The Patrimonial Value of the Betic Ophiolites: Rocks from the Jurassic Ocean Floor of the Tethys

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Abstract

The Betic ophiolites consist of numerous tectonic slices of eclogitized mafic and ultramafic rocks together with oceanic metasediments. They form a tectonic Unit of the Mulhacén Complex in the Betic Cordillera (SE Spain), intercalated between two crustal units named Caldera (below) and Sabinas (above). A comprehensive review of the petrological, geochemical and geochronological characteristics of the Betic ophiolites shows notable similarities with other MORB-type ophiolites from the Alps–Apennines system and the different lithologies forming the Atlantic Ridge. This suggests that they represent relics of an oceanic lithosphere deriving from the Western Tethys. Consistent magmatic ages of around 185 Ma were determined by U–Pb dating with SHRIMP (sensitive high resolution ion micro probe) of zircon grains selected by cathodoluminescence images of several eclogitized metagabbros from the main outcrops (Lugros, Cobdar and Algarrobo) and a metadolerite dyke intruded in ultramafic rocks (Almirez outcrop). This age marks the beginning of Betic oceanic magmatism, with T-MORB to N-MORB (Transitional to Normal Mid Oceanic Ridge Basalt) geochemical affinities, corresponding to ultra-slow mid-ocean ridge spreading from the Lower Jurassic to the Cretaceous, following the Pangaea break-up between the Iberian and African plates. The Betic oceanic-floor segment represents the earliest oceanic accretion process in the Western Tethys Ocean. Subsequently, this ocean floor continued to develop from the Betic oceanic basin northeastward to the Ligurian and Alpine Tethys domains, mainly from 165 to 140 Ma, and to the western rift zone up to contact with the Central Atlantic Ocean. According to radiometric datings of the Betic Ophiolites and palaeogeographic reconstructions for the Pliensbachian, these ophiolites are the only preserved relics of the westernmost end of the former Mesozoic Tethys Ocean. They are, therefore, of considerable scientific value for their potential in the palaeogeographic, petrogenetic and geodynamic reconstructions of the Betic Cordillera. Moreover, because of their big hardness and density some outcrops of these eclogitized ophiolites (Caniles de Baza) have been quarried from prehistoric times in the making of hammers and axes, which can be found in many human settlements in the area. Consequently, the Betic Ophiolites have a number of extremely interesting scientific, educational and cultural characteristics giving their outcrops a great patrimonial value, despite which most of their outcrops have been partly destroyed, or are at risk of destruction for use as ballast in industry.

Resumen

Las Ofiolitas Béticas están formadas por numerosas escamas tectónicas de rocas eclogitizadas procedentes de materiales máficos, ultramáficos y de metasedimentos oceánicos, que forman una unidad tectónica del Complejo del Mulhacén de la Cordillera Bética (SE España). Esta unidad ofiolítica se encuentra intercalada entre dos unidades corticales del mismo complejo denominadas Caldera (debajo) y Sabinas (encima). Una revisión detallada de las características petrológicas, geoquímicas y geocronológicas de las Ofiolitas Béticas muestra notables analogías con otras ofiolitas tipo MORB de los Alpes y los Apeninos, así como con las diferentes litologías que forman la Dorsal Atlántica, indicando que representan reliquias de una litosfera oceánica procedente del Tethys Occidental. Dataciones U-Pb con SHRIMP (Microsonda iónica de alta resolución) realizadas en puntos de circón, seleccionados mediante estudio de sus imágenes de catodoluminiscencia, sobre cristales aislados de varios metagabros eclogitizados de los principales afloramientos (Lugros, Cóbdar y Algarrobo) y de un dique de metadolerita intruida en rocas ultramáficas (Almirez), suministran edades magmáticas consistentes de alrededor de 185 Ma. Esta edad marca el comienzo del magmatismo oceánico bético, de afinidad geoquímica entre T-MORB y N-MORB (Transicional a Normal Basalto de Dorsal Oceánica), correspondiente a una dorsal centro-oceánica ultra-lenta, que se desarrolló desde el Jurásico Inferior al Cretáceo, siguiendo la ruptura de la Pangea entre las placas Ibérica y Africana. El segmento del suelo oceánico del que derivan las Ofiolitas Béticas se originó durante el inicio del proceso de acreción del Océano Tethys Occidental. Subsecuentemente, el suelo oceánico continuó desarrollándose desde la cuenca oceánica bética hacia el NE a lo largo de los dominios del Tethys Ligur y Alpino, principalmente entre 165 y 140 Ma., y hacia la zona de rift del W hasta contactar con el Océano Atlántico Central. De acuerdo con las dataciones radiométricas de las Ofiolitas Béticas y de las reconstrucciones paleogeográficas para el Pliensbachiense, estas ofiolitas representan las únicas reliquias preservadas del extremo más occidental del actualmente desaparecido Océano Tethys Mesozoico. Este hecho les confiere un gran valor científico por su extraordinario potencial en las reconstrucciones paleogeográficas, petrogenéticas y geodinámicas de la Cordillera Bética. Además, algunos afloramientos de estas ofiolitas eclogitizadas (Caniles de Baza) debido a su gran dureza y densidad han sido usados desde la Prehistoria como canteras para la fabricación de utensilios, tales como martillos y hachas, que están presentes en numerosos asentamientos humanos en sus alrededores. Consecuentemente, las Ofiolitas Béticas presentan una serie de características científicas, pedagógicas y culturales, extremadamente interesantes, que dan a sus afloramientos un gran valor patrimonial, a pesar de lo cual la mayor parte de sus afloramientos están parcialmente destruidos, o en riesgo de destrucción, para utilizar sus materiales como balastro en la industria.

Key-words: *: Betic Ophiolites, Geological and arqueological heritage, Jurassic Tethys Ocean, Betic Cordillera, Spain.*

1. Introduction. Definition and types of ophiolites

Ophiolites are outcrops measuring from metres to kilometres in extent and basically consisting of ultramafic rocks, gabbros, basalts and sedimentary rocks, deriving from an oceanic floor. These lithological assemblages were delaminated from the ocean floor and stacked as tectonic slabs on a continental margin during a compressive stage between tectonic plates, following on the previous distensive phase in which the corresponding oceanic floor had been created.

Depending on the geodynamic context in which the original oceanic floor developed, there are two types of ophiolites known as Mid-Oceanic-Ridge (MOR), and Supra-Subduction-Zone (SSZ), also known as Back-Arc-Basin (BAB).

Fig. 1 schematically illustrates the two types of geodynamic context in which oceanic floors can be developed:

a) A MOR context caused by separation of continental plates and the rise of asthenospheric matter as convection cells leading to basic melting. On solidifying on the ocean floor these melts mainly form basalts, gabbros, dolerites and residual ultramafic rocks that make up most of the oceanic lithosphere.

b) Subduction of MOR oceanic floor under contiguous continental plates, or other segments of the oceanic lithosphere, creates island arcs by partial fusion of the subducted oceanic floor and the overlying continental lithosphere. Behind such arcs locally distensive situations are created, accompanied by the development

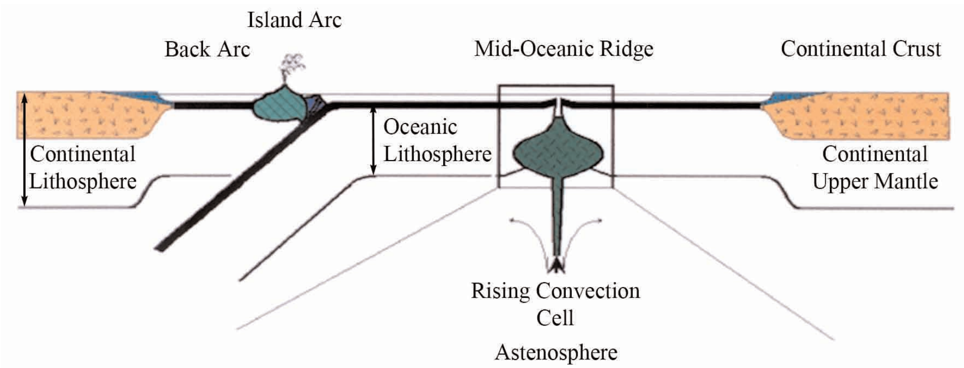


Fig. 1. Genetic conditions of MOR and SSZ-type oceanic floors under distensive conditions found on ridges and suprasubduction back-arc basins.

of Back-Arc oceanic floor (BAB or SSZ type), characterized by a transition from basic to acidic igneous lithologies, which differentiates SSZ-type from MOR-type oceanic floors.

Fig. 2 illustrates a compressive situation between continental plates leading to subduction of the oceanic floor which is mainly lost in the asthenosphere, although a small portion can be exhumed and overlap nearby continental margins creating ophiolite assemblages.

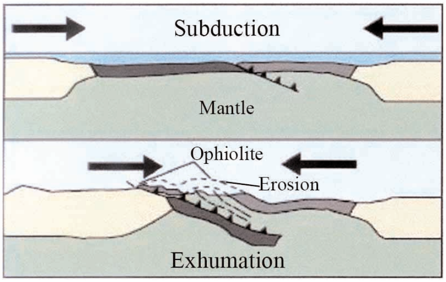


Fig. 2. Subduction of oceanic floor under compressive conditions between continental plates, possibly followed by exhumation of part of this floor on the continental margin.

The lithostratigraphic columns of *Fig. 3* show the main differentiating lithological characteristics between the MOR and SSZ ophiolites, which are at present found throughout the Alpine orogenic chain in areas of ancient continental margins of the Tethys Ocean (Beccaluva et al., 2005). The most common lithologies in both types are indicated, from the basal mantle sequence, upwards through the intrusive, effusive and sedimentary sequences, with relative thicknesses of each. These reconstructions also indicate the high Ti contents of MOR ophiolites as against the low, or very low-Ti contents of the SSZ type, which is an important differentiating geochemical characteristic between them.

