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A. Castro · C. Fernández · H. El-Hmidi · M. El-Biad
M. Díaz · J. de la Rosa · F. Stuart

Age constraints to the relationships between magmatism, metamorphism and tectonism in the Aracena metamorphic belt, southern Spain

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Abstract The Aracena metamorphic belt (AMB), southwest Iberian peninsula, is characterized by the following geological elements: (a) a high-temperature/low-pressure (HT/LP) metamorphic belt a few kilometres wide and more than 200 km long; (b) a linear belt of oceanic amphibolites with a low-pressure inverted metamorphic gradient; (c) crustal-scale ductile shear zones; and (d) mafic, noritic intrusions of high-Mg andesite (boninite) composition. The relationships between these elements led to the proposal of a model of ridge subduction for this sector of the Hercynian belt of Europe. This interpretation is supported by the age relationships displayed between the main rock units considered representative of the main tectonic and petrological processes responsible for the geological elements mentioned previously. The results of a geochronological study (Ar–Ar, Rb–Sr and Sm–Nd) clearly support a Late Paleozoic tectonic evolution at an active continental margin. The time evolution of the metamorphism in the oceanic domain, ranging from 342.6 ± 0.6 Ma in the west to 328.4 ± 1.2 Ma in the east, over a distance of 70 km along the metamorphic belt, support a tectonic model of triple-junction migration responsible for the creation at depth of a slab-free window with decisive consequences for the thermal evolution of the region. The origin of the linear metamorphic belt of HT/LP regime may be explained by the migration along a continental margin of a punctual thermal anomaly induced by the creation of a triple-junction at the continental margin.

Key words Hercynian belt · Iberian massif · Aracena metamorphic belt · Migmatites · Norites · Ar ages · Sm–Nd · Rb–Sr

Introduction

The Aracena metamorphic belt (AMB), located in southern Spain, has been an area of great geological interest in the European Variscan belt. This small area of the Iberian massif contains petrological and structural elements of relevance for the understanding of the mechanisms of mountain building and crustal evolution in the past. These geological elements are: (a) a HT/LP metamorphic belt a few kilometres wide and more than 200 km long; (b) a linear belt of oceanic amphibolites with a low-pressure inverted metamorphic gradient; (c) crustal-scale ductile shear zones; and (d) mafic, noritic intrusions of high-Mg andesite (boninite) composition. These elements and the relationships between them have led us to propose a model of ridge subduction (Castro et al. 1996a, b) for this sector of the Variscan belt of Europe. As the area is possibly located at the edge of the Gondwana supercontinent, the proposed tectonic model may have implications in the understanding of the plate tectonics scenario during the Upper Paleozoic. The knowledge of the time relationships between the aforementioned elements is crucial in constraining this interpretation. Previously, we used field relationships and microstructures as the main elements to reconstruct the timing between tectonism, metamorphism and magmatism in the AMB (Castro et al. 1996a, b). However, for a more accurate model absolute age determinations were necessary. The results of a geochronological study on igneous and metamorphic rocks, representing the main tectonothermal processes that occurred in the AMB, are presented in this paper.

A. Castro (✉) · C. Fernández · H. El-Hmidi · M. El-Biad
M. Díaz · J. de la Rosa
Department of Geology, University of Huelva,
E-21819 Huelva, Spain
Fax: +34 (9) 59 53 03 10
E-mail: dorado@uhu.es

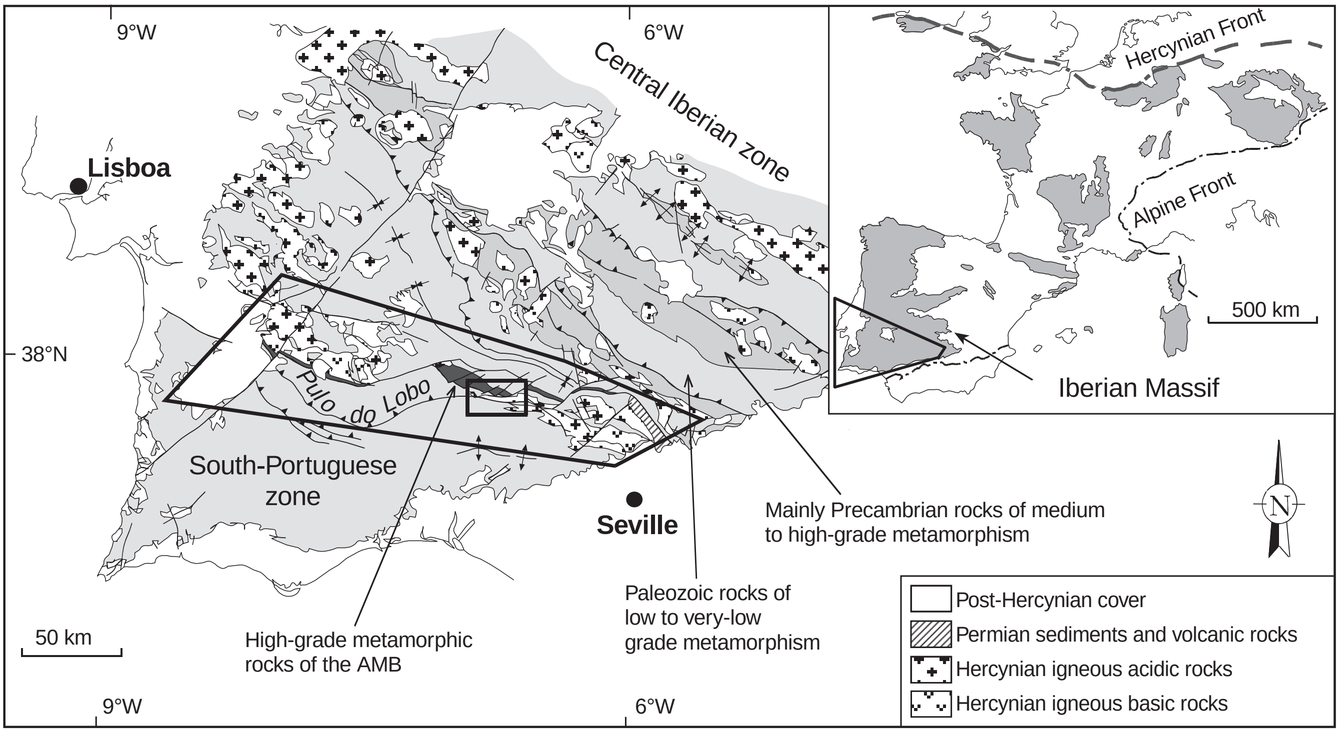
F. Stuart
Isotope Geosciences Unit, SURRC, East Kilbride, Scotland

