples considered in this study, the within-sample structural heterogeneity was found to be generally small. In more than 90% of the samples, the standard deviation on the R2 values is lower than 0.07 contributing to a maximum uncertainty of 10 °C in temperature (at the $1-\sigma$ confidence level for n spectra).

When CM structure is close to crystalline graphite, the Raman spectrum is very sensitive to the smallest variations of CM structure (see Beyssac *et al.*, 2003 and references therein). In that particular case, microcrystalline graphite with minor structural defects can appear as less ordered than it actually is. For instance, the respective orientation of the laser beam and graphite structure can affect the spectrum and generate a faint D1 band. Such problem was encountered in the original calibration paper where a sample from the Beni Bousera HP kinzigite was studied: CM was clearly pristine graphite and temperature was estimated at 760–820 °C by petrography, but R2 was not zero and was equal to 0.03. In the highest-grade samples from both the Rif and Betics, spectra were obtained corresponding to perfect crystalline graphite (no defect band) together with spectra with a very faint Dl defect band (R2 values around 0.02–0.03). In those samples CM typically appears as small individual graphite grains and the temperature is considered to be higher than 640 °C.

RSCM TEMPERATURE ESTIMATES IN THE RIF AND THE BETICS

The whole data set consist of 110 samples, among which 69 were collected in the lower Sebtide and Ghomaride nappes in the Rif (Figs 2 & 6) and 41 in the Alpujárride and Maláguide complexes in the Betics (Figs 4 & 7). CM was not found within the Permo-Triassic rocks from both the Sebtide and Alpujárride complexes. In the following, the results are presented in terms of temperature for more clarity and a brief outline is given concerning the Raman spectra and corresponding R2 ratios evolution. More details regarding graphitization can be found in Beyssac *et al.* (2002a,b). Whenever possible, the main mineralogical assemblage of the studied rock is also given.

RSCM temperature through the Rif

Lower Sebtides (Filali unit)

To decipher the spatial variations of temperature and its relation with the deformation pattern within the Filali unit, samples were collected along six radial transects from the Beni Bousera peridotite. For each sample, the main metamorphic assemblage of the sample is described so as to give an approximate comparison with our estimated RSCM temperature mineralogy (Table 1). In the Filali unit, andalusite was observed in almost all samples and its textural habit systematically suggests late crystallization. A subset of representative Raman spectra from the Filali units is depicted in Fig. 5. These spectra show a thin G band

Table 1. Samples from the Filali schists with observed metamorphic assemblages, number of Raman spectra (Sp.), R2 ratio (mean value and standard deviation) and RSCM temperature (mean value and $1-\sigma$ uncertainty). The absolute uncertainty on RSCM temperature is ± 50 °C (Beyssac *et al.*, 2002a).

			R2		Temperature (°C)	
Sample	Metamorphic assemblage	Sp	Mean	SD	Mean	1 σ
FI0101	Bt–Ms	11	0.31	0.03	503	4
FI0102	Grt–St–Bt	11	0.18	0.04	560	6
FI0103	Bt–Sil–And	10	0.12	0.06	588	8
FI0104	Bt–Sil–Crd	11	0.13	0.03	582	5
FI0105	Ms–Bt–Sil	10	0.12	0.05	588	7
FI0113	Grt–Bt–Ms	12	0.27	0.05	521	7
FI0114	Grt–Bt	26	0.25	0.03	529	3
FI0201	Grt–Bt–Ms–And	13	0.29	0.03	510	4
FI0202	Grt–Bt–Ky–And	12	0.19	0.05	555	6
FI0203	Grt–Bt–And	11	0.21	0.06	548	8
FI0206	Grt–Bt	16	0.13	0.03	582	4
FI0208	Bt–Sil–Crd	13	0.15	0.05	573	6
FI0210	Grt–Bt–Crd	10	0.17	0.04	565	6
FI0212	Chl–Ms	8	0.33	0.04	496	7
FI0213	Grt–Bt–Ms	8	0.15	0.03	573	5
FI0214	Grt–Bt–Sil	11	0.16	0.04	571	6
FI0217	Bt–And	26	0.22	0.05	545	4
FI0218	Bt–Sil	18	0.10	0.04	595	4
FI0219	St–Sil–And	9	0.12	0.08	587	12
FI0301	Grt–Bt–And	9	0.30	0.06	510	9
FI0302	Grt–Bt–Sil–Crd	7	0.00	–	> 640	–
FI0305	Grt–Bt–St–Ctd	10	0.27	0.03	523	4
FI0306	Grt–Bt–And	13	0.23	0.04	538	5
FI0307	Grt–St–Bt–And	10	0.19	0.05	558	7
FI0309	Grt–St–Ky–Bt–And	9	0.24	0.06	536	9
FI0313	Grt–Bt–And	11	0.26	0.05	527	7
FI0315	Bt–Ky–Sil–And	9	0.10	0.04	596	6
FI0316	Grt–St–Ky–And	11	0.15	0.03	573	4
FI0318	Grt–St–Bt–Sil–And	10	0.13	0.04	571	5
FI0319	Grt–St–Bt–And	10	0.17	0.04	567	5
FI0321	Grt–St–Bt–And	10	0.25	0.02	529	3
FI0323	Ctd	10	0.25	0.06	532	8
FI0325	Grt–St–Bt–And	10	0.21	0.03	547	4
FI0326	Grt–St–Bt–And	20	0.14	0.03	578	4
FI0327	Grt–St–Bt–And	13	0.25	0.03	530	4
FI0329	Grt–Ctd	19	0.30	0.03	509	3
FI0330	Grt–Ctd–Chl	10	0.26	0.04	526	5
FI0334	Bt–And	11	0.30	0.05	507	6
FI0335	Bt–And	11	0.29	0.04	511	6
FI0336	Chl–Bt	10	0.28	0.03	515	5
FI0338	Bt–And	10	0.26	0.03	524	4
FI0339	Bt–And	10	0.24	0.07	533	9
FI0340	Grt–Chl–Bt	11	0.25	0.03	529	4
FI0341	Sil–(Grt)–And	11	0.06	0.03	613	4

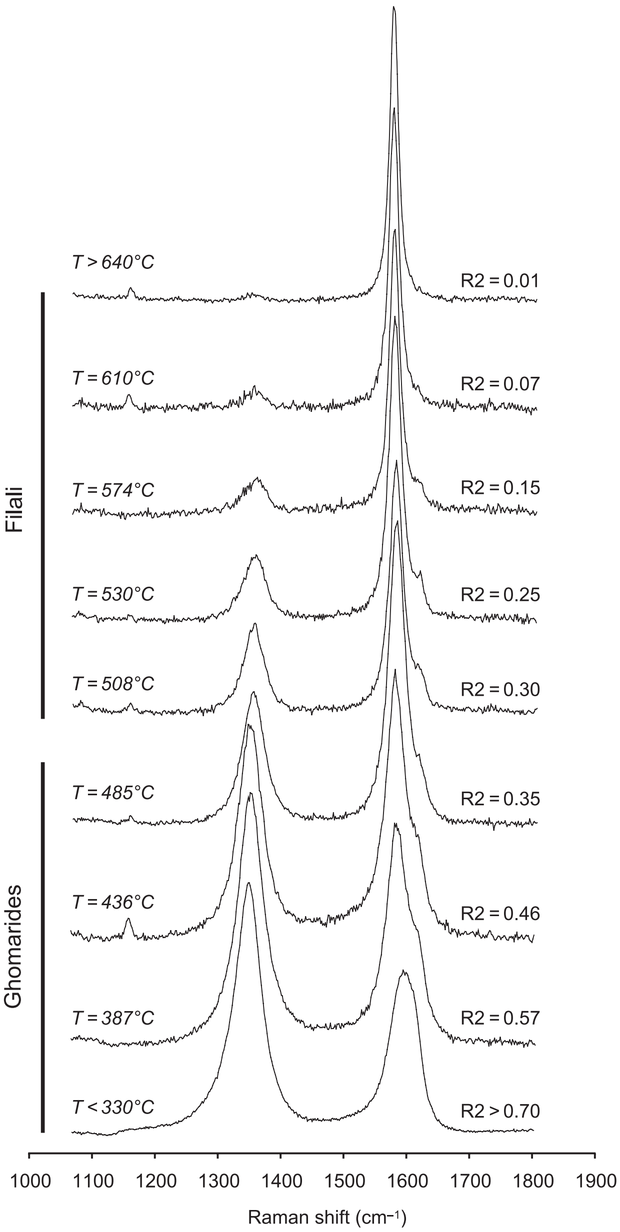

Fig. 5. Representative Raman spectra obtained from samples collected in the Alboran Domain in the Rif. The R2 ratio value and corresponding temperature are given for each spectra.

with a Raman shift in the range 1580–1585 cm^{-1} and faint D1 and D2 bands. The corresponding R2 ratio is in the range 0.00–0.30 indicating that the CM is generally well-ordered in these units and can be locally present as pristine graphite (Table 1). However, some spatial trends are observed along these transects and discussed below.