2. The Betic Ophiolites

These ophiolites were first identified as MOR-type by Puga (1990), mainly because of their basic, ultramafic igneous lithologies and their similarity with the rocks of the Atlantic Ridge. Later petrological, geochemical and radiometric dating studies *(Puga et al., 1999, 2000, 2002, 2005, 2009, 2011)* have corroborated this hypothesis and restricted their origin to a band of oceanic floor in the Western Tethys that developed to the SE of Iberia during the Early Jurassic.

2.1. Geological context

The Betic Ophiolites are represented by numerous tectonic slabs ranging in size from metres to kilometres and made up of metamorphosed ultramafic, basic and/or sedimentary rocks, whose outcrops are found discontinuously between the provinces of Granada and Murcia *(Fig. 3)*. This figure shows the locations of the most significant ophiolite outcrops from which most of the petrological, geochemical and geochronological data mentioned in this study have been obtained. Geologically these ophiolites are exclusively located in the Mulhacen Complex of the Nevadofilabride Domain, which crop out in the central and eastern sectors of the Betic Cordillera, and are never found in the underlying Veleta Complex. This suggests the existence of different palaeogeographic domains for these two complexes during the Jurassic-Cretaceous period when the ophiolites were originated from a MOR oceanic floor *(Puga*

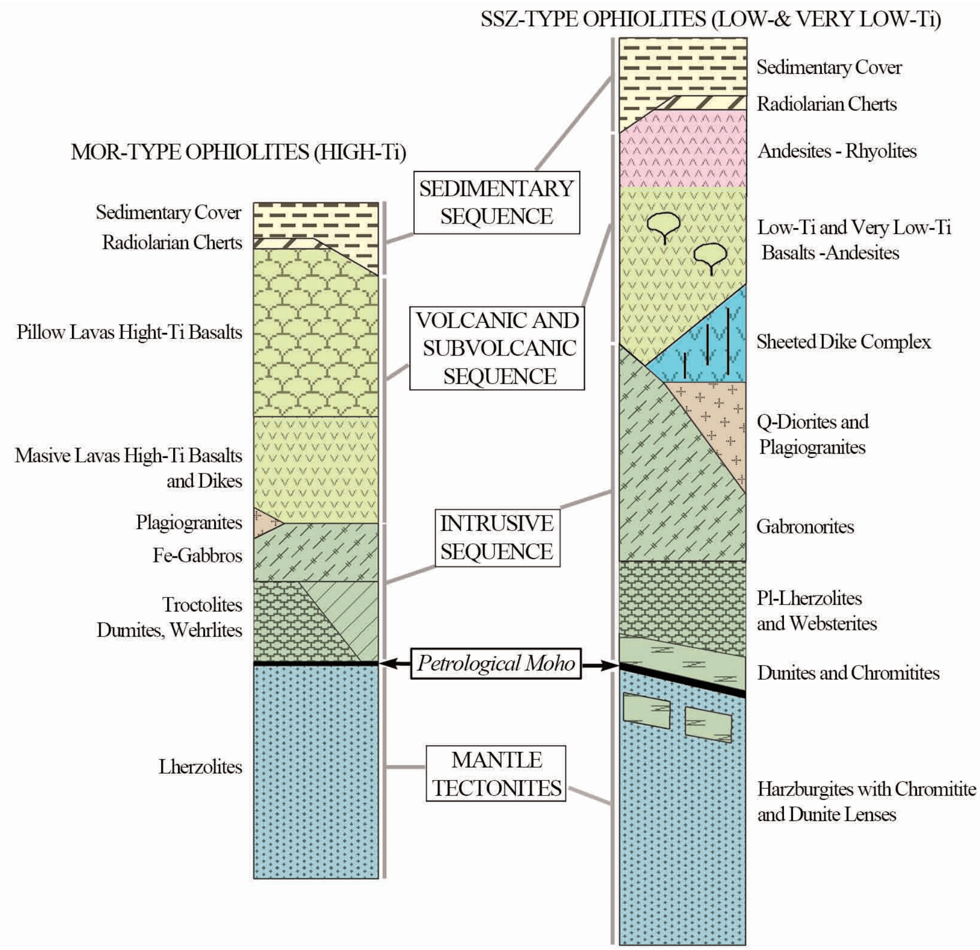


Fig. 3. Lithostratigraphic diagrams for MOR and SSZ ophiolite types.

et al., 2005, 2011; Tendero et al., 1993). They would later have been tectonically superimposed on the crustal rocks of the nearby continental margin, which now form the Caldera crustal unit of the Mulhacen Complex. At present the rocks of the Veleta Complex (VC) crop out forming several tectonic windows below the Mulhacen Complex (MC) *(see Fig. 4)*. The outcrops of the Betic ophiolites form the tectonic Ophiolite Unit, intercalated between the Caldera (underlying) and Sabinas (overlying) crustal units of the MC *(Fig. 5)*. Each of these consists of rocks with a Hercynian basement and a mainly Triassic covering, both with abundant granite and rhyolite orthogneisses. The identification of a Jurassic-Cretaceous ophiolite unit, of oceanic origin, intercalated between two Palaeozoic-Triassic crustal units is a factor of first order in determining the tectonic evolution, from the Mesozoic on, of the plates intervening in the stacking of the tectonic units of the Nevadofilabride Domain.

The VC lies beneath the MC and is mainly formed by a Palaeozoic basement several thousand metres thick, mainly consisting of graphitic micaschists and quartzites, together with little occasional amphibolite lenses, formed from basic magmas of intraplate continental origin. Unlike the MC, this complex has no acidic orthogneiss and its degree of Hercynian metamorphism is clearly lower, indi-

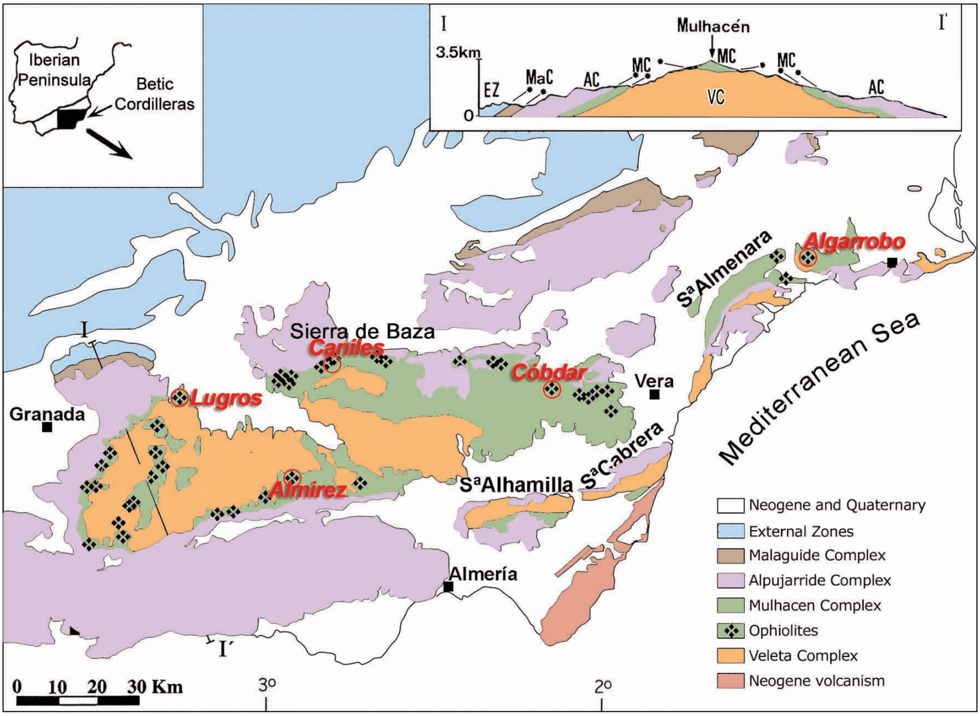


Fig. 4. *Geological sketch of the central-eastem sector of the Betic Cordillera, with differentiation of the Veleta and Mulhacen Complexes, forming the Nevadofilabride Domain, and the situation of the main outcrops of Betic ophiolites, shown as black four.-pointed stars. The most significant outcrops (Lugros, Almirez, Caniles, Cóbdar and Algarrobo) are marked by red-lettered italics. The upper inset shows a simplified version of the present tectonis relations of the Nevadofilabride complexes, with Veleta (VC) beneath and Mulhacen (MC) on top, on which the Alpujarride (AC) and Malaguide (MaC) complexes and the External Betic Zones (EZ) are superposed.*

cating superposition of both complexes after the Hercynian Orogeny. Moreover, there are no ophiolite intercalations in the VC and its Eo-Alpine metamorphism is also of lower degree than that of the MC, suggesting that the stacking of the two complexes took place late in the Alpine Orogeny *(Puga et al., 2002a,2004a)*.

2.2. Palaeogeographic reconstruction

Figs. 6 and 7 show the palaeogeographic reconstruction of the former Tethys Ocean and the Central Atlantic for the Jurassic *(Schettino and Turco, 2010)* and for the early Cretaceous *(Guerrera et al., 2003)*. In *Fig. 6a* the red-coloured bands represent the zones of fracture and crustal thinning (rifting) marking the break-up of the Pangaea supercontinent from the Triassic on, by where the Eurasian and African plates separated in this area. The first ocean floors of the Central Atlantic and western Tethys, marked here in blue, began to develop following these rifting patterns approximately 185 Ma ago in the Early Jurassic (Pliensbachian). The area marked BT (Betic Tethys) between the tectonic microplates located to the SE of Iberia during the Mesozoic would correspond to the ridge where the Betic Ophiolites originated. This hypothesis is firmly supported by U/Pb radiometric dating with SHRIMP (sensitive high resolution ion microprobe) of the zircons separated from eclogitized gabbros and dolerites of the Betic Ophiolites, whose absolute ages for magmatism correspond to the Pliensbachian *(Fig. 8, Puga et al., 2005, 2011)*. The oceanic floors continued to develop throughout the Jurassic in both the Central Atlantic and the Western Tethys, as shown by the palaeogeographic reconstruction of *Fig. 5b* for the Tithonian (Late Jurassic).

