# Isotope geochemistry evidence for Laurussian-type sources of South Portuguese Zone Carboniferous turbidites (Variscan Orogeny)

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**Abstract:** New Rb–Sr isotopic data from South Portuguese Zone (SPZ) turbidites show that the $^{87}Sr/^{86}Sr(t)$ ratio increases from the basal Mértola Formation (Visean–Serpukhovian: 0.706–0.707), through the Mira Formation (Serpukhovian–Bashkirian: 0.706–0.712) to the uppermost Brejeira Formation (Bashkirian–Moscovian: 0.713–0.715). In addition, estimated Nd $T_{DM}$ model ages for the Mértola (1.29–1.09 Ga), Mira (1.58–1.1 Ga) and Brejeira (1.73–1.37 Ga) formations indicate inverted stratigraphy for their isotopic sources. The isotope geochemical data indicate significant changes in the sources from which the SPZ Carboniferous turbidites are derived, consistent with the progressive denudation of a continental magmatic arc built on the Laurussian margin. Mértola turbidites inherited their geochemical and isotopic characteristics from an adjacent dissected Middle–Late Devonian continental magmatic arc with an intermediate–felsic composition: that is a Laurussian (Rheic magmatic arc)-type source. The progressive erosion of its plutonic roots and older host continental basement rocks are indicated in the Mira and Brejeira formations by the increasing contribution of recycled ancient continental crust. The pronounced similarity between the Nd $T_{DM}$ model ages and the detrital zircon populations of the Mira and Brejeira formations (SW Iberia) suggest that they share a common Laurussian (West Avalonia/Meguma terrane)-type source but a contribution from Gondwanan (Ossa-Morena)-type sources cannot be discarded.

The chemical composition of siliciclastic sedimentary rocks is mainly determined by the provenance of terrigenous sediments, and thus by the original composition of the source rocks (McLennan *et al.* 2003). These sources may comprise a complex mixture of igneous, metamorphic and recycled sedimentary rocks (McLennan *et al.* 1993), which makes it difficult to distinguish between provenances using only petrographical studies. During the last two decades, major- and trace-element geochemistry and radiogenic isotopes for bulk samples have been successfully used in provenance studies (Rollinson 1993; Murphy and Nance 2002; McLennan *et al.* 2003; Ugidos *et al.* 2003; Fuenlabrada *et al.* 2016). Improvements in detrital zircon U–Pb geochronology techniques have also provided a powerful tool for enabling the recognition of the range of different sources for siliciclastic sediments and sedimentary rocks (Gehrels 2012).

It has been demonstrated that the combined use of petrography, geochemistry and geochronology enables the recognition of different sources, identifies changes in provenance during the filling of sedimentary basins, and constrains the relevance of the tectonic setting in which siliciclastic sedimentary rocks were deposited (Dickinson *et al.* 1983; Thomas 2011). This approach can determine the relative contributions of distinct sources which provide detritus to the basins of a developing mountain chain as these settings commonly reflect evolving changes in source (Thomas *et al.* 2004).

In this paper, we investigate the provenance of Carboniferous siliciclastic strata from the synorogenic basins of SW Iberia in order to determine source terranes during the amalgamation of Pangaea during the Carboniferous (Appalachian–Variscan mountain belt). In SW Iberia, Carboniferous strata occur in three main tectonic units of the Variscan

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orogenic belt: the Ossa-Morena Zone (OMZ), the Pulo do Lobo Zone (PLZ) and the South Portuguese Zone (SPZ). Previous geological mapping, stratigraphy and structural geology studies have suggested that SPZ Carboniferous turbidites resulted from syn-orogenic deposition in a foreland basin sourced by older OMZ basement rocks (Oliveira 1990; Silva *et al.* 1990). Recent studies of sedimentary petrography, whole-rock geochemistry and detrital zircon U–Pb geochronology have revealed that SPZ turbidites may also be derived from other sources (Pereira *et al.* 2012*a*, 2014; Rodrigues *et al.* 2014), a proposition that is still under discussion. In this study, we present new major- and trace-element geochemistry data, and, for the first time, Sm–Nd and Rb–Sr isotope data for SPZ Carboniferous turbidites. We present new Sr–Nd isotope compositions of SPZ Carboniferous turbidites which, together with their whole-rock geochemical features, enables the recognition of changing contributions of detrital material derived from distinct sources, while Nd $T_{DM}$ model ages indicate the average crustal residence duration of all contributing (mixed) sources. Finally, we discuss the provenance of SPZ Carboniferous turbidites (i.e. distinct source terranes in the Appalachian–Variscan belt), comparing their detrital zircon age populations with those of the pre-Carboniferous siliciclastic rocks of SW Iberia and Nova Scotia. Nova Scotia Paleozoic terranes were chosen because palaeogeographical reconstructions and previous studies suggest that they were juxtaposed with the SPZ Carboniferous basins before the opening of the Atlantic Ocean. For this purpose, we use a compilation of published U–Pb geochronology data and multi-dimensional scaling diagrams (MDS in Isoplot-R, produced by Vermeesch 2018) which