The longest profile with the best outcrops was found along the coast on the north-western side of the peridotite massif, from Cape Zaouia to Bou Ahmed (Fig. 6). Along this profile, RSCM temperature rapidly increases from ~500 °C at the contact with the Ghomarides (Cape Zaouia), to ~600 °C in deeper levels (sample FI0218). This temperature increase is correlated with the appearance of staurolite (sample FI0102, 560 °C) followed by that of sillimanite (sample FI0218, 595 °C). Towards the SE, an almost constant RSCM temperature (~590–600 °C, samples FI0218, FI0103, FI0219 & FI0104) and significant sillimanite crystallization are observed towards the peridotite massif (Fig. 6). Near Bou Ahmed, in the final part of the section, perfect graphite is observed in a sample near the contact with the underlying gneisses. RSCM is then not applicable and temperature is considered to be higher than 640 °C, in agreement with the occurrence of sillimanite + K-feldspar in the studied sample. Between Cape Zaouia and Bou Ahmed, the Filali schists show intense and complex ductile deformation patterns making impossible any estimation of the structural distance between the samples.

Three samples showing a biotite–andalusite foliation were collected along Oued Tarhera, and present similar RSCM temperatures clustered around 510 °C, although they correspond to different structural levels (Fig. 6). Further south, along Oueds Kanar and Bouyha, RSCM temperature increases from 520 to 580 °C. These two profiles are nearly perpendicular to the main foliation and are thus supposed to reflect increasing maximum temperature with depth in the structural pile. The lowest temperatures (520 °C) were found in samples with kyanite–chlorite assemblages and rare chloritoid occurrences, near Souk el Had. Along the two profiles, staurolite appears at an RSCM temperature around 550 °C whereas the highest temperatures (~580–600 °C) are recorded in the sillimanite-bearing samples.

In the southern part of the area, the Oued Mter section provides a transect roughly perpendicular to the main foliation (Fig. 6). Along most of the transect, RSCM temperatures in the range 510–530 °C are maintained corresponding to garnet ± chloritoid ± chlorite ± biotite mineralogical assemblages. However, in the very last part of the section, RSCM temperature abruptly increases to 580 °C in a sillimanite-bearing schist collected immediately above the underlying gneisses. In the last transect along the coast southeast of Mter, a RSCM temperature around 500 °C is obtained below the contact with the overlying Ghomarides and an increase is observed moving downsection: ~550 °C in garnet-biotite ± kyanite schist up to 580 °C in sillimanite-bearing schist. In this area, the foliation mainly dips towards the NE but the Filali schists and gneisses and the peridotite massif are much more affected by late brittle faults. Therefore, the RSCM temperatures cannot be directly interpreted in terms of spatial thermal variations, because of late tectonic reorganization. However, these temperatures are in agreement with those observed along the other transects for similar metamorphic assemblages.

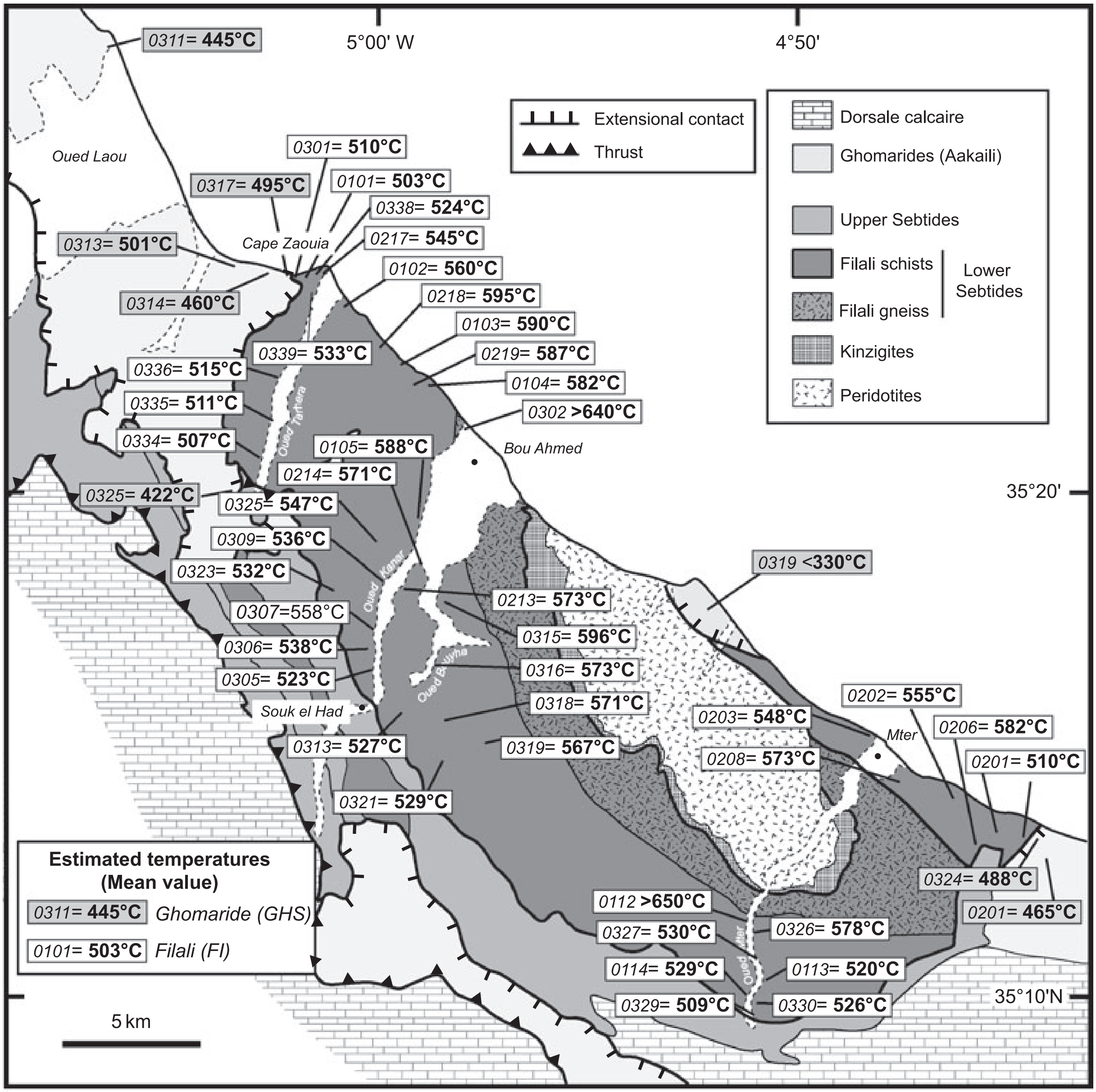

Fig. 6. Geological map of the Alboran Domain around the Beni Bousera peridotite massif (modified after Kornprobst, 1974 preliminary geological maps) showing temperatures estimated by the RSCM method in the Ghomaride and lower Sebtide complexes (see location on the map in Fig. 2). The absolute uncertainty on RSCM temperatures is ± 50 °C.

