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ORIGINAL PAPER

Provenance of upper Triassic sandstone, southwest Iberia (Alentejo and Algarve basins): tracing variability in the sources

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Abstract Laser ablation ICP-MS U–Pb analyses have been conducted on detrital zircon of Upper Triassic sandstone from the Alentejo and Algarve basins in southwest Iberia. The predominance of Neoproterozoic, Devonian, Paleoproterozoic and Carboniferous detrital zircon ages confirms previous studies that indicate the locus of the sediment source of the late Triassic Alentejo Basin in the pre-Mesozoic basement of the South Portuguese and Ossa-Morena zones. Suitable sources for the Upper Triassic Algarve sandstone are the Upper Devonian–Lower Carboniferous of the South Portuguese Zone (Phyllite–Quartzite and Tercenas formations) and the Meguma Terrane (present-day in Nova Scotia). Spatial variations of the sediment sources of both Upper Triassic basins suggest a more complex history of drainage than previously documented involving other source rocks located outside present-day Iberia. The two Triassic basins were isolated from each other with the detrital transport being controlled by two independent drainage systems. This study is important for the reconstruction of the late Triassic paleogeography in a place where, later, the opening of the Central Atlantic Ocean took place separating Europe from North America.

Keywords U–Pb zircon geochronology · Provenance analysis · Upper Triassic basins · Pangaea

Introduction

Detrital zircon geochronology is a commonly used tool for provenance studies because of the widespread occurrence of zircon in sedimentary systems and the growing ability to determine ages with reasonable precision, accuracy, and efficiency (Corfu et al. 2003; Fedo et al. 2003; von Eynatten and Dunkl 2012). The U–Pb age of a detrital zircon grain provides a proxy for the age of the source rock in which the zircon originally formed (Sircombe and Hazelton 2004). In provenance studies of ancient basins, it is critical to consider tectonics, exhumation processes, erosion and sedimentary recycling because availability of zircon to erosion and transport from either primary crystalline or recycled sources requires that the zircon-bearing rocks be exposed at the appropriate time, and recycling from older sedimentary deposits may constitute a more significant source than from primary crystalline rocks (Thomas 2011).

During Permian to Triassic time, the paleogeography of Iberia was dominated by a series of coalescing, alluvial-deltaic wedges and axial braided rivers that filled continental rift basins (Palain 1976; Wilson 1988; Arche and López-Gómez 1996; López-Gómez et al. 2005; Sánchez Martínez et al. 2012; Soares et al. 2012). In Portugal, Permian–Triassic

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strata unconformably overlies pre-Mesozoic basement composed of Ediacaran to Carboniferous rocks, defining one of the most profound unconformities in Iberia. This unconformity records the transition from the last stages of the Carboniferous Variscan Mountain building to the early stages of Permian–Triassic continental rifting. Mountain building during late Paleozoic time and later denudation involved production of significant amounts of siliciclastic sediment. An issue that still raises uncertainty concerns the source areas that contributed to the Triassic deposition.

In the present study, a data set of detrital zircon ages obtained with laser ablation inductively coupled mass spectroscopy (LA-ICP-MS) from four samples of Triassic sandstone of the Alentejo and Algarve basins (southwest Iberia; Vilallonga 2013) is presented. The obtained U–Pb ages are used to: (i) trace potential sediment sources of the Upper Triassic basins based on detrital zircon spectra from the southwest Iberian pre-Mesozoic basement (South Portuguese and Ossa-Morena zones) and other sources outside Iberia and ii) test the paleogeographic reconstructions of Pangaea supercontinent in late Triassic times in a place where occurred later the opening of the Central Atlantic Ocean separating North America from Europe.

Geological setting

Pre-Mesozoic basement of southwest Iberia

The pre-Mesozoic basement of the Alentejo and Algarve regions in Portugal is composed of Neoproterozoic to Carboniferous sedimentary, metamorphic and igneous rocks of the Ossa-Morena and South Portuguese zones (Figs. 1, 2). These two tectonostratigraphic zones are part of the Variscan-Appalachian belt formed by the collision of Gondwana and Laurussia that led to the assembly of Pangaea during late Paleozoic time (Martínez-Catalán et al. 2007; Pereira et al. 2012a, 2013). The Cambrian to Lower Devonian sedimentary rocks of southwest Iberia derived from the erosion of the Neoproterozoic rocks of the Ossa-Morena Zone, composed of back-arc basin sedimentary and magmatic arc rocks related to the late Neoproterozoic–early Cambrian Cadomian orogeny that took place in North Gondwana (Nance et al. 2008; Pereira et al. 2008, 2011, 2012b, c; Pereira 2015). Cambrian to Lower Ordovician stratigraphy is characterized by significant amounts of volcanic rocks interbedded in carbonate and siliciclastic rocks (Pereira et al. 2007; Chichorro et al. 2008; Sánchez-García

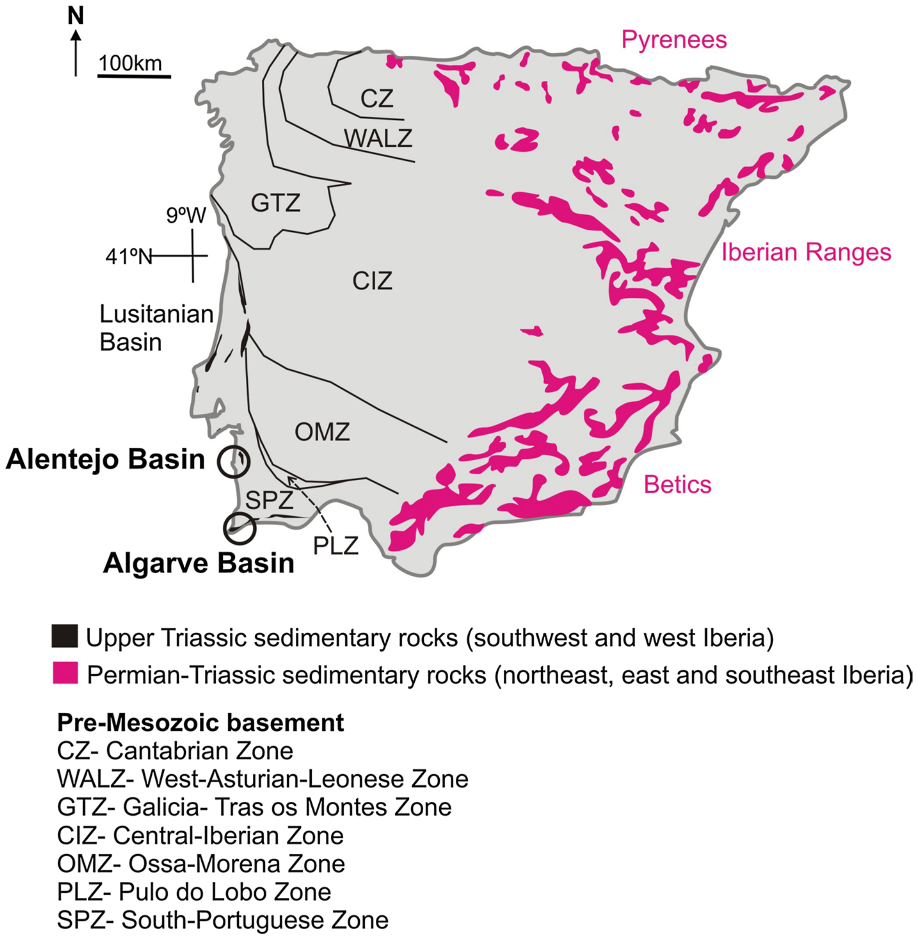


Fig. 1 Permian–Triassic basins of Iberia (adapted from Oliveira and Wagner Gentis 1983; López-Gómez et al. 2005) and the main pre-Mesozoic basement units of Iberia. The late Triassic Alentejo and Algarve basins of southwest Iberia are marked with circles