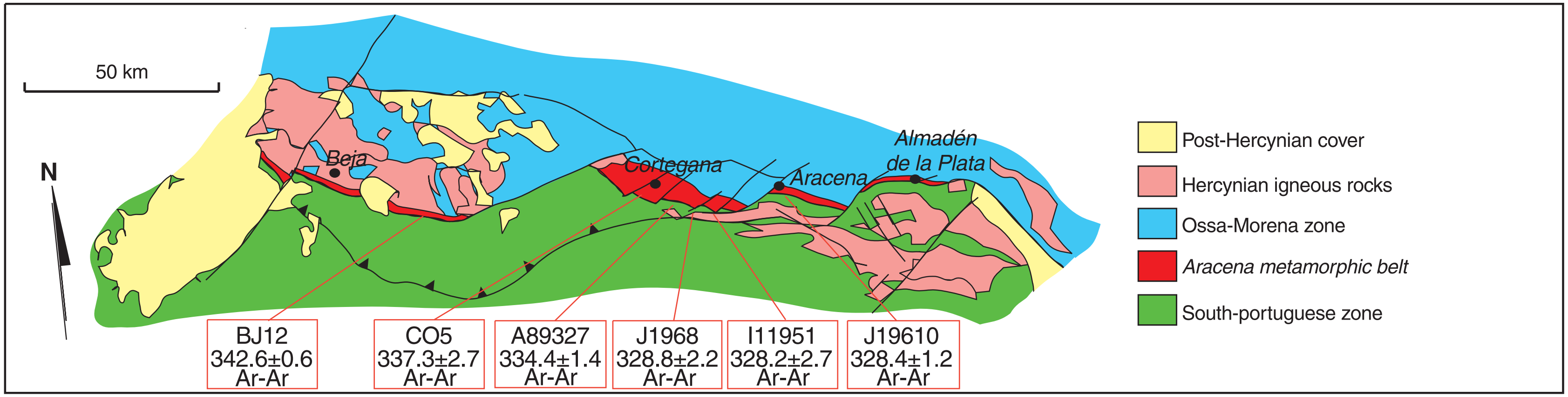
Geology of the Aracena metamorphic belt

The Aracena metamorphic belt (AMB) is located in the Ossa-Morena zone (OMZ) of the Iberian massif (Fig. 1). One of the most relevant characteristics of the Ossa-Morena zone is the alternation of metamorphic and plutonic bands that follow the trend of the regional structures (NW–SE). Most of the metamorphic and magmatic events of the OMZ occurred during the Hercynian orogeny in the Upper Paleozoic. Recent radiometric dating in the northern contact of the OMZ (Azor et al. 1995) confirms the existence of Lower Paleozoic intrusions (García-Casquero et al. 1985) as protoliths of gneissic rocks deformed and metamorphosed during the Upper Paleozoic, forming a suture that separates the OMZ from the Central Iberian zone (Azor et al. 1995). The AMB constitutes a high-grade metamorphic band, parallel to the former, at the southernmost part of the Ossa-Morena zone. The AMB also comprises one of the most important sutures of the Hercynian belt of western Europe. This suture, separating the OMZ from the southern terrains of the Pulo do Lobo and South Portuguese zones, is marked by oceanic amphibolites (Acebuches amphibolites; Bard 1969; Bard and Moine 1979) strongly foliated at their southern edge by the South Iberian shear zone (Crespo-Blanc and Orozco 1988).

Castro et al. (1996a, b) distinguished two lithological domains in the AMB: (a) a southern, oceanic domain (OD), composed of amphibolites and mafic schists derived from metamorphism of an oceanic crust, as well as terrigenous sediments interpreted as an accretionary prism overthrust by the oceanic crust (Eden 1991); and (b) a northern, continental domain (CD), composed of pelitic and calc-silicate gneisses, marbles, amphibolites and granulites (Fig. 2). Apart from composition, both domains are clearly separated according to their structural and metamorphic evolutions. The CD was affected by a clockwise metamorphic path with the peak assemblages recording ultra-high temperatures for comparatively low pressures (ca. 1000 °C and <4 kb; Patiño-Douce et al. 1997). An asymmetrical metamorphic zonation is also observed in the CD (Castro et al. 1996a, b), with the highest temperature zone located at the southern edge, at the immediate contact with the OD. The peak assemblages show post-tectonic growth with respect to the deformation phases responsible for the main fabrics in the CD. Later folding and shearing episodes affected the metamorphic isogrades, but they did not produce important penetrative fabrics in the rocks. It is important to realize that the tectono-metamorphic evolution of the OD is very distinct from that of the CD. In the OD the metamorphic grade increases towards the structural top (towards the north), i.e. opposite to the metamorphic zonation in the CD. The structures in the CD do not affect the OD. In particular, the axial traces of the later folds are arranged in an en echelon pattern, oblique with respect to the boundary with the amphibolites of

Fig. 1 Sketch of the southernmost part of the Iberian massif shows the distribution of metamorphic belts in the Ossa-Morena zone (division by Julivert et al. 1974, and Quesada 1991). The *inset* depicts the location of this area in the context of the western European Hercynides. *Thick-trace polygons* are for locations of maps in Fig. 2: *large polygon* corresponds to the upper panel and *small rectangle* to the lower panel. *AMB* Aracena metamorphic belt




50 km
N
Beja
Cortegana
Aracena
Almadén
de la Plata
Post-Hercynian cover
Hercynian igneous rocks
Ossa-Morena zone
Aracena metamorphic belt
South-portuguese zone
BJ12
342.6±0.6
Ar-Ar
CO5
337.3±2.7
Ar-Ar
A89327
334.4±1.4
Ar-Ar
J1968
328.8±2.2
Ar-Ar
I11951
328.2±2.7
Ar-Ar
J19610
328.4±1.2
Ar-Ar

