Lithos 290–291 (2017) 34–47

Contents lists available at ScienceDirect

Lithos

journal homepage: www.elsevier.com/locate/lithos

U–Pb detrital zircon ages from the Paleozoic Marbella Conglomerate of the Malaguide Complex (Betic Cordilleras, Spain). Implications on Paleotethyan evolution

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ARTICLE INFO

Article history:
Received 30 August 2016
Accepted 27 July 2017
Available online 03 August 2017

Keywords:
Betic Cordilleras
Malaguide Complex
Marbella Conglomerate
U–Pb geochronology

ABSTRACT

The Marbella Conglomerate (Betic Cordilleras, SW Spain) is a poorly sorted and polymictic rock of vaguely constrained Late Carboniferous age interlayered within a sandy sequence. It contains variable amounts of pebbles of quartzite, gneiss, deformed granitoid, schist, aplite, dacite and other volcanic rocks among others, which makes it a potential target for detrital zircon provenance studies. In order to decipher provenance we combined U–Pb SHRIMP and LA–ICP-MS analyses on zircons obtained from single pebbles of deformed rocks (schist, granitoids) and detrital zircons from the sandy sequence, respectively. The age spectra of the detrital zircons indicates that at least the sedimentation took place soon after the start of the Permian according to the youngest detrital zircon age (≈286 Ma), and it involved the denudation of terranes with rocks bearing Paleoproterozoic, Neoproterozoic, Cambro-Ordovician, Devonian and Carboniferous zircon age clusters. In contrast with the Permian age of the detrital zircons from the sandstones, igneous (*ca.* 532 and 516 Ma) and metamorphic (*ca.* 356 Ma) U–Pb SHRIMP Concordia ages were obtained from the pebbles. The different age clusters observed could be correlated to igneous, metamorphic and detrital rocks from an already eroded terrane similar to the Ossa-Morena Zone of the Iberian Variscan Belt. Therefore, we propose that most of the sedimentation of the Marbella Conglomerate took place along the western border of the Paleotethys at the north margin of Gondwana during the dismantling of the Variscan orogenic edifice and/or the Neotethys ocean opening and the birth of the Cimmerian ribbon continent.

1. Introduction

The geodynamic evolution of the northern margin of Gondwana is still under discussion due to discrepancies in its paleogeographic reconstructions over the course of the Paleozoic (Stampfli, 2000; Stampfli et al., 2013; von Raumer et al., 2003, 2015). Such diverging reconstructions arise largely from differences in interpretations of the number, location and origin of the ribbon continents formed during the opening of oceans like the Rheic, Prototethys or Paleotethys. The paleogeographic assembly and the continental fragments fitting, is particularly difficult in the case of the Mediterranean puzzle of the Alpine belts that are dispersed inland along their borders. The great complexity of the peri-Mediterranean Alpine belts also results from intense overprinting, including significant radiometric age resetting, due to the extent of high-grade metamorphism in the internal domains of these belts. In this regard, in the Alboran domain of the Betic Cordilleras and the Rif (Southern Spain and northern Morocco, respectively; Fig. 1A) the Alpine Orogeny overprinted older orogenic processes to a great extent, making difficult the interpretation of its pre-Alpine evolution.

Regarding the paleogeography of the Alboran domain during the Paleozoic, the differing interpretations concern both its location relative to Proto-Iberia and its integration within the diverse Gondwana-derived microcontinents. On the first issue, some authors have proposed that during the Ordovician it should be located far to the east of its present location, in close relationship to the Alps, in an intermediate palaeogeographic position towards the Carnics Alps (see figure 7 of Rodríguez-Cañero et al., 2010) or the Adria Terrane (see figure 4 of Stampfli et al., 2002). Instead, other authors (Stampfli et al., 2013) propose a more westerly position, between the Ossa-Morena and Moroccan Meseta terranes (see figure 3 of Stampfli et al., 2013). Concerning the second point, although the Alboran domain is thought to be a Peri-Gondwanan terrain drifted away from the northern border of Gondwana from Paleozoic times onwards, it has been linked to the European Hunic Terranes (Martín-Algarra et al., 2009; Stampfli, 2000; Stampfli et al., 2013; von Raumer et al., 2003, 2015) or to the Cimmerian

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http://dx.doi.org/10.1016/j.lithos.2017.07.022
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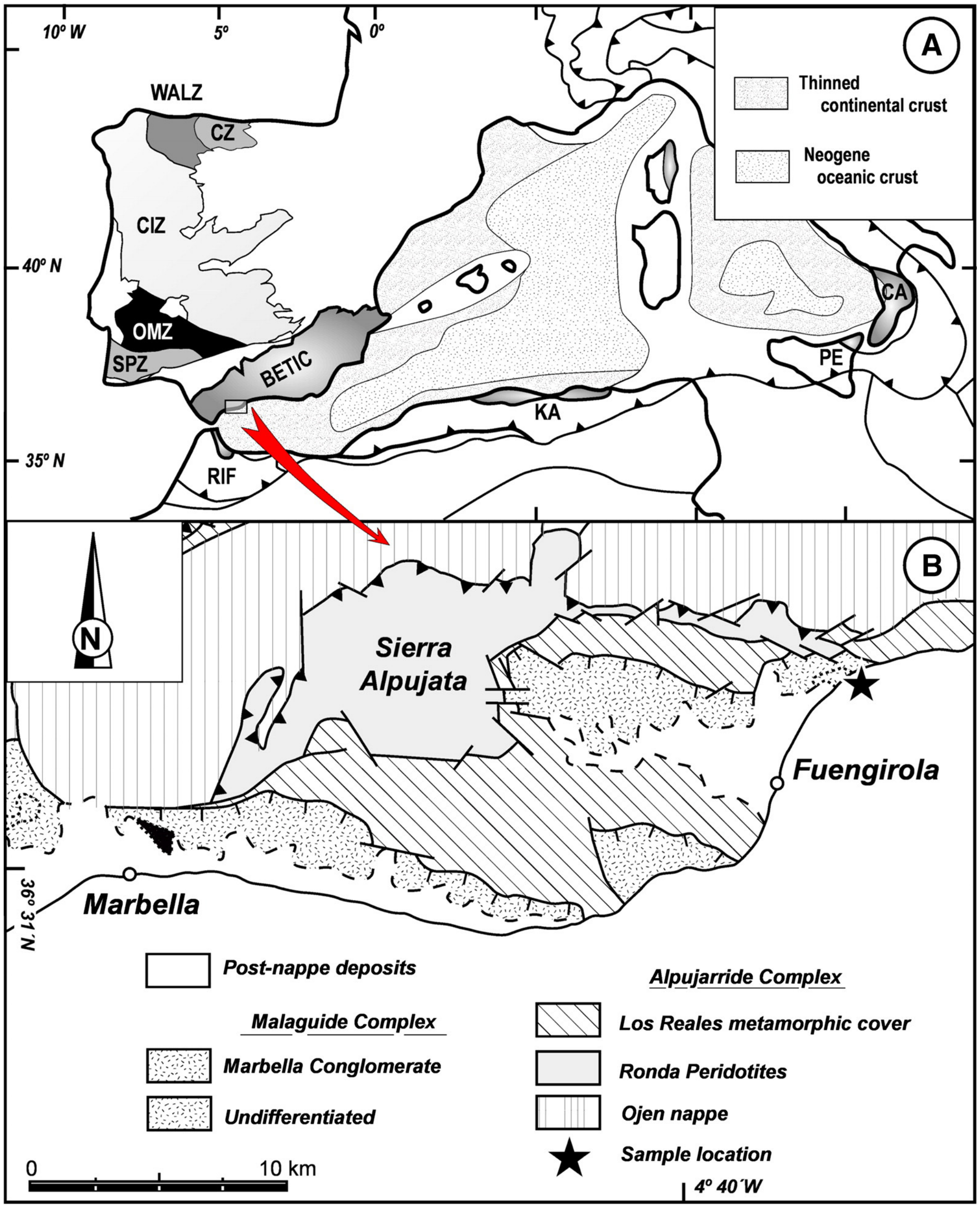

Fig. 1. A) Schematic tectonic map of the Western Mediterranean. Iberian Variscan belt: CZ — Cantabrian Zone; WALZ — Western Asturian-Leonese Zone; CIZ — Central Iberian Zone; OM — Ossa-Morena Zone; SPZ — South Portuguese Zone; KA — Kabilides; PE — Peloritain; CA — Calabria. B) Tectonic map of the western Internal Zone of the Betic Cordillera showing the main outcrops of the Marbella Conglomerate.

Terranes (Esteban et al., 2011). The disagreement persists when more recent Paleozoic times are considered. By way of illustration, the tectonic evolution of syn- to post-Variscan, Carboniferous-Permian basins located within the Alboran domain rely on the interpretation of the sedimentary deposits present in the Malaguide Complex and their equivalent Ghomaride units in Morocco in two different ways: a) they have been traced through the West-Mediterranean Paleotethys in paleogeographic connection with similar deposits that crop out in the Menorca island (Herbig, 1985; Herbig and Stattegger, 1989) or, b) they have been interpreted as the eastward prolongation of the Central Iberian Zone of the Iberian Variscan belt (Sanz de Galdeano et al., 2006).

With the aim to shed light on this controversial matter, this work discusses the geochronology and provenance of the Marbella Conglomerate, a formation of vaguely constrained Late Carboniferous age that belongs to the Malaguide Complex of the Betic Cordilleras (southern Spain). The Marbella Conglomerate stands out as an interesting target to search for evidence of old orogenic events, since it did not experience any high-grade overprinting during the Alpine tectono-metamorphic cycle. In order to constrain the age and possible source areas of the Marbella Conglomerate, we have conducted a geochronological research based on sixty-four U–Pb SHRIMP zircon analyses from three pebbles of the Marbella Conglomerate and one hundred and eighty one (one hundred and twenty six were concordant) U–Pb LA–ICP-MS analyses on detrital zircons from the matrix sandstone that hosts the pebbles.