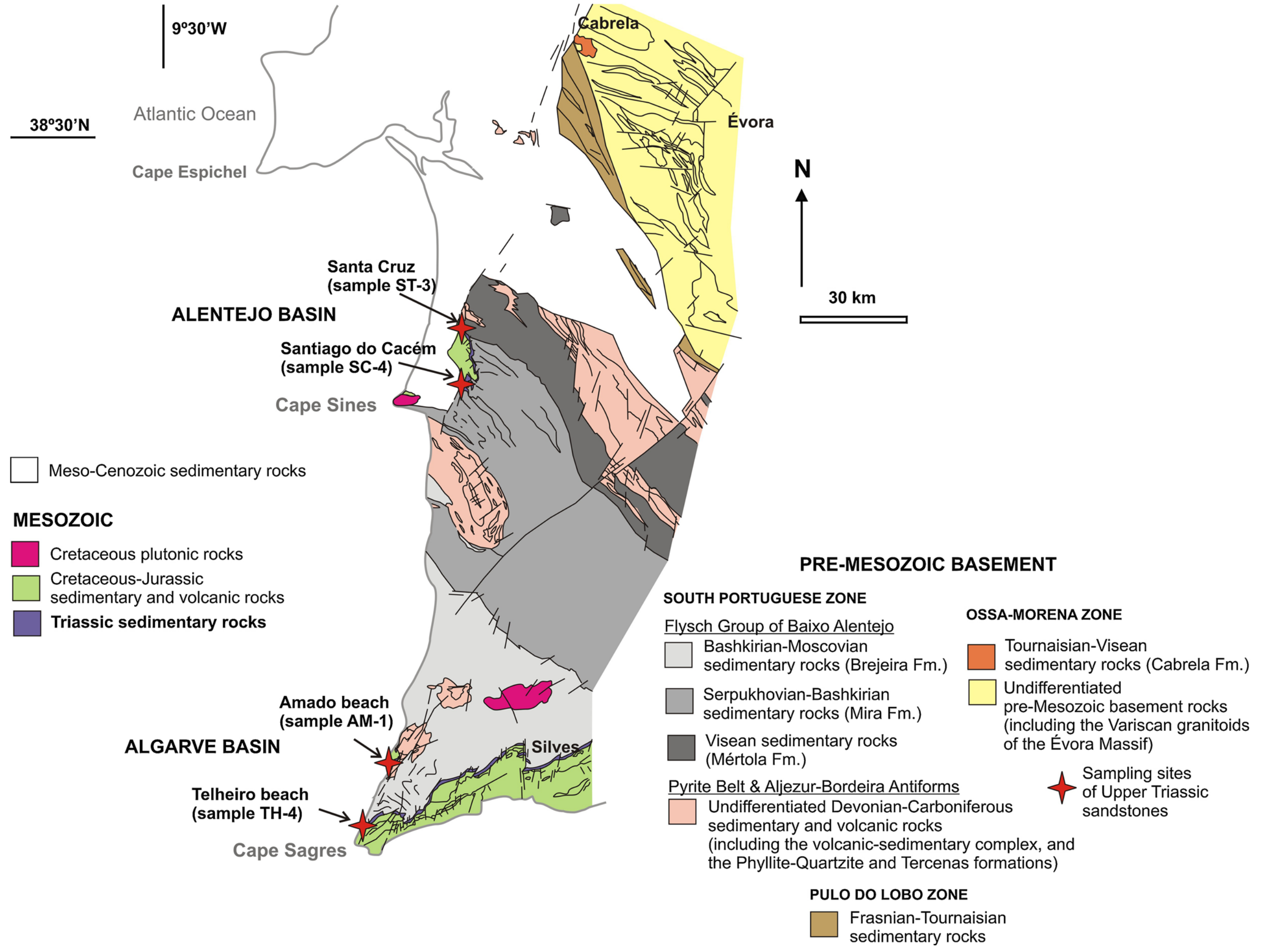


Fig. 2 Schematic geological map of southwest Iberia after Oliveira and Wagner Gentis (1983). Sampling locations of Upper Triassic sandstone from the Alentejo (Santa Cruz and Santiago do Cacém) and Algarve (Amado and Telheiro beaches) basins are indicated with *red stars*

et al. 2010, 2013). The Silurian includes a condensed sequence of graptolitic shale and chert that passes upwards to shales and limestones of lowermost Devonian (Robardet and Gutiérrez Marco 2004). Middle-Upper Devonian rocks almost are absent in the Ossa-Morena Zone. In the South Portuguese Zone, the oldest rocks known are Devonian sedimentary and volcanic rocks (Oliveira et al. 2013). These deposits are exposed in the cores of Variscan anticlines, such as the Pyrite Belt and Aljezur-Bordeira Antiform with the Upper Devonian Phyllite–Quartzite Formation and the Upper Devonian–Early Carboniferous Tercenas Formation (Fig. 2). The Phyllite–Quartzite Formation is overlain by the Upper Devonian–Lower Carboniferous Volcanic–Sedimentary Complex (Rosa et al. 2008). The Lower Carboniferous stratigraphy of the Cabrela Basin is similar both in the Ossa-Morena Zone and the South Portuguese Zone with the Mertola Formation (lower part of the Flysch Group of Baixo Alentejo; Fig. 2). As a consequence of early Carboniferous Variscan oblique convergence, deformation of the ductile basement under high-temperature metamorphic conditions promoted partial melting and the formation of syn-kinematic crustal-derived magma that interacted with magma of mantle origin in southwest Iberia (Pereira et al. 2009, 2015a, b). Later, during the Upper Carboniferous, sedimentation was essentially detrital and typically terrestrial in the Ossa-Morena Zone (Quesada et al. 1990), whereas in the South Portuguese Zone a thick succession of turbidites was deposited (Oliveira 1990).

The post-orogenic terrestrial deposition related to uplift and subsidence during continental rifting that occurred after the late Paleozoic Pangaea assembly was diachronic in Iberia, first in Spanish and then in Portugal. In Spain, this extensional tectonic event is represented by sedimentary sequences deposited in continental rift basins during the transition from late Permian to early Triassic time (Pyrenees, Iberian Ranges and Betics; López-Gómez et al.

2005; Sánchez Martínez et al. 2012). In Portugal, the sedimentary deposition began during middle to late Triassic time (Lusitanian, Alentejo and Algarve basins) and there is a major stratigraphic gap marked by the absence of Permian to Lower-Middle Triassic sedimentary rocks (Fig. 1; Azerêdo et al. 2003 and references therein; Alves et al. 2006; Soares et al. 2012; Pereira et al. 2015a).

Triassic basins of southwest Iberia

In southwest Iberia, Mesozoic sedimentation began during late Triassic time, with the deposition of a thick sequence of continental deposits that passes upwards to marine carbonate sedimentation in Jurassic (Rocha 1976; Palain 1979; Manuppella 1988) associated with ca. 198 Ma (Verati et al. 2007; Martins et al. 2008) basic volcanism. The Upper Triassic sedimentary rocks of the Alentejo and Algarve basins rest with an angular unconformity on Carboniferous (Visean to Moscovian) turbidites of the South Portuguese Zone (Baixo Alentejo Flysch Group; Fig. 3; Oliveira 1983, 1990). In the Alentejo Basin, Upper Triassic sandstone unconformably overlies a kilometer-thick Lower Carboniferous sequence mainly composed of graywacke, siltstone and mudstone (Mértola, and Mira formations; Oliveira 1990) that were deformed before Triassic deposition (Pereira et al. 2013). These Paleozoic sedimentary rocks contain ammonoids of Visean (Mértola Formation; Korn 1997) and Serpukhovian age (Mira Formation; Oliveira and Wagner Gentis 1983). Upper Triassic strata of the Algarve Basin unconformably overlies a Carboniferous turbiditic sequence composed of graywacke and pelite containing goniatite and miospore associations of Carboniferous (Bashkirian to Moscovian) age (Fig. 3; Mira and Brejeira formations; Oliveira 1990; Pereira et al. 1997).