Ghomarides

Studying the supposedly low- to non-metamorphic Ghomaride nappes using the RSCM method allows temperature to be estimated where no data are available because of the lack of index mineral assemblages, and the investigation of the temperature field on top of the Sebtide complex. The only reliable indicator of metamorphic grade in the Ghomaride nappes is the occurrence of biotite in the lowest Aakaili rocks (Chalouan & Michard, 1990). Illite crystallinity measurements were also made in these nappes by the same authors suggesting upper greenschist facies conditions in the lowermost Ghomaride levels. Samples within the Ghomaride nappes were therefore collected taking into account their position within the Ghomarides pile.

The Raman spectra of CM in the Ghomaride nappes show significant variation of the CM structural organization (Fig. 5). In the uppermost levels, CM exhibit a broad G band including both the G and D2 bands, a D3 band and a very wide D1 band. When going deeper within the nappes graphitization progresses as shown by the decrease of the D2 shoulder on the G band, the disappearance of the D3 band and the decrease of the relative area of the D1 band (Fig. 5). In the Ghomaride nappes, the R2 ratio progressively decreases with depth from > 0.70 down to 0.31 (Table 2).

The profile along the coast from Cape Zaouia to Tetouan is almost continuous and offers a section through the Aakaili nappe of the Ghomarides. The lowermost sample was collected close to the faulted contact between the Filali and the Ghomarides (Zaouia fault) and yielded an RSCM temperature of 495 °C. More generally, all the temperatures in the deepest levels overlying the Filali unit fall in the range 460–500 °C, in good agreement with the presence of biotite–andalusite assemblages (Fig. 6). This suggests that there is no significant temperature break between the base of the Ghomarides and the top of the Filali schists. The RSCM temperature decreases gradually going upsection from the Filali contact from $\sim$500 °C down to less than 330 °C when approaching Tetouan (Fig. 2). Such a temperature variation is also observed close to Jebha, south of the Beni Bousera peridotite, although the Ghomarides (Aakaili) are extremely thinned in this area. RSCM temperatures in the range 465–490 °C are obtained in biotite–andalusite schists close to the Filali whereas a temperature below 330 °C was estimated in a sample (GHS0320) collected in the uppermost levels immediately below the overlying Dorsale Calcaire (Fig. 2).

Near Cabo Negro, north of Tetouan, an RSCM temperature of 420 °C (sample GHM0303) is recorded in the Aakaili nappe overlying a small outcrop of Filali schist and gneisses (Fig. 2). A lower temperature of 333 °C (sample GHM0302) was obtained farther from the contact. Close to Ceuta, the situation is much more complicated with two tectonic windows. The first one (Ceuta) presents a stacked sequence of orthogneiss-peridotite–kinzigites from bottom to top, whereas the second one (Beni Mzala antiform) is exclusively composed of the Federico units (Permo-Triassic). All the RSCM temperature obtained in the Aakaili unit (Ghomarides) over these two windows are below 330 °C (Fig. 2), while CM was not found in the Permo-Triassic series of the Beni Mzala antiform (upper Sebtides).

Table 2. Samples from the Ghomaride complex with number of Raman spectra (Sp.), R2 ratio (mean value and standard deviation) and RSCM temperature (mean value and 1 – σ uncertainty). The absolute uncertainty on RSCM temperature is ± 50 °C (Beyssac *et al.*, 2002a).

			R2		Temperature (°C)	
Sample	Metamorphic assemblage	Sp	Mean	SD	Mean	1 σ
GHN0301	–	14	≥ 0.70	–	≤ 330	–
GHN0302	–	8	> 0.70	–	< 330	–
GHN0303	–	6	> 0.70	–	< 330	–
GHN0304	–	6	> 0.70	–	< 330	–
GHN0308	–	4	> 0.70	–	< 330	–
GHM0302	–	9	0.69	0.04	333	6
GHM0303	Bt–And	15	0.50	0.02	420	4
GHS0201	Bt–And	15	0.40	0.05	465	5
GHS0301	–	6	> 0.70	–	< 330	–
GHS0303	–	6	> 0.70	–	< 330	–
GHS0304	–	6	> 0.70	–	< 330	–
GHS0305	–	6	> 0.70	–	< 330	–
GHS0306	–	6	0.70	0.03	330	5
GHS0307	–	6	0.70	0.04	330	7
GHS0308	–	13	0.54	0.03	402	4
GHS0309	–	10	0.48	0.06	426	9
GHS0311	–	10	0.44	0.04	445	6
GHS0313	–	16	0.31	0.04	501	4
GHS0314	Bt	10	0.41	0.04	460	5
GHS0317	Bt–And	10	0.33	0.03	495	5
GHS0319	–	6	> 0.7	–	< 330	–
GHS0320	–	6	> 0.7	–	< 330	–
GHS0324	Bt	11	0.34	0.06	488	8
GHS0325	Bt–And	11	0.49	0.04	422	6
GHT0301	–	6	> 0.70	–	< 330	–

RSCM temperature through the Betics

Lower Alpujárrides (Jubrique unit)

The samples were collected in the Jubrique unit over the Sierra Bermeja peridotites close to Jubrique village (Fig. 7). This area presents the most complete Alpujárride sequence with a main foliation defining a dome around the peridotite (Balanyá *et al.*, 1993, 1997). These samples were collected with special attention paid to their structural position and to the field metamorphic isograds defined by Balanyá *et al.* (1997). In the Jubrique unit, the Raman spectra are very similar to those described above in the Filali units and show that CM is systematically well-ordered with R2 ratios standing in the range 0.00–0.34 (Table 3).

In the uppermost levels of the Palaeozoic schists (Fig. 3), RSCM temperatures associated with biotite–andalusite parageneses systematically are in the range 480–490 °C (Fig. 7). Deeper in the metapelitic sequence, RSCM temperature increases to around 530 °C (samples JU0307, JU0308) in garnet–biotite-bearing schists north of Jubrique, and finally reach values around 600 °C (sample JU0322) within the transition between the schists and the gneisses of the Jubrique unit (Fig. 7). This increase of temperature corresponds to the appearance of both staurolite and sillimanite. Lastly, small grains of pristine graphite (with no defect band in the Raman spectra) occur in the gneisses and the corresponding RSCM temperature is considered as higher than 640 °C (sample JU0323).

Maláguides

As in the Ghomarides, all the samples from the Maláguides were collected taking into account their position in the Maláguide lithostratigraphic succession. Samples were collected in the Sierra Bermeja area, farther east near Coín and north of Malaga where the most complete Maláguide lithostratigraphic succession is found (Fig. 4). The Raman spectra present a wide range of variations of CM structural organization very similar to that described above in the Ghomarides. The corresponding R2 ratio varies from values higher than 0.70 down to 0.31 (Table 3).