2. Geological setting

The Alboran domain of the Betic Cordilleras in southern Spain is composed, from bottom to top, of three main tectonic complexes made up mainly of Paleozoic and Triassic materials: the Nevado-

Filabride, Alpujarride and Malaguide Complexes. Due to the convergence between the African and Iberian plates from the Cretaceous onward, the Alpine reworking in the Alboran domain led to structures related to crustal thickening that were subsequently overprinted by extensional tectonics. Nowadays, the main tectonic contacts between the aforementioned complexes are interpreted as extensional detachments (García-Dueñas et al., 1992; Platt et al., 2013) and their absolute chronology begins to be clarified (Esteban et al., 2013). Whereas the Alboran domain forms the Internal Zone of the Betic Cordilleras, the External Zone comprises deformed Mesozoic and Cenozoic sedimentary rocks deposited on the southern paleomargin of the Iberian Variscan belt.

In contrast with the metamorphic nature of the two underlying complexes (Nevado-Filabride and Alpujarride), the Malaguide Complex consists mainly of a Paleozoic series unconformably overlain by (Permo)-Triassic red beds and a Mesozoic-Tertiary sedimentary sequence (Azéma, 1961; Mäkel, 1985) (Fig. 2A). The Permian age of the lowermost part of this sedimentary cover has been a matter of discussion for some time, although a Triassic age is now widely accepted based on the presence Triassic pollen in these rocks (Martín-Algarra, 1995). The Alpujarride Complex also displays a Triassic metamorphic cover that is mainly formed by carbonated rocks. The red siliciclastic facies of the Malaguide cover is consistent with Triassic deposits of Germanic type, while the Triassic cover of the Alpujarride Complex is of Alpine affinity. It is worth underlining that the sharp lithological contrast between these Triassic covers and the lack of Cenozoic deposits in the Alpujarride Complex point to different paleogeographic evolutions of the Alpujarride and Malaguide complexes at least from Triassic ages. Only locally, the lowermost levels of the Malaguide Complex contain fine-grained, andalusite (garnet)-bearing schists (Tubía, 1985; Tubía and Navarro-Vilá, 1984). These schists are gradually replaced by grey phyllites with sparse beds of strained quartz-pebble conglomerates and dark limestones attributed to the Silurian (Agard et al., 1958; Geel, 1973). The phyllites grade into intensely folded detrital Devonian limestones (Kockel, 1963), locally referred to as the “calizas alabeadas” (de Orueta, 1917) and progressively to Carboniferous slates and greywackes. This greywacke-slate member begins with thin-bedded lidites, dated as Tournasian by means of radiolarians (O'Dogherty et al., 2000). The top is composed of several beds of polymictic conglomerates, known as Marbella Conglomerate (Blumenthal, 1949), which are the object of this study (Fig. 1B). This post-Visean conglomerate is unconformably covered by a Mesozoic-Cenozoic condensed sequence (Fig. 2A) dated up to Chattian-Aquitanian times (Jutson, 1980; Mäkel, 1985). All the Paleozoic series up to the “calizas alabeadas” are cut by a dolerite dyke swarm of Oligocene age (Esteban et al., 2013; Torres-Roldán et al., 1986).

The Marbella Conglomerate (“*Conglomerado de Marbella*”) named after the limestone-bearing conglomerates cropping out near Marbella (Blumenthal, 1949) is a poorly sorted rock consisting of layers with a small lateral continuity (Fig. 2A), which occurs within a predominantly sandy sequence. The Marbella Conglomerate thickness is highly variable, up to 400 m in Marbella (Tubía, 1985) but often not exceeding several meters. Some layers of finer grained conglomerates grade upwards into shales and greywackes (Geel, 1973). The Marbella Conglomerate is polymictic, heterometric and it mainly contains variable amounts of

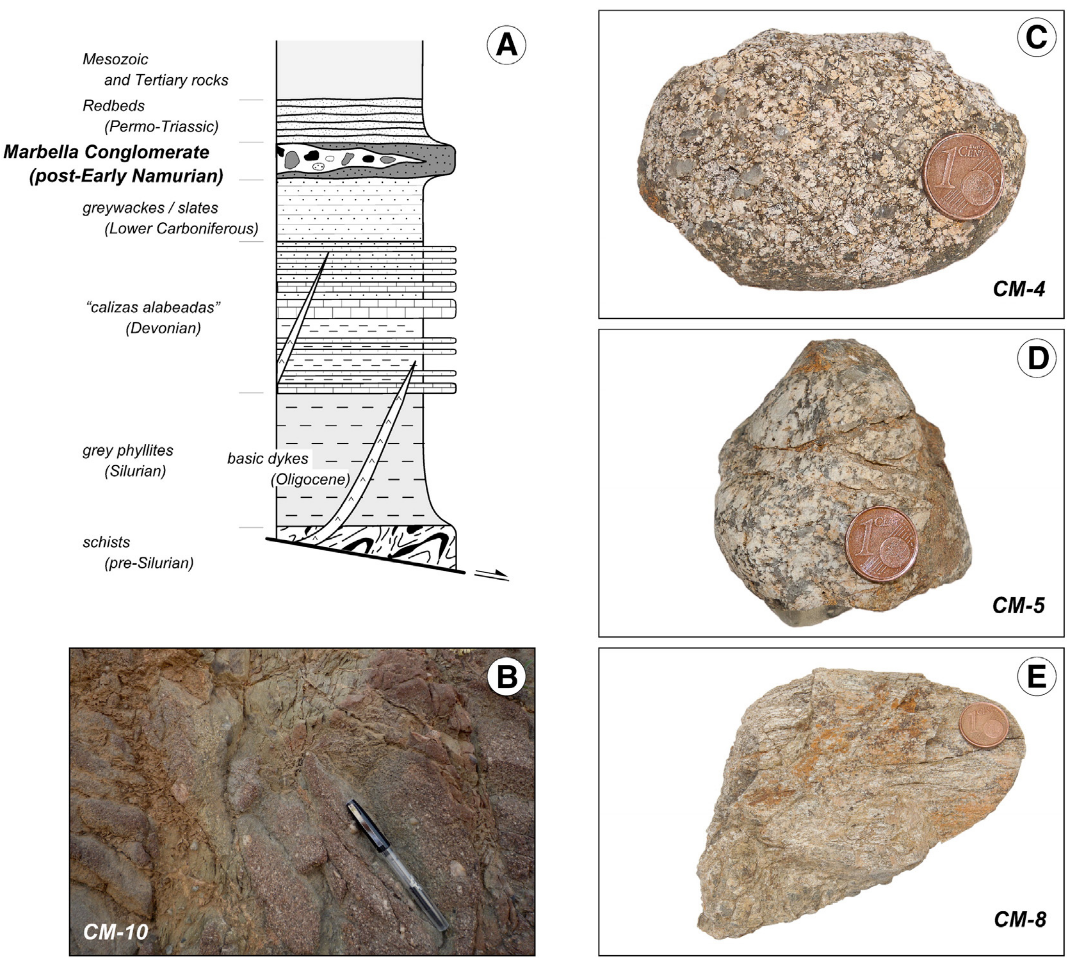

Fig. 2. A) Synthetic log of the Malaguide Complex and hand/field aspect of dated samples. B) CM-10 — brown-reddish matrix sandstone. C) CM-4 — deformed granitoid. D) CM-5 — porphyric orthogneiss. E) CM-8 — Quartz-schist.
Panel A was modified from Esteban et al. (2013).

rounded pebbles constituted by lidite, quartz veins, quartzite, gneisses with varied mineralogy, granite, schist, aplite, dacite and other volcanic rocks. The rounded shape of such pebbles contrasts with the angular phyllite, slate, greywacke and even dark-grey shallow-water limestone clasts sourced from the formations that make the Malaguide substrate of the Marbella Conglomerate. These pebbles are enclosed within a brown coarse-grained sandstone matrix that locally has cross bedding (Fig. 2B). These clasts vary in size from a few cm to more than 10 m. Although most of the angular clasts in the conglomerate come from the underlying sequence, the origin of the granitic and metamorphic pebbles remains unknown since neither gneiss nor high-grade schist are exposed at lower levels of the Malaguide or the Ghomaride Complexes, its equivalent in the Rif belt of Morocco. According to Michard et al. (2008), the nearest similar basement rocks could be found in the Algerian Kabylie, more than 750 km to the West in the present day geography.

Some authors have suggested that the Marbella Conglomerate represents a regional unconformity (Blumenthal, 1949; Bourgeois, 1978; Felder, 1978; Mollat, 1968). Alternatively, the basal contact of these conglomerates has also been interpreted as a local unconformity, related to continental debris flow deposits (Herbig, 1983), being the major regional unconformity placed below the Triassic sedimentary cover that rest on different levels of the Paleozoic Malaguide sequence deformed in the Variscan Orogeny. In general terms, the Paleozoic sedimentary record of the Malaguide has been interpreted to reflect the transition from a passive margin to a collisional environment (Herbig and Stattegger, 1989), where the Carboniferous siliciclastic turbidite sediments should be deposited syn-tectonically, with the lidites recording the maximum deposition depths and the Marbella Conglomerate late debris flow deposits.

The age of the Marbella Conglomerate has been constrained by means of fossils, present in some limestone boulders that yield ages ranging between Upper Visean and Lower Bashkirian (Azéma, 1961; Blumenthal, 1949; Geel, 1973; Michelau, 1943), leading to a post-Baskirian age for the deposition of the conglomerate. This paleontologically constrained maximum depositional age contrasts with the older radiometric age of 535 ± 75 Ma, obtained by Soediono (1971) on an orthogneiss pebble.

3. Textural analysis of basement pebbles

We have analysed the textures of the main groups of the "exotic" pebbles (Fig. 2) that have been dated in this work labelled CM-4 and CM-5 together with samples from the quartzites and schists group (CM-8).