The sedimentary record of the Triassic starts with the Silves sandstone (Manuppella 1988) that represents the lower sequence of the "Grés de Silves" (Choffat 1887) in the Algarve and Alentejo basins. In the Algarve Basin,

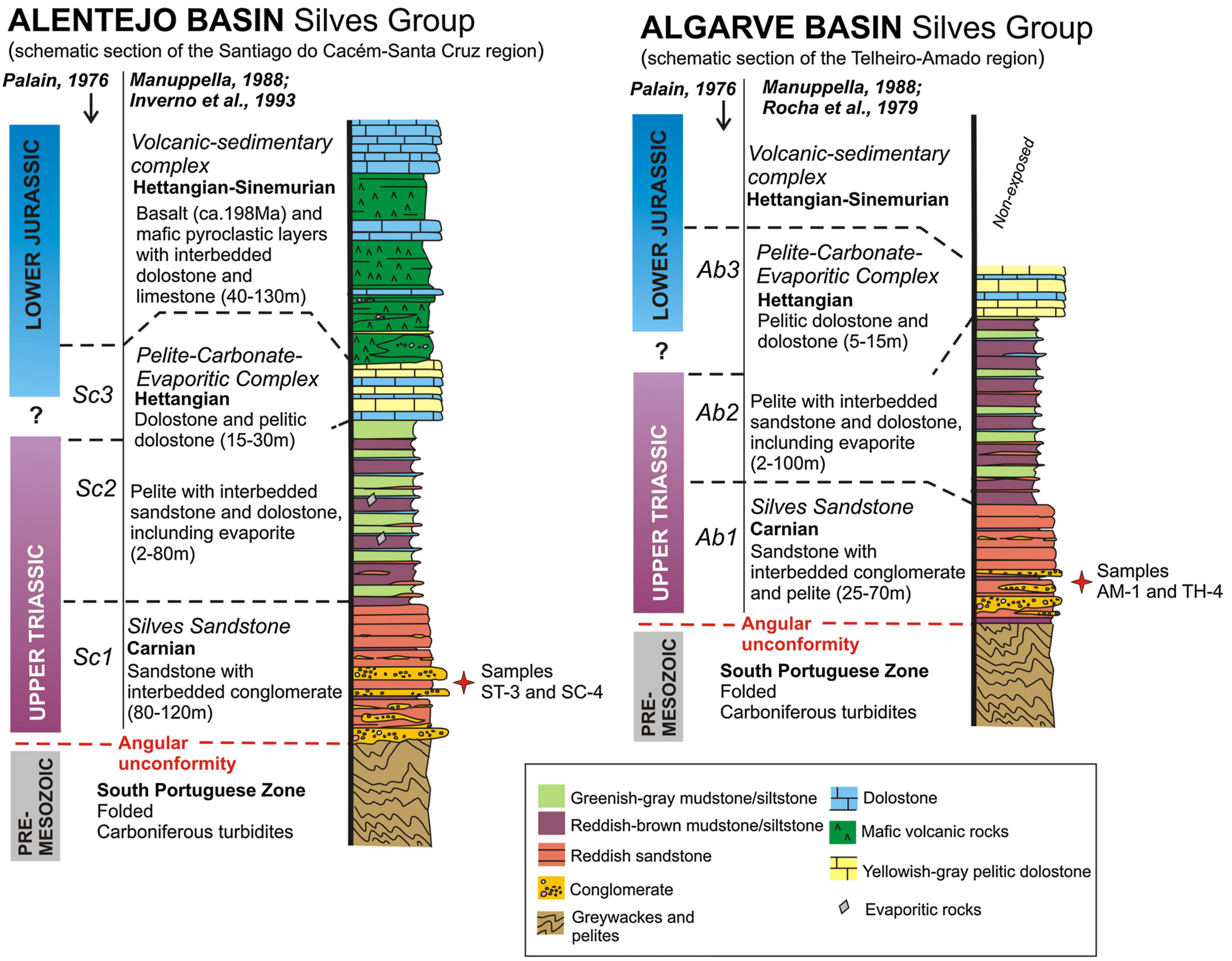


Fig. 3 Schematic stratigraphy of the Alentejo and Algarve Basins (adapted from Palain 1976; Manuppella 1988; Inverno et al. 1993)

the Silves sandstone includes an up to 100-m-thick discontinuous member of brown-reddish mudstone with interlayered siltstone (AA unit of Palain 1976; São Bartolomeu de Messines Mudstone of Manuppella 1988). This member, exclusive of the Algarve Basin, is overlain by a 10- to 150-m-thick sedimentary sequence mainly composed of sand- and conglomerate-rich beds (AB1 unit in the Algarve Basin and SC1 unit in the Alentejo Basin of Palain 1976; upper part of the Silves sandstone defined by Manuppella 1988). This sedimentary sequence is mainly made up of reddish to yellowish, fine- to coarse-grained sandstone with parallel and oblique bedding, including paleochannels filled with conglomerate. Clast-supported and matrix-supported conglomerate is moderately to poorly sorted, with variable-sized (0.3–10 cm) rounded to sub-angular clasts of quartz, graywacke, quartzite, jasper and pelite (Fig. 4). Conglomerate and mudstone also occur as discontinuous units intercalated with the sandstone (Palain 1976). The conglomerate is polygenic, containing pebbles of quartz, quartzite, graywacke and pelite with a sandy matrix and cement of iron oxide and carbonate. The Upper Triassic terrigenous sequence was deposited in continental rift basins under semi-arid climate conditions with formation of evaporitic rocks (Choffat 1887; Palain 1976, 1979; Azerêdo et al. 2003). The depositional environment was characterized by alluvial fans separated by rivers and alluvial plains with temporary meander-form rivers (Palain 1976, 1979).

Overlying the Silves sandstone, a 50- to 180-m-thick sequence composed of reddish and greenish mudstone, siltstone and yellowish dolostone is interlayered with discontinuous beds of fine-grained sandstone and evaporitic rocks (AB2 unit in the Algarve Basin and SC2 unit in the Alentejo Basin of Palain 1976; Pelite-Carbonate-Evaporite Complex of Manuppella 1988). This complex was deposited in a shallow-marine and/or coastal lagoon environment (Azerêdo et al. 2003).

The Upper Triassic age of the Algarve sandstone is based on rare paleontological remains of terrestrial and semi-aquatic vertebrate found in the pelites of the AB2 unit. Bones and teeth of phytosaur specimen are consistent with an Late Triassic (late Carnian–early Norian) age for AB2 unit (Steyer et al. 2011; Mateus et al. 2014) that was previously attributed to the a latest Triassic or even earliest Jurassic age (Witzmann and Gassner 2008). A Jurassic sequence composed of discontinuous gray-yellowish dolostone beds interlayered with basalt, mafic breccia and tuff (AB3 unit in the Algarve Basin and SC3 unit in the Alentejo Basin of Palain 1976; Volcanic-Sedimentary Complex; Manuppella 1988; Martins et al. 2008) overlie the Triassic strata.

Methods

Four samples of Upper Triassic sandstone of the (2 from AB1 unit of the Algarve Basin and 2 from SC1 unit of the Alentejo Basin; Figs. 2, 3) were collected in southwest Iberia for petrography (Fig. 5) and U–Pb geochronology on detrital zircon (Fig. 6). Two samples were taken from the Alentejo Basin northeast of Cape Sines (Santa Cruz, sample ST-3 and Santiago do Cacém, sample SC-4) and two from the Algarve Basin, north of Cape Sagres (Amado beach, sample AM-1 and Telheiro beach, sample TH-4). The sandstone samples were prepared and analyzed using LA-ICP-MS for U–Pb detrital zircon geochronology in order to investigate provenance. Methodology of sample preparation, data acquisition and treatment and the U–Th–Pb data are presented as supplementary material. In this study, ^{207}Pb/^{206}Pb ages were used for the interpretation of zircons with ages older than 1.0 Ga and ^{206}Pb/^{238}U ages for younger grains. Only zircon ages with 90–110 % concordance were used to estimate percentages and build a probability plot for each sample.

The Kolmogorov–Smirnov test was used to statistically test hypotheses of correlation between the populations of zircon ages within the same basin, and comparisons are made with known provenance (DeGraaff-Surpless et al. 2003; Barbeau et al. 2009; Vermeesch 2013). This statistical test was designed by comparing the zircon ages of two different populations separately (e.g., Dickinson et al. 2010; Guynn and Gehrels 2010). The distance between the cumulative curves is proportional to the degree of similarity between them: the closer they are together, the greater the similarity (Fig. 7).

Results

Petrography

The sampled sandstone of the Alentejo Basin (samples ST-3 and SC-4) are medium to very coarse grained and poorly sorted, with sub-angular to sub-rounded grains (Fig. 5a, b). Quartz grains are dominant in both. Rock fragments are well represented in the Alentejo sandstone (Fig. 5a, b). They are mostly fragments of cleaved pelite and quartzite with an elongated shape and schistose texture as result of derivation from a deformed source rock. Other rock fragments are of sandstone, chert, polycrystalline quartz (quartz vein) and igneous rocks consisting mainly of quartz and feldspar. The matrix contains grains of quartz, mica and feldspar in calcite cement (sometimes ferruginous).