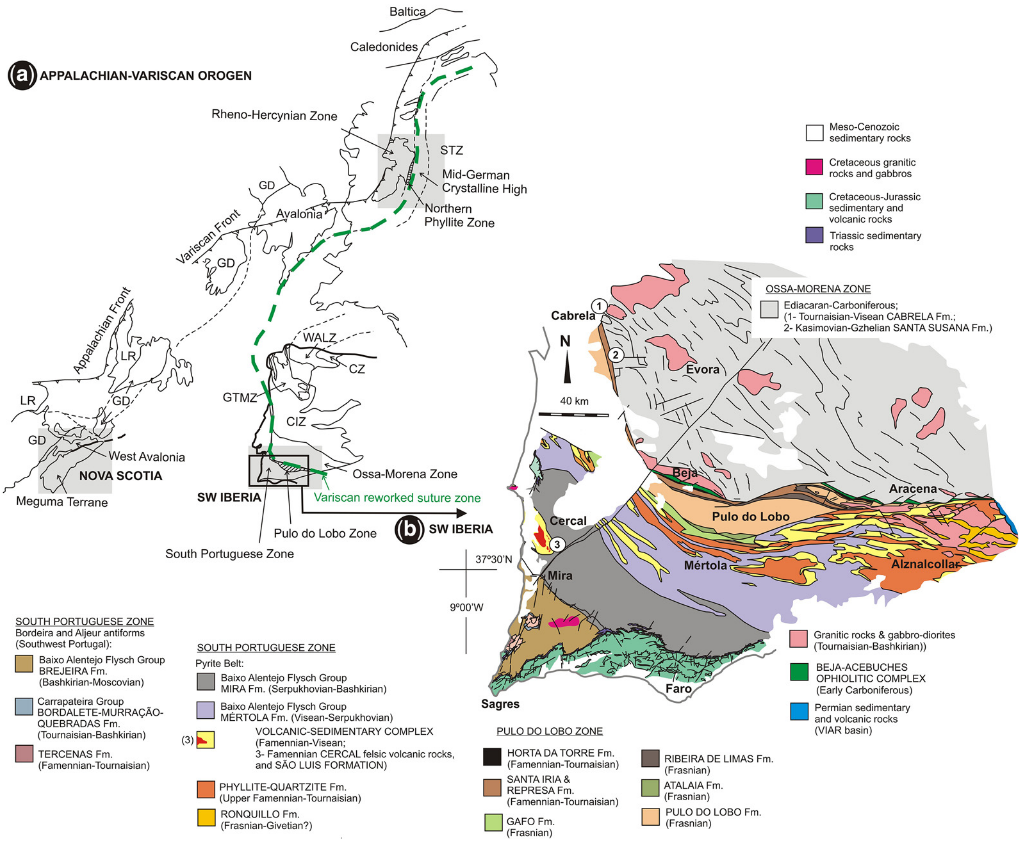


**Fig. 1.** (**a**) Inset with location of the South Portuguese, Pulo do Lobo and Ossa-Morena zones (SW Iberia) in the Variscan belt, and adjoining terranes: CIZ, Central Iberian Zone; CZ, Cantabrian Zone; WALZ, West Asturian–Leonese Zone; GTMZ, Galicia-Trás-os-Montes Zone; STZ, Saxo-Thuringian Zone; GD, Ganderia; LR, Laurentia (modified from van Staal and Barr 2012; von Raumer *et al.* 2017; Pereira *et al.* 2017, 2019). (**b**) Simplified geological map of SW Iberia showing the South Portuguese, Pulo do Lobo and Ossa-Morena zones (modified from Oliveira 1990; Pérez-Cáceres *et al.* 2017; Pereira *et al.* 2017, 2019).

have proved useful in discriminating between Laurussian-type and Gondwanan-type sources. An improved understanding of the provenance of SPZ Carboniferous siliciclastic rocks is crucial to the debate surrounding existing geodynamic models of Rheic Ocean closure. This paper was produced as a tribute to the academic career of Damian Nance, who dedicated much of his research work to providing an understanding of the origin and evolution of the supercontinent cycles, including the birth and demise of the Rheic Ocean.

## Geological setting

SW Iberia forms the southwesternmost segment of the Western and Central Europe Variscan belt that extends to North America as part of the Appalachian belt (Fig. 1). The Appalachian–Variscan orogen was formed during the Devonian–Carboniferous as the result of the closure of the Rheic Ocean (Matte 2001; Martínez Catalán *et al.* 2007), and that of other closely related oceanic basins (Franke 2000; Simancas *et al.* 2009; Ribeiro *et al.* 2010; Eckelmann *et al.* 2014; Díez Fernández *et al.* 2016; Pereira *et al.* 2017; von Raumer *et al.* 2017), over the course of the protracted continental collision between Laurussia and Gondwana (Martínez Catalán *et al.* 2009; Nance *et al.* 2010; Arenas *et al.* 2014). SW Iberia includes three major tectonic units presenting differences in terms of stratigraphy and magmatism which may represent the two continental margins involved in the late Paleozoic collision, separated by the complex Rheic suture (Fig. 1): the OMZ (on the Gondwanan side), and the PLZ and SPZ (on the Laurussian side) (Pereira *et al.* 2017 and references therein).