The CM-4 group (Fig. 2C) includes a set of heterogeneously deformed granitoids with *ca.* 3 mm-sized zoned megacrysts of anhedral K-feldspar and plagioclase with globular quartz grains. Plagioclase grains have euhedral growth zoning produced when the crystal was growing in the magma. Minor amounts of biotite and/or muscovite and accessory minerals as zircon, apatite, tourmaline, sphene and opaque minerals complete the mineralogy of this group. Although the phenocrysts are generally inferred to have grown before other minerals, this order cannot be determined microstructurally (Vernon, 2004). This group of granitoids shows a discrete tectonic foliation but some primary magmatic textures can still be recognized (Vernon, 2004) like fractured megacrysts of K-feldspar with inclusions and simple twinning K-feldspar – rare in metamorphic rocks – and only marginal recrystallization (Fig. 3A). The surrounding quartz forms "blocky" subgrains (Vernon, 2004) caused by intersecting sets of subgrains. High-angle S–C structures are sometimes present (Passchier and Trouw, 2005). The foliation is marked by fractured feldspar porphyroclasts and by elongate grains of quartz with undulose extinction with small misorientation of subgrains, subgrains with sharp kink bands of marked misorientation and grain boundary migration recrystallization. Biotite porphyroclasts frequently show kink bands and neoblasts along their margins (Fig. 3B). The dynamic recrystallization of quartz, the partial recrystallization of feldspar and the myrmekite development around plagioclase point to a solid-state deformation of these granitoids at temperature conditions above the upper greenschist facies.

The CM-5 group (Fig. 2D) includes orthogneisses with mylonitic textures. Its mineralogy is similar to the CM-4 group but the great extent of mylonitization led to the obliteration of possible magmatic microstructures. Many of the studied samples depict primary minerals as K-feldspar, plagioclase and biotite strongly retrogressed into carbonate, sericite and chlorite. Large K-feldspar porphyroclasts ("augens") show typical core and mantle textures (Passchier and Trouw, 2005) and are surrounded by the fine-grained aggregates of quartz and biotite that compose the foliated matrix. The mylonitic foliation is deflected to form pressure shadows around the K-feldspar porphyroclasts (Fig. 3C). Minor porphyroclasts of plagioclase and biotite and accessory zircon, apatite, tourmaline, sphene and opaque minerals are present. Plagioclase exhibits kink-band structures with folded polysynthetic twins. Quartz is concentrated into well-oriented "ribbons" of fine-grained recrystallized aggregate bands. S–C microstructures are widespread, with the C planes delineated by biotite and very fine-grained retrograde aggregates, suggesting a retrograde formation in a ductile shear zone (Passchier and Trouw, 2005). The aforementioned features indicate intermediate temperature deformation conditions.

Some well-rounded pebbles correspond to rhyolite with porphyritic texture and an aphanitic matrix characterized by a marked flow foliation (Fig. 3D). They preserve phenocrysts of feldspar, plagioclase and bipyramidal quartz. The largest hypidiomorphic quartz crystals have embayments that are characteristic for magmatic growth in a fine-grained matrix. Unfortunately, these acid volcanic rocks did not provide any zircons. Similar acid volcanic rocks have been described in the Ceuta Unit (Durand-Delga and Kornprobst, 1963), at the base of Carboniferous assigned to the Alpujarride/Sebtide Complex and later (Kornprobst, 1974) to the Malaguide/Ghomaride.

The CM-8 group (Fig. 2E) includes schists and quartzites with a penetrative schistosity. The major components are quartz, muscovite, biotite and plagioclase. Minor amounts of tourmaline and garnet (Fig. 3F) with opaque minerals and zircon appear as accessory components. A distinctive lenticular domainal structure that reflects the tendency of deformation to be partitioned into high- and low-strain domains (Fig. 3E) is observed. The domains with high strain are thin, fine-grained and rich in aligned biotite, white mica, chlorite and dark, carbonaceous and iron-titanium oxide. These domains compose an anastomosed network of bands that isolate lens-shaped domains with large recrystallized grains of quartz. Many samples show quartz ribbons and some of them are arranged in domains. Mica fish and kink-bands are developed in some muscovite crystals.

4. Analytical methods

4.1. Zircon LA–ICP-MS dating

Zircons from the brown–reddish matrix sandstones (CM-10; N36° 34′ 9.8″ W4° 35′ 40.4″) of the Marbella Conglomerate (Figs. 1B, 2B) were separated at the University of the Basque Country (UPV/EHU). After crushing and sieving the <250 μm fraction, the heavy mineral concentrate was isolated by using heavy liquids (methyl iodide) and an isodynamic magnetic separator (Frantz). The final selection of the zircon grains for U–Pb dating was achieved by handpicking under a binocular microscope. Zircons of all grain sizes, color and morphological types were selected, mounted in epoxy resin and polished to approximately half of their thickness. The zircon grains were examined regarding their cathodoluminescence signal using an EVO 50 Zeiss Scanning Electron Microscope (Senckenberg Naturhistorische Sammlungen, Dresden) prior to U–Pb analysis. This helps to distinguish different growth and metamorphic zones within the zircon grains. The selected zircons were analysed for U, Th, and Pb isotopes by LA–ICP-MS

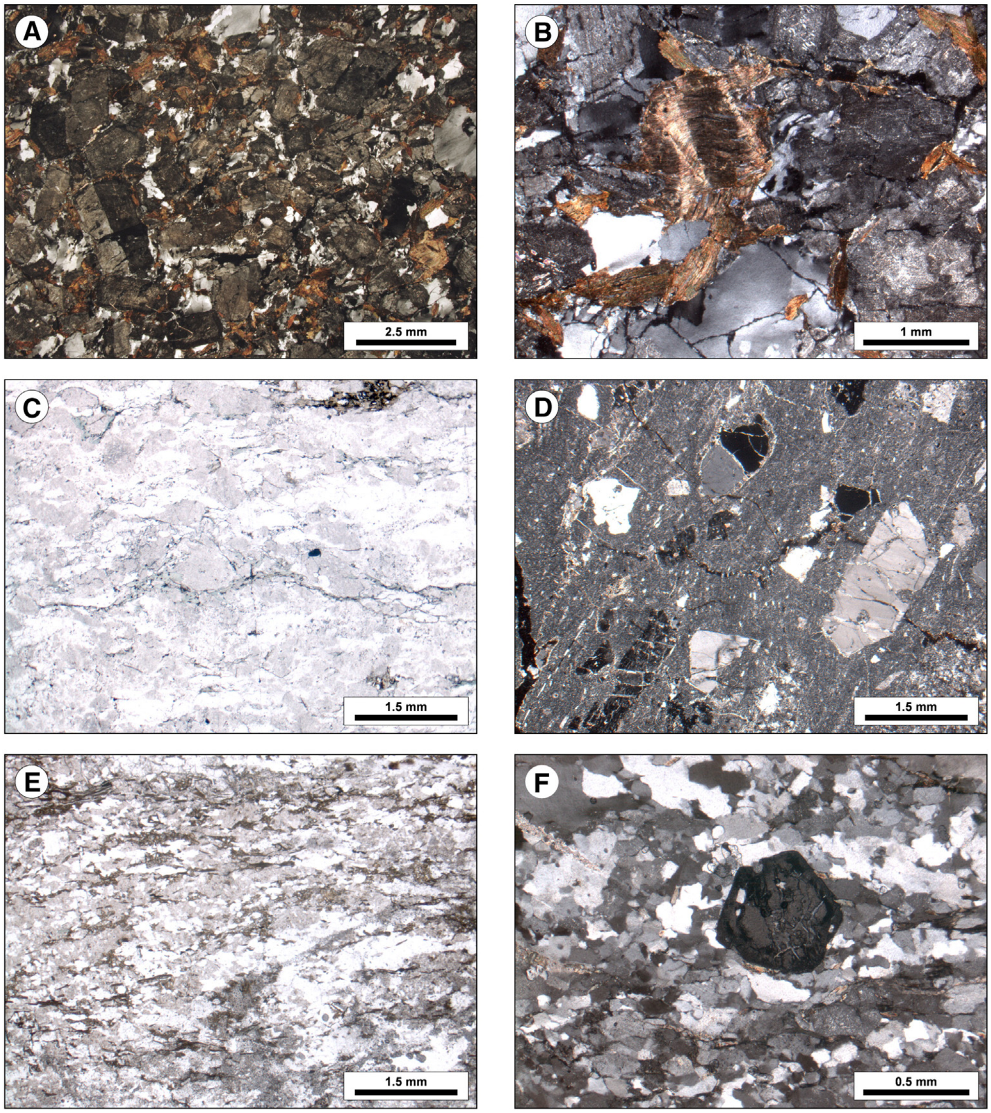

Fig. 3. Photomicrographs of textures in basement pebbles A) Deformed granitoid of the CM-4 group showing residual fractured phenocrysts of K-feldspar with simple twinning and euhedral zoning growth of magmatic origin. The grains of quartz display subgrains and recrystallization. Biotite is kinked during deformation. Crossed polars. B) Detail of the same thin section of 3A showing the axial planes of biotite with kink bands that are parallel to the subgrain boundaries in deformed quartz. C) Mylonite from the CM-5 group. Feldspar "augens" are surrounded by quartz, biotite and very fine-grained aggregates that define the mylonitic foliation. Plane-polarized light. D) Rhyolite with large grains of quartz and K-feldspar. The idiomorphic shape of bipyramidal quartz with embayments, the weak undulatory extinction and the strong contrast between the large crystals with the well oriented fine-grained matrix points to the magmatic origin of this rock. Crossed polars. E) Lenticular domains in schist of the CM-8 group. Biotite, muscovite and dark aggregates define the schistosity anastomosed around recrystallized domains of quartz and feldspar. Crossed polars. F) Detail of garnet porphyroblast in schist of the CM-8 group. The garnet has a sharply defined inclusion free idiomorphic rim showing several stages of metamorphic conditions during its growing. Polars at 60°.

techniques at the Senckenberg Naturhistorische Sammlungen, Dresden (Museum für Mineralogie und Geologie, Sektion Geochronologie), using a Thermo-Scientific Element 2 XR sector field ICP-MS coupled to a New Wave UP-193 Excimer Laser System. A teardrop-shaped, low volume laser cell (modified version of the NERC Isotope Geosciences Laboratory in UK; see Bleiner and Günther, 2001; Gerdes and Zeh, 2006) was used to enable sequential sampling of heterogeneous grains (*e.g.* growth zones) during the time resolved data acquisition.