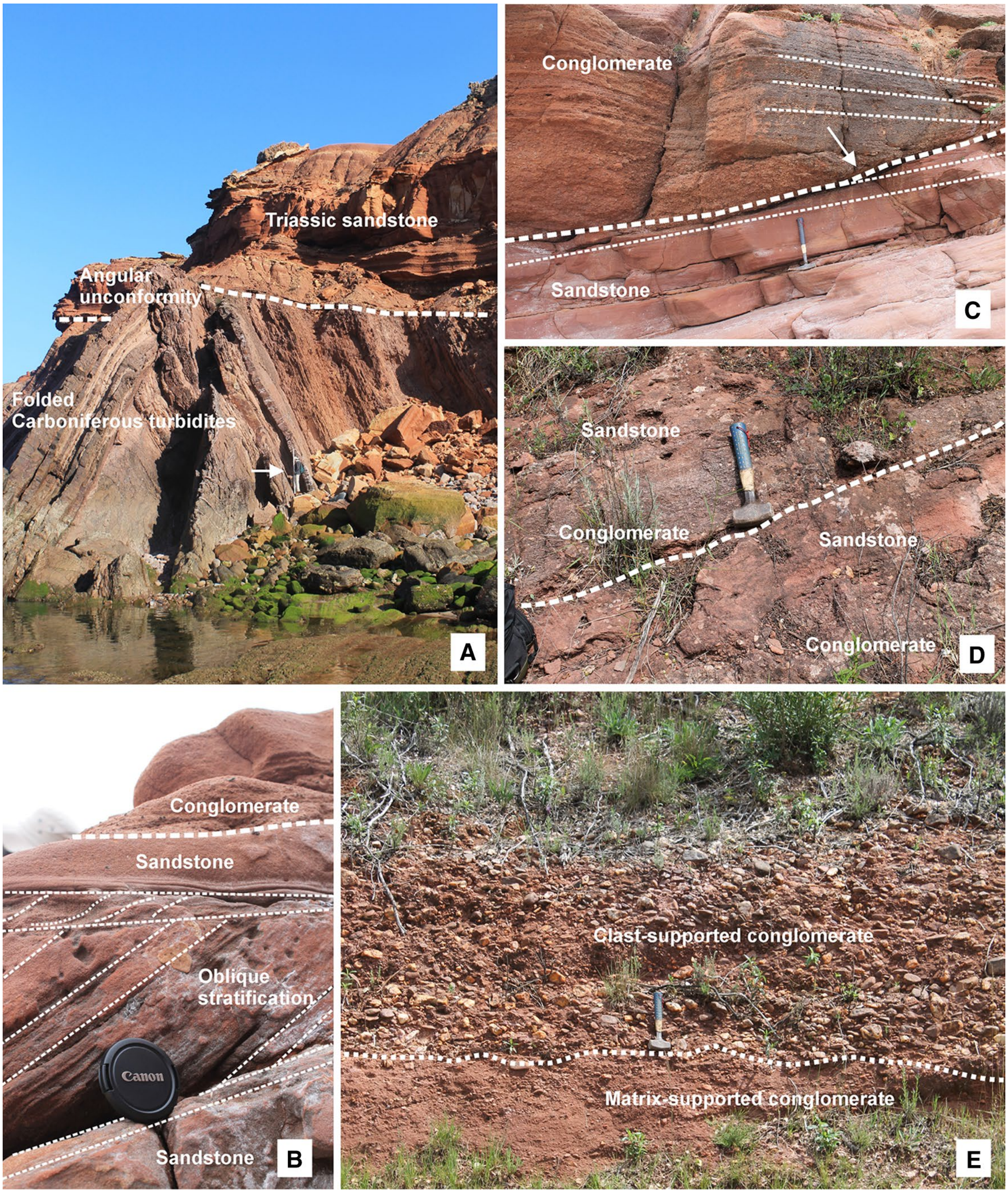


Fig. 4 The sampling sites of Upper Triassic sandstone: **a** Angular unconformity at Telheiro beach indicated by slightly dipping beds of Upper Triassic sandstone and mudstone of the Algarve Basin deposited on folded Moscovian turbidites of the South Portuguese Zone; **b** Oblique stratification in Upper Triassic sandstone (Amado beach, Algarve Basin); **c** Coarse-grained deposits filled a channel carved in the sand (Amado beach, Algarve Basin); **d** Decimeter-thick beds of sandstone and conglomerate (Santiago do Cacém, Alentejo Basin); **e** A meter-thick bed of clast-supported conglomerate with pebbles of quartz, graywacke and pelite overlying coarse-sandy matrix-supported conglomerate (Santiago do Cacém; Alentejo Basin)

The Algarve sandstone (samples AM-1 and TH-4) is fine to medium-grained and moderately to well-sorted, with sub-rounded to rounded grains. They include rock fragments of pelite, and grains of muscovite and feldspar are also present (Fig. 5c, d). The cement composition is generally siliceous, carbonaceous or ferruginous.

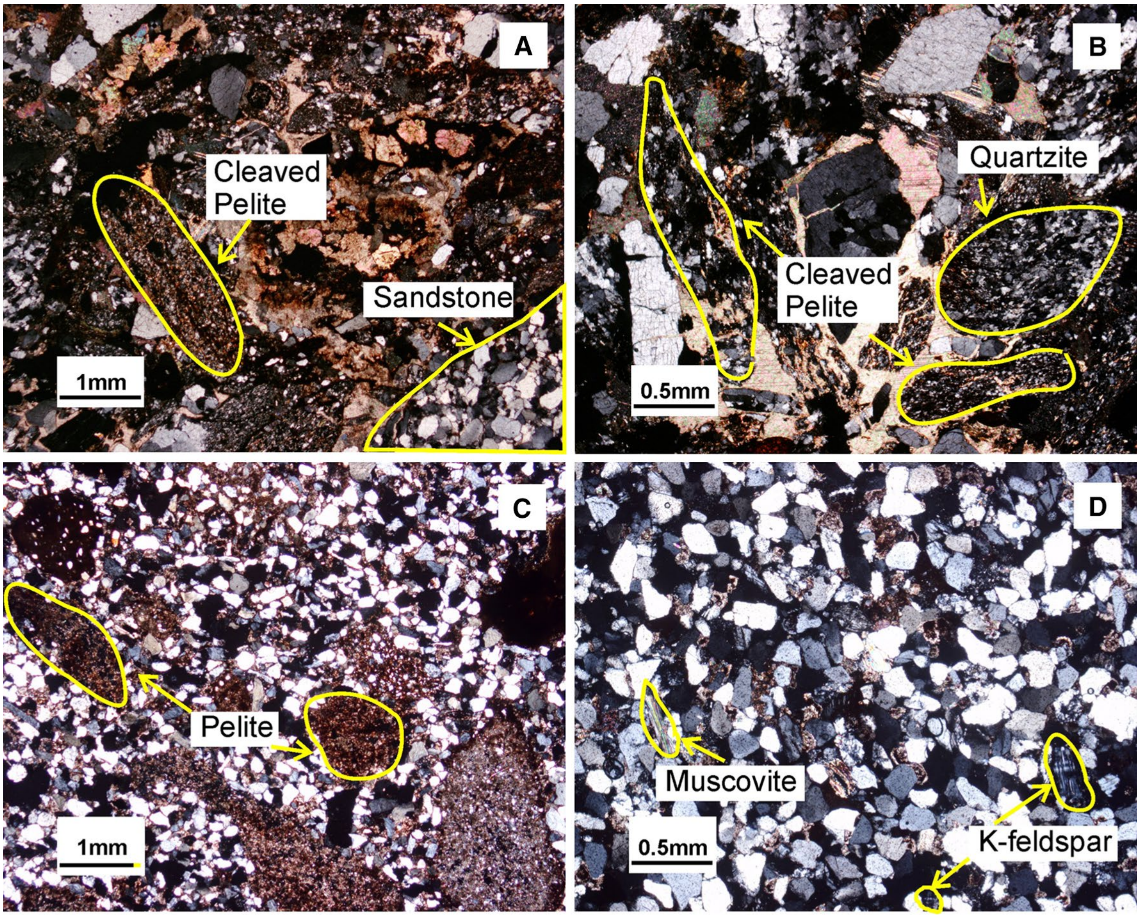


Fig. 5 Petrographic images of the Alentejo and Algarve Triassic sandstone. **a**, **b** Immature Alentejo sandstone of poor sorting and consisting of a high percentage of rock fragments (quartzite, sandstone and cleaved pelite) in carbonate cement (sample SC-4); **c**, **d** moderately to well-sorted Algarve sandstone consisting almost entirely of quartz with pelite clasts and few grains of muscovite and K-feldspar (sample AM-1). All images are taken with crossed polarized light

U–Pb detrital zircon geochronology

Of a total of 486 measured spots, 369 yielded 90–110 % concordant ages. The distribution of detrital zircon ages of the Alentejo sandstone is quite different from populations that characterize the Triassic Algarve Basin, because it includes a large subpopulation of Paleozoic ages, mostly Devonian–Carboniferous grains (Figs. 6, 8).