### *Gondwanan side*

The oldest recorded OMZ stratigraphy includes Ediacaran sedimentary and volcanic rocks (Fig. 2a), associated with the development of the continental active margin (Cadomian magmatic arc: Quesada 1990; Eguíluz *et al.* 2000; Pereira *et al.* 2008; 2012*b*). Early Cambrian (Early Rift Volcanism: Sánchez-García *et al.* 2010, 2014) sedimentary sequences and volcanic rocks mark a transition to an intracontinental rift, reaching the main volume of volcanism in the Middle–Late Cambrian (Main Rift Volcanism: Sánchez-García *et al.* 2003, 2010), with Nd $T_{DM}$ ages ranging from 1.3 to 0.8 Ga (Chichorro *et al.* 2008; Sánchez-García *et al.* 2010) (Fig. 2a). The maximum stretching of the continental crust and the last magmatic pulses occurred in the Early Ordovician (Díez Fernández *et al.* 2015; Cambeses *et al.* 2015), just before the deposition of Middle Ordovician–Early Devonian passive-margin mostly siliciclastic sequences (Fig. 2a) associated with the opening of the Rheic Ocean (Robardet and Gutiérrez-Marco 2004). Nd $T_{DM}$ ages for Ediacaran–Early Devonian siliciclastic rocks of the OMZ range from 2 to 1.4 Ga (Chichorro *et al.* 2008; López-Guijarro *et al.* 2008; Rojo-Pérez *et al.* 2019) (Fig. 2a). Significant volumes of igneous rocks characterize the Ediacaran–Ordovician interval in the OMZ (Sánchez-García *et al.* 2003, 2010; Robardet and Gutiérrez-Marco 2004; Díez Fernández *et al.* 2015).

Lying structurally above the OMZ, there are allochthonous units (Ribeiro *et al.* 2010 and references therein) showing tectonostratigraphic similarities with those from the NW Iberia Galicia-Trás-os-Montes Zone (Díez Fernández *et al.* 2016). The SW Iberia allochthonous complex comprises (Díez Fernández *et al.* 2017): (i) a Basal Unit that includes high-pressure rocks, which has been interpreted as being a slab of the continental margin of Gondwana subducted during the Variscan collision; and (ii) ophiolitic units inferred to have been derived from the Rheic Ocean lithosphere and/or Devonian intra-Gondwana oceanic basins. On the Gondwanan side, Middle–Late Devonian strata and magmatism are absent in the OMZ, representing an important stratigraphic gap (Robardet and Gutiérrez-Marco 2004). Carboniferous stratigraphy includes Tournaisian–Visean marine siliciclastic rocks associated with volcanism of the Cabrela and Toca da Moura volcanic–sedimentary complexes (Quesada *et al.* 1990; Pereira *et al.* 2006) that are unconformably overlain and intruded by Baleizão Serpukhovian (?)–Bashkirian(?) felsic porphyries. Kasimovian molasses of the Santa Susana Formation unconformably overlie the Toca da Moura volcanic–sedimentary complex and the Baleizão felsic porphyries, including pebbles of these two older units (Machado *et al.* 2012 and references therein).

### *Laurussian side: SW Iberia*

The PLZ is exposed along with the contact zone between the SPZ and a narrow belt of amphibolites (i.e. Beja-Acebuches Ophiolitic Complex: Fonseca and Ribeiro 1993), and represents the southern boundary of the OMZ (Fig. 1). This ophiolite was initially regarded as an Early–Middle Devonian oceanic lithosphere formed in a narrow intra-arc or back-arc basin, developed in the Gondwana active margin during the Rheic Ocean subduction (Quesada *et al.* 1994; Fonseca *et al.* 1999). However, this interpretation was called into question because U–Pb zircon ages from Beja-Acebuches mafic rocks yielded *c.* 340–332 Ma for protolith crystallization (Azor *et al.* 2008). Based on this geochronological data, Beja-Acebuches mafic rocks are now regarded as likely to be associated with an intra-collisional extensional stage that occurred in SW Iberia after