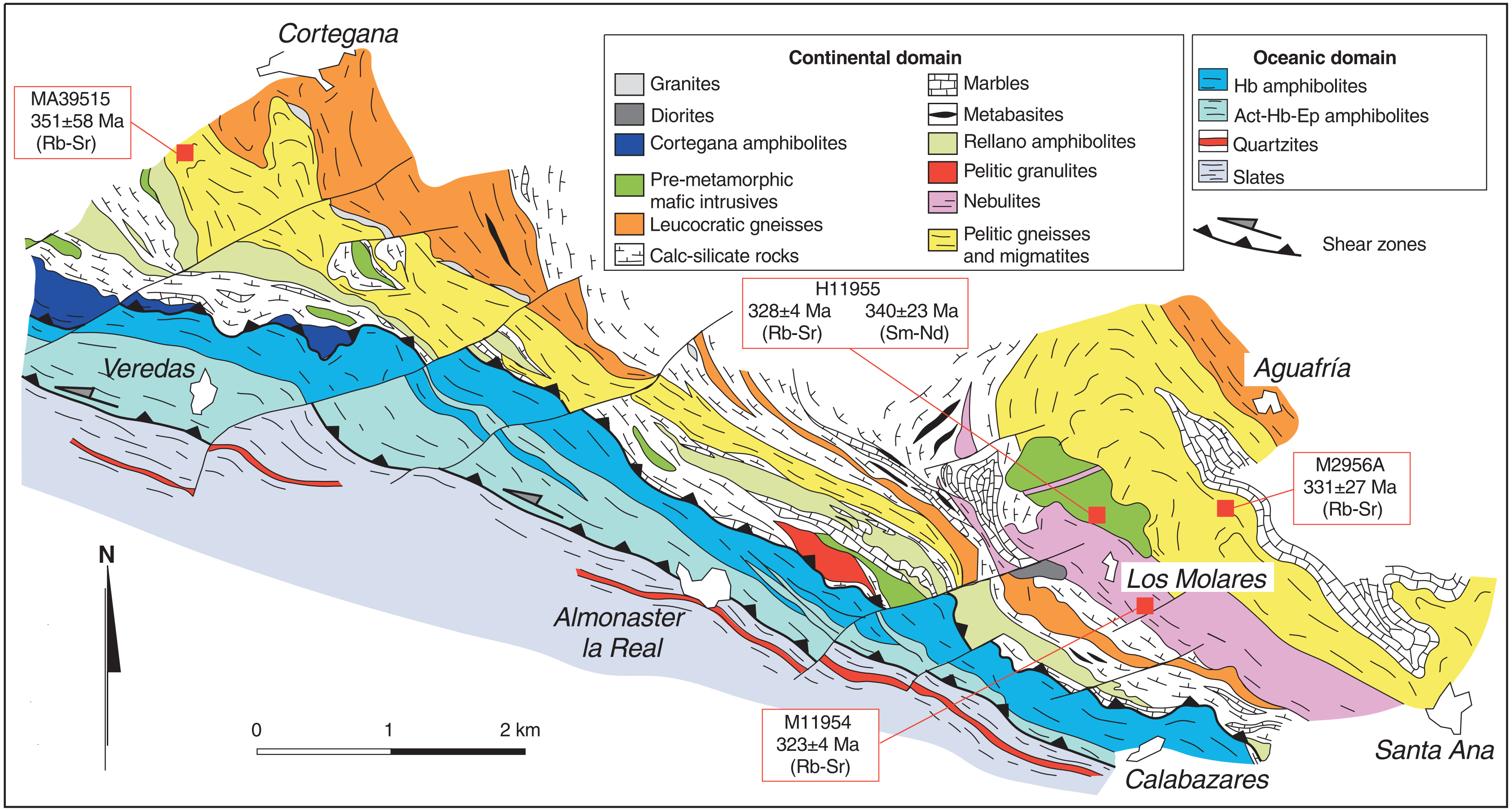

Cortegana
MA39515
351±58 Ma
(Rb-Sr)
Continental domain
Granites
Diorites
Cortegana amphibolites
Pre-metamorphic
mafic intrusives
Leucocratic gneisses
Calc-silicate rocks
Marbles
Metabasites
Rellano amphibolites
Pelitic granulites
Nebulites
Pelitic gneisses
and migmatites
Oceanic domain
Hb amphibolites
Act-Hb-Ep amphibolites
Quartzites
Slates
Shear zones
H11955
328±4 Ma
(Rb-Sr)
340±23 Ma
(Sm-Nd)
Aguafría
M2956A
331±27 Ma
(Rb-Sr)
Veredas
Los Molares
Almonaster
la Real
N
0
1
2 km
M11954
323±4 Ma
(Rb-Sr)
Calabazares
Santa Ana

Fig. 2 Map of the entire amphibolite belt ofthe southern Iberian massif (*upper panel*) showing the location of samples of amphibolites from the oceanic domain analysed by $^{40}Ar/^{39}Ar$ datings in this study (samples in the *lower row*) and by Dallmeyer et al. (1993; samples 1–5 in the *upper row*). The *lower panel* shows the map of a sector of the AMB between Cortegana and Santa Ana, showing the oceanic domain (Acebuches amphibolite and Pulo do Lobo zone) and the southern part of the continental domain. It also shows the location, ages and dating methods of the samples from the continental domain studied in this work. *MA39515* Cortegana flebitic migmatites; *H11955* Los Molares norites; *M11954* Los Molares nebulites. *M2956A* Los Romeros migmatitic gneisses

the OD. The OD traverses the whole mapped area without any deflection related to those folds or older structures in the CD (Fig. 2).

For this geochronological study we selected the main rock types considered representative of the main magmatic and metamorphic events in the continental and oceanic domains of the AMB, and the results are presented in this paper. These selected rocks are migmatites (layered migmatites and nebulites) and mafic, noritic intrusives that appear spatially associated in the CD and MORB-derived amphibolites of the oceanic domain (Fig. 2). Age constraints have been addressed through a combination Rb–Sr, Sm–Nd and Ar–Ar techniques. A brief description of the main rock units studied with this purpose in mind is given herein.

Layered migmatites

Layered migmatites are part of the older sequence of the AMB which consists of pelitic gneisses and graphitic quartzites with calc-silicate metasediment intercalations. These rocks were partially melted giving rise to migmatitic complexes and nebulites which appear in elongated bands at the cores of antiforms due to the post-metamorphic deformation phase. The contact between the migmatitic gneisses and the nebulites is not always clear, but when it is seen, it is transitional. From migmatites to nebulites the amount of melt and the grain size increase.

The main mineral assemblage of these rocks is: Qtz + Pl + Bt + Kfs + Crd ± Grt ± Sil ± Ms ± Spl ± Opx ± Ap ± opaques. The Pl has an average composition of An_{22} and it is usually zoned. The Kfs is Or and sometimes Mc. When present, the Sil appears as fibrolite. The samples that are the object of this study show palaeosomes with three different assemblages: (a) Qtz + Kfs + Bt ± Pl ± Sil; (b) Pl + Bt; and (c) Bt + Qtz + Ap (Fig. 3). The first one is the most common. Neosomes are more homogeneous and show a simpler assemblage: Qtz + Pl ± Bt ± Kfs (Fig. 3). The migmatitic layering, parallel to the regional foliation, is well defined by melanosome and leucosome bands, and it is pervasively folded at the outcrop scale, with NW/