Each analysis consisted of 15 s background acquisition followed by 30 s data acquisition, using a laser beam of 20–25 μm size. A common-Pb correction based on the interference and background-corrected ^{204}Pb signal and a model Pb composition (Stacey and Kramers, 1975) was carried out if necessary. Raw data were corrected for background signal, common Pb, laser induced elemental fractionation, instrumental mass discrimination, and time-dependent elemental fractionation of Pb/Th and Pb/U using an Excel® spreadsheet developed by Gerdes (Gerdes and Zeh, 2006). Reported uncertainties were propagated by quadratic addition of the external reproducibility obtained from the standard zircon GJ-1 (~0.6% and 0.5–1% for the ^{207}Pb/^{206}Pb and ^{206}Pb/^{238}U, respectively) during individual analytical sessions and the within-run precision of each analysis. Concordia diagrams (2σ error ellipses) and Concordia ages (95% confidence level) were produced using Isoplot/Ex 3.0 (Ludwig, 2003) and frequency and relative probability plots using DensityPlotter v.2.2 (Vermeesch, 2012). Th/U ratios are obtained from the LA–ICP-MS measurements of the analysed zircon grains. This ratio has been used to discriminate between magmatic (Th/U > 0.1) and metamorphic (Th/U < 0.1) zircons (*e.g.* Hoskin and Ireland, 2000; Hoskin and Schaltegger, 2003; Rubatto, 2002). U and Pb content and Th/U ratio were calculated relative to the GJ-1 zircon standard and are accurate to approximately 10%.

4.2. Zircon U–Pb SIMS SHRIMP dating

Three representative samples of the most common metamorphic and magmatic pebbles from the Marbella Conglomerate were processed according to the previously described zircon separation routine. With a 0.2 to 0.3 kg weight, the samples correspond to a deformed granite (CM-4), a porphyritic orthogneiss (CM-5) and a quartz-schist (CM-8), taken from an outcrop at latitude 36° 34′ 8.4″ north and longitude 4° 35′ 41.8″ west (Fig. 1B). The selected zircons were mounted in epoxy resin together with the TEMORA 1 and 91500 reference zircons, sectioned approximately in half and polished. Cathodoluminescence (CL) images were used to reveal the internal structures of the zircon grains and thereby define target areas within them. *In situ* U–Pb analyses were performed on a SHRIMP-II SIMS in the Centre of Isotopic Research (CIR) at VSEGEI (Saint Petersburg, Russia). The results were obtained with a secondary electron multiplier in peak-jumping mode following the procedure described by Williams et al. (1998) and Larionov et al. (2004). U–Pb ion microprobe data were processed with the SQUID 1.02 and Isoplot/Ex 3.00 (Ludwig, 2003) software, using the decay constants of Steiger and Jäger (1977) and ^{206}Pb/^{238}Pb age frequency and relative probability plots using DensityPlotter v.2.2 (Vermeesch, 2012).

5. Results

5.1. Zircon LA–ICP-MS dating

One hundred and eighty one U–Pb sample analyses have been performed. After data reduction and age calculations, the ^{206}Pb/^{238}Pb age of those zircons with a degree of concordance in the range of 95–105% are classified in this paper as concordant because of the overlap of the error ellipse with the Concordia. The number of concordant (non-rejected) analyses is 126 (70% of the total amount). Selected analyses are presented in order of increasing ^{206}Pb/^{238}U age in Supplementary Table 1. All the U–Pb data are plotted in Tera-Wasserburg diagrams, kernel density estimation and probably density distribution plots (Fig. 4).

The 56% of the analysed zircons are Precambrian in age and mostly yield Neoproterozoic (540–700 Ma/44%) and Paleoproterozoic (1800–2500 Ma/9%) ages, with the rest being Mesoproterozoic (980–1060 Ma/1%) and Archean (2500–2900 Ma/2%) (Fig. 4). The remaining 44% of zircons define four Paleozoic populations of Cambrian to Ordovician (25%), Devonian (7%), Carboniferous (9%) and Permian (3%) ages. The youngest concordant ^{206}Pb/^{238}U Permian analyses (b15; Supplementary Table 1) yield an age of 286 Ma, which represents the maximum age for the deposition of the Marbella Conglomerate.

5.2. Zircon U–Pb SIMS SHRIMP dating

The deformed granite, CM-4 (Fig. 2C), contains zircons with a clear core-rim structure (Fig. 5). Twenty-one U–Pb analyses have been carried out on 11 cores and 10 rims of selected zircon grains (Supplementary Table 2). The cores are anhedral and display oscillatory and convoluted zoning with Th/U values higher than 0.27 (Supplementary Table 2), typically of intermediate-felsic igneous rocks. They yield ^{206}Pb/^{238}U ages from 2290 to 502 Ma, but most of them are concentrated around *ca.* 530 Ma. The Concordia age of 532 ± 7 (2σ) Ma is obtained from 6 zircons and is interpreted as the youngest recognized igneous zircon crystallization age. The external rims are euhedral, display oscillatory growth zoning and show dark luminescence and low Th/U ratios (~0.01), suggesting high-grade metamorphic zircons (*e.g.* Williams and Claesson, 1987), such as those linked to anatexis (*e.g.* Zeck and Whitehouse, 1999). In spite of these characteristics, the results of the rims are difficult to interpret as ^{206}Pb/^{238}U ages range from *ca.* 249 to 360 Ma. The most probable explanation for such scattering is that the youngest ages, characterized by high common Pb content, are affected by Pb-loss. Eight spots from rims with the lowest ^{204}Pb-contents yield the Concordia age of 356 ± 2 (2σ) Ma, which we attribute to a deformational Variscan event linked to high-grade metamorphic conditions.

The porphyritic orthogneiss sample, CM-5 (Fig. 2D), is characterized by the presence of euhedral and subhedral zircons (Fig. 6) with well-develop oscillatory igneous zoning (Th/U > 0.27). They all depict very thin and bright luminescence external rims. Locally (spots 17.1 and 18.1), rounded anhedral cores have also been recognized. Eighteen of the twenty-two analysed zircons are characterized by low ^{204}Pb-contents and provide the Lower Cambrian Concordia age of 516 ± 2 (2σ) Ma that is interpreted as the crystallization age of the igneous protolith.

The grains of zircon from the quartz-schist sample, CM-8 (Fig. 2E), mainly display subhedral to euhedral morphology, some bearing cores with oscillatory growth zoning and Th/U ratios higher than 0.24 with overgrowth of extremely light luminescent thin rims (Fig. 7). In spite of the effort to date these rims, they are not large enough to obtain a coherent isotopic characteristic (Supplementary Table 2). These rims yield ages ranging 282–340 Ma, and even do not show ^{206}Pb/^{238}U age agreement between analyses taken on similar areas of zircons (Supplementary Table 2; spot 20.1RE and 20.2RE). Such characteristics

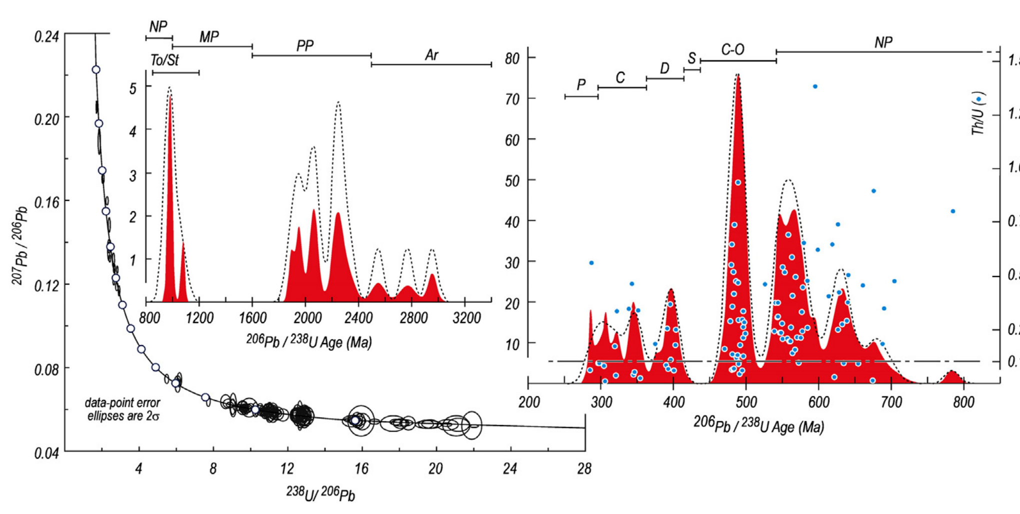

Fig. 4. Tera-Wasserburg diagram, probability density age (in red) and Kernel estimation (dotted line) density plots for the brown-reddish matrix sandstone of the Marbella Conglomerate: Ar — Archean, PP — Paleoproterozoic, MP — Mesoproterozoic, NP — Neoproterozoic, To — Tonian, St — Stenian, C–O — Cambrian-Ordovician, S — Silurian, D — Devonian, C — Carboniferous, P — Permian. The circles in the Neoproterozoic and Phanerozoic age span show the Th/U ratios of the dated zircons. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