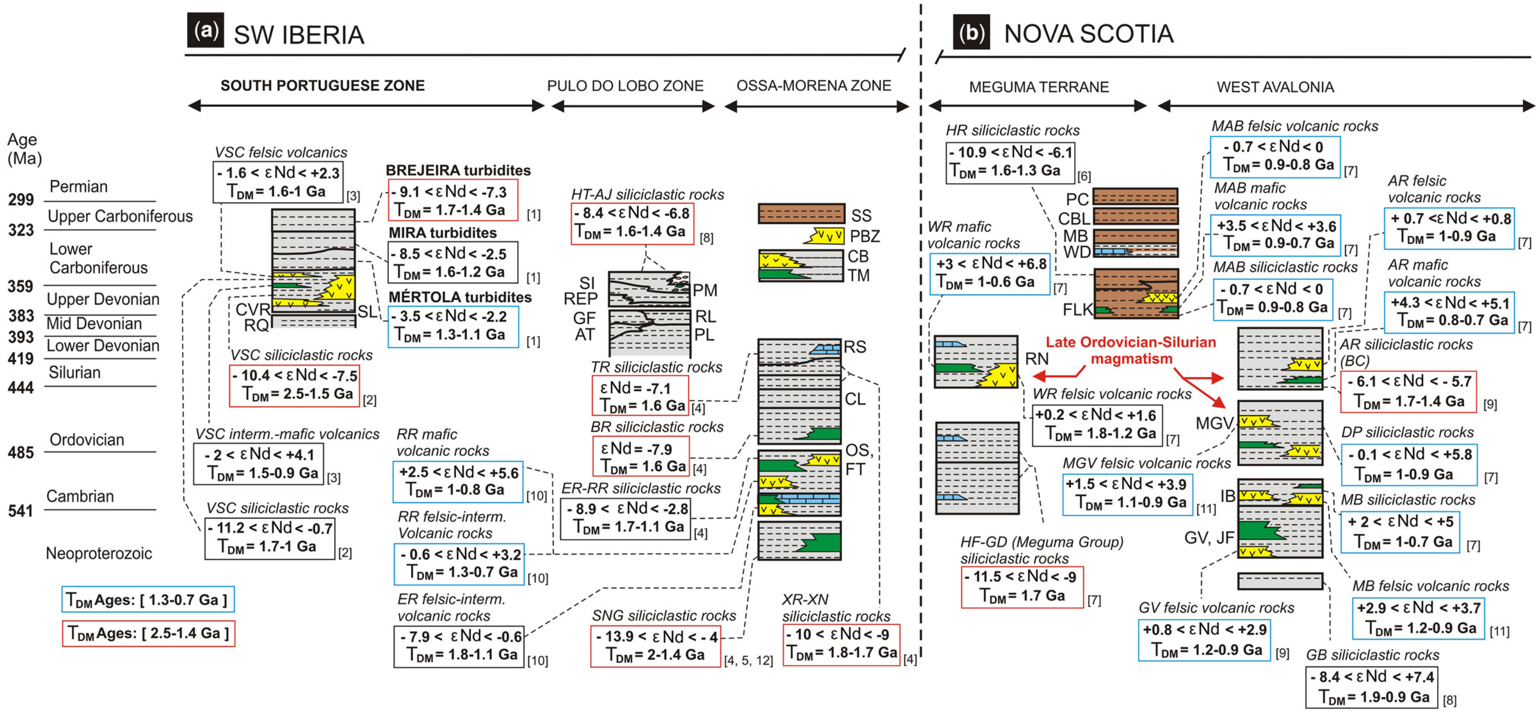


**Fig. 2.** (**a**) Summary of the stratigraphy of the South Portuguese, Pulo do Lobo and Ossa-Morena zones of SW Iberia (modified from Oliveira 1990; Robardet and Gutiérrez-Marco 2004; Pereira *et al.* 2017, 2019 and references therein). South Portuguese Zone: RO, Ronquillo Formation; PQ, Phyllite–Quartzite Formation; SL, São Luis Formation; CVR, Cercal porphyries, VSC, Pyrite Belt Volcanic–Sedimentary Complex. Pulo do Lobo Zone: PL, Pulo do Lobo Formation, AT, Atalaia Formation; GF, Gafo Formation; REP, Represa Formation; RL, Ribeira de Limas Formation; SI, Santa Iria Formation; HT, Horta da Torre Formation; PM, Péramora Mélange; AJ, Alájar Mélange. Ossa-Morena Zone: SNG, Serie Negra Group; ER, Early Rift Volcanism; RR, Main Rift Volcanism; OS, Ossa Formation; FT, Fatuquedo Formation; BR, Barrancos Formation; CL, Colorada Formation; XN, 'Xistos com Nódulos' Formation; XR, 'Xistos Raiados' Formation; RS, Russianas Formation; TR, Terena Formation; CB, Cabrela Volcanic–Sedimentary Complex; SS, Santa Susana Formation; TM, Toca da Moura Volcanic–Sedimentary Complex. (**b**) Summary of the stratigraphy of the Meguma terrane and West Avalonia of Nova Scotia (modified from Waldron *et al.* 2013; Sues and Olsen 2015; Murphy *et al.* 2018; White *et al.* 2018). Meguma terrane: GD, Goldenville Group; HF, Halifax Group; RN, Rockville Notch Group; WR, White Rock Formation. West Avalonia: GB, Gamble Brook Formation; GV, Georgeville Group; JF, Jeffers Group; IB, Iron Brook Group; MDB, McDonalds Brook Group; DP, Dunn Point Formation; MGV, McGillivray Formation; AR, Arisaig Group. Meguma terrane/West Avalonia: MAB, McArras Brook Formation; FLK, Fountain Lake Group; HR, Horton Group; WD, Windsor Group; MB, Mabou Group; CBL, Cumberland Group; PC, Pictou Group. Compiled $\varepsilon_{Nd}(t)$ values and Nd $T_{DM}$ model ages from: (1) this study; (2) Braid (2010); (3) Mitjavila *et al.* (1997); (4) López-Guijarro *et al.* (2008); (5) Chichorro *et al.* (2008); (6) Murphy (2000); (7) Keppie *et al.* (1997); (8) Murphy (2002); (9) Murphy and Nance (2002); (10) Sánchez-García *et al.* (2010); (11) Murphy *et al.* (2018); (12) Rojo-Pérez *et al.* (2019).

the Devonian Rheic Ocean consumption (Pérez-Cáceres *et al.* 2015 and references therein).