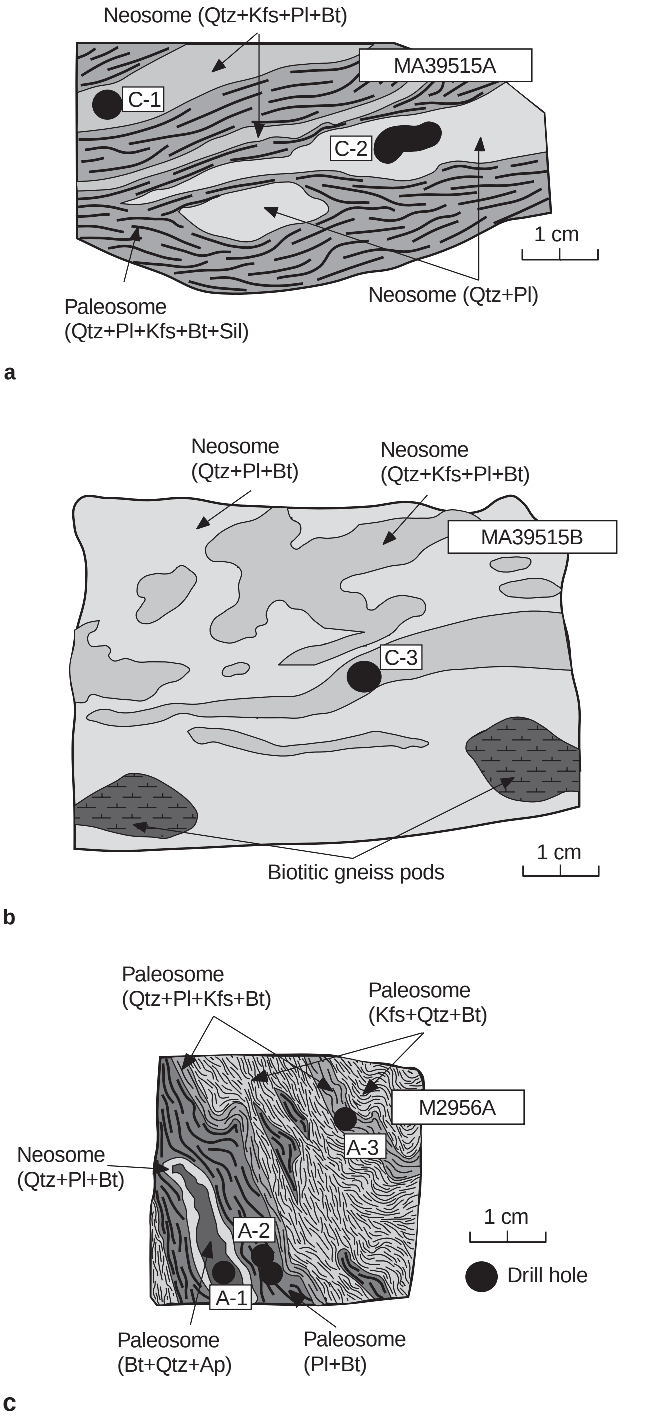


Fig. 3a–c Line drawings from photographs of the three hand specimens of migmatites selected for Rb/Sr dating. **a** A flebitic migmatite from Cortegana (sample MA39515A). **b** A granitic band from the same migmatite (sample MA39515B). **c** A migmatitic gneiss from Los Romeros (sample M2956A). Mineral abbreviations after Kretz (1983)

SE-oriented fold axes, parallel to the large-scale folds formed during the post-metamorphic deformation.

Two types of neosome, granitic (s.s.) and trondhjemitic, were identified from field and petrographic observations. The differences in composition are possibly related to local heterogeneities in the source rocks. In both cases a sequential, igneous texture is identified, with euhedral plagioclase in the trondhjemitic melts and subhedral K-feldspar and zoned plagioclase in the granitic (s.s.) ones. Mostly, these neosomes are concordant with the migmatitic foliation and the palaeosome bands. However, they also appear in veins injected through a set of fractures crosscutting all the previous structures but connected with the concordant bands mentioned previously.

Nebulites

Nebulites are nearly massive rocks generated by partial melting of a pelitic source. These melts remained nearly in situ as suggested by the transitions observed from these nebulites towards the layered migmatites and migmatitic gneisses in the Los Molares area (Fig. 2). It is common that the development of melanocratic schlieren define a foliation that embraces several kinds of xenoliths, restites and resisters. This foliation is affected by folds that trend in a NW–SE to NNW–SSE direction.

The petrography is similar to that of the migmatitic gneisses and the mineral assemblage is complex as well: Qtz + Pl + Bt + Crd + Kfs ± Grt ± Sil ± Spl ± Ap ± Tur ± Im ± Zrn. The plagioclase, with euhedral to subhedral texture, is zoned being basic oligoclase (An_{22-27}) at the cores and acid andesine (An_{30-33}) at the rims. The K-feldspar is usually perthitic. The garnet is rich in almandine and pyrope components, and although there are no sillimanites in the core, it reacts with the cordierite to form fibrolite. There are large, centimetric cordierite blasts that contain fibrolite as well as biotite inclusions.

Los Molares metanorites

The other rock type included in this study was a mafic intrusion of high-Mg andesite composition (Los Molares metanorites; Fig. 2). These rocks are characterized by high silica content (52–58 wt.%), high magnesia 5–18 wt.%, high refractory element concentrations, Cr up to 900 ppm, and low concentrations of high-field-strength elements. On the basis of this peculiar chemistry and their mineralogical features, basic and intermediates intrusions of AMB are considered as the plutonic equivalents to modern boninites lavas defined by Meijer (1980), Cameron (1985), Crawford et al. (1989) and Bloomer and Taylor (1995). These rocks have suffered HT/LP metamorphism. The mineral association of Opx + Cpx + Hb + Pl ± Bt ± Qz ± Rt is characteristic of high-amphibolite to granulite facies. Magmatic, sequential-like textures have been recognized in many samples. However, these textures are normally modified by recrystallization during the HT/LP metamorphism with the development of typical granoblastic textures. For this reason these rocks are normally referred either as norites (plutonic rocks) or metanorites. For reasons of clarity we use the term metanorite in this paper.

Amphibolites of the oceanic domain

The oceanic domain (OD) is composed primarily of amphibolites with subordinate metadolerites and mafic schists. These amphibolites outcrop as a long (>100 km), narrow (ca. 1 km) band with a rough E–W azimuth and dipping >50° to the north. This band is disrupted by late, brittle strike-slip faults (Fig. 2). To the north, the amphibolitic band is in contact with the continental domain of the AMB. To the south it overlies the Pulo do Lobo zone, recently interpreted as an accretionary prism (Eden 1991). The present thickness of the amphibolitic pile is of approximately 600 m in the studied area.

Three main deformational phases are identified in this domain. The first phase (OD-D_1) is very penetrative and responsible for the development of a metamorphic banding and foliation. The intensity of this fabric decreases towards the top, where undeformed igneous textures are easily recognizable. Structural analysis points to a non-coaxial deformation regime for OD-D_1, and reveals a complex kinematic frame, with a top-to-the-south thrust component, and a sinistral strike-slip component (Castro et al. 1996b). Coeval to OD-D_1 is an inverted metamorphic gradient. The peak temperatures estimated for this metamorphism are ca. 800 °C (Díaz et al. 1997), calculated by the amphibole–plagioclase thermobarometer of Holland and Blundy (1994), approximately 200 °C lower than the peak temperatures in the CD.

During the second phase (OD-D_2) ductile shear zones are developed which have particularly affected the bottom of the amphibolite pile, where >150 m of mylonites can be recognized (Crespo-Blanc and Orozco 1988). However, an anastomosing network of thinner shear bands traverses the entire amphibolite pile, isolating fish-shaped portions of less deformed rock. The kinematics of the second deformational phase is similar to that of the first one, but with a stronger strike-slip component (Castro et al. 1996b). The OD-D_2 develops a greenschist facies retrometamorphism over the amphibolites (mafic schists with actinolite–chlorite). A third, ductile phase of deformation (OD-D_3) produced the shear zones which locally appear at the boundary between the oceanic and continental domains. These are centimetre- to metre-scale shear bands, producing a strong mylonitization and retromorphism of high-grade amphibolites. Locally, they penetrate the continental domain, leaving intact the original, pre-shearing contact between amphibolites and continental rocks. The kinematic indicators in the shear zone suggest a top-to-the-south thrust motion (Castro et al. 1996b).