Fig. 7 shows the palaeogeographic reconstruction for the Early Cretaceous of the central-western area of the Mediterranean. In this figure, N-F Ocean indicates the area of oceanic floor where the Betic Ophiolites originated, as well as the most probable location at SE of the Iberian margin for the original palaeogeographic domains of the tectonic units in which the ophiolites are intercalated. From West to East these coloured bands indicate the Mesozoic location of the Subbetic margin, the present VC, and the different original domains of the tectonic units making up the MC (Caldera and Sabinas) on both margins of the Betic Ocean, or Nevadofilabride Ocean, following eastwards the corresponding dominions of the Alpujarride (AC) and Malaguide (MaC) Complexes. According to this reconstruction, at the start of the Cretaceous the Betic Ocean would have connected the Piemontese-Ligurian (Pi-Li) and the Maghreb (Mag) Oceans with the Central Atlantic Ocean.

2.3. Geochronological characterization

The most reliable geochronological dating of the ophiolites is that made using the U/Pb method with SHRIMP on their zircons. This type of dating mainly corresponds to the absolute age of the oceanic magmatism in which these ophiolites originated, although ages corresponding to their metamorphic recrystallization can also be inferred from some of the zircons *(Fig. 8, Puga et al, 2005, 2011)*. Other radiometric datings using Sm/Nd, Ar/Ar and K/Ar methods have also been carried out on different minerals of both the ophiolites and other lithologies of the Nevadofilabride Complexes *(see Puga et al., 2002a, 2005, 2011)*.

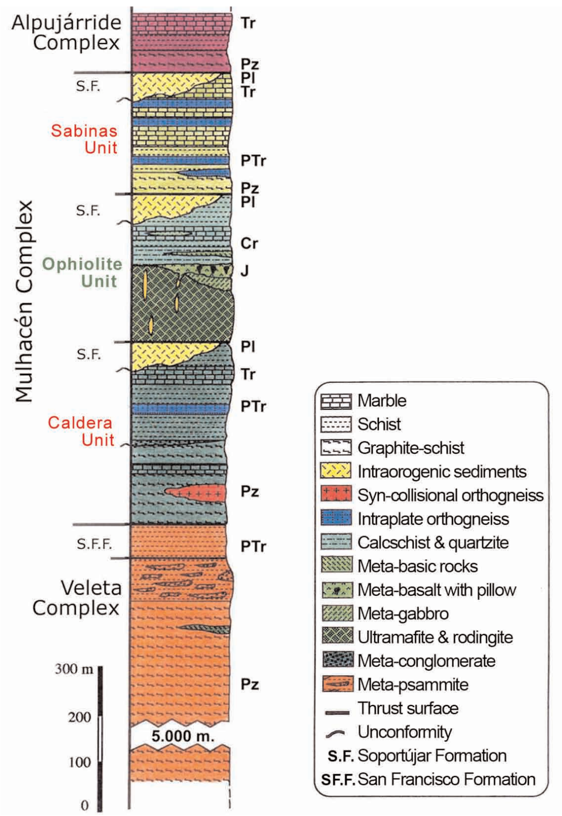


Fig. 5. Simplified lithostratigraphic column showing the main rock types of the different tectonic units and formations making up the Veleta and MUlhacen Complexes, together with the lithostratigraphy (not to scale) of the overlying Alpujarride Complex. Abbreviations:
PZ = Palaeozoic, PTr =Permian-Triassic, T = Triassic, J = Jurassic, Cr = Cretaceous, Pl = Palaeocene.

Fig. 8 shows the cathodoluminescence images of some representative zircons from the main Betic Ophiolite outcrops. These images allow differentiation within these submicroscopic crystals of areas with idiomorphic edges and oscillatory zoning, indicating their igneous origin, from other lighter areas with irregular edges, apparently caused by metamorphic recrystallization of the igneous zircons *(Puga et al., 2005, 2011)*. Examination of the igneous parts of the zircons provides precise dating for the start of this magmatism to a 190 to 180 Ma range (Early Jurassic). Two other, less well defined age groups can be interpreted as corresponding to two stages of metamorphic recrystallization: one in the Late Jurassic, possibly corresponding to an stage of ocean floor metamorphism present in these rocks *(Puga et al., 2005)*, and the other varying between the Late Cretaceous and the Palaeocene (90 to 60 Ma). This last stage of recrystallization, whose effects can be seen in the irregular whitish areas of the dated Lugros and Almirez zircons *(Fig. 8)*, corresponds with the Eo-Alpine metamorphism that transformed the igneous lithotypes containing these zircons into eclogites. The subsequent Meso-Alpine and Neo-Alpine metamorphic events identified in the ophiolites and other nevadofilabride rockscaused hardly any recrystallization of zircons in the ophiolitic metabasites. However, other methods of radiometric dating have shown that these metamorphic events were, respectively, Oligocene and Miocene (Puga et al., 2002a, 2005,

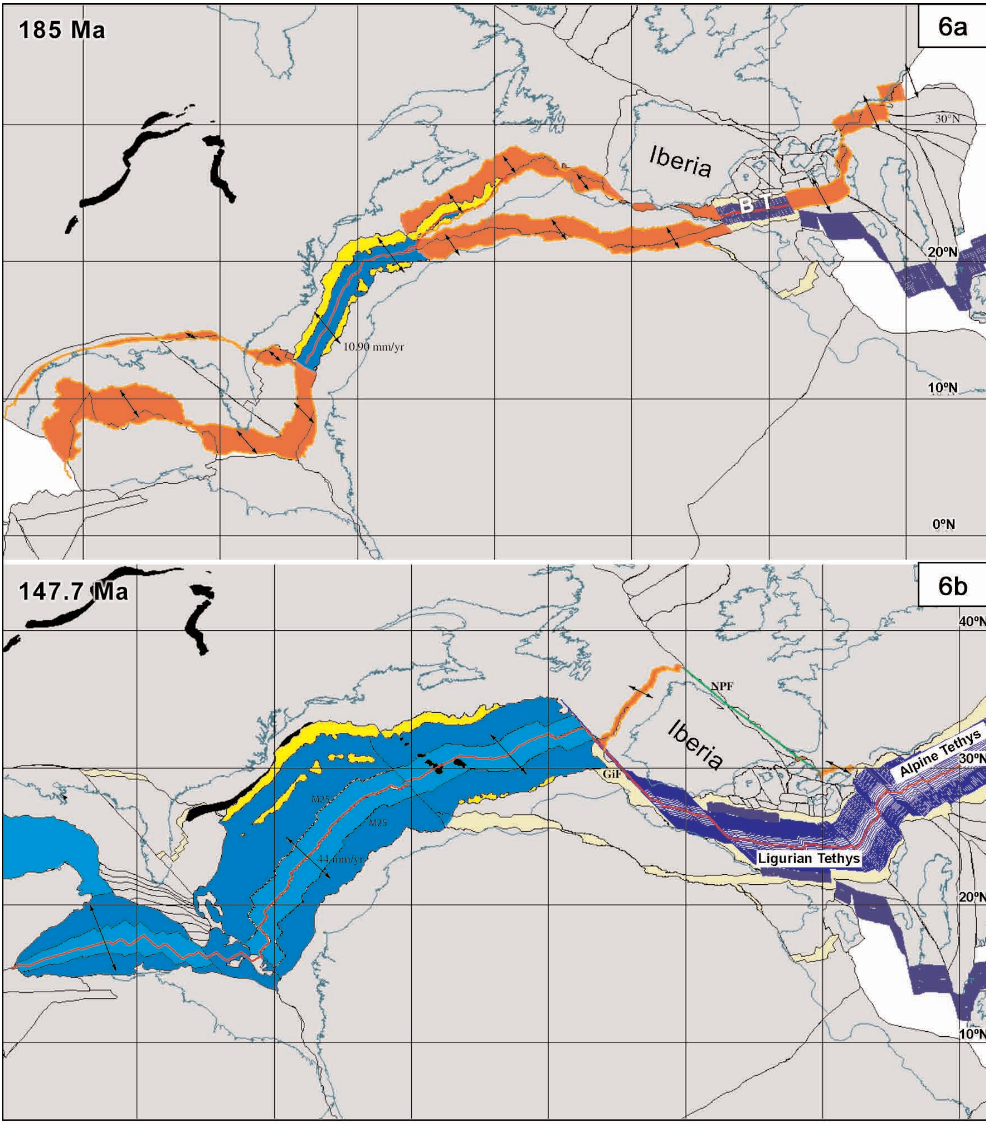


Fig. 6. Palaeogeographic reconstruction of the Western Tethys and the Central Atlantic for 185 Ma (Pliensbachian) (5a) and 147,7 Ma (5b), by Schettino and Turco (2010). Bt = Betic Tethys; GiF = Gibraltar Fault; NPT = North Pyrennean Fault.

2011 and references herein).