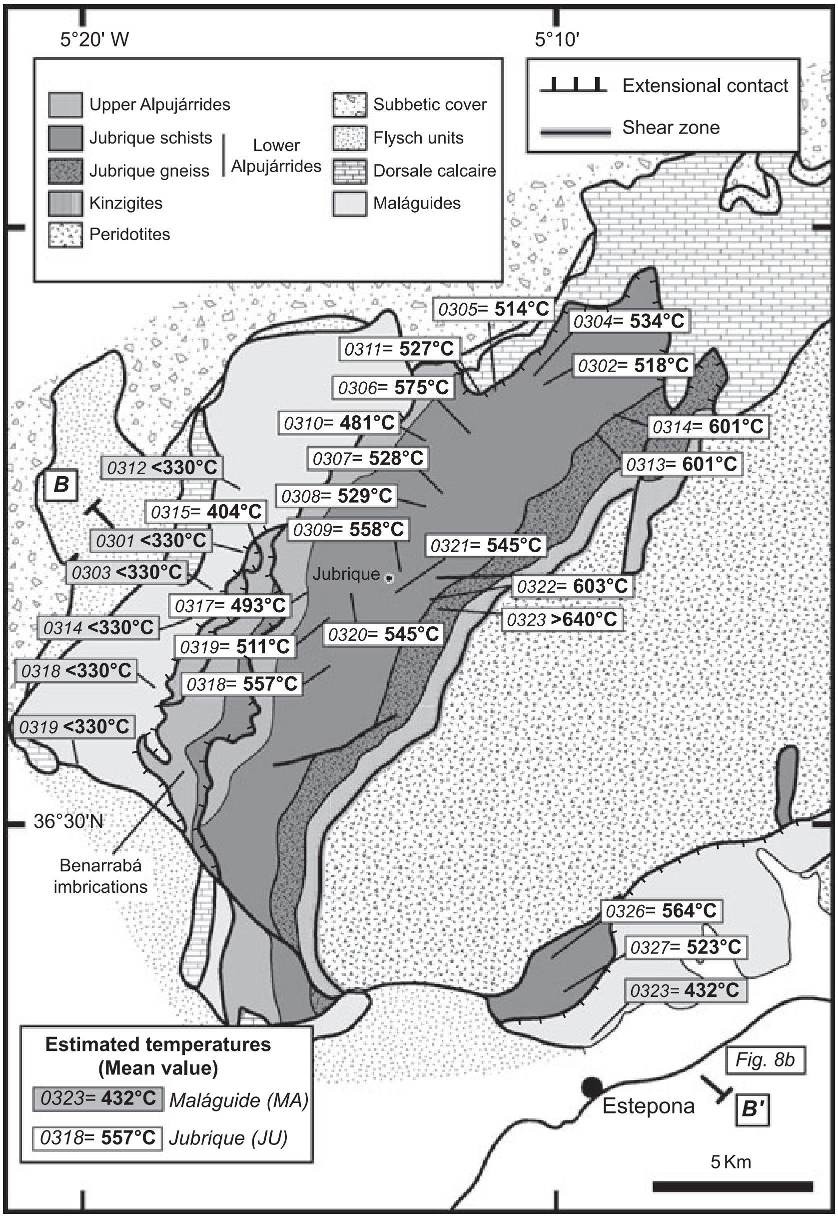

Fig. 7. Geological map of the Alboran Domain in the Sierra Bermeja area (modified after Balanyá *et al*., 1997) showing distribution of RSCM temperatures in the Alpujárride and Maláguide complexes over the Sierra Bermeja peridotites. See location on the map in Fig. 4. The absolute uncertainty on RSCM temperatures is ± 50 °C.

Northwest of the Sierra Bermeja, all the RSCM temperatures in the Maláguides are systematically below 330 °C. A single temperature of 432 °C was obtained from one sample (MA0323) of the Maláguides overlying the HT–LP Palaeozoic schists of the Jubrique unit (Fig. 7). Farther east, north of Coín, three samples yielded very scattered RSCM temperatures ranging from < 330 to 487 °C (Fig. 4).

Based on the geological maps of the area, the highest temperature samples come from the lowest stratigraphic level (i.e. Early Palaeozoic), whereas the other samples belong to higher levels (Middle to Late Palaeozoic). North of Malaga, samples from the uppermost levels of the Maláguides show RSCM temperatures below 330 °C. In the intermediate levels, an RSCM temperature of 387 °C (sample EMA0307) was obtained and in the deepest levels a temperature of 502 °C (sample EMA0308) (Fig. 4). In the latter sample, the presence of biotite and late andalusite overprinting the main foliation, suggest peak temperatures within the stability field of andalusite in agreement with the RSCM temperature.

RSCM temperatures and the Alboran Domain nappe structure

We have reported the RSCM temperature data set on general schematic cross-sections of the inner Rif (Fig. 8a) and the Western Betics (Sierra Bermeja) (Fig. 8b) in order to assess the relations with the nappe

Table 3. Results of RSCM thermometry in the Alpujárride (Jubrique unit) and Maláguide complexes, including observed index minerals, number of Raman spectra (Sp.), R2 ratio (mean value and standard deviation) and temperature estimate (mean value and 1 − σ uncertainty). The absolute uncertainty on RSCM temperature is ± 50 °C (Beyssac *et al.*, 2002a).

			R2		Temperature (°C)	
Sample	Metamorphic assemblage	Sp	Mean	SD	Mean	1 σ
JU0302	Bt–And	10	0.28	0.03	518	4
JU0304	Bt–And	10	0.24	0.06	534	9
JU0305	Bt–And	10	0.29	0.04	514	6
JU0306	Bt–And	10	0.15	0.04	575	6
JU0307	Bt–St–And	10	0.25	0.04	528	6
JU0308	Grt–Bt	10	0.25	0.06	529	8
JU0309	Grt–Bt	10	0.19	0.06	558	8
JU0310	Bt–And	10	0.36	0.05	481	6
JU0311	Grt–Bt–(Ky)–And	10	0.26	0.05	527	7
JU0313	Grt–Bt–Sil	10	0.09	0.04	601	6
JU0314	Bt–(St)–Sil	10	0.09	0.06	601	8
JU0315	Chl–Ms	10	0.53	0.07	404	10
JU0317	Bt–And ?	10	0.33	0.06	493	8
JU0318	Bt–And	10	0.19	0.03	557	4
JU0319	Bt–And	10	0.29	0.06	511	8
JU0320	Bt–St–And	10	0.25	0.09	529	12
JU0321	Bt–And	10	0.22	0.06	545	8
JU0322	Bt–(Ky)–Sil	10	0.09	0.04	603	5
JU0323	Bt–(Ky)–Sil	10	–	–	> 640	–
JU0326	Bt–St–Ky–And	10	0.17	0.08	564	11
JU0327	And ?	10	0.27	0.03	523	5
MA0301	–	5	> 0.70	–	< 330	–
MA0303	–	5	> 0.70	–	< 330	–
MA0305	–	5	> 0.70	–	< 330	–
MA0306	–	13	0.57	0.06	390	7
MA0312	–	5	> 0.70	–	< 330	–
MA0314	–	5	> 0.70	–	< 330	–
MA0318	–	5	> 0.70	–	< 330	–
MA0319	–	5	> 0.70	–	< 330	–
MA0320	–	5	> 0.70	–	< 330	–
MA0323	Bt	10	0.47	0.04	432	6
OJ0302	Grt–Bt–And	11	0.20	0.05	552	7
OMA0301	Bt–And	12	0.35	0.05	487	7
OMA0302	–	13	0.68	0.03	340	4
OMA0303	–	7	> 0.70	–	< 330	–
OMA0308	–	5	> 0.70	–	< 330	–
EMA0301	–	6	> 0.70	–	< 330	–
EMA0302	–	10	0.68	0.02	338	7
EMA0303	–	6	> 0.70	–	< 330	–
EMA0307	–	10	0.57	0.06	387	9
EMA0308	Bt–And	10	0.31	0.07	502	10

structure of the Alboran Domain on both sides of the Gibraltar Strait.

In the Rif, conventional thermometry indicates that the highest temperatures are recorded in the kinzigites (~800–850 °C) and the Filali gneisses (~700 °C) above the peridotites (Fig. 3). This study extends these data upsection and shows that temperature decreases from 640 to 500 °C in the Filali schists (Fig. 8a). The base of the Ghomarides located on top of the Filali units also recorded temperatures of ~480–500 °C and temperature decreases towards the NW upward in the Ghomaride structural pile down to < 330 °C (Fig. 8a). A temperature of ~615 °C is obtained in sillimanite-bearing schists cropping out near Cabo Negro, similar to the temperature obtained over the Beni Bousera antiform further south (Fig. 8a). The Ghomarides overlying these schists recorded lower temperature than in the southern part as shown by the 420 °C RSCM temperature. Further north, over the Beni Mzala antiform, RSCM temperatures are below 330 °C in the Ghomaride nappes, consistent with a temperature of ~300 °C estimated in the underlying Federico unit (Fig. 8a) (Bouybaouène *et al.*, 1995).

In the Western Betics (Sierra Bermeja area), similar to the Sebtides in the Rif, the temperature increases gradually towards the base of the Alpujárride sequence located at the top of the Sierra Bermeja peridotite massif (Fig. 8b). The range of temperatures recorded in the Jubrique unit is very similar to that observed in the Filali unit: minimum temperatures (480–490 °C) are recorded on top of the Jubrique Palaeozoic schists and temperatures gradually increase to ~600 °C at the base of the sequence in the sillimanite-bearing schists and finally temperatures higher than 640 °C are observed in the Jubrique gneiss (Fig. 8b). In contrast to the Rif, the Permo-Triassic metapelites of the Jubrique unit recorded lower temperature conditions than the Federico units located in the same structural position (Fig. 3). Temperatures below 330 °C in the Maláguides on top of the Jubrique metapelitic sequence are in fair agreement with those observed in the Ghomaride complex over the Beni Mzala window and in agreement with temperatures estimated in the uppermost levels of the Jubrique unit (Fig. 3). Higher temperatures are recorded in the lowermost levels of the Maláguide Complex (North of Coín and Malaga) similar to those recorded in the lower Ghomarides on top of the Filali unit.