Dallmeyer et al. (1993) presented seven $^{40}Ar/^{39}Ar$ mineral ages of the AMB and Beja area. Two samples were collected in the post-kinematic Beja gabbro. The other five samples correspond to amphibolites and give plateau ages ranging between approximately 335 and 342 Ma (samples 1–5 in Fig. 2). Samples 1, 4 and 5 belong undoubtedly to the continental domain as defined by Castro et al. (1996a, b).

Sample location and descriptions

Three different samples of migmatites, selected for Rb–Sr analysis, have been chosen, two from SW of Cortegana (MA39515A and MA39515B) and the other close to Los Molares (M2956A; Figs. 2, 3). MA39515A and MA39515B have been collected from the same outcrop over a distance less than 1 m from one to another. Figure 3a shows a flebitic migmatite (MA39515A) with leucosome and melanosome bands embracing a trondhjemitic neosome which is concordant with the general foliation of the rock. Microsamples for analysis have been drilled from the two neosome bands (C-1 and C-2). Figure 3b shows two melt generations in the Cortegana migmatite (MA39515B); one is granitic (s.s.), from which the powder for analysis was taken (C-3), and the other is trondhjemitic. The line drawing of M2956A in Fig. 3c shows a migmatitic gneiss with several folded palaeosome layers. The dark-grey layers have slightly zoned plagioclase and oriented biotite. The light-grey layers are rich in K-feldspar and quartz with granoblastic texture. There are two intermediate bands, rich in quartz and plagioclase with scarce K-feldspar and biotite. Concordant with them there is an aggregate of restitic biotites, surrounded by a trondhjemitic melt, containing euhedral plagioclase. Powder was obtained from the biotite aggregate (A-1), the palaeosome with plagioclase and biotite (A-2) and the intermediate palaeosome layer (A-3).

The nebulite sample M11954 is a granitoid rock with coarse quartz grains, euhedral Pl, Bt, Kfs, Grt, Tur and Zrn. It shows a weak foliation defined by biotite. Xenoliths and restites were eliminated before the separation of biotite, garnet and whole-rock for Rb–Sr analysis.

Other rock types included in this study are the metanorites of high-Mg andesite composition from the mafic intrusions of the AMB (Los Molares, Fig. 2). Concentrates of Opx, Pl and Bt were separated from sample H11955, an Opx–Cpx cumulate used for Rb–Sr and Sm–Nd analysis. In this sample, Opx has bronzitic composition and constitutes approximately 20–30 vol.% of the rock. The clinopyroxene has diopside composition and constitutes approximately 14–30 vol.% of the rock.

The amphibolites of the oceanic domain are composed of plagioclase–amphibole ± clinopyroxene ± sphene ± epidote ± ilmenite ± magnetite ± quartz ± apatite with amphibole and plagioclase constituting >90 vol.% of the rock. They display a compositional homogeneity. However, the grain size of the rock is very variable from coarse to very fine grain size. Ar analyses of hornblende have been performed in medium grained (1–4 mm) amphibolites with hornblende and plagioclase constituting >90 vol.% of the rock and without clinopyroxene. The sample location is indicated in Fig. 2 and Table 3.

Sampling methods and analytical procedure

Rb–Sr and Sm–Nd techniques

Due to the compositional heterogeneity of migmatitic rocks, in which neosome bands composed of quartz and alkaline feldspar alternate with bands composed of refractory material (sillimanite, cordierite, biotite), and to the inference that these partially molten rocks equilibrated above the 600 °C, we have assumed that Sr-isotope equilibrium was reached at least at the scale of a hand specimen. In this sense, we can use the compositional bands to establish an isochron because, at the time of thermal equilibration, all the zones had a common Sr-isotope ratio but distinct Rb/Sr ratios. Fresh rock samples of flebitic migmatites were cut adequately in order to have all the distinct compositional bands in a single section. The selected surface was etched with HF acid and stained by immersion within a sodium cobaltinitrite solution revealing the distribution of K-feldspar and plagioclase. The selected bands were sampled with a drilling machine and the powder prepared by crushing in agate mortars. Mineral separates from compositionally homogeneous rocks, such as the nebulites and the Los Molares boninites, were prepared using the classical techniques of heavy liquids and magnetic barrier separator (Franz LB1). Mineral separates were finally purified by handpicking. Other samples were completely crushed for whole-rock analyses. This is the case for several samples from the mafic intrusions (Los Molares) which were selected after trace element analyses were used to demonstrate a magmatic fractionation process. These samples were dated in order to establish the age of the high-Mg andesite magmatism.

One tenth of a gram of each sample was etched with a HNO_3-HF mixture (3:2) within pressured Teflon (DuPont) reactors in a microwave oven. After three cycles of drying and dissolution in concentrated HNO_3, the final residue was dissolved in 100 ml of HNO_3 4%. Rb, Sr, Sm and Nd determinations were caried out with an Elan-5000 Perkin Elmer ICP-MS at the University of Granada. Calibration was performed using Rb, Sr, Sm and Nd pure dissolutions with a $^{87}Sr/^{86}Sr$ ratio of 0.707265 and a $^{143}Nd/^{144}Nd$ ratio of 0.512236. The precision of the method, calculated on ten replicates of the WSE standard and analysed over 2 months, is better than 1.2% (2 σ). The final value used is the mean

Table 1 Rb–Sr isotopic ratios for metanorites, migmatites and nebulites from the Aracena metamorphic belt

Sample	Description	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	Error (2 σ)
Los Molares metanorites						
H11955-Bt	Biotite	355	8.63	119	1.263168	±25
H11955-Pl	Plagioclase	8.33	371	0.0650	0.708399	±14
H11955-Opx	Orthopyroxene	1.99	4.17	1.38	0.714274	±14
H11955-Wr	Whole rock	22.1	114	0.559	0.710604	±21
Los Molares nebulites						
M11954-Wr	Whole rock	12.4	1.71	20.8	0.806354	±48
M11954-Grt	Garnet	101	85.4	3.42	0.729076	±15
M11954-Bt	Biotite	482	3.09	452	2.794055	±84
Los Molares migmatites						
M2956.A1	Palaeosome (Bt + Qtz + Ap)	310	8.30	103	1.203810	±84
M2956.A2	Palaeosome (Pl + Bt)	88.6	63.3	3.87	0.735838	±22
M2956.A3	Palaeosome (Qtz + Pl + Kfs + Bt)	140	108	3.57	0.733801	±22
Cortegana migmatites						
MA39515.C1	Neosome (Qtz + Kfs + Pl + Bt)	94.3	108	2.53	0.724563	±22
MA39515.C2	Neosome (Qtz + Pl)	10.6	84.1	0.364	0.713876	±21
MA39515.C3	Neosome (Qtz + kfs + Pl + Bt)	66.6	103	1.86	0.721466	±22

$^{87}Sr/^{86}Sr$ ratios normalized to $^{88}Sr/^{86}Sr = 8.375209$

Table 2 Sm–Nd isotopic ratios for metanorites from Los Molares intrusion of the Aracena metamorphic belt

Sample	Description	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	Error (2 σ)
H11955-wr	Whole rock	2.08	7.15	0.1726	0.512326	±25
H11955-Bt	Biotite	0.69	2.30	0.1821	0.512322	±8
H11955-Px	Orthopyroxene	0.31	0.99	0.1902	0.512323	±13
H11955-Pl	Plagioclase	0.14	1.25	0.0725	0.512179	±15

$^{143}Nd/^{144}Nd$ normalized to $^{146}Nd/^{144}Nd = 0.7219$

value of three replicates of the same sample. All reactants used were obtained by sub-boiling distillation of Merck Suprapur products.