Santa Cruz sandstone (ST-3; Alentejo Basin)

Of a total of 120 measured spots in sample ST-3, 72 yielded 90–110 % concordant ages. Fifty-eight percentage of ages are Paleozoic, 40 % Proterozoic and one grain is Neoarchean (ca. 2.5 Ga; Fig. 6). Paleozoic ages range from ca. 539–327 Ma and are mostly Carboniferous (24 %; ca. 355–327 Ma) and Devonian (22 %; ca. 460–410 Ma). Also Cambrian (8 %; ca. 539–508 Ma) and Ordovician (4 %; ca. 485–468 Ma) grains occur. The Neoproterozoic grains (23 %) are widespread at ca. 821–631 Ma (13 % Cryogenian), ca. 626–560 Ma (10 % Ediacaran), and ca. 857 Ma (1 % Tonian; only 1 grain). Paleoproterozoic zircon (13 %) is ca. 2.1–1.6 Ga (Rhyacian to Statherian), and Mesoproterozoic ages (4 %) are 1.2–1.1 Ga (Stenian). The five youngest grains yield a weighted mean of 337.1 ± 4.7 Ma (95 % confidence level, c.l.; Visean), significantly older than the sedimentary age inferred from biostratigraphic data (Upper Triassic).

Santiago do Cacém sandstone (SC-4; Alentejo Basin)

Of a total of 134 measured spots in sample SC-4, 75 yielded 90–110 % concordant ages. Seventy percentage are Proterozoic, 29 % Paleozoic and rare Neoarchean (1 %; only 1 grain) (Fig. 6). The Proterozoic population is dominated by Neoproterozoic (39 %; Cryogenian- ca. 791–631 Ma, Ediacaran- ca. 618–555 Ma and Tonian-ca. 902 Ma) and Paleoproterozoic (20 %; ca. 2.1–1.6 Ga) detrital zircons

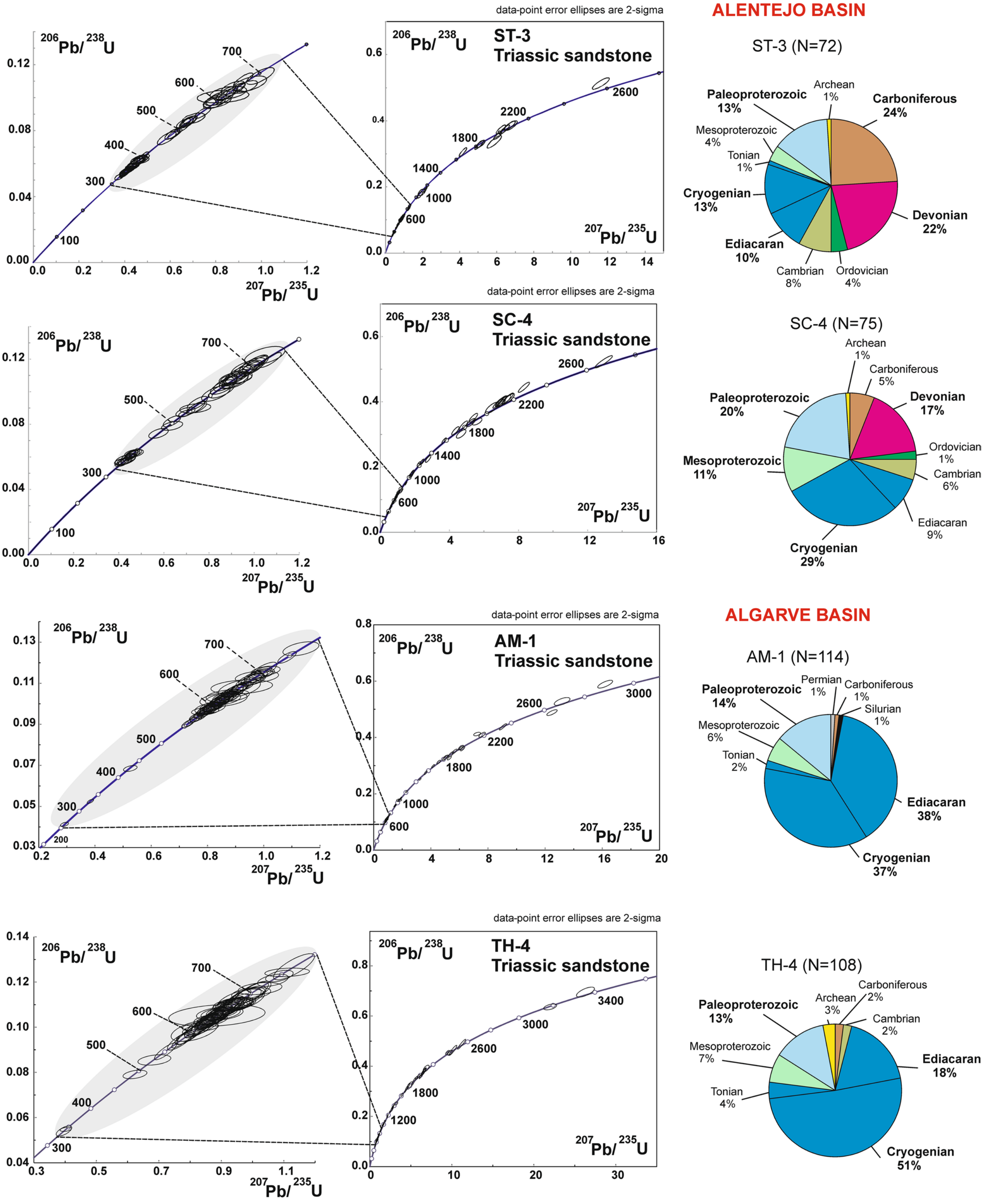
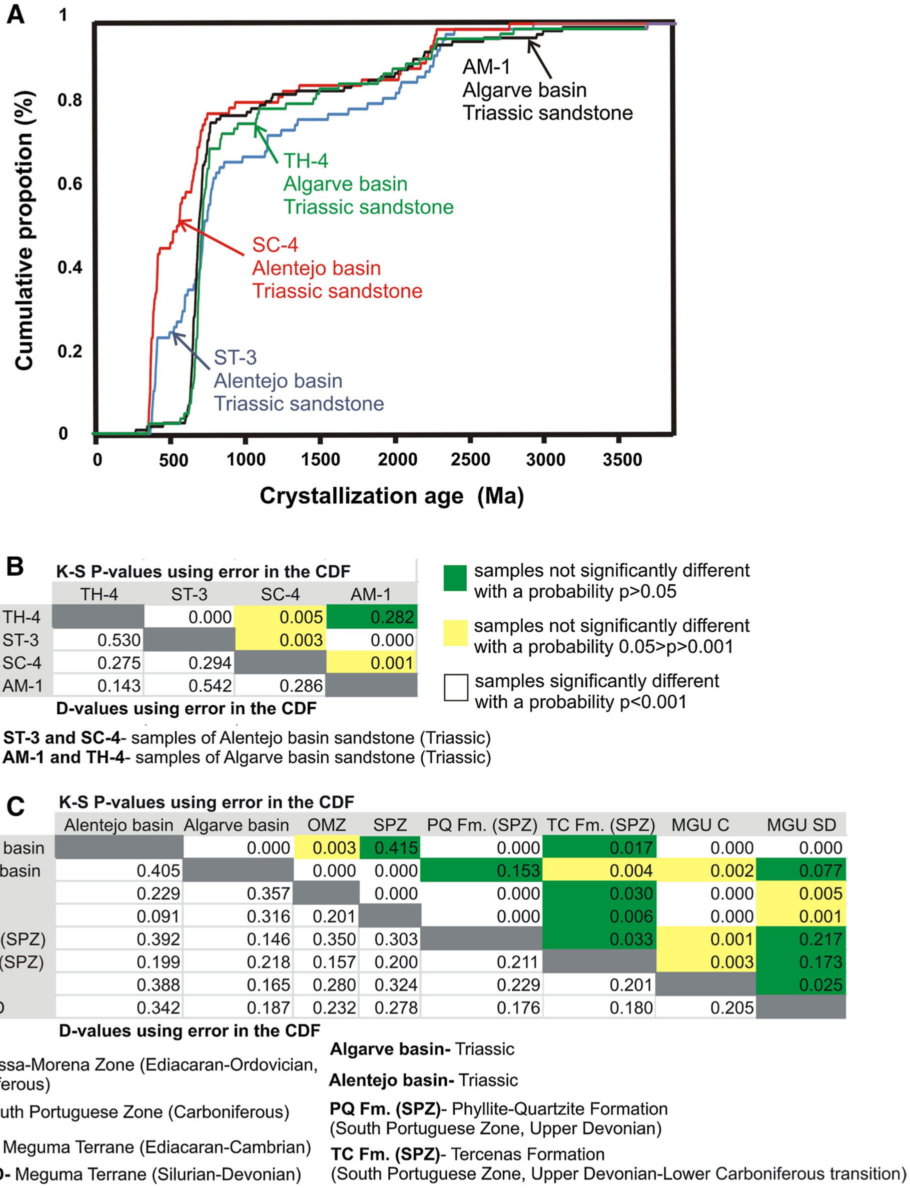