The MOR-type ophiolites found at different locations in the Alps and Apennines *(Fig. 9)* were chronologically dated using different radiometric techniques, of which the most reliable for inferring the age of magmatism were U/Pb and Sm/Nd applied to zircons from gabbros, complemented with dating of radiolarians preserved in the sedimentary sequences of some poorly metamorphosed ophiolites. *Fig. 9 by Bortolotti and Principi (2005)* shows the results of these dating and the techniques used on the ophiolites from each location. Some of the radiometric dating of Betic ophiolites by Puga et al. (2002a and 2005) were also included for comparison. If we take into account only the dating carried out by U/Pb with SHRIMP on zircons, the mean absolute age for the magmatism originating the oceanic floor from which

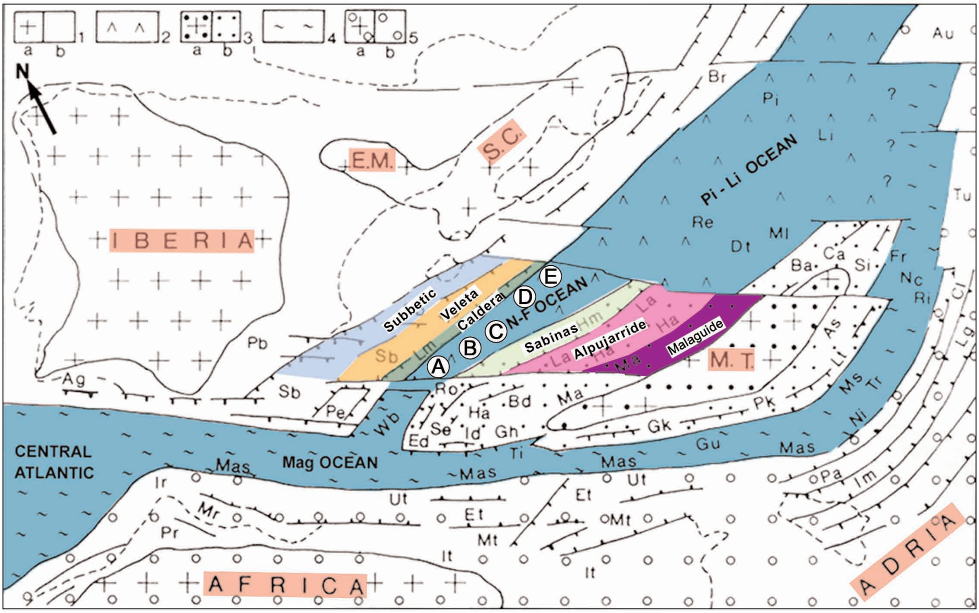


Fig. 7. Palaeogeographic reconstruction for the initial Cretaceous of the central-western region of the Mediterranean and distribution of oceanic basins around the Meso-Mediterrenean (MT) terrain, including the Nevadofilabride (N-F) Ocean, by Guerrera et al. (1993), where the explanation of the remaining abbreviations in this figure can be found. The letters A, B, C, D and E, indicate the approximate relative provenance of the ophiolitic outcrops of Lugros, Almirez, Caniles, Cóbdar and Algarrobo respectively.

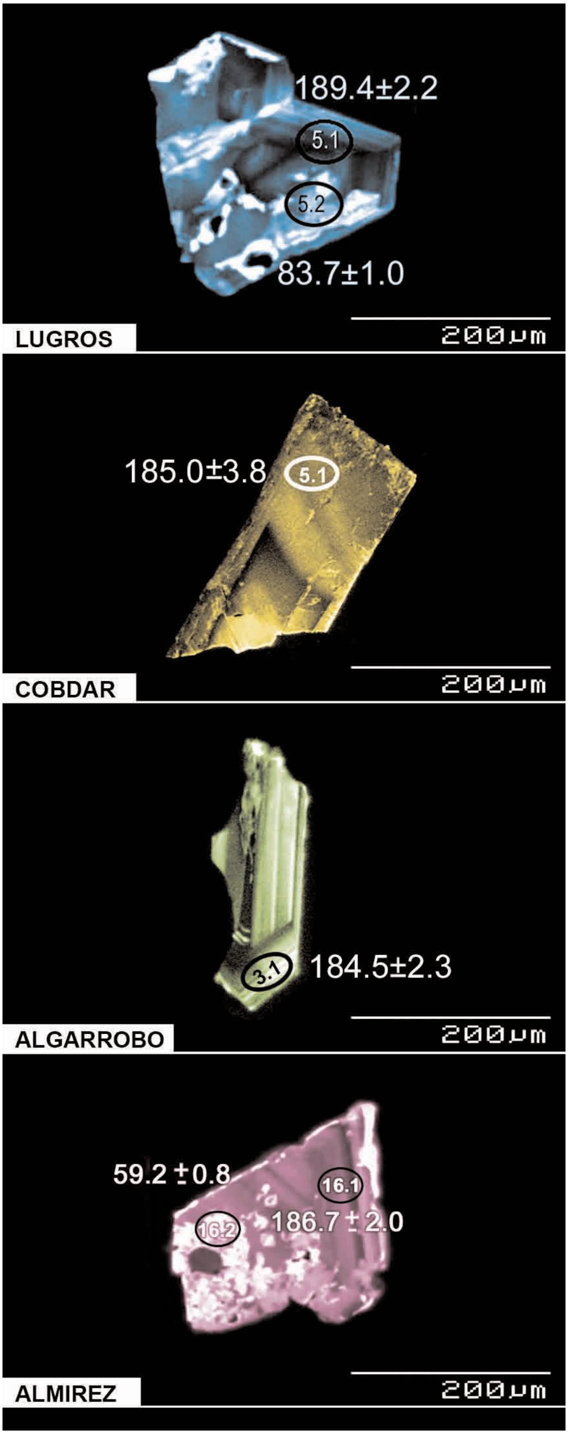
the ophiolites derive ranges from 190 to 180 Ma, with an average age close to 185 Ma (Pliensbachian). This has been confirmed by more recent dating *(Puga et al., 2011 and Fig. 8)*, whereas the segments of the Ligurian and Alpine Tethys from which the Alpine-Apennine Ophiolites derive have radiometric ages over 165 Ma. The fact that the Betic Ophiolites predate those from the Alps and Apennines by about 20 Ma is an important scientific peculiarity, meaning that the Betic Ophiolites would be the only preserved relics along the Alpine Chain deriving from the westernmost end of the Tethys, which is also Pliensbachian in age *(Fig. 6a)*.

2.4. Lithologies and petrologic evolution

The lithologies making up the Betic Ophiolitic Assemblage have been reconstructed in *Fig. 5* as they should hypothetically have been in the original ocean floor before being affected by Alpine tectonics. From bottom to top, they are as follows:

a) Partially serpentinized spinel-lherzolites (Serp) *(Fig. 10a-1)*, formed by antigorite (Atg) with relics of diopside (Di) and neoformed tremolite (Tr) *(Fig. 10a-2)*. These rocks present gradual transition to metamorphic rocks consisting of acicular aggregates of olivine (Ol) and enstatite (En), known as secondary harzburgites *(Fig. 10-3)*. Both types of ultramafites contain numerous rodingitized and/or eclogitized boudinaged dykes *(Fig. 10a-4)*. This figure shows a thin section view of a dolerite dyke transformed into eclogite, formed by almandine (Alm) omphacite (Omp) and rutile (Rt) paragenesis, partially amphobilitized with development of albite (Ab), epidote (Ep) and kataphoritic amphibole (Ktp). These rocks of the mantle sequence can be found directly overlayered by rocks of the sedimentary sequence *(Fig. 5)*, formed by pure quertzites (Quartz.), probably deriving from radiolarites *(Fig. 10a-1)*, followed onward to quartz-micaschists, micaschists and calc-schists with ankerite nodules, in which some relics of foraminifer probably cretaceous in age have been found *(Tendero et al., 1993)*.

b) Cumulate troctolites *(Fig. 10b-1)* and olivine-pyroxene gabbros *(Fig. 10b-2),* intruded by



dolerite dykes and mainly transformed into eclogites *(Fig. 10b-4)* and/or amphibolites. that preserve The plutonic or porphyric structures are commonly preserved in them *(Fig. 10b-1)* and locally also the igneous paragenesis formed by olivine (Ol), augitic clinopyroxene (Cpx) and calci plagioclase (Pl) *(Figs. 10b-2, 3)*. In *Fig. 10b-4* a coronitic eclogite originated from a cummulitic gabbro is shown. In this metamorphic rock the igneous olivines have been pseudomorphosed by a garnet corona (Gr) surrounding an aggregate of omphacite (Omp) and amphibole (Amp), whereas the igneous plagioclases have been pseudomorphosed by an aggregate of albite (Ab) and clinozoisite (Czo).

c) Olivine-pyroxenic basalts with good preservation of flow structures and pillow lavas with volcanic vacuolar texture and radial disjunction, surrounded by amphibolitized basaltic interpillow material *(Figs. 10c-1,2)*. *Fig. 10c-1* represents a minipillows aggregate with well preserved volcanic structure, despite the complete eclogitization of the igneous paragenesis shown in *Fig. 10c-4*. This microscopic photo shows a well preserved variolitic texture, formed by a fibrous aggregate of volcanic microcrystals of plagioclase, included in a almandine garnet poeciloblast (Alm), which together omphacite (Omp) and barroisite (Bar) forms the eclogite paragenesis and its later partly amphibolitization. In some basaltic levels the effects of the ocean-floor metamorphism can be locally preserved giving rise to high temperature Ti-pargasite (Ti-Prg) brown amphibole *(Fig. 10c-3)*. Above some outcrops of basic rocks, intrusive and, more commonly volcanic, a oceanic sedimentary sequence similar to that previously described onto the ultramafic rocks may be found.