PLZ stratigraphy only includes Devonian–Carboniferous strata (Fig. 2a). The oldest sequence of Frasnian age, consisting of slate, phyllite, quartzite and metagraywacke (Pulo do Lobo, Atalaia, Gafo and Ribeira de Limas formations), is unconformably overlain by Famennian–Tournaisian shale, greywacke and sandstone (Represa, Santa Iria and Horta da Torre formations). The PLZ formations were classically regarded to represent an accretionary prism formed in the Gondwana active margin, associated with the subduction of the Rheic Ocean under the OMZ (Eden and Andrews 1990; Quesada 1990; Ribeiro *et al.* 2010; Braid *et al.* 2011). Alternatively, it was proposed that the PLZ formations were deposited in a back-arc basin developed on the Laurussia active margin during the closure of the Rheic Ocean, as suggested for the Rheno-Hercynian Zone (Pereira *et al.* 2017 and references therein). A peculiar feature of the PLZ is the presence of a significant population of *c.* 1.9-1.1 Ga detrital zircon grains in the Horta da Torre Formation which is characteristic of sources from Laurentia/Baltica (Braid *et al.* 2011). These zircon grains may be derived from the recycling of a tectonically transported crustal fragment from the Southern Uplands Terrane of the British Caledonides (Braid *et al.* 2011), and/or from the early Neoproterozoic siliciclastic rocks of West Avalonia (Pereira *et al.* 2019).

The pre-Frasnian basement unexposed on the Laurussian side has been tentatively associated with the Avalonia–Meguma terrane, based on the discovery of a population of inherited zircon grains and Nd $T_{DM}$ ages that are distinct from those recognized in the OMZ, in Early Carboniferous granitic rocks intruding both the SPZ and the PLZ (de la Rosa *et al.* 2002; Braid *et al.* 2012). In the SPZ, the oldest exposed rocks belong to a Frasnian sedimentary sequence consisting of phyllite and quartzite (Ronquillo Formation: Simancas 1983) with a maximum depositional age of *c.* 400 Ma (Pérez-Cáceres *et al.* 2017), unconformably overlain by quartzite and shale with Famennian fossils (Phyllite–Quartzite Formation: Oliveira 1990). The Phyllite–Quartzite Formation includes a group of young detrital zircon grains that yielded a Tournaisian maximum depositional age (Pérez-Cáceres *et al.* 2017). Atop the Phyllite–Quartzite Formation, there is a Famennian–Visean Pyrite Belt volcanic–Sedimentary Complex with massive sulfide deposits (Oliveira 1990), including siliciclastic rocks, intermediate–mafic and felsic volcanic rocks with Nd $T_{DM}$ ages ranging from 1.7 to 1 Ga (Braid 2010), 1.5 to 0.9 Ga and from 1.6 to1 Ga, respectively (Mitjavila *et al.* 1997) (Fig. 2a). SPZ stratigraphy is dominated by Carboniferous turbiditic sedimentation (Baixo Alentejo Flysch Group: Oliveira 1984), consisting of (Fig. 2a): Visean greywacke, shale and conglomerate (Mértola Formation); Visean–Bashkirian shale and greywacke (Mira Formation); and Bashkirian–Moscovian sandstone, shale and greywacke (Brejeira Formation). U–Pb dating of detrital zircon grains indicates a change in the sources during the Carboniferous (Pereira *et al.* 2012*a*, 2014; Rodrigues *et al.* 2014). The number of pre-Devonian zircon grains in the Mértola Formation (22%) is smaller than in the Mira (74%) and Brejeira (92%) formations. In the Bordeira and Aljezur anticlines (SW Portugal), Famennian–Tournaisian quartzites and shales (Tercenas Formation) are overlain by Carboniferous terrigenous and carbonate rocks (Carrapateira Group: Oliveira 1990; Pereira *et al.* 2007). Detrital zircon grains of the Ronquillo, Phyllite–Quartzite and Tercena quartzites are mostly of pre-Devonian age, including Early Silurian and Mesoproterozoic ages probably derived from source areas of the Laurussian margin (Braid *et al.* 2011; Pereira *et al.* 2012*a*; Pérez-Cáceres *et al.* 2017).

### *Laurussian side: Nova Scotia*

In Nova Scotia (Fig. 1), the Meguma terrane is separated from West Avalonia by the Minas Fault Zone (Murphy *et al.* 2011). These two Paleozoic terranes drifted away from the Gondwanan margin in the Early Ordovician and both were part of the Laurussian margin from the Silurian (Keppie and Krogh 2000; Murphy *et al.* 2004; Shellnutt *et al.* 2019). However, there is no consensus as regards this interpretation and some other authors consider the initial collision of West Avalonia with the Laurentia margin to have occurred in the Late Silurian, followed by later Meguma terrane accretion (van Staal *et al.* 2009; van Staal and Barr 2012).