Considering the variations of temperature in the Filali and Jubrique units of the Palaeozoic metapelitic sequence, it is possible to estimate 'field thermal gradients'. In the Filali schists the average thickness is ~3 km (Fig. 3), which allows a 'field temperature gradient' of ~47 °C km^{-1} to be estimated in the whole schist sequence. Similarly the Jubrique Palaeozoic sequence has a structural thickness of ~3 km. The 'field temperature gradient' is ~40 °C km^{-1}, which is similar to the one observed in the Filali unit. Another important point is that temperature never exceeds 500 °C in the Ghomarides and Maláguides. The tectonic contact between the Ghomarides–Maláguides and the underlying Sebtides–Alpujárrides, described as a ductile extensional fault in the Rif (Zaouia Fault, Chalouan & Michard, 2004) roughly corresponds to the 500 °C isotherm on both sides of the Gibraltar Strait.

DISCUSSION

Comparison between RSCM temperatures and conventional thermometry

In a recent study on the thermal metamorphism of the Lesser Himalaya in Nepal, Beyssac *et al.* (2004) have shown that RSCM temperature estimates are in excellent agreement with those obtained by conven-

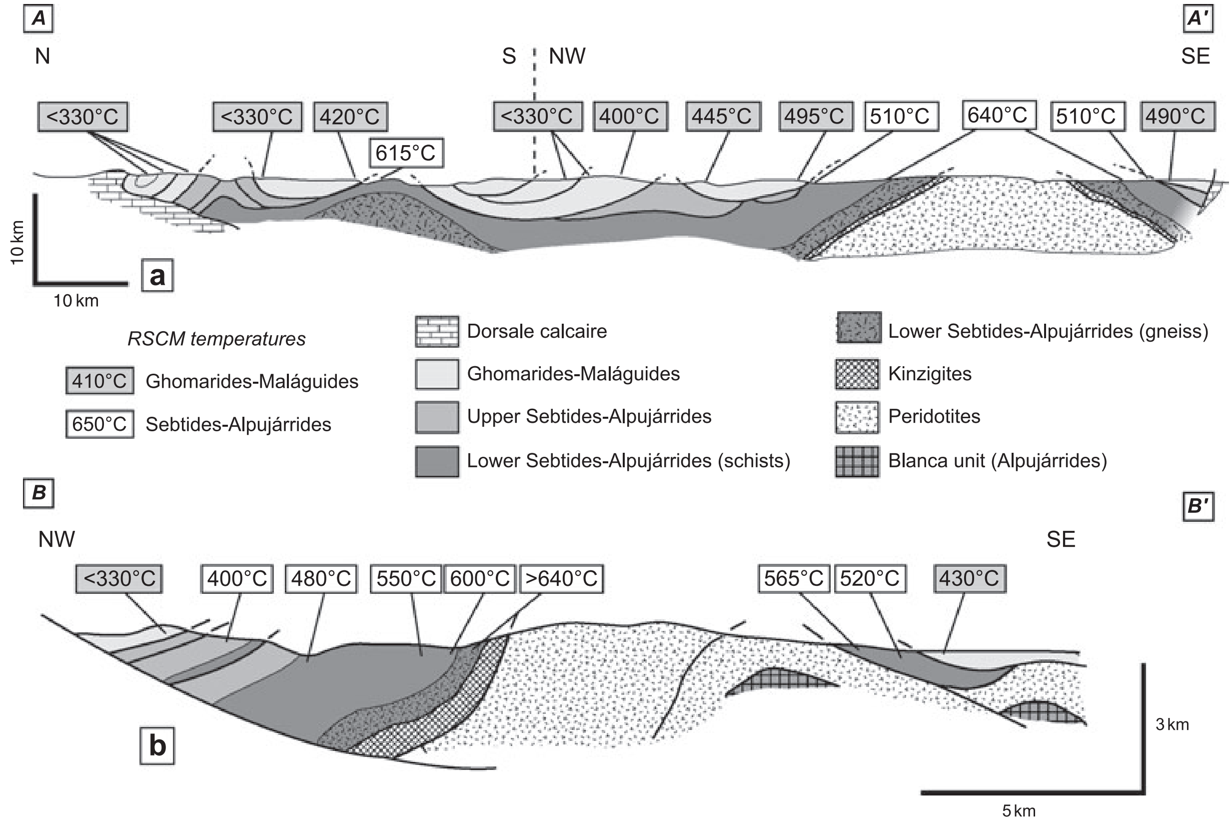

Fig. 8. (a) Cross-section of the Alboran Domain in the inner Rif showing the distribution of RSCM temperatures in the Sebtide and Ghomaride complexes (modified after Chalouan & Michard, 2004). The cross-section is located in Fig. 2. (b) Cross-section of the Alboran Domain in the Sierra Bermeja area (modified after Balanyá *et al.*, 1997) showing the distribution of temperatures obtained by the RSCM method in the Alpujárride and Maláguide complexes. The cross-section is located in Fig. 7. The absolute uncertainty on RSCM temperatures is ± 50 °C.

tional petrology in the range 500–550 °C. The present study offers the possibility to extend such comparison, mainly towards higher temperatures. First, it should be emphasized that the RSCM temperatures are consistent with the stability field of metamorphic assemblages observed in the studied samples, as given e.g. by Spear (1993) (see Table 1 for the Rif or Balanyá *et al.*, 1997 for the Betics). In Fig. 9, a compilation of our RSCM data is presented with the corresponding temperature estimates available in the literature for the Rif (El Maz & Guiraud, 2001) and for the Betics (Balanyá *et al.*, 1993; García-Casco *et al.*, 1993; García-Casco & Torres-Roldán, 1996; Balanyá *et al.*, 1997; Tubía *et al.*, 1997; Argles *et al.*, 1999).

In the Rif, El Maz & Guiraud (2001) have estimated temperature in the Filali schists using Thermocalc

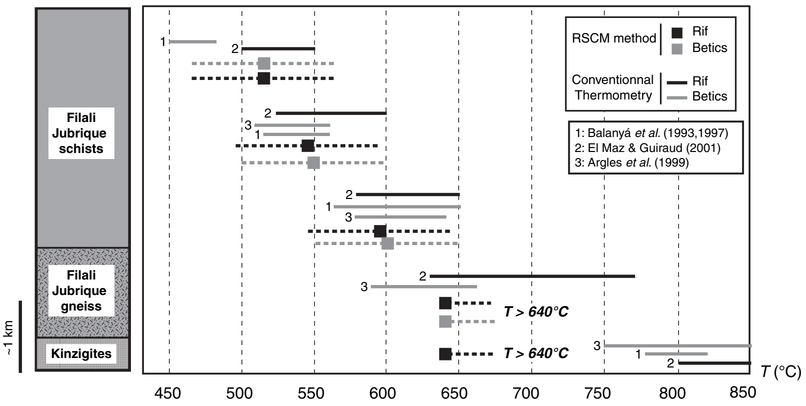

Fig. 9. Comparison of RSCM temperatures with those derived from classical thermobarometry in the different structural levels of the Alpujárride (Western Betics) and Sebtide (Rif) complexes. Mean RSCM temperatures are given for each structural level with an absolute uncertainty of ± 50 °C.

software. They have obtained temperatures from 500 to 550 °C in the shallower levels increasing up to ~600 °C in the sillimanite-bearing schists located at the base of the sequence. At the very base of the Filali schists, they obtained temperatures in the range 580–650 °C near the contact with the gneisses. Although our sampling is much denser and our sampling locations are generally slightly different, the RSCM temperature are in good agreement with those estimates, with an increase from 500 to 520 °C in the shallower levels up to 580–600 °C in the sillimanite-bearing schists and finally reaching temperatures higher than 640 °C in the gneisses where pristine graphite is found.