Fig. 8. Representative cathodoluminescence images, with false colour, of zircons dated by the U/Pb method with SHRIMO in Lugros, Cóbdar, Algarrobo and Almirez outcrops. The areas analyzed are delimited with little ellipses on the photos of each crystal. The numbers of each analysis are shown into ellipses, and together them are the absolute ages (Ma) yielded by the dating of each area.

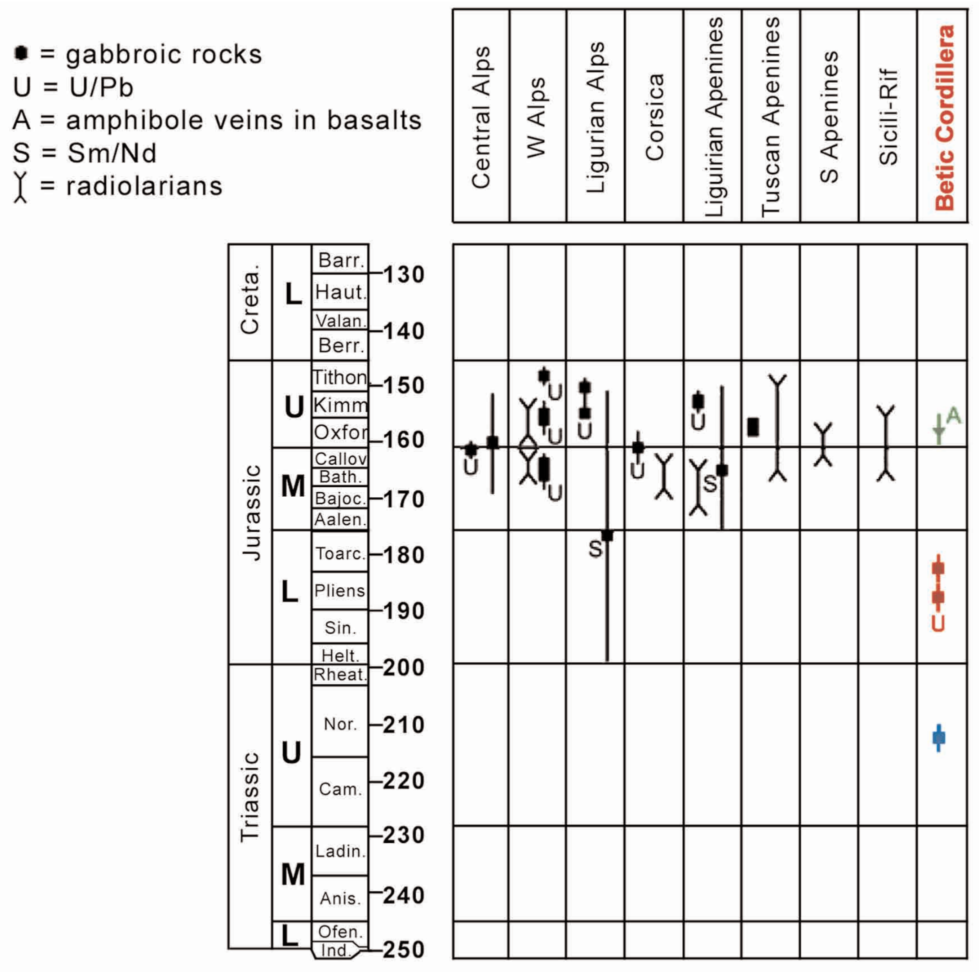


Fig. 9. Comparative chronological data on Alpine-Apennine and Betic Ophiolites deriving from the Jurassic Western Tethys.

The metamorphic evolution that can be inferred from the study of the igneous and sedimentary lithotypes composing this ophiolitic assemblage has two complex stages:

a) A first stage of ocean floor metamorphism and metasomatism, that produced the first serpentinization stage of the ultramafic rocks and rodingitization of the doleritic dykes contained in them (*Puga et al., 1999a, 2011*), as well as paragenesis of very high gradient amphibolite facies, characteristic of ocean floor metamorphism, of which abundant relics are preserved in some gabbros and basalts (*Puga et al., 1999b, 2000, 2002b; Ruiz Cruz et al., 2007*).

b) A second stage of orogenic metamorphism, beginning with subduction of the ocean floor during an initial metamorphic event known as Eo-Alpine. This was followed by exhumation of part of this subducted floor onto the continental margin, during which the Meso-Alpine and Neo-Alpine metamorphic events of the Oligocene and Miocene took place (*Fig. 12 and Puga et al., 2002a; Ruiz Cruz et al, 1999*). The successive parageneses of eclogite, Ab-Ep amphibolite and green schist facies took place during these metamorphic events (*Puga et al., 1999a, b; 2000; 2002a, b*).

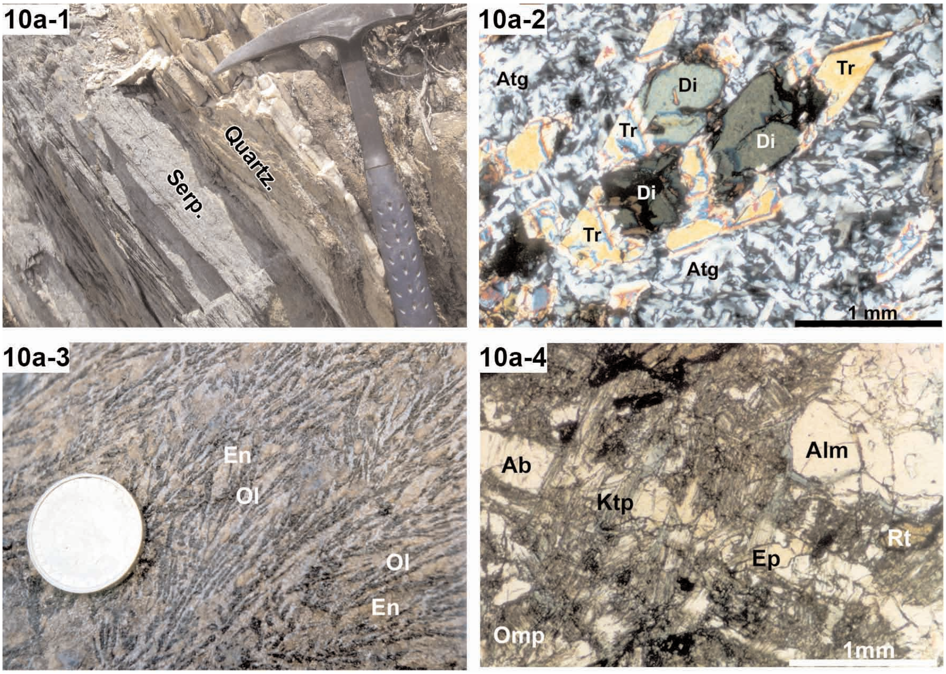


Fig. 10a. Most representative lithologies of the mantle sequence: (1) Serpentinites (Serp) and quartzites (Quartz), (2) microscopic view of serpentinite, (3) secondary harzburgite, (4) microscopic view of eclogitized dolorite dyke.

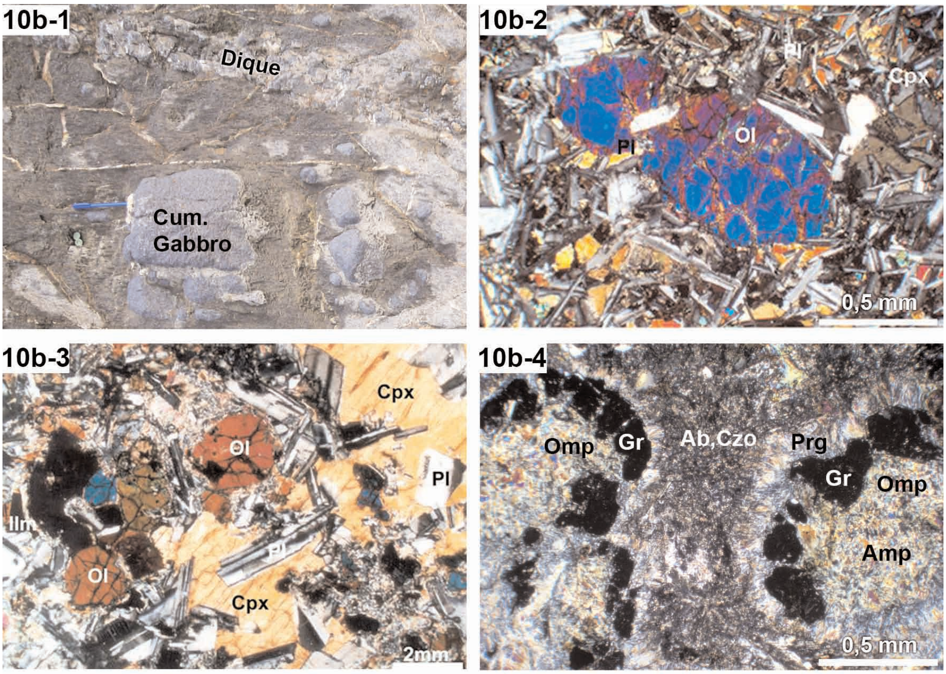


Fig. 10b. Most representative lithologies of the intrusive sequence: (1) Troctolitic gabbro. Microscopic views of: (2) olivine gabbro, (3) pyroxene-olivine gabbro and (4) coronitic eclogite.