Rb and Sr were separated using Biorad AG 50 W8 ion-change resins. Analytical determinations were performed with a Finnigan MAT 262 thermal ionization mass spectrometer with a precision better than 0.0028% (2 σ) calculated from repeated measurements of the WSE standard. The measured mean value of the NBS-987 standard was 0.710250 and the calculated accuracy was better than 0.0007% (2 σ). The normalizing value for $^{87}Sr/^{86}Sr$ was $^{88}Sr/^{86}Sr = 8.375209$. A similar method was used for Sm- and Nd-isotope separation and determination. The normalization value for $^{143}Nd/^{144}Nd$ was $^{146}Nd/^{144}Nd = 0.7219$. The measured mean value of the La Jolla standard was 0.511847 and the calculated accuracy was better than 0.0018% (2 σ). The measured TIMS blanks for Sr and Nd were 0.6 and 0.09 ng, respectively. Isochrons were fitted using Isoplot software (Ludwig 1994) with errors of 0.9 and 1.2% (2 σ) for the $^{147}Sm/^{144}Nd$ and $^{87}Rb/^{86}Sr$ ratios, respectively, and the errors in Tables 1 and 2 for the $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ ratios.

$^{40}Ar/^{39}Ar$ dating technique

Laser fusion $^{40}Ar/^{39}Ar$ dating of six hornblende samples from the Aracena amphibolites were used to constrain the thermal evolution of the Aracena metamorphic belt. Ages were obtained from five or more splits of a small number of grains from each sample. Hornblendes were separated by classical techniques of magnetic and heavy liquid separation, and the least altered material was hand-picked under a binocular microscope prior to irradiation. Approximately 50 mg of each sample was wrapped in aluminium foil and irradiated along with splits of GA1550 biotite monitor (McDougall and Harrison 1988) at 1 MW for 120 h in the Triga research reactor at Oregon State University. The calculated J-value was 0.02337 ± 0.000045. Argon was extracted from minerals using a focused 20-W Nd:YAG laser with an external shutter focused through a modified petrographic microscope. Samples were fused for 2 min and the released gases were purified for 10 min on two Saes GP-50 getters at 300 °C. The Ar isotopes were analysed on a Map 215 mass spectrometer with Nier-type source in static mode. A detailed description of the Scottish Universities Research and Reactor Centre experimental procedure is given by May (1997). The resulting analyses were corrected for blanks, ^{37}Ar decay and neutron interferences. The correction factors used were $(^{39}Ar/^{37}Ar)$ Ca = 0.00078, $(^{36}Ar/^{37}Ar)Ca = 0.00078$ and $(^{40}Ar/^{39}Ar)K = 0.031$.

Results

The results of this study are presented in Fig. 4 and Tables 1–3.

Continental domain

Mineral separates from the mafic intrusion of Los Molares yield a good isochron for Sm–Nd (Fig. 4a) with an age of 340±23 Ma and an MSWD of 1.76. This age is 12±23 Ma older than the Rb–Sr age (328±4 Ma) obtained from the pair Pl–Bt of the same sample (Fig. 4b). This age increment results from differences in the respective closure temperatures for both isotope systems. An Rb–Sr isochron using microsamples from different layers of a migmatite from Los Molares (M2956A; Figs 2, 3c) yields an age of 331±27 Ma with an MSWD of 18.3 (Fig. 4c). This age is similar to the one obtained from mineral separates (Fig. 4d) of a nebulite (323±4 Ma) collected close to the former migmatite (Fig. 2). These differences in ages may result from a more effective isotope reequilibration at the scale of minerals as compared with layers of different composition. A layer-sampling isochron (Fig. 4e) was also obtained for the Cortegana migmatites, away from the Los Molares area. This isochron yields an age of 351±58 Ma (MSWD = 5.5), the oldest obtained in this study. Although the error of this age determination is high, it is very similar to the Ar–Ar age obtained by Dallmeyer et al. (1993) for amphibolites of the continental domain very close to the Cortegana migmatites.

Oceanic domain

Data from the Ar–Ar study are displayed in Table 3. Uncertainties for the ages are quoted at the 2-σ level. The analysed samples give concordant ages which display only small scatter around the isochron ages. As a generalization, these data display a trend of increasing age from east to west along the Aracena metamorphic belt. The two easternmost samples (I-1195.1 and J-196.10) give ages that are identical within error, 328.2±2.7 and 328.0±1.2 Ma, respectively. Ages increase progressively westwards with the most westerly samples (BJ-12) being 342.6±0.6 Ma.