In the Betics, Balanyá *et al.* (1993, 1997) have estimated the temperature using the garnet/biotite geothermometer in the Jubrique unit of Sierra Bermeja. They have obtained temperatures in the range 517–560 °C in the staurolite-bearing schists and 565–650 °C in the sillimanite-bearing schists (Balanyá *et al.*, 1993, 1997). Moreover, Argles *et al.* (1999) have obtained temperatures in the range 510–560 °C for the staurolite–andalusite-bearing schist and 580–640 °C for the sillimanite-bearing schists in the Jubrique unit cropping out over the Carratraca peridotites northeast of Sierra Bermeja. All these data are in good agreement with our RSCM temperatures as shown in Fig. 9. The small shift observed between RSCM temperatures and conventional thermometry in the lower Filali–Jubrique levels is mainly due to (1) different sampling locations and (2) mean RSCM temperature values calculated from several samples in a given level of the unit.

Thermal structure and tectono-metamorphic evolution of the lower Sebtide–Alpujárride units

The Filali unit is characterized by a main foliation structurally parallel and coherent with the main tectonic contacts separating the different units (Fig. 10). This main foliation corresponds to the ductile thinning episode of the Filali unit during exhumation (Saddiqi *et al.*, 1988). From uppermost to deepest levels, the synfolial minerals are successively chlorite–muscovite, biotite and finally biotite–sillimanite in the deepest levels. Andalusite is ubiquitous in the whole sequence and shows syn- to post-kinematic habits. These textural relationships therefore suggest that the main foliation was developed under HT–LP conditions with higher temperature conditions at the base of the

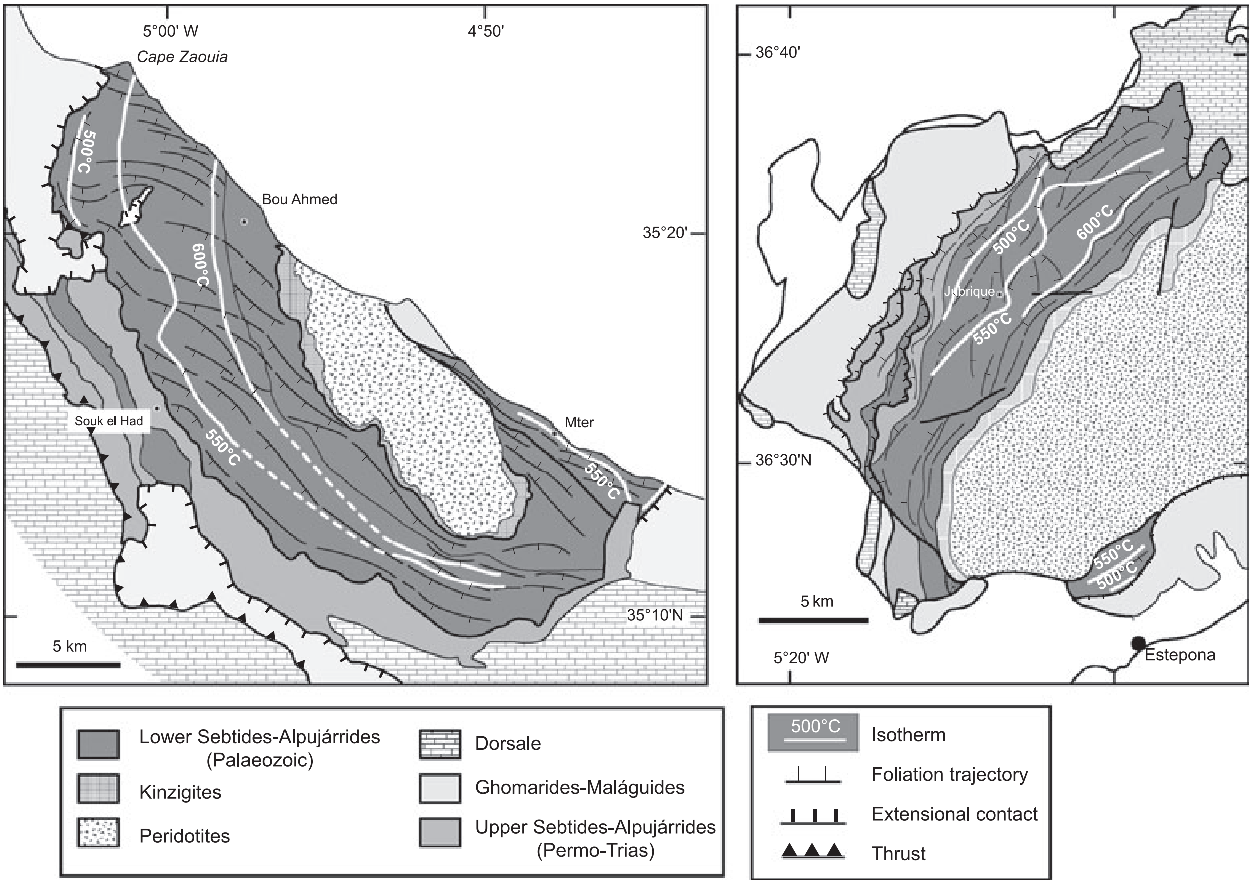

Fig. 10. Maps of foliation trajectories and isotherms derived from RSCM temperatures in the Rif and Western Betics. Foliation data are from this study, Saddiqi (1995) for the Rif and Balanyá (1991) for the Betics.

structural pile. Such correspondence between an HT–LP event and the main deformation phase is also supported by (1) the presence of andalusite within sheared and late quartz veins and (2) the fact that the main stretching lineation is marked by elongated andalusite crystals or sillimanite fibres.

In the Western Betics, the structure of the Alpujárride units is similar to that of the Sebtides (Fig. 10). Furthermore, similar deformation features have been described in the Jubrique unit. West of Sierra Bermeja, minerals like sillimanite or andalusite have a syn- to post-kinematic habit, indicating HT–LP conditions during the development of the main foliation (Balanyá *et al.*, 1993, 1997). Similar textural relationships have also been reported in the Jubrique unit which crops out in Sierra Alpujata and Sierra de Carratraca (Fig. 4) (Tubía *et al.*, 1997; Argles *et al.*, 1999).

Therefore, the RSCM temperatures (i.e. peak temperatures) estimated in both the Filali and Jubrique units likely correspond to the development of the main foliation and were reached during the thinning and exhumation of the Sebtide–Alpujárride units. The good spatial resolution of the sampling allows us to better constrain the link between the observed temperature and the structure of the Sebtide and Alpujárride nappes, by comparing the field isotherms (derived from our RSCM temperatures) with the foliation trajectories and the nappe contacts. These isotherms are given in Fig. 10, together with the foliation trajectories drawn from our own and literature data (Balanyá, 1991; Saddiqi, 1995).

In most of the Western Betics and over the Beni Bousera antiform, the peak temperature field isotherms are roughly parallel to the main foliation trajectories in the Sebtide and Alpujárride Palaeozoic schists. This geometry, together with the textural relationships and the similar estimated 'field temperature gradients', supports the idea of severe ductile thinning under HT–LP conditions which condensed the isotherms at least in this part of the Alboran Domain section. However, two differences between the Rif and the Western Betics can be pointed out:

- In the north-western part of the Beni Bousera massif (Fig. 10), the isotherms locally crosscut these foliation trajectories, suggesting that peak temperature was reached after ductile thinning of the Filali unit, during late stages of exhumation. This point also agrees with field observations that show widespread crystallization of post-kinematic andalusite.
- In the Betics, lower temperatures are observed in the lower Alpujárrides (Palaeozoic) than in the Filali unit (Fig. 3). Furthermore, our observations show that late andalusite and cordierite are widespread in the Rif in the upper Sebtides (Federico units – Permo-Triassic), whereas these minerals have not been described in equivalent upper Alpujárride units of the Betics (Balanyá *et al.*, 1997) (Fig. 3). Therefore, the Sebtide units probably underwent a late metamorphic evolution at higher temperature than the Alpujárrides.