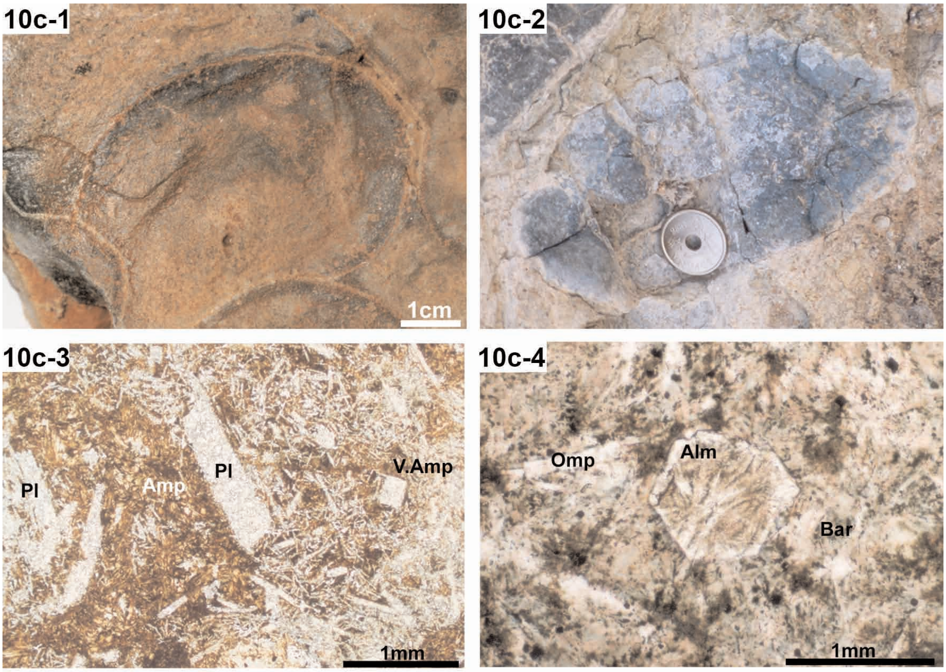


Fig. 10c. Most representative lithologies of the volcanic sequence: (1) Eclogitized minipillows, (2) amphibolitized pillow lavas. Microscopic view of: (3) amphibolitized porphyric basalt, (4) eclogitized pillow basalt.

2.5. Geochemical characteristics and geodynamic context

The chemical composition of the most representative rocks of the various outcrops of Betic Ophiolites are shown in some diagrams for the genetic context of the basaltic magmas, together with the mean values of these current magma types for comparison *(Fig 11)*. The symbols for the different types of ophiolitic rocks are explained in the legend at the foot of the figure, together with the original outcrops of these rocks and the meaning of the acronyms used for the different present-day geodynamic contexts in which the basic magmas are formed. It can be inferred that the geochemical affinity of the different types of basic rocks in the Betic Ophiolitic Assemblage is T-MORB, and locally N-MORB, Ti-rich tholeiitic magmatism *(Fig. 11 A-D)*, which is characteristic of Ti-rich ophiolites from oceanic floor created on an oceanic ridge *(Fig. 1 and 3)*. The broad isotopic variation of the Sr^{87}/Sr^{86} ratio in the Betic Ophiolites *(Fig. 11 B)* can be explained by the different degrees of metasomatism undergone by the basic and ultramafic rocks at the ocean floor. The geochemical characteristics of the Betic Ophiolites are similar to those forming the Alpine-Apennine ophiolitic chain, which also derive from the Jurassic oceanic floor of the Western Tethys *(Puga et al., 2011)*.

Tholeiitic magmas similar to those that formed the Betic Ophiolites, evolve at present on slowly expanding oceanic ridges, such as the Atlantic, caused by the development of prior continental rift in a period of maximum distension, during which accretion of oceanic floor occurred. In the Mulhacen Complex, the period of maximum Jurassic distension, when the oceanic floor from which the ophiolites derive was developed *(Puga, 2005; Puga et al., 2011)*, followed on a period of Permian-Triassic continental rifting when several levels of piroclastic acidic orthogneisses formed, alternating with meta-sediments in the units of the complex deriving from the continental crust *(Figs. 5 and 12; Nieto et al., 2000; Puga et al., 2002a)*.

3. Genetic and evolutionary pattern of the Betic ophiolites and other units of the Mulhacen and Veleta Complexes

Fig. 12 shows the pattern of the origin and evo-

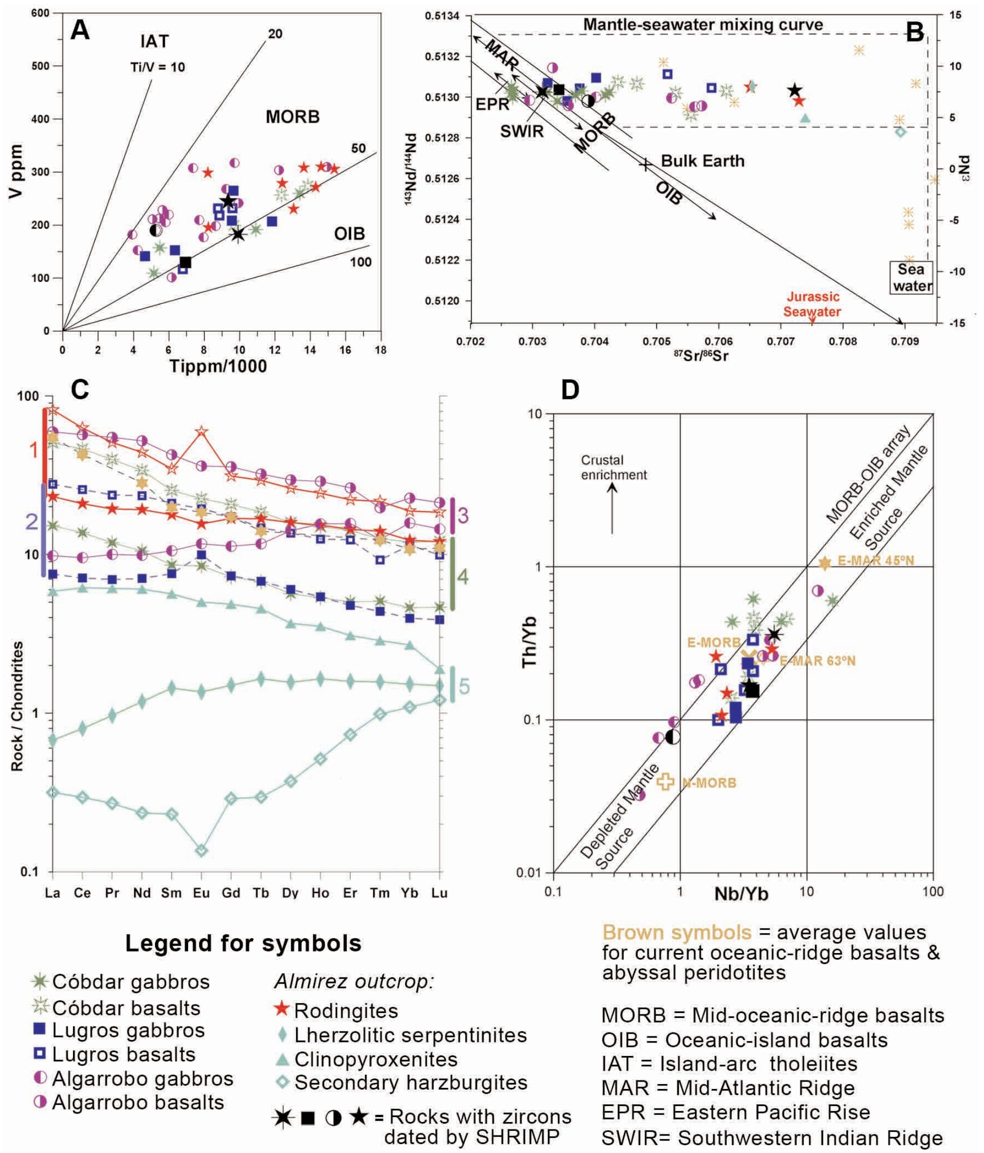


Fig. 11 A-D. Projection of the values of some few mobile trace elements (A), or their ratios (D), the REE values normalized to chodrites (C) and the isotopic ratios of Nd vs. Sr (B), of the different lithologies of the Betic Ophiolites on the principal discriminating diagrams of genetic context for basic magmas.

lution of the Betic Ophiolites based on the study of the successive parageneses and textures preserved in them and their thermodynamic formation conditions, together with the radiometric dating of some of their minerals, particularly zircons, and the geochemistry of their different lithologies, as well as those of the tectonic units in which they are at present intercalated. This model (based on data *published in Puga et al., 1996, 1999, 2000, 2002, 2004, 2005, 2007, 2009, 2011; Nieto 1996; Nieto et al., 2000 and Ruiz Cruz et al., 1999, 2007),* shows the schematic geodynamic evolution of the Veleta and Mulhacen Complexes from the Carboniferous to the Miocene. It also includes the evolution of the various units comprising the