West Avalonia stratigraphy (Fig. 2b) presents a Neoproterozoic unit of older rocks consisting of pelite, psammite and quartzite, with a *c.* 975 Ma maximum depositional age (Gamble Brook Formation: Murphy 2002; Henderson *et al.* 2016), and Nd $T_{DM}$ ages ranging from 1.8 to 1.5 Ga (Murphy 2002). The unit is overlain by Ediacaran turbidites interbedded with *c.* 628–618 Ma volcanic rocks (Georgeville and Jeffers groups). Nd $T_{DM}$ ages for felsic volcanic rocks of the Georgeville Group range from 1.2 to 0.9 Ga (Murphy and Nance 2002). In addition, Ediacaran siliciclastic strata are intruded by *c.* 607–604 Ma granitic rocks (Murphy *et al.* 1997, 1999). Cambrian–Early Ordovician stratigraphy mostly includes terrestrial siliciclastic rocks and a few shallow-marine limestones, interbedded with bimodal volcanic rocks with Nd $T_{DM}$ ages ranging from 1.2 to 0.9 Ga (McDonalds Brook and Iron Brook groups: Keppie *et al.* 1997 and references therein). Volcanism increases towards the top, with the presence of *c.* 460-455 Ma volcanic rocks interbedded in siliciclastic rocks (Dunn Point and McGillivray Brook formations: Hamilton and Murphy 2004; Murphy *et al.* 2012). Nd $T_{DM}$ ages for the McGillivray felsic volcanic rocks range from 1.1 to 0.9 Ga (Murphy *et al.* 2018) (Fig. 2b). However, Silurian–Early Devonian stratigraphy is dominated by marine fossiliferous sandstone and shale with a few ash beds (Arisaig Group: Murphy *et al.* 2008). Nd $T_{DM}$ ages for the Silurian siliciclastic rocks of the Beechill Cove Formation (Arisaig Group) range from 1.7 to 1.4 Ga (Murphy and Nance 2002); while for the felsic and mafic volcanic rocks, Nd $T_{DM}$ ages range from 1 to 0.7 Ga (Keppie *et al.* 1997) (Fig. 2b).

Meguma terrane stratigraphy (White and Barr 2010 and references therein) includes Cambrian–Early Ordovician turbidites (Goldenville and Halifax groups). These turbidites are unconformably overlain by Silurian–Early Devonian shallow-marine siliciclastic and volcanic rocks (Rockville Notch Group) consisting at the base of shale and sandstone and/or volcanic rocks dated at *c.* 446–434 Ma (White Rock Formation: Keppie and Krogh 2000; White *et al.* 2018), and are conformably overlain by shale, sandstone, and a few layers of carbonate rocks and ironstone (Torbrook Formation: White 2010; White and Barr 2012). Nd $T_{DM}$ ages for the Late Ordovician–Silurian White Rock mafic volcanic rocks range from 1 to 0.6 Ga (Keppie *et al.* 1997) (Fig. 2b). Early Paleozoic stratigraphy is intruded by *c.* 382–357 Ma plutons (including the South Mountain Batholith: Moran *et al.* 2007 and references therein).

In Nova Scotia, the Late Devonian sequence includes siliciclastic rocks interbedded with basalts (McAras Brook Formation: Braid and Murphy 2006) and felsic volcanic rocks (Fountain Lake Group), which are probably linked to plutonism dated at *c.* 363–350 Ma (Doig *et al.* 1996; Pe-Piper *et al.* 2004; Murphy *et al.* 2018 and references therein). The McAras Brook felsic volcanic and siliciclastic rocks show Nd $T_{DM}$ ages ranging from 0.9 to 0.7 Ga (Keppie *et al.* 1997) (Fig. 2b). Late Devonian–Early Carboniferous fluvial and lacustrine siliciclastic rocks (Horton and Fountain Lake groups) unconformably overlie both the West Avalonia and Meguma terrane stratigraphy described above, and are overlain by Early Carboniferous marine siliciclastic, carbonate and evaporitic rocks (Windsor Group: Murphy *et al.* 2008; Waldron *et al.* 2013 and references therein). The stratigraphic transition to the late Carboniferous includes terrestrial siliciclastic sequences (Mabou and Cumberland groups) that are overlain by Late Carboniferous–Early Permian (Pictou Group) and Permian (Honeycomb Point Formation of the Fundy Group: Sues and Olsen 2015 and references therein) terrestrial siliciclastic rocks (Fig. 2b).

## Analytical methods

The samples of SPZ Carboniferous turbidites studied belong to the Baixo Alentejo Flysch Group: Mértola (Visean–Serpukhovian: samples Gs-1, Gs-3, Gs-5, Sp-107 and Mr-1), Mira (Serpukhovian–Bashkirian: samples Gs-7, Gs-9, Gs-11, SC-6, Al-3 and Sbm-5) and Brejeira (Bashkirian–Moscovian: samples Am-3, Gs-13, Gs-15, Th-5, Sp-201, Cpt-1, Tel-1 and Pru-1) formations. Rock samples were prepared (milled) at Universidade de Évora (Portugal). Eight samples (Al-3, Cpt-1, Mr-1, Pru-1, Sbm-5, Sp-107, Sp-201 and Tel-1) were analysed at Activation Laboratories Ltd (Actlabs, Canada) for lithogeochemical investigation. Whole-rock major- and trace-element analyses were performed in accordance with the 4Lithores method. After the performance of lithium metaborate/tetraborate fusion–ICP for sample preparation, ICP-MS (inductively coupled plasma mass spectrometry) analyses were carried out using a PerkinElmer Sciex ELAN 6000, 6100 and 9000. Three blanks and five controls were analysed per group of samples. The results are given in Table 1.