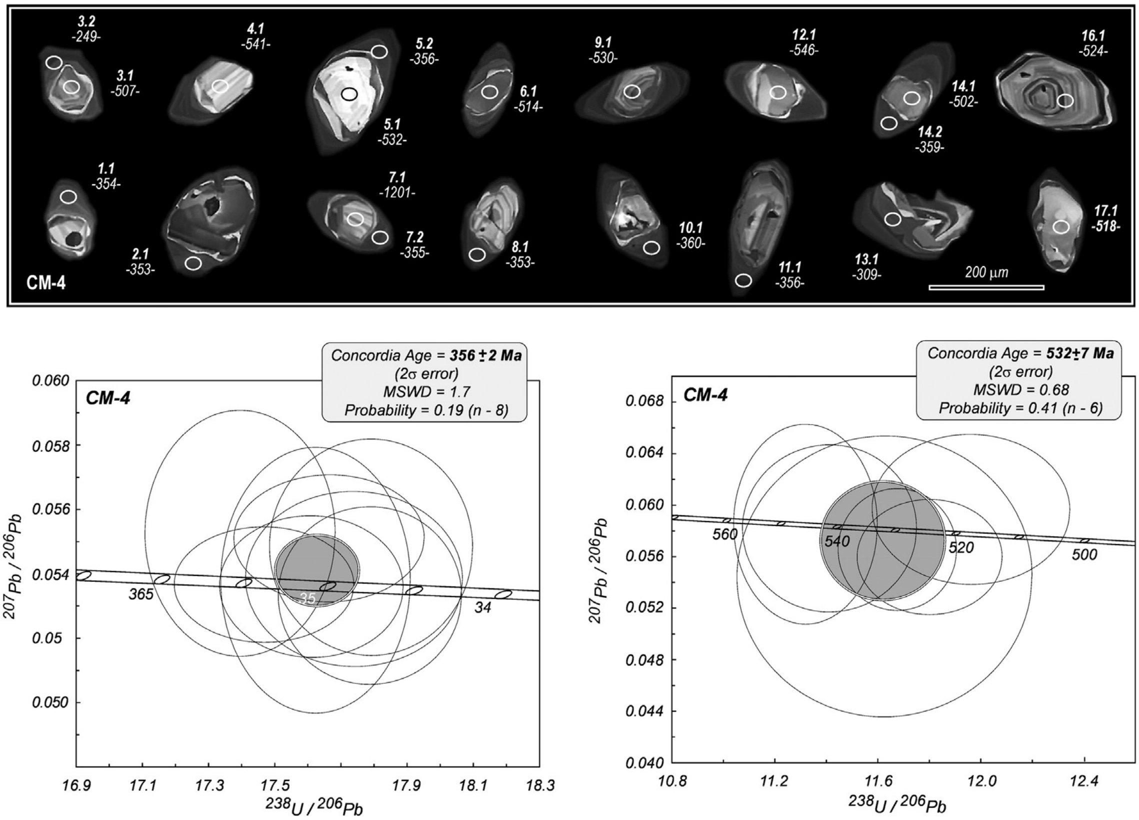

Fig. 5. Tera-Wasserburg diagrams and cathodoluminescence images of representative dated zircons of CM-4 sample (deformed granitoid).

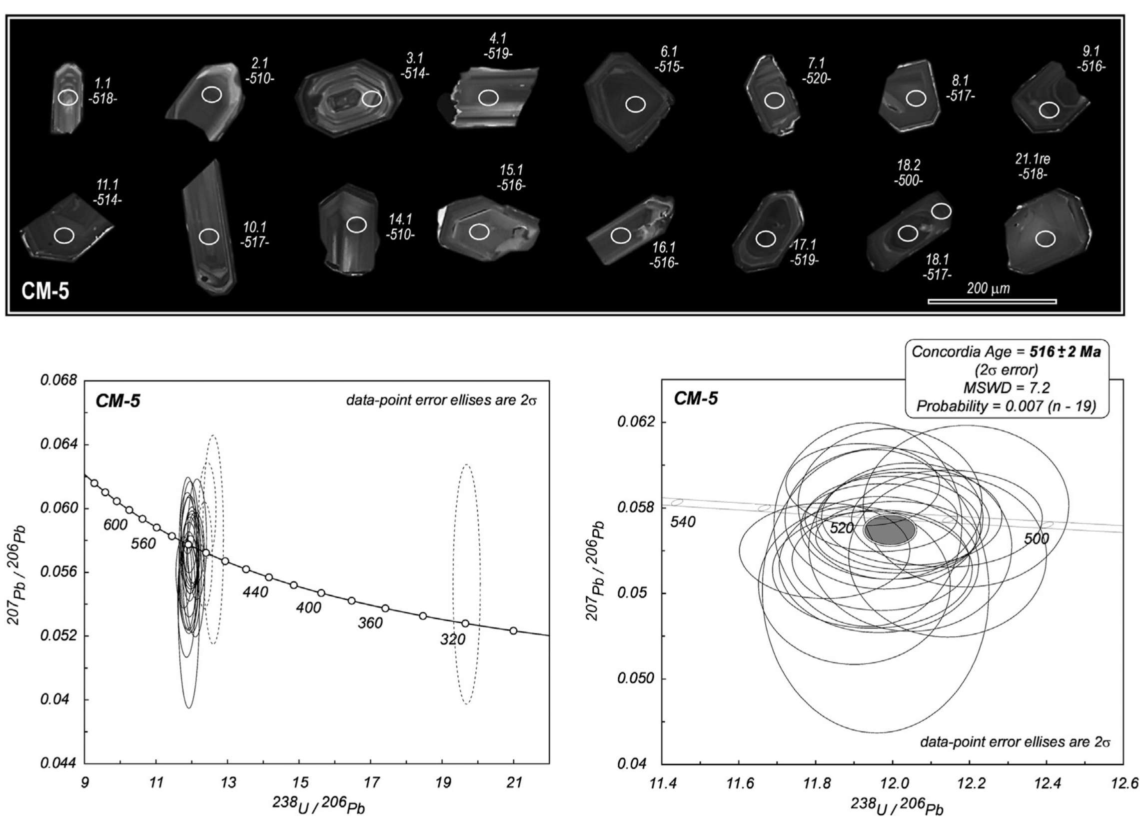

Fig. 6. Tera-Wasserburg diagrams and cathodoluminescence images of representative dated zircons of CM-5 sample (porphyric orthogneiss).

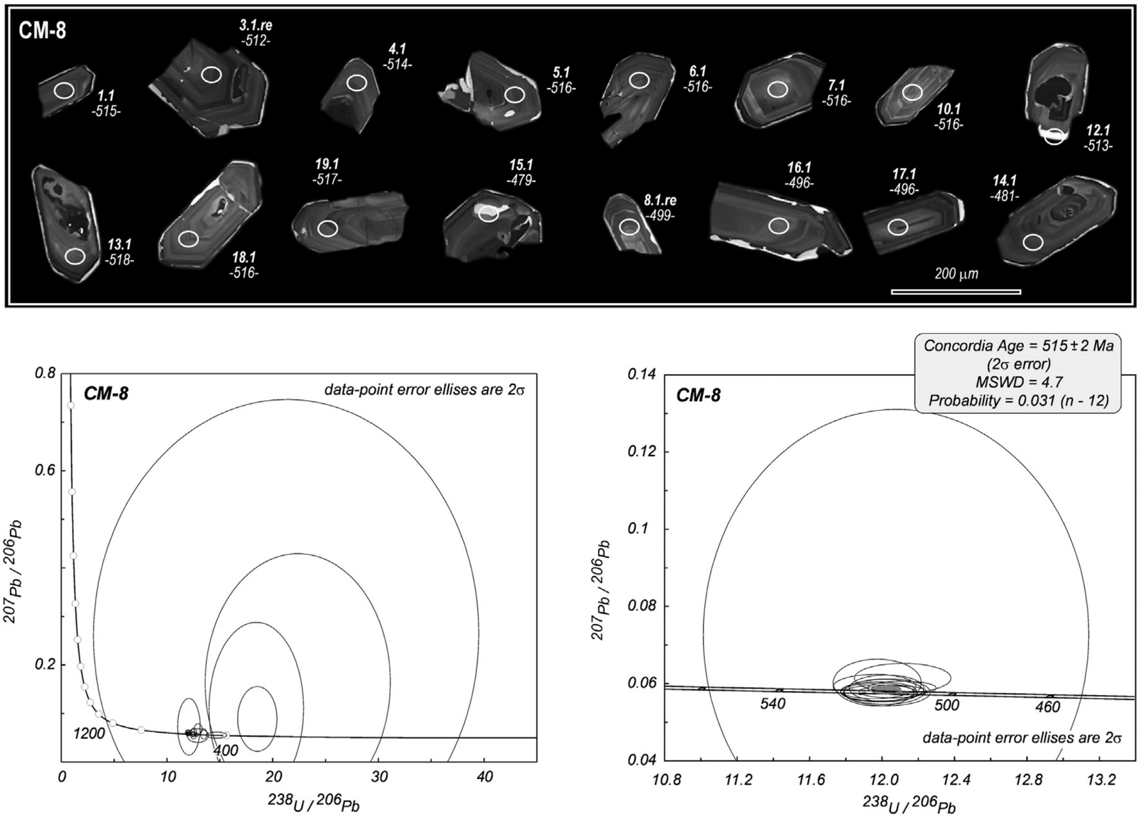

Fig. 7. Tera-Wasserburg diagrams and cathodoluminescence images of representative dated zircons of CM-8 sample (quartz-schist).

could support a Pb-loss of the youngest zircons as they do have the highest measured common Pb values (8–63%). Another cause of the dispersion of results could be an incomplete isotopic re-equilibration in these recrystallization rims, along with apparent age spread due to low U and Pb, responsible for poor accuracy. Seventeen core analyses were performed yielding scattered $^{206}Pb/^{238}U$ ages between 461 and 518 Ma. Eleven of them (Supplementary Table 2) provide the Concordia age of 515 ± 2 (2σ) Ma, the same age as that of the CM-5 orthogneiss, which is interpreted as an igneous event of zircon growth. However, the $^{206}Pb/^{238}U$ age scattering cannot be directly interpreted, as some of the analysed zircons do yield Cambrian-Ordovician ages (461–499 Ma).