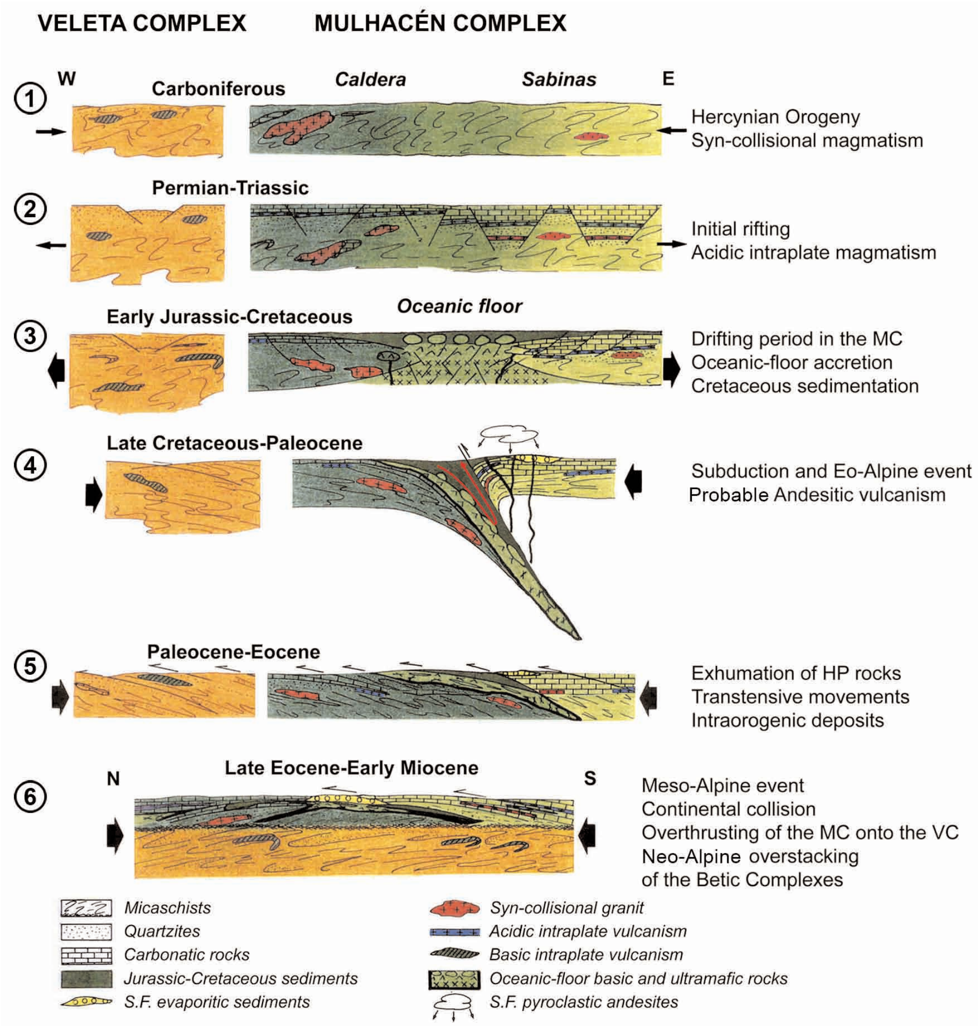


Fig. 12. Petrogenetic and geodynamic evolution model for the different tectonic units forming the Nevadofilabride Complexes.

latter complex, one of which is the Ophiolite Unit. Development in time has been divided into several episodes in *Fig. 12*, numbered 1 to 6 on the diagram, to which correspond the geodynamic conditions graphically shown and enumerated on the right of the diagram.

The oceanic floor from which the Betic Ophiolites derived was formed in episode 3 by asthenospheric rise, under distensive conditions, that continued throughout the Jurassic and Cretaceous, along a rifting zone on the continental crust of the MC located between the Caldera (W) and Sabinas (E) units. Among other Pre-Alpine metamorphic rocks, this continental crust contained orthogneisses derived from Hercynian granites and Permian-Triassic rhyolites formed in the episodes 1, 2 and preceding. In episode 4, the Jurassic-Cretaceous oceanic floor was subducted as a result of the approaching of the Iberian and African plates beginning in the Late Cretaceous, which caused the Eo-Alpine metamorphism in eclogite facies. During episode 5 a small part of the subducted rocks, metamorphosed at depths of 50-100 km, were exhumed as tectonic slabs, imbricated between the crustal materials of

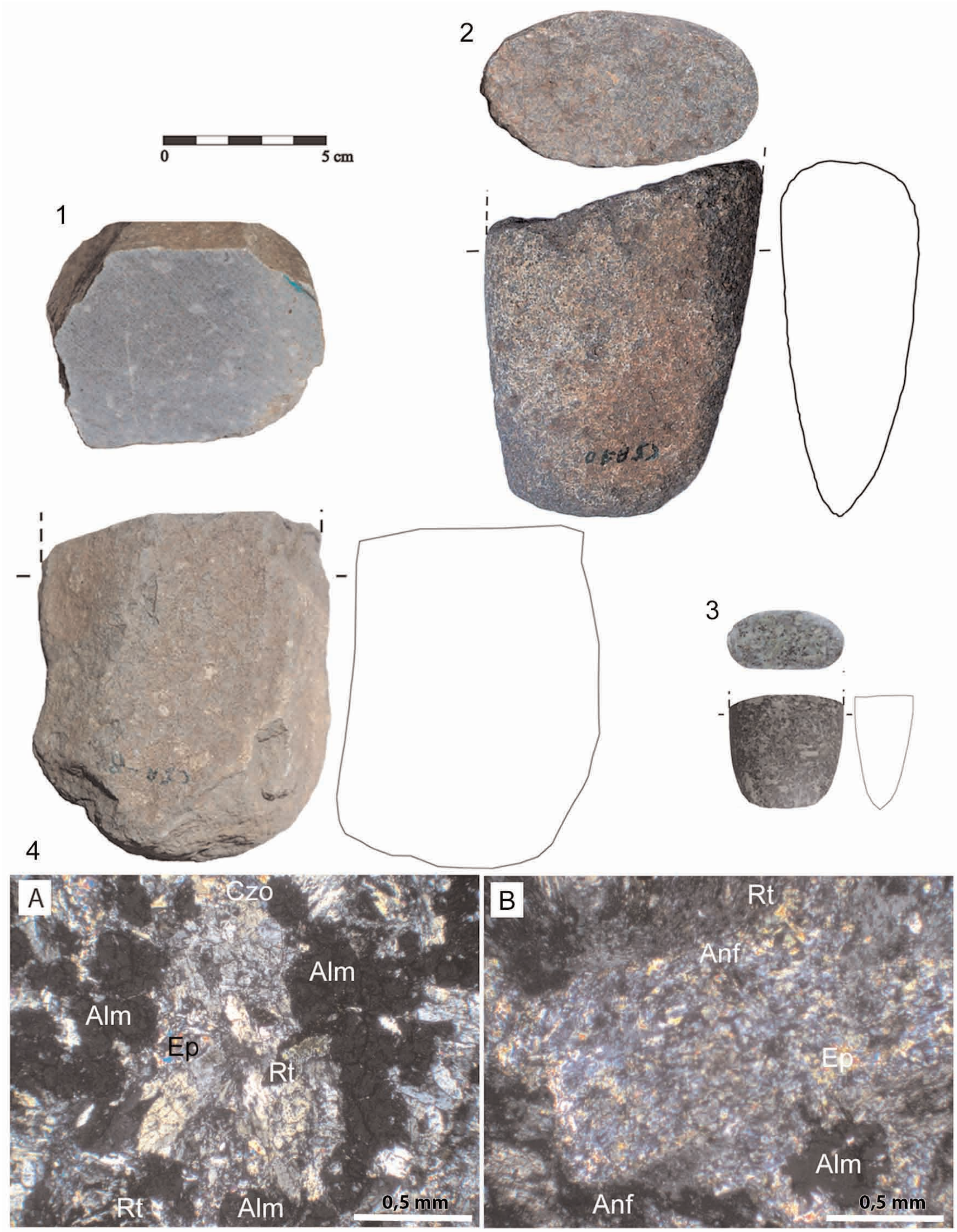


Fig. 13. Prehistoric tools manufactured on ophiolites from Caniles de Baza outcrops and microscopical view of these archaeological objects on thin sections.

the continental margin and forming an initial stacking between the units of the MC. Finally, episode 6 consisted of the stacking of the MC onto the VC, accompanied and followed by more Alpine metamorphic and deformative processes, culminating in the superposition of the Alpujarride and Malaguide Complexes on the Nevadofilabride Complexes.

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4. Use of ophiolites in archaeology

In the European Neolithic (c. 8000-7000 B.P.) the raw materials for stone utensils became more diversified as a result of the new technique of polishing and emerging needs of new ways of life. The exploitation of new raw materials such as basic igneous rocks and their metamorphic derivatives for making the various types of polished objects (axes, adzes, chisels, hammers, etc.) lead to technological development that culminated in the Bronze Age *(Fig. 13).*

In the Iberian Peninsula, the analyses of these objects have to date focused on finished tools and, therefore, on their descriptive characteristics, functions and lithological characterization to locate possible sites of origin for the raw materials. However, there is a significant lack of studies on the manufacture of these objects. This gap in research is not a response to the archaeological reality, but is rather due to various factors, such as the previous inexistence of geo-archaeological research projects focused on the prospection of archaeological traces in outcrops of rocks suitable for manufacture of these tools, as well as a widespread lack of awareness of the distinction of the knapping stigmata of the igneous and metamorphic rocks.

In our multidisciplinary study of the ophiolites in the Sierra de Baza, we recently identified evidence of prehistoric usage in the Rambla del Agua and Cerro de San Cristóbal outcrops (Lozano et al., in preparation). Their usage is restricted to Recent Prehistory, when certain types of hard, blow-resistant tools such as hammers *(Fig. 13.1)* and polished axes *(Fig. 13.2 and 13.3)* were needed for grinding cereals and woodwork, among other usages. Archaeological evidence suggests that these outcrops of ophiolitic rocks were used as quarries to extract certain materials, which were then subjected to a long process of shaping by direct percussion to obtain the desired shape of tool which, in the case of axes, involved sharpening of the blade. This shaping process is reflected in multiple archaeological remains found in the outcrops of Sierra de Baza.

We have determined by examination of thin sections that these prehistoric tools were mainly made out of eclogites, in order to take advantage of the high density and hardness of these rocks, deriving from high pressure metamorphism of gabbros *(Fig. 13.2)*, dolerites *(Fig. 13.3)* and ophiolitic basalts *(Fig. 13.1)*. The importance of the exploitation of ophiolitic rocks is underlined by the location of numerous prehistoric settlements around these outcrops, such as the named Montones de Piedras deposit *(Sanchez Quirantes, 1990)*.