Fig. 6 Concordia plots and pie diagrams with U–Pb detrital zircon ages for all four analyzed samples (90–110 % concordance; remaining data are presented in Table 1 of the supplementary material). *Numbers* refer to ages in Ma



B K-S P-values using error in the CDF

	TH-4	ST-3	SC-4	AM-1
TH-4		0.000	🟨 0.005	🟩 0.282
ST-3	0.530		🟨 0.003	0.000
SC-4	0.275	0.294		🟨 0.001
AM-1	0.143	0.542	0.286	

D-values using error in the CDF

🟩 samples not significantly different with a probability p>0.05

🟨 samples not significantly different with a probability 0.05>p>0.001

☐ samples significantly different with a probability p<0.001

ST-3 and SC-4- samples of Alentejo basin sandstone (Triassic)
AM-1 and TH-4- samples of Algarve basin sandstone (Triassic)

C K-S P-values using error in the CDF

	Alentejo basin	Algarve basin	OMZ	SPZ	PQ Fm. (SPZ)	TC Fm. (SPZ)	MGU C	MGU SD
Alentejo basin		0.000	🟨 0.003	🟩 0.415	0.000	🟩 0.017	0.000	0.000
Algarve basin	0.405		0.000	0.000	🟩 0.153	🟨 0.004	🟨 0.002	🟩 0.077
OMZ	0.229	0.357		0.000	0.000	🟩 0.030	0.000	🟨 0.005
SPZ	0.091	0.316	0.201		0.000	🟩 0.006	0.000	🟨 0.001
PQ Fm. (SPZ)	0.392	0.146	0.350	0.303		🟩 0.033	🟨 0.001	🟩 0.217
TC Fm. (SPZ)	0.199	0.218	0.157	0.200	0.211		🟨 0.003	🟩 0.173
MGU C	0.388	0.165	0.280	0.324	0.229	0.201		🟩 0.025
MGU SD	0.342	0.187	0.232	0.278	0.176	0.180	0.205	

D-values using error in the CDF

OMZ- Ossa-Morena Zone (Ediacaran-Ordovician, Carboniferous)

SPZ- South Portuguese Zone (Carboniferous)

MGU C- Meguma Terrane (Ediacaran-Cambrian)

MGU SD- Meguma Terrane (Silurian-Devonian)

Algarve basin- Triassic

Alentejo basin- Triassic

PQ Fm. (SPZ)- Phyllite-Quartzite Formation (South Portuguese Zone, Upper Devonian)

TC Fm. (SPZ)- Tercenas Formation (South Portuguese Zone, Upper Devonian-Lower Carboniferous transition)

Fig. 7 **a** U–Pb age cumulative frequency plots for all four analyzed samples. **b**, **c** Results of the Kolmogorov–Smirnov test. This is a nonparametric test that calculates the maximum probability distance between two cumulative distribution functions (CDF) of two age distributions, producing a probability p of two samples derived from the same population: if $p > 0.05$ it is likely that the two age distributions are derived from the same population; if there is a 95 % probability that the difference between the two tested populations is not due to random sampling error but rather it is probable that the two samples were from different populations. *D* value represents the maximum distance between the cumulative frequency curves of the two tested populations

and smaller amount of grains with Mesoproterozoic ages (11 %; ca. 1.5–1.0 Ga). The Paleozoic population includes Devonian (17 %; ca. 390–360 Ma), Carboniferous (5 %; ca. 358–349 Ma), Cambrian (6 %; ca. 541–490 Ma) and Ordovician (1 %; c. 463 Ma) grains. The youngest four zircons yield a weighted mean of 353.5 ± 4.7 Ma (95 % c.l.; Tournaisian), significantly older compared to the sedimentary age inferred from biostratigraphic data (Upper Triassic).

Amado sandstone (AM-1; Algarve Basin)

Of a total of 119 measured spots in sample AM-1, 114 yielded 90–110 % concordant ages. Ninety-seven yielded Precambrian ages, and only 3 % Paleozoic ages (Fig. 6). The Proterozoic population is dominated by Neoproterozoic grains (77 %; Cryogenian- ca. 769–630 Ma, Ediacaran- ca. 627–558 Ma), Paleoproterozoic (14 %; ca. 2.8–1.6 Ga) and Mesoproterozoic (6 %-ca. 1.5–1.0 Ga). Neoarchean grains are rare (ca. 2.8–2.7 Ga). Paleozoic ages range from ca. 426 Ma (Silurian) to ca. 329 Ma (Carboniferous) and ca. 260 Ma (Permian, only 1 grain).

Telheiro sandstone (TH-4; Algarve Basin)

Of a total of 113 measured spots in sample AM-1, 108 yielded 90–110 % concordant ages. Ninety-three are Proterozoic and the remaining grains are Paleozoic (4 %) and Archean (3 %) (Fig. 6). The Precambrian population is dominated by Neoproterozoic grains (73 %; Cryogenian- ca. 776–631 Ma, Ediacaran- ca. 624–551 Ma and Tonian- ca. 991–551 Ma), followed by Paleoproterozoic (13 %; ca. 2.4–1.8 Ga) and Mesoproterozoic grains (7 %; ca.

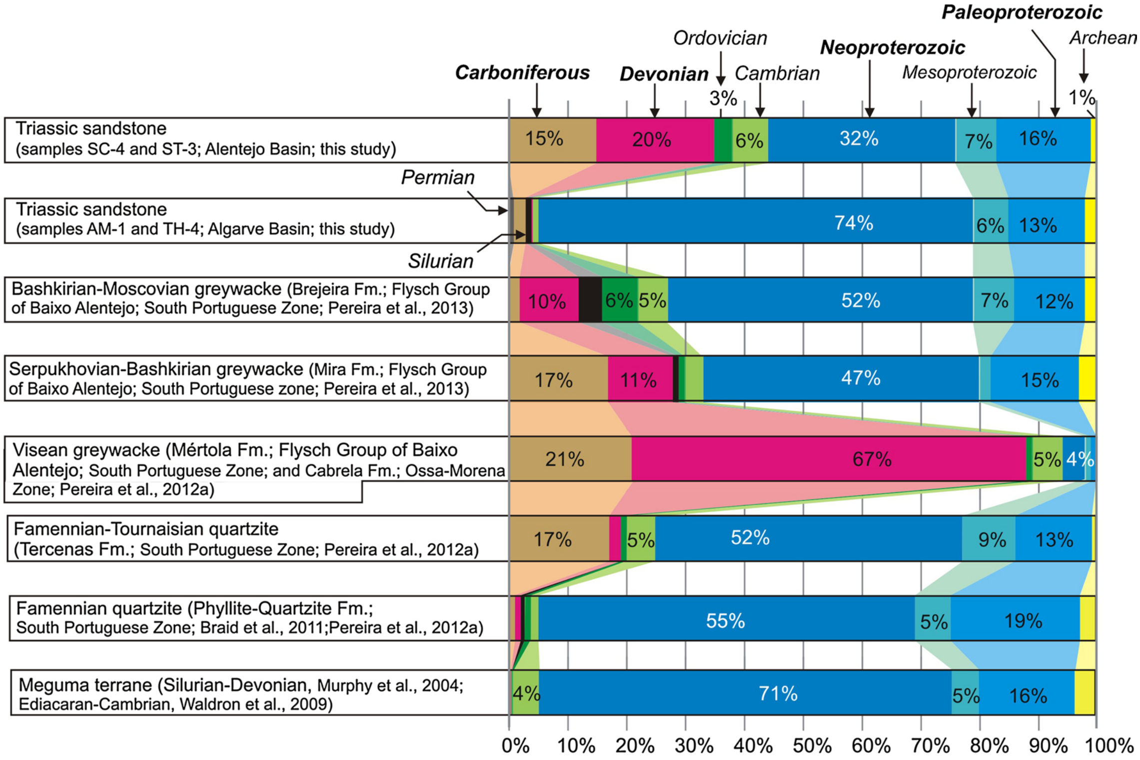


Fig. 8 Percentages of U–Pb detrital zircon ages from this study (the results obtained with the Kolmogorov–Smirnov test indicate that U–Pb age distributions in Triassic sandstone in the same basin are not significantly different and can therefore be joined) and comparison with detrital zircon ages of Upper Devonian–Carboniferous sedimentary rocks of southwest Iberia (data from Pereira et al. 2012a, 2013) and Ediacaran-Cambrian and Silurian–Devonian sedimentary rocks of the Meguma Terrane from Nova Scotia (Murphy et al. 2004; Waldron et al. 2009)

1.4–1.2 Ga) and rare grains with Archean (ca. 3.3–2.5 Ga). The Paleozoic population is represented by Carboniferous (2 %; ca. 343 Ma and ca. 339 Ma), and Cambrian (2 %; ca. 528 Ma and ca. 490 Ma) grains. The youngest two zircons yield a weighted mean of 342.3 ± 4.3 Ma (95 % c.l.; Visean), although it represents an age based only on two ages is significantly older compared to the sedimentary age inferred from biostratigraphic age (Upper Triassic).