Alpine thermal record in the Ghomaride–Maláguide units

The Ghomaride–Maláguide units represent an important part of the structural pile and are widespread through the Rif and the Western Betics. Therefore, they are critical in assessing the Alboran Domain metamorphic evolution, but until now the lack of index metamorphic assemblages made reliable *P–T* estimates impossible. Thanks to RSCM it is now possible to quantify the temperature variations in these complexes and therefore have a first-order idea of the thermal structure of the whole Alboran Domain.

In the Ghomarides, RSCM temperature decreases from ~500 °C in the deepest levels down to < 330 °C at the top. Along the same transect, K–Ar isotopic dating of white mica shows a partial resetting of apparent ages from 25.3 ± 0.9 Ma at the base close to the contact with the underlying lower Sebtides to 183 ± 6 Ma at the top of the Aakaili nappe and 259 ± 5 Ma in the overlying Beni Hozmar nappe (Chalouan & Michard, 1990; Michard *et al.*, 1991) (Fig. 2). The 25.3 ± 0.9 Ma age at the base is interpreted as a fully reset age, while the other K–Ar data may represent partial resetting of mica during Alpine evolution (Chalouan & Michard, 1990). In this context, and assuming (i) the absence of a temperature break between the Filali and the Ghomarides and (ii) a decrease of temperature with distance to the peridotite, our study shows that the Ghomarides did experience a thermal metamorphism during the Alpine phase in continuity with the one described in the underlying lower Sebtides and quantified by RSCM.

In the Western Betics, all the samples collected over the Benarrabá imbrications in the Maláguides yielded temperatures below 330 °C. However, southwest of the Sierra Bermeja, a temperature of 432 °C was obtained from a Maláguide sample which is consistent with the temperature in the underlying HT–LP lower Alpujárrides (~520 °C) (Fig. 7). Farther east, near Coín, another Maláguide sample shows a temperature of around 490 °C. Both these samples correspond to the deepest levels of the Maláguides (i.e. Early Palaeozoic). North of Malaga, where the most complete Maláguide section crops out, temperature increases with depth within the complex from < 330 to ~500 °C (Fig. 4). As in the Rif, there is no significant temperature break between the base of the Maláguides and the lower Alpujárrides which crop out farther east. Furthermore, Platt *et al.* (2003b) have reported Oligocene zircon fission-track ages and a 18.6 ± 1.8 Ma ^{40}Ar–^{39}Ar age on white mica from a biotite–andalusite-bearing schist sampled at the very base of the Maláguides (Fig. 4). By contrast, Triassic to Jurassic apatite fission-track ages from the uppermost levels of the Maláguides correspond to RSCM temperatures below 330 °C (Fig. 4). The situation is therefore similar to the Rif and supports the idea that the Maláguides were heated during the Late Oligocene–Early Miocene as well.

Large-scale distribution of temperatures and its relation to the present Alboran Domain nappe structure

The present structure of the Alboran Domain is the result of its tectonic and metamorphic evolution since the Oligocene. This geometry is complex, especially in the Western Betics where peridotites crop out within the Alpujárride metamorphic units. Figure 11 shows the maximum temperatures reached in the different units of the Alboran Domain in the Rif and Western Betics. These maps are mainly based on our RSCM temperatures completed by a compilation of *P–T* estimates available in the literature (Kornprobst, 1974; Kornprobst & Vielzeuf, 1984; Tubía *et al*., 1993, 1997; Balanyá *et al*., 1997; Argles *et al*., 1999; El Maz & Guiraud, 2001).

In the Rif, the thermal structure of the Alboran Domain is roughly coherent: the maximum temperatures are mainly localized around the Beni Bousera peridotite massif and temperatures decrease upward in the crustal sequence radially around the peridotite body (Fig. 11). In the Cabo Negro region, a similar distribution is observed and probably reflects a situation equivalent to that described for the southern units. Lastly, although HT units are found near Ceuta, no significant heating is recorded in the overlying Ghomaride units, a feature that may be connected with the absence of the lower Sebtides in this region. Therefore in this particular region, the present structure probably reflects a late tectonic reorganization of the units under LT conditions (< 330 °C). A similar feature is observed in a small part of the Aakaili unit on the north-eastern side of the Beni Bousera peridotites (Figs 2 & 11).

The Western Betics units display a more complex situation (Fig. 11). The thermal structure is coherent over the Sierra Bermeja as in the Rif but, elsewhere cold (i.e. < 330 °C) Maláguide units lying directly on top of HT Alpujárride units and peridotites are observed. This is evidence that, although temperatures recorded in both Alpujárride and Maláguide units are similar to the Rif, the Alboran Domain in Western Betics has been probably much affected by late tectonic reorganization under brittle conditions during final exhumation stages. Furthermore, the metamorphic gaps across tectonic contacts are in agreement with excision due to extensional faulting during exhumation as proposed by Argles *et al*. (1999) for the Carratraca area in the Western Betics. Therefore, the original geometry of the Alpujárride and Malaguide units is less preserved in the Betics, although they experienced the same extensional episode than the Sebtide and Ghomaride units in the Rif (Fig. 10).

Thermal structure and the exhumation history of the Alboran Domain

The present thermal structure of the Alboran Domain together with the geometry of the isotherms and their relation with deformation patterns, both derived from the RSCM temperatures, allows us to propose a tentative sketch for the thermal and tectonic evolution

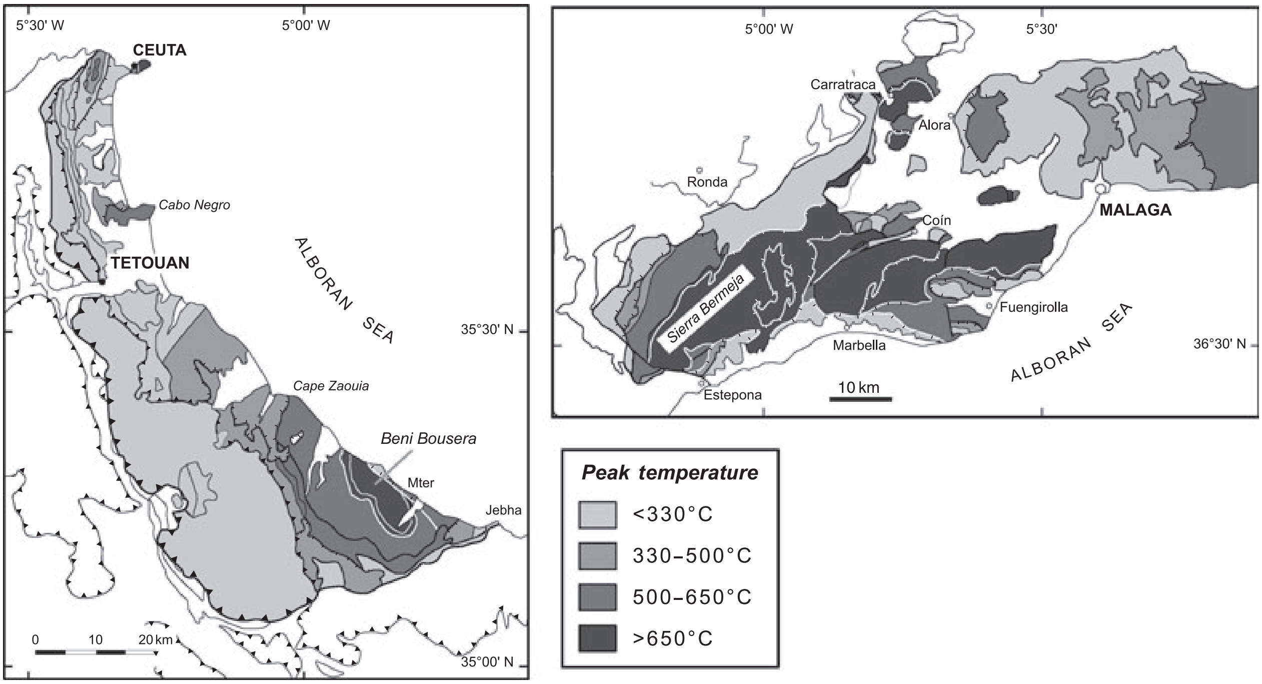

Fig. 11. Maps of the inner Rif and Western Betics showing peak temperatures in the Alboran Domain units. Peak temperatures correspond to RSCM data and available *P–T* estimates in the literature (see text for references).