In this sense, the prehistoric quarries of Rambla del Agua and Cerro de San Cristóbal bring out the importance of interdisciplinary research of the primary geological contexts. They also exemplify the singularity of a unique geological and cultural heritage that requires protection.

5. Patrimonial value of the Betic ophiolites

As explained above, the main interest in the Betic Ophiolites as a geological, educational and cultural heritage, worth preserving, resides in the fact of they are extremely valuable relics, from a scientific point of view, of a Mesozoic oceanic floor that disappeared through subduction, mainly during an initial compressive Alpine stage, occurring in the Late Cretaceous due to approaching of the European and African plates. Some slabs of this subducted oceanic floor were fortunately exhumed in a Palaeocene transtensive stage and incorporated onto the Betic continental margin, after undergoing high pressure metamorphism to eclogite facies at depths of 50 to 100 km. Studying these unique Pliensbachian relics of the westernmost Tethys, which are the Betic Ophiolites, we can carry out palaeogeographic, tectonic and petrogenetic reconstructions of the deepest metamorphic complexes of the Betic Cordilleras, and infer the genesis and composition of the now disappeared Jurassic Tethys Ocean. For these reasons, we consider that the Betic Ophiolitic Assemblage should be recognised as a new Spanish Geological Context, worthy of being protected from its present state of destruction for industrial ends, given its considerable geological and geo-archaeological interest of international scale *(Puga et al., 2003, 2009, 2010, 2011).*

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References

Beccaluva L., Coltorti M., Saccani E., Siena F. & Zeda O. (2005) Triassic magmatism and Jurassic ophiolites at the margins of the Adria Plate. In: Finetti, I.R. (Ed.) Deep Seismic Exploration of the Central Mediterranean and Italy. CROP 1 Volume: University of Trieste, Italy. Elsevier. 607-621.

Bortolotti, V. & Principi, G., 2005. Tethyan ophiolites and Pangaea breakup. The Island Arcs 14, 442–470.

Guerrera, F., Martin-Algarra, A., & Perrone, V., 1993 Late Oligocene–Miocene syn-/-lateorogenic successions in Western and Central Mediterranean Chains from the Betic Cordillera to the Southern Apennines. Terra Nova 5, 525–544

Nieto, J.M., 1996. Petrología y geoquímica de los ortogneises del Complejo del Mulhacén, Cordilleras Béticas. Ph. D. Thesis, Universidad de Granada, 211 pp

Nieto, J.M., Puga, E. & Díaz De Federico, A. (2000) Late Variscan pyroclastic rocks from the Mulhacén Complex (Betic Cordillera, Spain), 217-24. In: H. Leyrit & Ch. Montenat (Eds) Volcaniclastic Rocks, from magmas to sediments. Gordon and Breach Science Publishers. 265 pp..

Puga E. (1990) The Betic Ophiolitic Association (Southeastern Spain). Ofioliti, 15-1, 97-117.

Puga, E., Nieto, J.M., Díaz de Federico, A., Portugal, M. & Reyes, E. (1996) The intra-orogenic Soportújar Formation of the Mulhacén Complex: Evidence for the polycyclic character of the Alpine orogeny in the Betic Cordilleras. Eclogae geologicae Helvetiae, 89, 1, 129-162

Puga, E., Nieto, J.M., Díaz De Federico, A., Bodinier, J.L. & Morten, L. (1999a) Petrology and metamorphic evolution of ultramafic rocks and dolerite dykes of the Betic Ophiolitic Association (Mulhacén Complex, SE Spain): Evidence of eo-Alpine subduction following an ocean-floor metasomatic process. Lithos, 49, 1-2, 107-140. RE

Puga, E., Ruiz Cruz, M.D. & Díaz De Federico, A. (1999b) Magnetite-silicate inclusions in olivine of ophiolitic meta-gabbros from the Mulhacén Complex (Betic Cordillera, SE Spain). Canadian Min. 37, 5, 1191-1209. RE

Puga, E., Nieto, J.M. & Díaz De Federico, A. (2000) Contrasting P-T paths in eclogites of the Betic Ophiolitic Association (Mulhacén Complex, SE Spain). Canadian Min. 38, 5, 1137-1161.

Puga, E., Díaz De Federico, A. & Nieto, J.M. (2002a) Tectono-stratigraphic subdivison and petrological characterisation of the deepest complexes of the Betic Zone: A Review. Geodinamica Acta, 15, 1, 23-43.

Puga, E., Ruiz Cruz, M.D. & Díaz De Federico, A. (2002b) Polymetamorphic amphibole veins in metabasalts from the Betic Ophiolitic Association (SE Spain): Relics of ocean-floor metamorphism preserved throughout the Alpine Orogeny. Canadian Min. 40, 67-83.

Puga, E., Díaz De Federico, A. & Nieto J.M. (2003) La Asociación Ofiolítica Bética: Un patrimonio geológico a preservar. In: Patrimonio geológico y minero y desarrollo regional. IGME ISBN 84-7840-497-X, 129-140.

Puga, E., Díaz De Federico, A., Nieto, J.M., Díaz Puga, M.A., Rodríguez Martinez Conde, J.A. & Manteca Martinez, J.I. (2004a) Argumentos petrológicos y geoquímicas para la subdivisión del Complejo Nevado-Filábride en los Complejos del Veleta y del Mulhacén. VI Congreso Geológico de España, Zaragoza (España). Geo-Temas, 6 (1), 101-104.

Puga, E., Díaz De Federico, A., Manteca Martinez, J.I., Rodríguez Martinez Conde, J.A. & Díaz Puga, M. A. (2004b) The Canteras-Galifa Neogene conglomerates: Evidence for an ophiolitic association submerged in the Mediterranean Sea at the eastern end of the Betic Chain. Ofioliti, 29 (2), 213-230.

Puga, E. (2005) A reappraisal of the Betic Ophiolitic Association: The westernmost relic of the Alpine Tethys Ocean). In: I.R. Finetti (Ed) Deep Seismic Exploration of the Central Mediterranean and Italy. CROP 1 Volume, University of Trieste, Italy. Elsevier, 665-704.

Puga, E., Fanning, C.M., Nieto, J.M. & Díaz de Federico, A. (2005) New recrystallisation textures *in zircons generated by ocean-floor and eclogite facies metamorphism: a cathodoluminescence and U-Pb SHRIMP study with constraints from REE elements. Canadian Mineralogist, 42 (Carmichael Volume), 1349-1368*

Puga E., Díaz de Federico A., Nieto J. M. & Díaz Puga M. A. (2007) "Petrología, georrecursos y evolución geodinámica del Espacio Natural de Sierra Nevada". Estudios Geológicos, 63/2, 19-40

Puga, E., Díaz de Federico, A., Nieto, J. M. & Díaz Puga, M.A. (2009a) The Betic Ophiolitic Association: a very significant geological heritage in urgent need of preservation. Geoheritage, 1, 11-31.

Puga, E., Rodríguez Martínez-Conde, J. A. Díaz de Federico, A., Manteca Martínez, J. I. & Díaz Puga, M. A. (2009b) Caracterización geoquímica y ambiente geodinámico de génesis de las metabasitas de la Sierra del Algarrobo (Cordillera Bética oriental). Geogaceta, 46, 11-14.

Puga, E., Fanning, C. M., Rodríguez Martínez-Conde, J.A., Díaz de Federico, A., Nieto, J. M. & Díaz Puga, M. A. (2010) Time information on Pangaea break-up and birth of the westernmost Tethys Ocean deduced from U-Pb geochronology of the Betic Ophiolites: another significant reason for their preservation. Abstracts Volume. First Meeting of ProGEO Regional Working Group SW Europe, pp. 237-239. Geological Heritage and the Role of the IGCP (Marcos A. Lamolda et al., Eds) Ayuntamiento de Caravaca de la Cruz. Deposito Legal: E-30400

Puga, E., Fanning, C. M., Diaz de Federico, A., Nieto, J. M., Beccaluva, L., Bianchini, G. & Diaz Puga, M. A. (2011). Petrology, geochemistry and U-Pb geochronology of the Betic Ophiolites: inferences for Pangea break-up and birth of the Westernmost Tethys Ocean. Lithos, 124, 255-272. Special Issue "Alpine Ophiolite and Modern Analogues"

Ruiz Cruz, M.D., Puga, E. & Nieto, J.M. (1999) Silicate and ore exsolutions in pseudo-spinifex olivine of the metaultramafic rocks from the Betic Ophiolitic Association: A TEM study. Amer. Min., 11-12, 1915-1924

Ruiz Cruz, M.D., Puga E. & Díaz de Federico A (2007) "Exsolution microstructures in amphiboles from metabasalts of the Betic ophiolitic association (SE Spain)". European Journal of Mineralogy, 19, 547- 556.

Sánchez Quirante, L. (1990) Prospección arqueológica superficial del sector occidental de la Sierra de Baza. Campaña 1990. En: Anuario arqueológico de Andalucía II. Actividades sistemáticas. Consejería de Cultura, Junta de Andalucía, Cádiz. 124-127.

Schettino, A. & Turco, E., 2010. Breakup of Pangaea and Plate Kinematics of the central Atlantic and Atlas region. Geophysical Journal Interior 178, 1078–1097.

Tendero, J.A., Martin-Algarra, A., Puga, E. & Díaz de Federico, A. (1993) Lithostratigraphie des métasédiments de l'association ophiolitique Nevado-Filabride (SE Espagne) et mise en évidence d'objets ankéritiques évoquant des foraminifères planctoniques du Crétacé: conséquences paléogéographiques. C.R. Acad. Sci. Paris, t. 316, Série II, , 1-10.