Kolmogorov–Smirnov test

The cumulative curves (Fig. 7a) indicate that U–Pb age distributions in samples of Triassic sandstone from the same basin are not significantly different and can therefore be joined for comparison with potential sources. Comparison of samples of Alentejo (ST-3 and SC-4) and Algarve (AM-1 and TH-4) sandstone reveals that there are remarkable differences (Fig. 7b).

When comparing Triassic Alentejo sandstone with the South Portuguese Zone (Carboniferous), both zircon populations are not enough significantly different (Fig. 7c), as with the Ossa-Morena Zone (Ediacaran–Ordovician and Carboniferous rocks) and the Upper Devonian Tercenas Formation.

The results obtained with the Kolmogorov–Smirnov test reveal that the zircon populations of the Triassic Algarve sandstone and the Upper Devonian Phyllite–Quartzite Formation are not significantly different (Fig. 7c), as for the Upper Devonian–Lower Carboniferous Tercenas Formation and for the sedimentary rocks of the Meguma Terrane (Silurian–Devonian and Cambrian).

Discussion

Potential sources of the Triassic sandstone of southwest Iberia

The zircon age spectra of the Alentejo Triassic sandstone is probably the result of sedimentary recycling from the Carboniferous sedimentary rocks of the South Portuguese Zone that mostly acted as an intermediate sediment repository of the Ossa-Morena Zone's older rocks. The oldest ages found in the Triassic sandstone resulting from recycling of the

South Portuguese and Ossa-Morena zones are similar to those of the Gondwana basement of southwest Iberia that indicate Archean zircon fertility events with West African Craton affinity (Leonian, ca. 3.3–3.0 Ga; Thiéblemont et al. 2004; and Liberian, 2.9–2.7 Ga; Key et al. 2008). Paleoproterozoic zircon ages match magmatic events related to the Eburnean orogeny in North Gondwana (ca. 2.2–1.8 Ga; Abouchami et al. 1990; Boher et al. 1992; Egal et al. 2002; Barbey et al. 2004; Schofield et al. 2006).

The few Mesoproterozoic-Tonian grains that are almost absent in the Ossa-Morena Zone (Linnemann et al. 2008; Pereira et al. 2008, 2012b, c) may derive from the Pulo do Lobo Zone that contains Devonian sedimentary units including zircons of the same age (Braid et al. 2011). Other possibilities include the continental blocks but are usually found in Laurentia, Avalonia, Ganderia and Meguma (Nance et al. 2008) and also, although less markedly, in North Africa (Meinhold et al. 2012; Gärtner et al. 2013). In the South Portuguese Zone, they are scarce in the Upper Devonian–Lower Carboniferous sedimentary rocks of the Phyllite–Quartzite and Tercenas formations and in the Upper Carboniferous Brejeira Formation (upper part of the Flysch Group of Baixo Alentejo; Braid et al. 2011; Pereira et al. 2012a, 2013).

The most prominent peak of Cryogenian–Ediacaran ages is probably related to zircon fertility events preserved in the Cadomian and Pan-African orogenic belts (ca. 700–545 Ma; Linnemann et al. 2004, 2008; Pereira et al. 2008, 2012b, c; Abati et al. 2010; Drost et al. 2011, and references therein; Pereira et al. 2011; Álvaro et al. 2014; Pereira 2015). They record the development of Late Neoproterozoic arc magmatism that was also common in other peri-Gondwanan terranes such as Meguma (Nance et al. 2008 and references therein).

The large subpopulation of Paleozoic ages of the Alentejo sandstone (Fig. 8) probably come from graywacke of the Flysch Group of Baixo Alentejo, South Portuguese Zone (Fig. 8; Pereira et al. 2012a, 2013). The small group of Cambrian and Ordovician ages reflect zircon fertility during the North Gondwana continental rifting (Chichorro et al. 2008; Linnemann et al. 2008; Sánchez-García et al. 2008, 2010, 2013; Pereira et al. 2012b; Díez-Fernández et al. 2014). Middle Devonian to Lower Carboniferous detrital grains coincide with the ages obtained from magmatic, sedimentary and metamorphic pre-Mesozoic rocks related to the Variscan orogeny, represented by the following potential sources: Middle-Upper Devonian to Lower Carboniferous volcanic-sedimentary complex of the Pyrite Belt (South Portuguese Zone; volcanic rocks with igneous zircon dated at ca. 374–346 Ma; Rosa et al. 2008; Oliveira et al. 2013), Upper Devonian–Lower Carboniferous quartzites and graywackes of the South Portuguese Zone (Phyllite–Quartzite and Tercenas formations; with detrital zircon in the age range of ca. 385–323 Ma; Pereira et al. 2013), Lower Carboniferous rocks of the Cabrela Formation (Ossa-Morena Zone; with detrital zircon in the age range of ca. 353–324 Ma; Pereira et al. 2012a) and the Variscan granitoids of the Évora Massif (Ossa-Morena Zone; with igneous zircons dated at ca. 345–323 Ma; Lima et al. 2012; Pereira et al. 2012d, 2015b).

Paleogeography of Iberia in late Triassic

In global and regional paleographic maps describing the plate configuration, paleoenvironment and lithofacies during the late Triassic time, Iberia is located in the core of supercontinent Pangaea and bounded at east by the Neotethys Ocean (e.g., Golonka 2007; Fig. 9). The separation of Laurussia (North America) and Gondwana (Europe) initiated by the early Triassic continued during the late Triassic in the area of the future Central Atlantic Ocean with continental interior clastic depositional systems (Golonka and Ford 2000).

Paleogeographic maps of Iberia for late Permian-early Triassic time based on paleocurrent directions and U–Pb ages of detrital zircons from the siliciclastic sequence of the Iberian Ranges (Fig. 1) indicate large-scale directions of sediment transport from source areas located in Laurussia (Avalonia) and local-scale directions indicating supply coming from Iberia pre-Mesozoic basement rocks (Sánchez Martínez et al. 2012). In the northeast and east Iberian basins, continental deposition (Buntsandstein facies) progressively evolved in middle-late Triassic to shallow-marine deposition with coastal carbonate (Muschelkalk facies) and coastal evaporitic environments (Keuper facies) (Arche and López-Gómez 1996).

In the west and Iberian basins, continental deposition (Buntsandstein facies) took place in late Triassic time (Rocha 1976; Palain 1979; Manuppella 1988). In the late Triassic siliciclastic rocks of the Lusitanian Basin (Fig. 1), paleocurrent directions and U–Pb ages of detrital zircons suggest local-scale directions of sediment transport from source areas located in the pre-Mesozoic basement of the Central Iberian and Ossa-Morena zones (Palain 1976; Soares et al. 2012; Pereira et al. 2015a).

In the Alentejo Basin, paleocurrent indicators consist with a transport of detritus coming from northeast (current geographic coordinates; Palain 1976) from the pre-Mesozoic basement of southwest Iberia. This study shows that the population of detrital zircon ages found in the late Triassic sandstones of the Alentejo Basin composed mostly of Neoproterozoic, Devonian, Paleoproterozoic and Carboniferous grains could support this interpretation, since all these zircon populations are typical of the Ossa-Morena and South Portuguese zones.