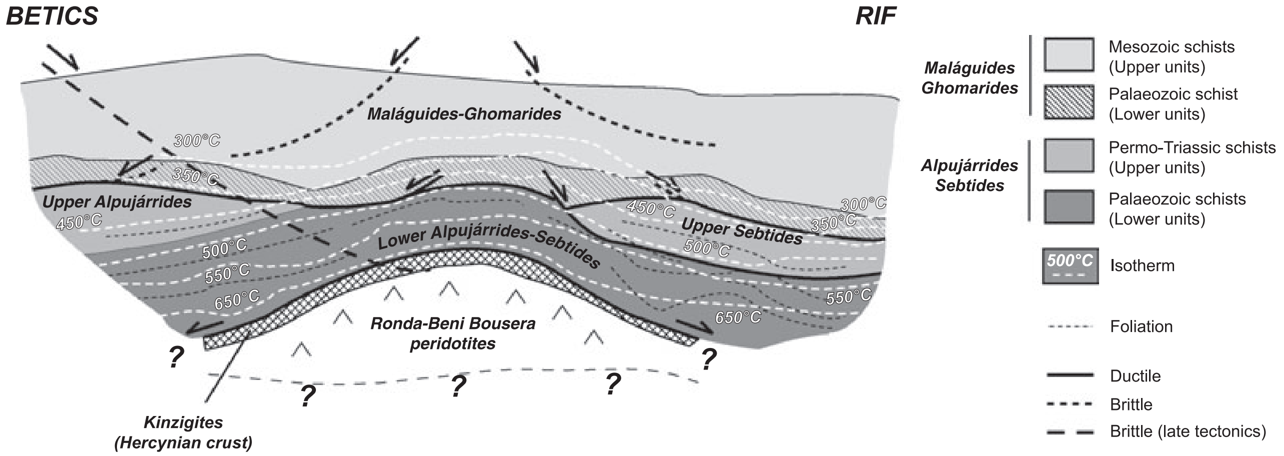

Fig. 12. Schematic model proposed for tectono-metamorphic evolution of the Alboran Domain during the Late Oligocene–Early Miocene. This model accounts for the relationship between isotherms derived from RSCM temperatures, the internal nappe structure and the main tectonic contacts during the extensional event. The present thermal structure observed in the Rif and the Western Betics has been also considered.

and the exhumation of the Alboran Domain in the Rif and the Western Betics. Figure 12 shows a possible organization of the units and the geometry of the isotherms during the thinning episode. The relations between the thermal structure, the main tectonic contacts and the stratigraphic organization are of particular interest. Higher temperatures are always observed in the oldest stratigraphic levels (i.e. Palaeozoic) and the main tectonic contacts correspond to a temperature of ~500 °C in the lowermost levels and to 350–300 °C in the upper levels.

The exhumation of the Sebtides–Alpujárrides is characterized by severe ductile thinning coeval with peak-*T*, as attested by the tightening of isotherms and the elevated metamorphic field gradients. An Alpine thermal metamorphism is also recorded in the Ghomaride–Maláguide units and the continuous decrease of temperature from base to top shows that this heating is related to the metamorphic evolution of the underlying Sebtides–Alpujárrides. The Ghomaride–Maláguide units were thus probably affected by thermal metamorphism as a result of heat advection in the underlying Sebtide–Alpujárride units and probably peridotites as well. Thus a common thinning episode can be proposed for the whole Alboran crustal sequence (Fig. 12) with ductile normal faults at depth (Sebtides–Alpujárrides) to brittle deformation in the upper levels (Ghomarides–Maláguides). However, in the Rif, peak temperature was locally reached during the final metamorphic evolution of the Sebtide units (Fig. 12), and the final thermal structure was probably acquired after the ductile thinning of the whole crustal sequence.

The available geochronological data show that all the cooling ages cluster around 20 Ma whatever the dating technique (K-Ar, ^{40}Ar-^{39}Ar, Rb-Sr, fission tracks) and/or the dated mineral (muscovite, biotite, zircon) in the lower Sebtides–Alpujárrides (Michard *et al.*, 1983; Monié *et al.*, 1994; Saddiqi, 1995; Sosson *et al.*, 1998; Platt & Whitehouse, 1999). In the Ghomarides–Maláguides as well, reset K–Ar or ^{40}Ar–^{39}Ar ages cluster between 25 and 19 Ma (Michard *et al.*, 1991; Platt *et al.*, 2003b). Furthermore in the kinzigites, U–Pb ages also cluster around 25–20 Ma in both Spain and Morocco and probably reflect peak temperatures (Sanchez Rodriguez, 1998; Platt & Whitehouse, 1999; Platt *et al.*, 2003a). These data indicate that the HT–LP event is likely Oligocene in age and that all the Alboran Domain units were rapidly exhumed during the Late Oligocene–Early Miocene during extensional thinning of the whole crust. Finally, Sm–Nd and Lu–Hf dating of garnet pyroxenite layers included in peridotites yielded Oligo-Miocene ages in both Ronda (Zindler *et al.*, 1983; Reisberg *et al.*, 1989) and Beni Bousera peridotites (Kumar *et al.*, 1996; Blichert-Toft *et al.*, 1999). Thus the evolution of the peridotites is most likely linked to the metamorphic history of the surrounding crustal rocks.

Considering the distribution of temperatures around the peridotite massifs, especially in the Rif (Fig. 12), the thermal event and related HT–LP metamorphism can be interpreted as due to the ascent of hot mantle units coeval with thinning of the whole lithosphere during an Oligo-Miocene extensional event. This process has been assigned to ascending hot asthenospheric mantle (Platt *et al.*, 2003b) or to lithosphere delamination (Tubía *et al.*, 2004).

During the Miocene, the final exhumation of the Alboran Domain rocks (under brittle conditions) led to late reorganization of the units (Fig. 12). This reorganization was more important in the Betics as shown by Fig. 11. Therefore a common metamorphic history can be proposed for the Alboran Domain on both sides of the Gibraltar strait, but with a late structural reorganization of the units on the Spanish side which is less pronounced in Morocco.

CONCLUSIONS

The results of this study based on temperature estimates by RSCM carried out in the Alboran Domain units of both the Rif and the Western Betics adds to the comprehension of their thermal structure and exhumation history.

In the lower Sebtide–Alpujárride units peak temperatures vary from ~480 to 500 °C at the top of the Palaeozoic metapelitic sequence to > 640 °C at the base. The relation between the spatial distribution of these temperatures and the internal nappe structure shows that peak temperature was almost coeval with thinning and exhumation of these units. However, the Rif units show higher-temperature late metamorphic evolution and peak temperature was locally reached after the thinning episode.

In the Ghomaride–Maláguide units, maximum temperatures of ~480–500 °C are recorded at the base of the Palaeozoic metapelitic sequence whereas in the upper Mesozoic levels, temperature did not exceed 330 °C. The relation between temperature and available geochronological data shows that these units experienced thermal metamorphism during the Late Oligocene–Early Miocene. Furthermore, the absence of a general temperature break with the underlying Sebtide–Alpujárride units links the metamorphic history of both complexes.

At a larger scale, the present thermal structure is very coherent in the Rif, with decreasing temperature radially around the Beni Bousera peridotites, whereas it is more complex in Western Betics. This thermal structure shows that the Western Betics units were much affected by late brittle tectonic reorganization.

We propose a tentative explanation for the thermal and tectonic evolution of the Alboran Domain with a thinning of the whole Alboran crustal sequence during the Late Oligocene–Early Miocene to account for the observed geometry of the isotherms. Considering the distribution of temperatures around the peridotite massifs, especially in the Rif, the metamorphic evolution of the Alboran Domain can be interpreted as the result of the ascent of hot mantle units coeval with thinning of the whole lithosphere during an Oligo-Miocene extensional event.

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