Rb–Sr and Sm–Nd isotopic analyses of 13 samples (Am-3, Gs-1, Gs-3, Gs-5, Gs-7, Gs-9, Gs-11, Gs-13, Gs-15, Sc-6, Sp-107, Sp-201 and Th-5) were carried out at the Laboratório de Geologia Isotópica of Universidade de Aveiro (Portugal). Sr was loaded onto a single Ta filament with $H_3PO_4$, while Nd was loaded onto a Ta outer-side filament with HCl, in a Ta–Re–Ta triple arrangement. Isotope ratios were determined using a VG Sector 54 multicollector thermal ionization mass spectrometer (TIMS). Data were recorded in multi-dynamic mode with peak measurements at 1–2 V to $^{88}$Sr and 0.8–1.5 V to $^{144}$Nd. Sr and Nd sotopes ratios were corrected for mass fractionation relative to $^{88}\mathrm{Sr}/^{86}\mathrm{Sr} = 0.1194$ and $^{146}\mathrm{Nd}/^{144}\mathrm{Nd} = 0.7219$. During the study, the SRM-987 standard yielded average values of $^{87}\mathrm{Sr}/^{86}\mathrm{Sr} = 0.710277 \pm 13$ ($N = 13$; confidence limit of 95%) and JNdi-1 standard $^{143}\mathrm{Nd}/^{144}\mathrm{Nd} = 0.512015 \pm 23$ ($N = 13$; confidence limit of 95%). The results are given in Tables 2 and 3, and are plotted on diagrams in Figures 3 and 4.

Sm–Nd isotopic analyses of six samples (Al-3, Cpt-1, Mr-1, Pru-1, Sbm-5 and Tel-1) were performed at the Geochronology and Isotope Geochemistry Service of the Universidad Complutense de Madrid (Spain), using isotope dilution thermal ionization mass spectrometry (ID-TIMS). Samples were spiked with a mixed $^{149}$Sm–$^{150}$Nd tracer and analysed in an IsotopX-Phoenix spectrometer (TIMS), in a single collection and dynamic multi-collection mode for Sm and Nd, respectively. Whole-rock samples, previously weighted in Teflon® vessels along with the mixed-spike solution ($^{149}$Sm–$^{150}$Nd: Oak Ridge), were dissolved in 5 ml of ultrapure HF and 3 ml of ultrapure $HNO_3$ (Merck-Suprapur™) and

**Table 1.** *Whole-rock major- and trace-element data of SPZ siliciclastic rocks*

| | Sample | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Sp-107 | Mr-1 | Al-3 | Sbm-5 | Sp-201 | Cpt-1 | Tel-1 | Pru-1 |
| $SiO_2$ | 65.11 | 63.89 | 79.88 | 60.67 | 67.92 | 73.12 | 79.85 | 73.97 |
| $Al_2O^3$ | 15.74 | 16.13 | 8.53 | 10.77 | 14.4 | 10.31 | 8.32 | 9.56 |
| $Fe_2O_3^{(T)}$ | 6.9 | 6.92 | 4.7 | 10.3 | 7.41 | 7.03 | 3.17 | 5.73 |
| MnO | 0.062 | 0.044 | 0.148 | 0.239 | 0.081 | 0.039 | 0.051 | 0.05 |
| MgO | 1.84 | 1.54 | 1.29 | 2.07 | 1.44 | 0.73 | 0.79 | 1.3 |
| CaO | 0.5 | 0.07 | 0.1 | 4.19 | 0.14 | 0.43 | 0.73 | 1.16 |
| $Na_2O$ | 2.94 | 1.5 | 2.04 | 0.27 | 0.51 | 0.32 | 0.95 | 0.34 |
| $K_2O$ | 1.85 | 2.03 | 0.53 | 1.25 | 2.3 | 1.54 | 1.26 | 1.66 |
| $TiO_2$ | 0.722 | 0.852 | 0.509 | 0.591 | 0.973 | 0.705 | 0.584 | 0.637 |
| $P_2O_5$ | 0.17 | 0.11 | 0.05 | 0.08 | 0.12 | 0.24 | 0.08 | 0.12 |
| LOI | 4.58 | 5.77 | 2.2 | 9.23 | 4.03 | 4.22 | 3.51 | 4.51 |
| Total | 100.4 | 98.87 | 99.97 | 99.65 | 99.33 | 98.69 | 99.3 | 99.04 |
| Sc | 13 | 16 | 8 | 16 | 14 | 10 | 7 | 9 |
| La | 25.1 | 34.6 | 15.1 | 15.1 | 36.7 | 23.8 | 27.6 | 24 |
| Ce | 51 | 69.3 | 30.3 | 31.6 | 74.1 | 46.7 | 57.2 | 49.7 |
| Pr | 5.71 | 7.67 | 3.43 | 3.64 | 7.54 | 5.39 | 6.81 | 5.94 |
| Nd | 26 | 28.3 | 12.8 | 14 | 26.4 | 20.4 | 25.6 | 22.6 |
| Sm | 5 | 5.4 | 2.5 | 3.3 | 5.5 | 4.3 | 4.9 | 4.9 |
| Eu | 1.08 | 1.24 | 0.6 | 0.86 | 1.27 | 1 | 0.98 | 1.04 |
| Gd | 4.8 | 4.3 | 2.7 | 3.5 | 6 | 4.3 | 3.9 | 4.2 |
| Tb | 0.7 | 0.7 | 0.4 | 0.6 | 1 | 0.8 | 0.6 | 0.7 |
| Dy | 4.2 | 4 | 2.6 | 3.4 | 6.2 | 4.6 | 3.6 | 4 |
| Ho | 0.8 | 0.8 | 0.5 | 0.6 | 1.2 | 0.9 | 0.7 | 0.8 |
| Er | 2.3 | 2.3 | 1.4 | 1.9 | 3.6 | 2.5 | 2 | 2.3 |
| Tm | 0.35 | 0.37 | 0.23 | 0.27 | 0.54 | 0.4 | 0.34 | 0.33 |
| Yb | 2.2 | 2.2 | 1.5 | 1.8 | 3.5 | 2.4 | 2.2 | 2.2 |
| Lu | 0.3 | 0.33 | 0.23 | 0.26 | 0.5 | 0.34 | 0.31 | 0.31 |
| Hf | 4.3 | 3.8 | 3.5 | 2.9 | 8.2 | 5.3 | 5.9 | 4.8 |
| Th | 1.2 | 11.5 | 4.5 | 5.8 | 0.6 | 7.4 | 6.9 | 6.7 |