Two main conclusions can be drawn from the results on the three pebble samples: a) the data obtained define three main $^{206}Pb/^{238}U$ age clusters at 532 ± 7, 515 ± 2 and 356 ± 2 Ma, and b) the Th/U ratios do agree with a Cambrian magmatic event and with a zircon overgrowth during a high-grade Carboniferous metamorphism. Moreover, the deduced Cambrian-Ordovician age (eight analyses; see Supplementary Table 2) raises the problem of whether it represents a new zircon growth population or if marks a late Pb-loss. Based on the similar ages obtained on the detrital zircon from the CM-10 sandstone (490 ± 2 Ma), we think that the Cambrian-Ordovician ages for samples CM-5 and CM-8 would represent a zircon growth event, for which a weighted average age of 495 ± 5 Ma is obtained.

6. Discussion

The geochronological study of zircons from the four samples of the Paleozoic Marbella Conglomerate of the Malaguide Complex (Betic Cordilleras, southern Spain) reveals a large dispersion, from Proterozoic to Permian, of the obtained ages. There are, however, two main clusters, ranging from Neoproterozoic to Early Ordovician and from Devonian to Permian times. In addition, a few but relevant results yielded Paleoproterozoic ages (Fig. 4).

Given the immature nature of the Marbella Conglomerate it is reasonable to assume a rather local provenance of the studied pebbles and detrital zircons present in the matrix. From this point of view we will explore the possible proximal sources of the different populations obtained and correlate them with their putative sources at Permian times. In addition, the fact that the studied rocks postdate the Variscan orogeny makes the interpretation of the possible sources more difficult, as several realms were amalgamated in the nearby Iberian Variscan belt (Fig. 1A), namely South Portuguese [SPZ], Ossa-Morena [OMZ] and the Central Iberian Zones [CIZ] with different sources along Neoproterozoic and Paleozoic times and the possible mixing of them due to the recycling of their variable zircon record. Finally, we will discuss and trace the possible sources of the different population of zircons found in this study.

6.1. Constraints from the Precambrian detrital zircons

The Proterozoic ages come entirely from the detrital zircons contained in the sandstone matrix of the Marbella Conglomerate. The obtained age distribution is characterized by the lack of Mesoproterozoic ages (1700 to 1000 Ma) and the paucity of Middle and Early Neoproterozoic (950 to 750 Ma) ages (Fig. 4). The scarcity of such Mesoproterozoic ages has also been noted in the Alpujarride nappes of the Betic Cordilleras (Fig. 8; Esteban et al., 2011; Zeck and Whitehouse, 1999, 2002). This age partitioning constrains the provenance of the Proterozoic detrital zircons of the Marbella Conglomerate. Specifically, the lack of Mesoproterozoic ages enables the Amazonian, Meta-Saharan cratons or Arabian-Nubian Shield (Fig. 9) to be discarded as primary possible source areas, as they usually provide numerous geochronological evidences on the Rodinia amalgamation between 1200 and 1000 Ma (Weil et al., 1998). Alternatively, the lack of Mesoproterozoic zircons and the scarcity of the Early Neoproterozoic ones is usually linked with a provenance of the detrital zircons from a likely area inside the West African Craton and close to the mobile

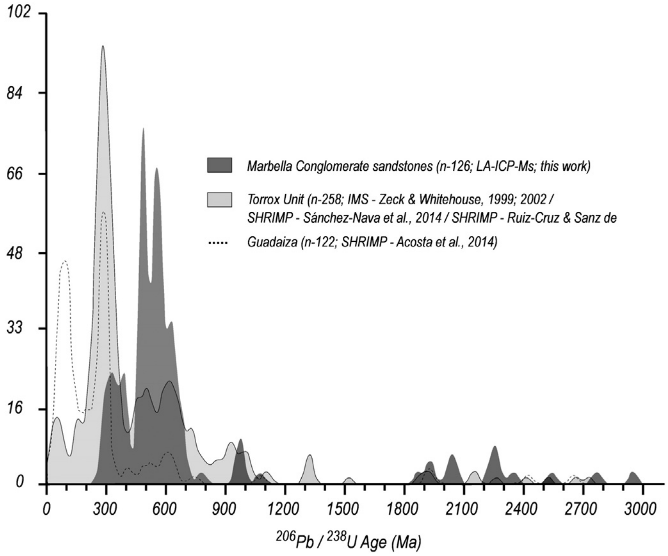

Fig. 8. Probability density age plots of Torrox gneiss/schist (data from Sánchez-Nava et al., 2014; Ruiz Cruz and Sanz de Galdeano, 2014; Zeck and Whitehouse, 1999, 2002), Guadaiza nappe (Acosta-Vigil et al., 2014) and Malaguide Conglomerate (this work).

Trans-Saharan belt, where Cryogenian-Tonian ages are common (*e.g.* Ennih and Liégeois, 2008).

The high proportion of the Ediacaran ages (26%) in the Marbella Conglomerate (Fig. 4) suggests a zircon provenance from the Avalonian or Cadomian belts generated along the northern periphery of the West African Craton (Fig. 9) during the subduction of the Iapetus Ocean between 590 and 550 Ma (*e.g.* Linnemann et al., 2008). However, the Cadomian arc is interpreted to have recycled ancient West African crust (3000–2000 Ma), while the Avalonian belt is thought to have derived from a younger domain (1300–1000 Ma) (Murphy et al., 2004), a significant contrast that would support a Cadomian affinity for the source area of the Marbella Conglomerate.

The divergence between the ages and isotopic data obtained in this work with those from the neighbouring Iberian Massif (Fig. 10) could be of assistance in the search for potential paleo-geodynamic settings that might supply the wide diversity of zircons preserved in the Marbella Conglomerate. To this end, the Gondwanan basement of the Iberian Variscan belt (SPZ, OMZ and CIZ; Figs. 1A and 10) provides different Precambrian age sets in their igneous, metamorphic and sedimentary record.

Within the SPZ, the oldest formation (Mértola Fm.) of the Devonian to Upper Carboniferous sediments lacks a significant proportion of Precambrian zircons while its uppermost formations (Mira and Brejeira Fms.) yield abundant Neoproterozoic zircons (Pereira et al., 2012a) within the age range found in the Marbella Conglomerate. In the OMZ, the presence of Neoproterozoic, Paleoproterozoic and Archean ages in the Ediacaran-Paleozoic sedimentary sequence, together with the lack of Mesoproterozoic ones are consistent with a Cadomian affinity for its inherited zircons (Fernández-Suárez et al., 2002; Pereira et al., 2011, 2012b) that also matches the Precambrian zircon populations found in the Marbella Conglomerate. Finally, the detrital zircon content of the CIZ affords two different sets of detrital zircons that can be found in its northern and southern sides. Ediacaran-Cryogenian, Tonian-Stenian, Paleoproterozoic and Archean age populations are present in the Neoproterozoic (*e.g.* Fernández-Suárez et al., 2014 and references therein) and Paleozoic rocks (Gutiérrez-Alonso et al., 2015; Shaw et al., 2014) of the northern part of the CIZ. In contrast, the Neoproterozoic rocks of the southern part provide zircon populations that resemble those of the OMZ with no or minor Tonian-Stenian age zircons (Pereira, 2015; Pereira et al., 2012b).

6.2. Paleozoic detrital zircons

Four clusters of Paleozoic zircon ages can be distinguished in the Marbella Conglomerate: a) Cambrian-Ordovician, c) Lower-Middle Devonian, d) Carboniferous and e) Permian.

The Cambrian-Ordovician cluster comes from the protolith ages of the studied pebbles, that yield Concordia ages of *ca.* 530 and 515 Ma, and also from 30 of the sandstone-derived zircons which range from 527 to 472 Ma. Noteworthy, the zircons obtained in the conglomerate matrix depict Ordovician ages, in contrast with the Cambrian ages found in the clasts.

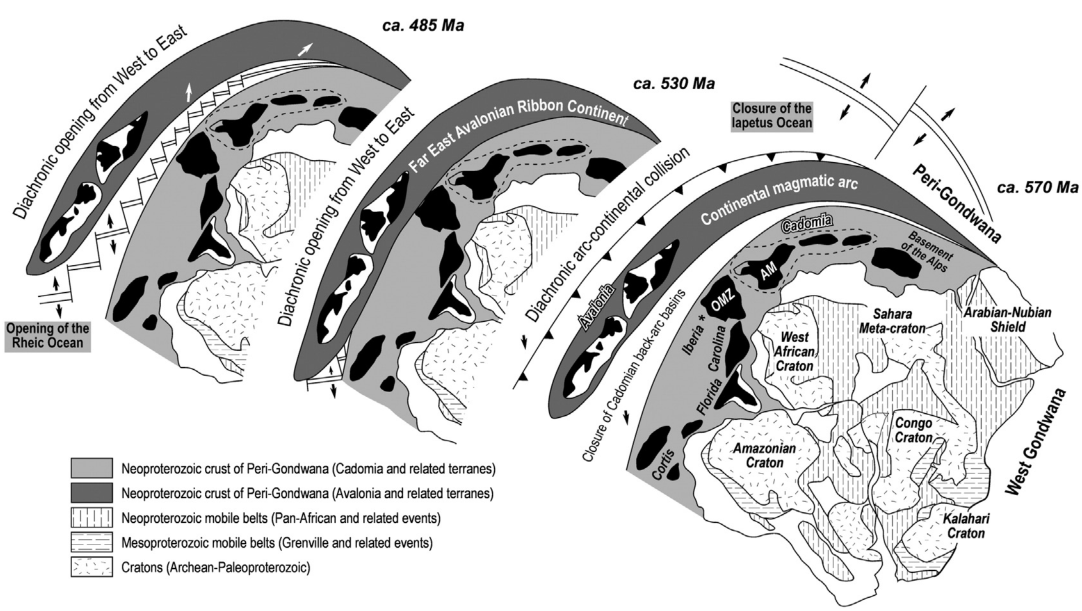

Fig. 9. Palinspastic reconstructions of the northern border of Gondwana at the Precambrian-Cambrian transition (*ca.* 545–570 Ma), Cambrian (*ca.* 530 Ma) and Ordovician (*ca.* 485 Ma), showing the main cratonic, Neoproterozoic Peri-Gondwana crust and mobile belts, areas from the closure of the Iapetus Ocean to the opening of the Rheic Ocean (OMZ: Ossa-Morena Zone/AM: Armorican Massif).
Taken and modified from Linnemann et al. (2008).