Discussion

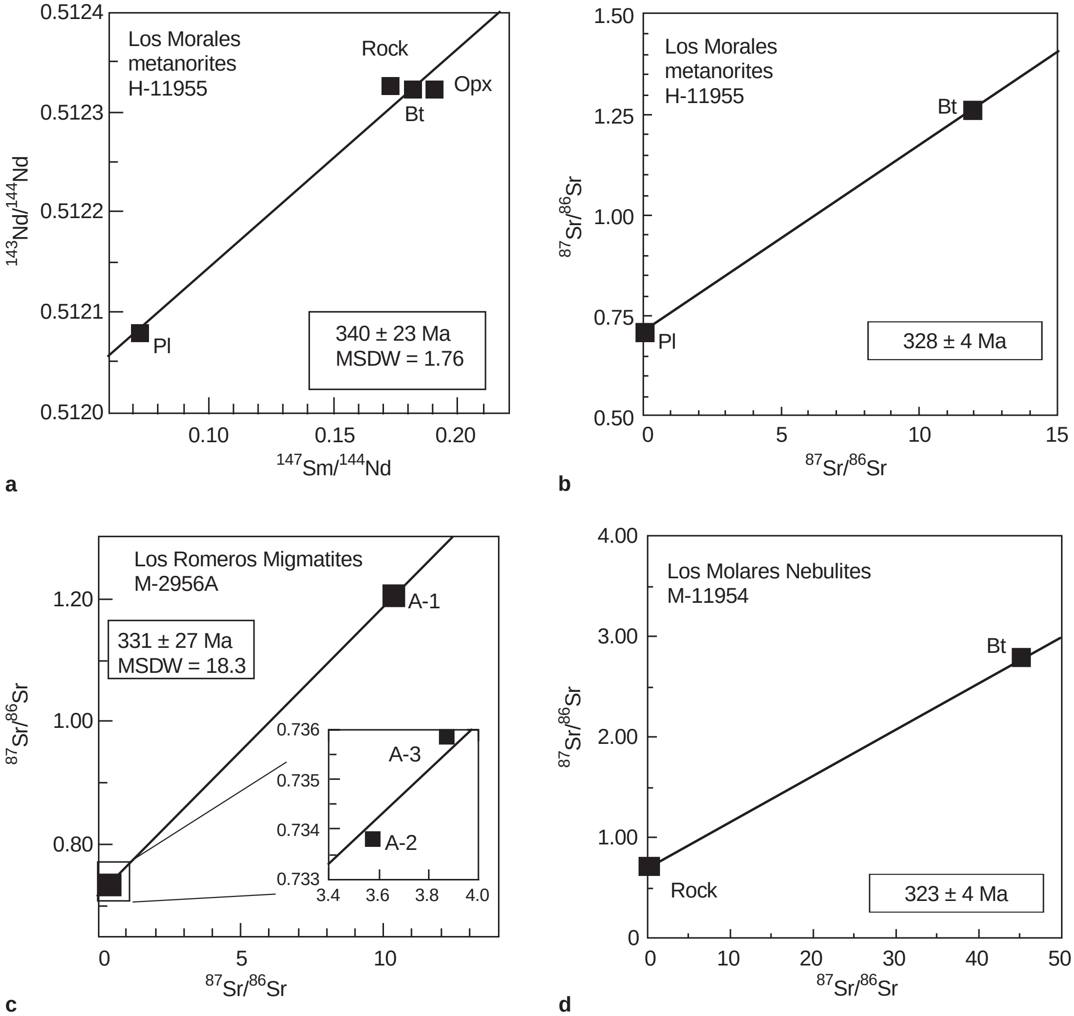
The results of this geochronological study of the Aracena metamorphic belt clearly show that the last thermal and tectonic events to affect the massif took place during the Upper Paleozoic Hercynian orogeny. These events resulted from subduction towards the north of an ocean plate under a thin continental margin (Castro et al. 1996a, b). The main Hercynian evolution of this sector of the Iberian belt occurred in a short period of approximately 20 Ma (from ca. 342 to 320 Ma) during Early Carboniferous (Visean to Namurian). However, within this age range we have found some differences due to (a) the application of distinct geochronometers and different sampling techniques and, (b) different locations of the studied samples along and across the metamorphic belt. These differences are in some cases significant and their interpretations require some detailed attention.

Along-belt age variations

The existence of an age evolution along the belt is inferred from the $^{40}Ar/^{39}Ar$ ages of the amphibolites of the oceanic domain. Hornblende separates for $^{40}Ar/^{39}Ar$ age determinations correspond to high-grade amphibolites not affected by the retrogression associated with the late shear zone that exhumated the AMB. Consequently, these ages, though they are cooling ages, may be indicative of the age of the thermal event related to the main deformation phase (metamorphic foliation) of the amphibolites and, there-

Table 3 ^{40}Ar–^{39}Ar ages of amphibolites from the Almadén–Aracena–Beja belt

Location	Aracena	Alájar	La Corte	Almonanter	Cortegana	Beja
Sample	J19610	I11951	J1968	A89327	CO5	BJ12
Latitude	37° 53′ 15″ N	37° 52′ 10″ N	37° 52′ 10″ N	37° 52′ 30″ N	37° 53′ 10″ N	37° 53′ 00″ N
Longitude	2° 52′ 50″ W	2° 58′ 40″ W	3° 03′ 00″ W	3° 05′ 30″ W	3° 08′ 50″ W	7° 42′ 00″ W
Hornblende age (Ma)						
	331.3±2.2	329.2±4	336.7±5	321.1±5.8	349.3±4	343±1
	328.1±3.4	326.9±5.8	329±3.6	332.8±4.9	332.5±7	336.9±2.7
	328.9±3.9	329.5±8.8	327.1±5.2	334.9±2.1	327.8±10.2	338±2
	324.5±4.7	327.9±5.6	323.6±4.6	334.2±4.2	330.5±7.4	335.3±1.9
	327.5±2.5	327.6±8.6		337.4±2.8		342.1±1.4
	326.4±2.6					347±1.1
Weighted plateau age						
	328±1.2	328.2±2.7	328.8±2.2	334.4±1.4	337.3±2.7	342.6±0.6
MSWD	0.65	0.038	1.24	1.57	4.66	0.84



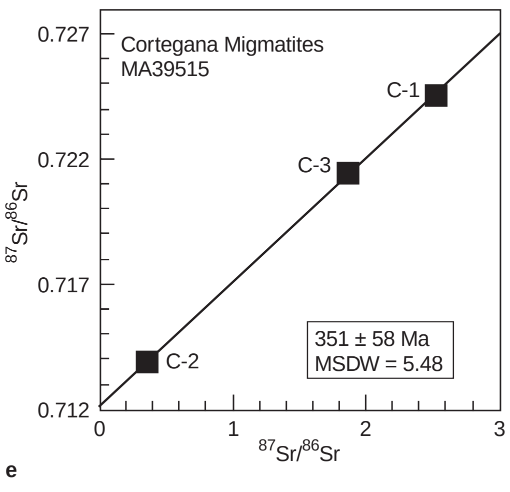


Fig. 4 **a** Sm–Nd mineral isochron for sample H11955. **b** Rb/Sr mineral isochron for sample H11955. **c** Rb–Sr layer isochron for sample M2956A. **d** Rb–Sr mineral isochron for sample M11954. **e** Rb–Sr layer isochron for sample MA39515. *Labels* in **c** and **e** correspond to layer samples in Fig. 3

fore, the age of the subduction process that produced the metamorphism of the oceanic domain of the AMB. The age of the oceanic amphibolites (Table 3) varies progressively from 328.0 ± 1.2 Ma (J.196.10) to the east (Aracena, Spain) to 342.6 ± 0.6 Ma (BJ.12) to the west (Beja, Portugal) over a distance of 80 km. This age evolution (Fig. 5) is interpreted in terms of migration of the thermal focus towards the east at a rate of around 0.5 cm a^{-1}.