The source rocks that best resemble the Algarve sandstone population of detrital zircons are the Upper

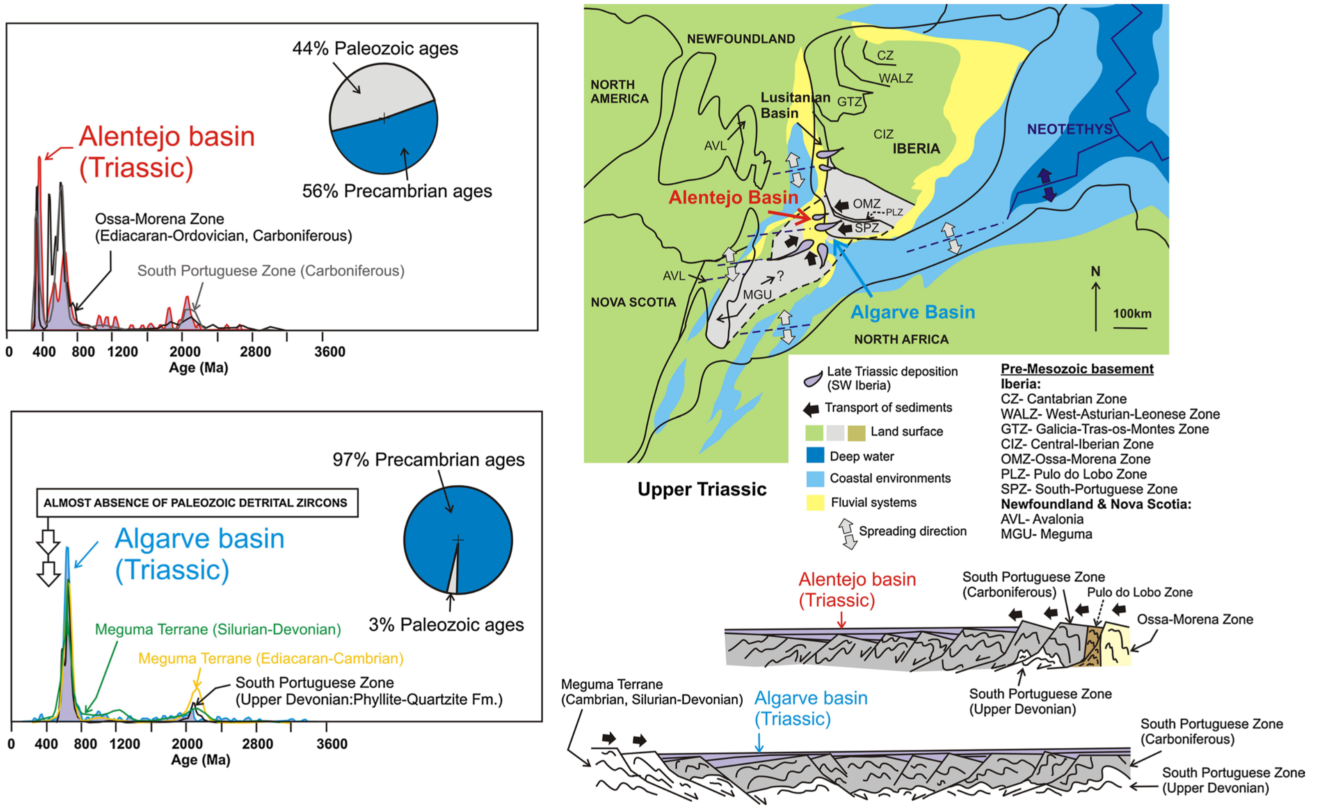


Fig. 9 Kernel density estimation of U–Pb detrital zircon ages from this study (including pie diagrams) and comparison with detrital zircon ages of Ediacaran–Ordovician and Carboniferous rocks of the Ossa-Morena Zone (data from Pereira et al. 2008, 2011, 2012a, c, 2015a, b; Díez-Fernández et al. 2014), Carboniferous rocks of the South Portuguese Zone (Rosa et al. 2008; Pereira et al. 2012a, 2013), Upper Devonian Phyllite–Quartzite Formation (Braid et al. 2011; Pereira et al. 2012a), Silurian Beechill and White Rock formations and Lower Devonian Torbrook and Stonehouse formations (Murphy et al. 2004) and Goldenville Group (Waldron et al. 2009) of the Meguma Terrane. Paleogeographic context of Upper Triassic continental rifting in southwest Iberia (adapted from Stampfli and Kozur 2006; Golonka 2007; Fortuny et al. 2011; Pereira et al. 2015a); *thick black arrows* show the possible currents responsible for sediment transportation from source areas located in Iberia and Nova Scotia

Devonian–Lower Carboniferous quartzite of the South Portuguese Zone (Phyllite–Quartzite and Tercenas formations) that have a large population of Neoproterozoic ages and include minor Mesoproterozoic and Silurian ages, and almost absence of late Devonian–Carboniferous detrital zircons (Figs. 8, 9). This population of zircon ages show striking similarities with the Meguma sedimentary rocks indicating that this terrane was connected to the Ossa-Morena Zone during late Devonian–early Carboniferous time (Braid et al. 2011; Pereira et al. 2012a, 2013), and might represent the unknown (not exposed) basement of the South Portuguese Zone. The transport of detritus from the South Portuguese Zone located at the East (current geographic coordinates) where the Phyllite–Quartzite and Tercenas formations crops out is supported by most paleocurrent directions found (Palain 1976). It appears that there are few outcrops of these rocks nearby that only crop out more than a hundred kilometers to the east in Iberia interior (Pyrite belt). However, at the western end of the Algarve Basin, near Cape Sagres (sampling sites of the Amado and Telheiro beaches; Fig. 2), paleocurrents indicate transport from Southwest and Southeast (current geographic coordinates; Palain 1976) (Fig. 9). If these paleocurrents represent local directions coming from offshore, we might admit the existence of Upper Devonian–Lower Carboniferous sedimentary rocks of the Phyllite–Quartzite and Tercenas formations in the Iberian continental shelf located west of the Algarve Basin. Yet, Upper Devonian–Lower Carboniferous sedimentary rocks were never been described in drilling reports (Matias et al. 2011). In accordance with paleographic reconstruction in late Triassic time, Iberia was connected with Nova Scotia before the opening of the Central Atlantic Ocean. In Nova Scotia, the Meguma Terrane is characterized by a Cambrian (and possibly older) to Lower Devonian stratigraphy. The widely exposed Meguma Supergroup includes turbidites of Cambrian or possible

Ediacaran age and of Lower Ordovician age (Waldron et al. 2009 and references therein). These Cambrian–Ordovician turbidites are overlain by Silurian volcanic and sedimentary rocks (White Rock and Beechill formations) passing up to Lower Devonian shallow-marine deposits (Torbrook and Stonehouse formations; Murphy et al. 2004 and references therein). Detrital zircon in the Meguma Supergroup yielded Archean, Paleoproterozoic and Neoproterozoic ages, indicating recycling of North Gondwana source rocks characterized by West Africa Craton affinity and related to Late Neoproterozoic arc magmatism (Waldron et al. 2009, 2011). In addition, the overlying Silurian–Devonian rocks are characterized by the presence of Mesoproterozoic-Tonian detrital zircon (Murphy et al. 2004). Therefore, it is reasonable to assume that the Meguma Terrane has also contributed to sedimentary infill of the westernmost end of the Algarve Basin during late Triassic time (Fig. 9).

Conclusions

The late Triassic Alentejo Basin mostly was fed from local source areas. From the Alentejo Basin, a population of detrital zircon dominated by Neoproterozoic, Devonian, Paleoproterozoic and Carboniferous age is documented that derived from sources to the northeast and southeast in the pre-Mesozoic basement of the South Portuguese and Ossa-Morena zones. Other sources were more distant than previously recognized.

The Triassic Algarve Basin sandstone yield zircon populations that differ significantly from the zircon populations of the underlying Carboniferous turbiditic rocks, and which might probably derived from source areas located in Iberia (Upper Devonian–Lower Carboniferous sedimentary rocks of the South Portuguese Zone) and/or outside Iberia (Cambrian to Devonian sedimentary rocks of the Meguma Terrane; Nova Scotia; Fig. 9).

Therefore, we suggest that the deposition in the southwest Iberia Triassic basins is marked by variability in sedimentary sources, involving the denudation of the pre-Mesozoic basement of southwest Iberia (Ossa-Morena and South Portuguese zones) with possible additional supplies coming from outside present-day Iberia (Meguma Terrane; Nova scotia). The late Triassic basins of southwest Iberia have different sources because they evolved separately with the detrital transport being probably controlled by two independent drainage systems.

This study proves to be very useful to understand the generation and evolution of the southwest Iberia intracontinental late Triassic basins and to confirm that the pre-Mesozoic basement of Iberia (Gondwana) was connected to Meguma Terrane (Laurussia) just before the opening of the Central Atlantic Ocean.

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