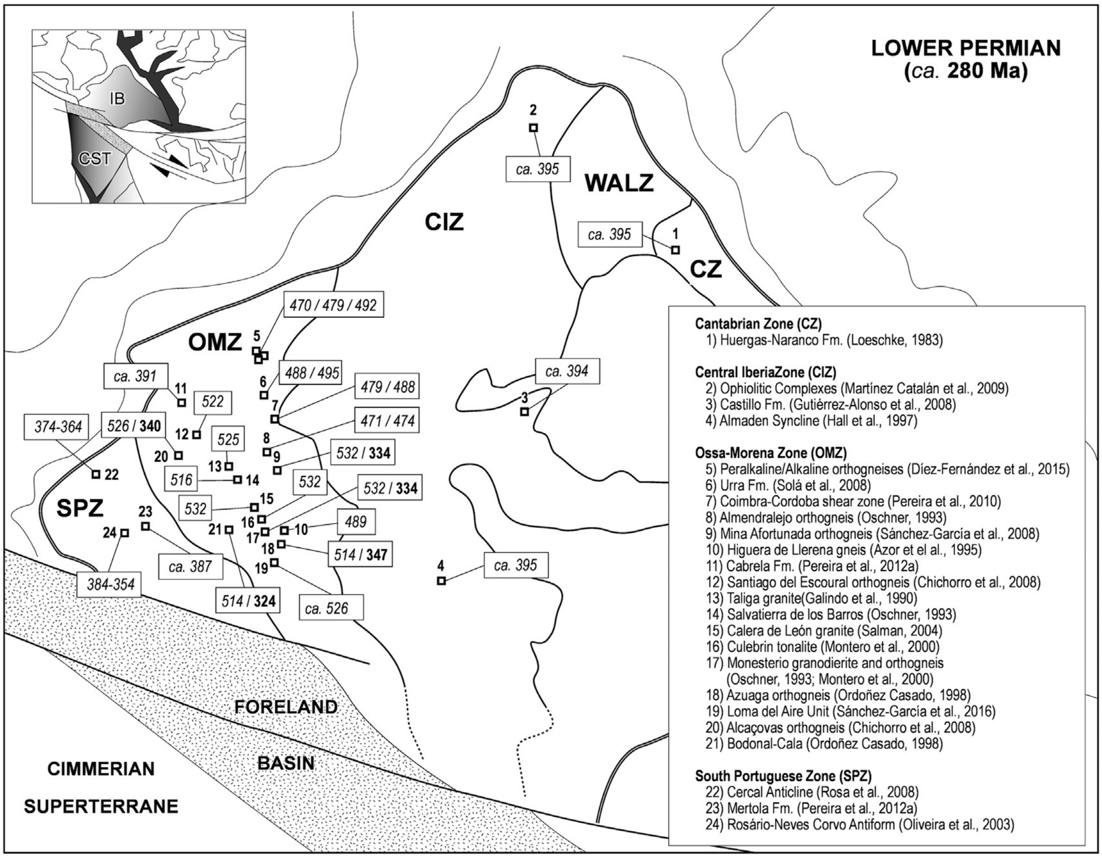

Fig. 10. Distribution of zircon ages of the main tectonic domains within the Iberian Variscan belt at Lower Permian (≈285 Ma) used in the discussion (italics: protolith igneous ages; bold ages: metamorphic ages; CST: Cimmerian Superterrane; IB: Iberia).

According to the protolith ages of the studied clasts and the available data in neighbouring tectonic domains, especially the OMZ (Fig. 10), the clast ages are consistent with sequential magmatic events that have been recognized in the OMZ (Iberian Variscan belt) and correlated with the Early (*ca.* 530–524 Ma) and the Main Rift-related Igneous Event (*ca.* 519–499 Ma) (Chichorro et al., 2008; Sánchez-García et al., 2003, 2010), respectively. The older event is interpreted to be responsible for the most voluminous emplacement of granitoids associated with anatectic processes in the upper and middle crust (Sánchez-García et al., 2014). In contrast, the younger event has resulted in formation of a heterogeneous suite of rocks, typical of within-plate magmatism derived from enriched asthenospheric sources (Chichorro et al., 2008).

Concerning the possible source(s) of rocks of similar Cambrian-Ordovician ages, our attention should be concentrated on those zircons with high Th/U values, common of igneous origin, as those found in our samples (Supplementary Table 2). In this regard, the OMZ displays a large age span (Fig. 9), ranging from 540 to 490 for igneous and ortho-derived rocks. The tonalite of the Culebrin (532 ± 4 Ma; Montero et al., 2000), the granodiorite of Monesterio (527 Ma; Oschner, 1993) and the granites of Táliga (525 ± 2.5 Ma; Galindo et al., 1990) and Calera de Leon (524 ± 4 Ma; Salman, 2004) yielded zircon intrusion ages of around 530 Ma. The vulcanites of the Loma del Aire Unit do provide ages of *ca.* 526 and 505 Ma for the eruption/deposition (Sánchez-García et al., 2016). The ortho-derived rocks related to the Mina Afortunada (532 ± 5 Ma; Sánchez-García et al., 2008), Monesterio (532 ± 5 Ma; Montero et al., 2000), Alcaçovas (526 ± 9.9 Ma; Chichorro et al., 2008) and Santiago del Escoural orthogneises (522.3 ± 5.1 Ma; Chichorro et al., 2008) yielded similar ages. Otherwise, igneous zircon ages of around 515 Ma were found in the granites of Salvatierra de los Barros (516 Ma; Oschner, 1993), Tablada (511 ± 8 Ma; Oschner, 1993), Bodonal-Cala (514 ± 9 Ma; Ordóñez Casado, 1998), Monesterio (510 ± 8 Ma; Montero et al., 1999) and the orthogneises of Azuaga (514 ± 8 Ma; Ordóñez Casado, 1998).

The *ca.* of 490–470 Ma ages are also common within the OMZ (Fig. 10), for instance in some peralkaline and alkaline syenites (Díez-Fernández et al., 2015), in volcanoclastic rocks of the Urra Formation (Solá et al., 2008), the metamorphic formations of Sierra Albarrana (Azor et al., 1995), the Almendralejo orthogneisses (Oschner, 1993) or at the Coimbra-Cordoba shear zone (Pereira et al., 2010). Together, these Ordovician ages suggest the continuity of the Cambrian rifting that culminates in the Rheic Ocean opening (*e.g.* Nance and Linnemann, 2008). The lack of Upper Ordovician, Silurian and Lower Devonian ages in detrital zircons from the sandstone matrix (Fig. 4; Supplementary Table 1) points to the lack of zircon growth events (or unavailability of sources) and raises the possibility of linking the Marbella Conglomerate with the spreading of the Rheic Ocean (Fig. 9) in the northern Gondwana passive margin (Avalonia drifting episode), similar to what Pastor-Galán et al. (2013) have already proposed for the NW part of the Iberian Variscan belt.

One of the most striking zircon ages gathered from the samples studied is the Lower-Middle Devonian zircon population (*ca.* 397 Ma). Zircons of Devonian age are almost absent or volumetrically insignificant in the Iberian Variscan Belt, with the exception of the SPZ and to a lesser extent the CIZ (Fig. 10 and references therein). Regarding the SPZ, Devonian ages are mostly obtained in the Variscan synorogenic basins that surround the SPZ-OMZ boundary and in the Pulo de Lobo terrain (Braid et al., 2011). Similar igneous ages (Fig. 10) are restricted to the sub-volcanic continental tholeiitic basalt of the Huergas-Naranco Formation (*ca.* 395 Ma; Loeschke, 1983) in the Cantabrian Zone, ophiolitic complexes of the NW Iberia (Martínez Catalán et al., 2008), the alkaline basalts and mafic volcaniclastic rocks of the Castillo Formation (394 Ma; Gutiérrez-Alonso et al., 2008) and the hydrothermal alteration of the

Almaden Syncline (395 Ma; Hall et al., 1997) within the Central Iberian Zone. The Cercal Anticline porphyritic felsic volcanic rocks (374–364 Ma; Rosa et al., 2008) and the Rosário-Neves Corvo antiform volcanic rocks (384–354 Ma; Oliveira et al., 2013) at the Iberian Pyrite Belt of the SPZ also yield similar ages. In this regard, it has been suggested that the Devonian volcanism could have been triggered by a regional extensional event related to coupling of the Rheic Ocean with the Iberian portion of northern Gondwana (Gutiérrez-Alonso et al., 2008). However, all of these domains, except the SPZ, should be discarded as provenance areas as they are far away at the time of the deposition of the Permian basin (*e.g.* Huergas-Naranco Formation, ophiolitic complexes…) or the paucity of the Tonian-Stenian ages in our samples. Therefore, an alternative provenance must be taken into consideration. For instance, the provenance analysis conducted by Pereira et al. (2012a) on the Upper Carboniferous turbidite sedimentary rocks of some synorogenic basins located on both sides of the presumed Rheic suture (Mertola at SPZ and Cabrela Formation at OMZ), revealed that they do contain abundant Lower- to Middle Devonian zircons (*ca.* 387 Ma for Mertola and *ca.* 391 Ma for Cabrela Formation) which were interpreted as derived from an apparently eroded short-lived volcanic arc. Such ages, agree again with those obtained in this study, and reinforce a local Cadomian terrane, similar to the Ossa-Morena Zone, for being the primary provenance area.