These along-belt ages differences cannot be attributed to differential cooling of separated blocks in relation to late faulting. There are several NE/SW-trending faults displacing kilometre-sized blocks in the amphibolite belt (Fig. 2); however, these faults are very late

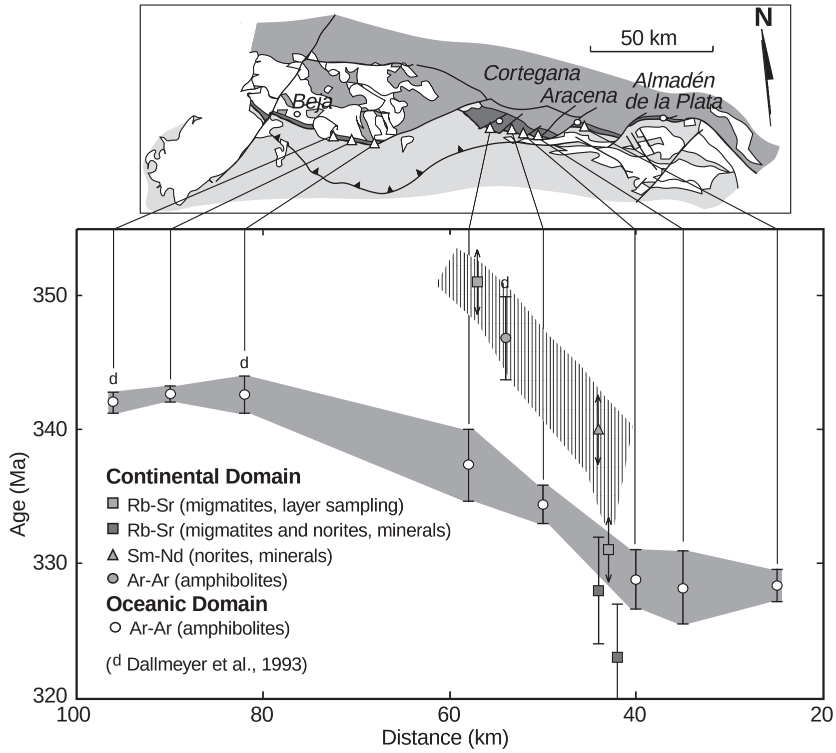


Fig. 5 Diagram showing the variation of age with distance along the amphibolite band (oceanic domain) of the Almadén de la Plata–Aracena–Beja belt (*lower panel*). The *upper panel* corresponds to the area of Fig. 1 marked by an irregular polygon. The distance is measured along the outcropping amphibolite band, discarding the effect of late displacements by faults. The origin is arbitrarily located in Almadén de la Plata. Ages obtained in the rocks of the continental domain are also shown (see text for discussion). The *arrows* are indicative of larger error bars

and unrelated to the cooling history of the AMB: they cross-cut the retrogressive shear zones, subparallel to the main foliation, responsible of the exhumation and cooling of the whole metamorphic belt.

This metamorphism of the oceanic domain has been attributed to the subduction of an oceanic plate towards the north under a previously heated continental margin (Castro et al. 1996a, b). Arguments for this interpretation are: (a) the inverted metamorphic gradient of the amphibolite pile; (b) the low-pressure regime of this inverted metamorphism; (c) the presence of ultra-high-temperature/low-pressure metamorphic rocks in the continental hangingwall; and (d) the presence in the continental block of high-Mg metanorites (with boninite affinities) possibly related to partial melting of a shallow mantle wedge (cf. Duncan and Green 1987; Klingenberg and Kushiro 1996).

The results of this study are in agreement with this tectonic model confirming the correct use of qualitative indications resulting from structural and metamorphic studies. Furthermore, the ages obtained by Dallmeyer et al. (1993) using the $^{40}Ar/^{39}Ar$ method on different amphibolites from this region are coincident with our age determinations (Fig. 5). It is worth noting that the samples studied by Dallmeyer et al. (1993) were collected in part from amphibolite rocks of the oceanic domain and in part from amphibolites of the continental domain, according to our zonal division of the AMB. The ages of the Beja amphibolites, determined by these authors (340.6 ± 1.3 Ma), is consistent with our $^{40}Ar/^{39}Ar$ ages on the same rock (BJ.12 : 342.6 ± 0.6 Ma). The $^{40}Ar/^{39}Ar$ age (Dallmeyer et al. 1993) of an amphibolite from the continental domain (Rellano amphibolites) is consistent (342.3 ± 2.6 Ma) with our Sm–Nd and Rb–Sr ages on other lithologies of the same domain.

Figure 5 shows that there is an age progression in the continental domain oblique to the pattern of the oceanic domain in the eastern sector of the AMB. The uncertainties of the ages determined by the Rb–Sr method in the continental domain do not allow precise correlation between thermal events in both domains. In general, the ages of the CD are older compared with the $^{40}Ar/^{39}Ar$ ages in the same traverse. The exceptions are the Rb–Sr ages obtained from mineral separates of migmatites and gneisses. These are low-temperature cooling ages and, therefore, they are expected to be younger than $^{40}Ar/^{39}Ar$ ages in hornblende.

Thermal evolution of the AMB

The Rb–Sr internal isochron of the Los Molares metanorites and that of the Los Molares nebulites are clearly low-temperature cooling ages that record the closure temperature of Sr in biotite at approximately 300 °C (Harrison and McDougall 1980). These ages are approximately 5 Ma younger than the Ar–Ar ages of the oceanic amphibolites in the corresponding traverse.

Furthermore, the Ar–Ar age of an amphibolite of the continental domain (342.3 ± 2.6 according to Dallmeyer et al. 1993) is similar to the central values of our Rb–Sr ages of the continental domain, in agreement with the interpretation that the metamorphism of the continental hangingwall was earlier than that of the oceanic domain.

The contact between both domains is locally marked by a south-verging thrust. Consequently, the observed differences in age can be attributed to the early cooling of the overriding continental block compared with the late cooling of the footwall (oceanic domain); however, this thrust fault is a low-temperature structure, late with respect to the main thermal episode of both domains. This thrust fault was cooler than the closing temperature of $^{40}Ar/^{39}Ar$ in hornblendes of the oceanic domain. Consequently, it cannot be responsible for the age differences between both domains. In contrast, these differences support the interpretation that the subducting oceanic slab was heated from the top by a previously heated continental hangingwall.

The time evolution of the metamorphism in both the oceanic and continental domains support a tectonic model of triple-junction subduction (Castro et al. 1996a, b) responsible for the creation at depth of a slab-free window with decisive consequences for the thermal evolution of the region. The origin of the linear metamorphic belt of HT/LP regime is explained by the migration along a continental margin of a punctual thermal anomaly induced by the creation of a triple junction at the continental margin.

Conclusion

The results of this geochronological study clearly support a Late Paleozoic age for tectonic activity at a continental margin in this sector of the Iberian massif. This tectonic activity implies subduction of an oceanic slab following a high-temperature metamorphic event in the continental hangingwall.

The main conclusions of this geochronological study are summarized as follows:

1. The evolution of metamorphic events in the oceanic domain of the Aracena metamorphic belt ranges from approximately 343 Ma to approximately 328 Ma with a progressive along-strike spatial variation from west (oldest ages) to east (youngest ages).
2. The main thermal, magmatic and metamorphic events of the Aracena metamorphic belt occurred within a relatively short period during the Upper Paleozoic.
3. The age relationships between thermal events and deformational processes point to a cause-and-effect relationship between HT/LP metamorphism of the continental margin and the subduction-related inverted metamorphic gradient of the oceanic amphibolites; however, these results are very limited by the errors of the Rb–Sr datings, and more precise radiometric methods have to be considered in the future.

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