Regarding the presence of Carboniferous ages in the studied zircons, it is noticeable that one of the deformed granitoid pebble (CM-4) displays zircon rims with a Concordia age of 356 ± 2 Ma (Lower Carboniferous) that contrast to the core ages (532 ± 7 Ma) (Fig. 5). These rims are characterized by lower Th/U ratios (~0.01) than their cores (0.88–0.27). Therefore they could attest to the overprinting of a Lower Carboniferous metamorphic event on Cambrian magmatic rocks. Orthogneisses of similar Carboniferous metamorphic ages are mainly found in the Badajoz-Cordoba shear zone, the Olivenza Monesterio antiform and even in the Evora-Aracena-Lora del Rio metamorphic band of the OMZ in the Iberian Variscan belt. Some of these ages are well represented within the Azuaga gneisses (347 ± 11 Ma; Ordóñez Casado, 1998), the anatectic gneiss domes of Monesterio and Mina Afortunada (334 ± 14 Ma, Ordóñez Casado, 1998; 339 ± 14 Ma, Quesada and Dallmeyer, 1994) and Alcaçovas (339.7 ± 5.5 Ma, Pereira et al., 2009). As in the case of the CM-4 sample of the Marbella Conglomerate, these ortogneisses yield crystallization ages ranging from *ca.* 533 to 514 Ma for the magmatic protoliths and late metamorphic recrystallization ages, from 347 to 334 Ma, for the zircon rims.

On the other hand, Carboniferous-Permian ages in the detrital zircons record three main age clusters that constrain the possible sources of the studied rocks. The first cluster at *ca.* 345 Ma is coincident with the ages found in the pebble's zircon rims (see above). The second cluster has an age of *ca.* 320 Ma, which is also common in the OMZ (*i.e.* Medina de las Torres Stock, Cambeses et al., 2015 and references therein). Finally, the Pennsylvanian-Early Permian ages (*ca.* 310–280 Ma) obtained from detrital and some zircons of the studied pebbles are interpreted to be associated to the latest magmatic episode, which is widespread throughout the whole Iberian Variscan belt (Gutiérrez-Alonso et al., 2011).

6.3. Paleogeographic location

Given the complex evolution of the northern Gondwana margin during the Ediacaran and most of the Paleozoic (Fig. 9), which includes different magmatic–metamorphic episodes with zircon generation, it is not straightforward to correlate the studied rocks with a source area within the adjacent realms. Taken into account the likeness of the zircon age populations and the nature of the studied pebbles with rocks of the OMZ, it could be interpreted that most of them would come from the OMZ or its nowadays non-exposed continuation, once the Variscan collision was completed.

Attempts to place the Alboran domain into paleogeographic reconstructions during the Upper Paleozoic within the Variscan belt at the northern border of Gondwana are only tentative. While some authors (Stampfli et al., 2013) consider the basement of the Alboran domain as part of the European Hunic terranes that drifted away from Gondwana during the Ordovician opening of the Paleotethys Ocean, others (Esteban et al., 2011, 2013) suggest that it would belong to the European Cimmerian terranes (Fig. 11) linked to the opening of the Neotethys during the Mesozoic. According to Esteban et al. (2011), the age record retained in zircon grains from the Alpujarride units (Guadaiza nappe and Yunquera Unit) underlying the Ronda peridotites, points to the West African Craton (WAC) and its surrounding Panafrican belts as a reliable source area for their sedimentary protoliths. In contrast, these new geochronological data from the Marbella Conglomerate of the Malaguide Complex are in agreement with a late to post-Variscan basin, which was likely filled mainly with sediments supplied by the Ossa-Morena Zone of the Iberian Massif but not excluding minor contribution from other zones. In this regard, it is important to note that the detrital geochronological data obtained from the deformed pebbles of the Marbella Conglomerate are significantly different from those obtained in other tectonic units that conforms the Alboran domain (*e.g.* Alpujarride Complex) (Fig. 8). From this point of view, while the gneiss and schist samples from Alpujarride units such as the Torrox Unit (Zeck and Whitehouse, 1999, 2002) or the Guadaiza Unit (Acosta-Vigil et al., 2014) display comparatively less Cambrian-Ordovician than Devonian ages, the Conglomerado de Marbella records quite the opposite: a major peak (25% of the obtained ages) of Cambro-Ordovician ages and only a minor peak (7%) of Devonian ages (Fig. 8). Such variance

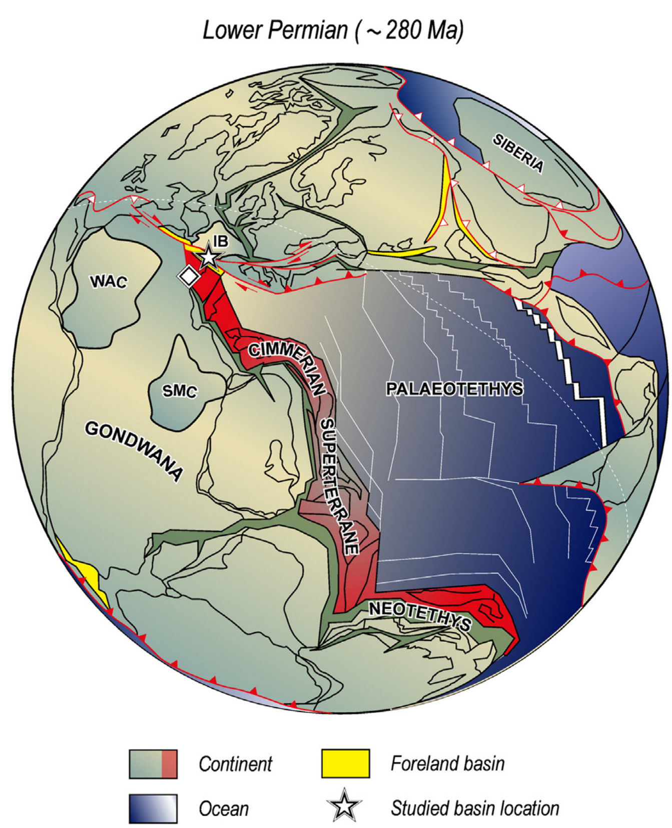

Fig. 11. Global reconstruction for the Lower Permian (*ca.* 280 Ma) and suggested location of the Marbella Conglomerate (star) at the foreland basin located within the Iberia and Cimmerian superterrane at the western termination of the Paleotethys Ocean. The square marks the suggested location of underlying units to the Ronda peridotites according to Esteban et al. (2011): WAC — West African Craton, SMC — Sahara Meta Craton; IB — Iberia.
Modified from Stampfli and Borel (2002).

precludes the recycling of these rocks from the same source, and likely adduces for the Alboran domain being a terrane of different affinity in the Permian time (~280 Ma) that may be linked to the later opening of the Neotethys. These new data also suggest that the contrast in the paleogeographic evolution of the Alpujarride and Malaguide complexes can be extended back to the pre-Triassic times. This interpretation could lead to constraining the Alboran domain location at the western border of the Paleotethys conforming to a continental rift associated to the passive north margin of Gondwana at Permian times, probably as part of the European Cimmerian terrane (Fig. 11).

Based on the petrographic features of granite pebbles in the Marbella Conglomerate, Sanz de Galdeano et al. (2006) suggested that the Malaguide Complex would be the eastern continuation of the Central Iberian/Western Leonese zones of the Iberian Variscan belt. However, taken indeed into account the new geochronological data from the deformed granite, schist pebbles and sandstones, we propose that the sedimentation of the Marbella Conglomerate took place from a Cadomian affinity terrane like the Ossa-Morena or its equivalent, along the western border of the Paleotethys once the Variscan orogeny had completed the Pangea amalgamation.

7. Conclusions

- New LA–ICP-MS U–Pb ages obtained on zircons extracted from the Marbella Conglomerate yielded mostly Neoproterozoic (44%), Cambro-Ordovician (25%), Paleoproterozoic (9%), Carboniferous (9%) and Devonian (7%) ages with minor Permian (3%), Archean (2%) and Mesoproterozoic (1%) components. This provides the first robust data supporting its provenance from the Ossa-Morena Zone of the Iberian Variscan belt or similar eroded Cadomian terranes.
- Igneous (*ca.* 532 and 516) and metamorphic (356 Ma) U–Pb SHRIMP ages obtained from the two single pebbles of deformed granites and schist (≈532, 516 and 356 Ma) confirm the foreign nature of the pebbles and link them to Rift-related Igneous Events and with the metamorphic/magmatic events identified along the northern and southern major sutures of the Ossa-Morena Zone.
- From the youngest detrital U–Pb LA–ICP-MS zircon analyses, a maximum age of ≈286 Ma (Lower Permian) is inferred for the deposition of the Marbella Conglomerate. Such an age is 30 Ma younger than the Carboniferous ages proposed before.
- According to the radiometric ages reported from zircon data of some Alpujarride units (Internal Zone) and the new data presented here, we propose that most of the Marbella Conglomerate was derived from a Cadomian terrane along the western border of the Paleotethys at the northern margin of Gondwana, as part of the European Cimmerian terranes involved in the Variscan orogeny.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.lithos.2017.07.022.

Acknowledgements

Two anonymous reviewers and the editor Sun-Lin Chung are thanked for their reviews and discussions that have improved the final manuscript.

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