Oxides are in weight percentage (wt%).
Trace elements are in parts per million (ppm).
LOI, loss on ignition.

placed into an oven for 65 h at a temperature of 120°C. After that time, vials were evaporated on a heat plate at 120°C. Once samples were completely dried, 1 ml of $HNO_3$ (Merck-Suprapur™) was added and placed back on the heat plate for evaporation at 120°C. Then, 4 ml of distilled HCL 6N were added to the dried samples and placed again inside an oven overnight at 120°C. After cooling the vials, samples were evaporated at 120°C and remains were dissolved in 3 ml of 2.5 N HCl (distilled and titrated). Samples were centrifuged at 4000 rpm for 10 min in order to separate the dissolved fraction from the residue, if any. Chromatographic separation of the total group of REE was performed using a previously calibrated cation-exchange resin Dowex 50W-X8 200–400 mesh. REE fractions recovered from the previous chromatographic stage were dried completely before being dissolved again in 200 µl HCl 0.18 N, and were passed through a new chromatographic resin (Ln Resin). The result is a complete separation between the Nd (using 0.3 N HCl as the eluent) and the Sm (using 0.4 N HCl as the eluent) fractions. Dried Sm and Nd fractions were dissolved in 2 µl of 0.05 M phosphoric acid, and loaded onto a side rhenium (Re) filament of a Re-filament triple arrangement. Nd ratios were analysed in a TIMS-Phoenix™ mass spectrometer, following a dynamic multi-collection method, through 160 cycles at a stable intensity of 1 V for the $^{144}Nd$ mass. In turn, Sm ratios were analysed in the same spectrometer, following a single static method, through 112 cycles maintaining a 1 V intensity for the $^{149}Sm$ mass. Along with the samples, the reference material BHVO-2 (USGS: Wilson 1997; Raczek *et al.* 2003) were analysed in order to test the isotope dilution process. The reference material presented average values of Sm = 5.4 ± 0.8 ppm, Nd = 21.8 ± 3.4 ppm and $^{143}Nd/^{144}Nd = 0.512994 \pm 0.000036$. $^{143}Nd/^{144}Nd$ ratios were corrected for $^{142}Ce$ and $^{144}Sm$ interferences, and normalized to

**Table 2.** *Whole-rock Rb–Sr isotope data of SPZ siliciclastic rocks*

| | Age* (Ma) | Sr (ppm) | Rb (ppm) | $^{87}Rb/^{86}Sr$ | Error ($2\sigma$) | $^{87}Sr/^{86}Sr$ | Error ($2\sigma$) | $^{87}Sr/^{86}Sr(t)$ | $\varepsilon_{Sr}(t)$ |
|---|---|---|---|---|---|---|---|---|---|
| Gs-15 | 315 | 60 | 63 | 3.04364557 | 0.086087297 | 0.7268957 | 0.00002 | 0.71325098 | 129.5461777 |
| Am-3 | 315 | 53 | 67 | 3.66532635 | 0.103671085 | 0.7294649 | 0.00002 | 0.713033173 | 126.4529016 |
| Th-5 | 315 | 51 | 57 | 3.240024012 | 0.091641718 | 0.72781 | 0.00002 | 0.713284911 | 130.0280744 |
| Gs-13 | 315 | 73 | 98 | 3.887977399 | 0.109968607 | 0.7178383 | 0.00001 | 0.700408424 | −52.84299845 |
| Sp-201 | 315 | 65 | 114 | 5.089346054 | 0.143948444 | 0.7378836 | 0.00002 | 0.715067966 | 155.3509042 |
| Gs-7 | 325 | 47 | 85 | 5.247252074 | 0.148414701 | 0.7364761 | 0.00002 | 0.712204067 | 114.8474519 |
| Gs-9 | 325 | 117 | 58 | 1.435160725 | 0.040592475 | 0.7140197 | 0.00002 | 0.707381127 | 46.35120221 |
| Gs-11 | 325 | 36 | 49 | 3.942758187 | 0.111518042 | 0.7198658 | 0.00003 | 0.701627919 | −35.35685712 |
| Sc-6 | 325 | 103 | 61 | 1.714457062 | 0.048492169 | 0.7134449 | 0.00003 | 0.705514395 | 19.83955401 |
| Gs-1 | 335 | 202 | 66 | 0.945618901 | 0.026746141 | 0.7108447 | 0.00002 | 0.706335675 | 31.67160701 |
| Gs-3 | 335 | 185 | 78 | 1.220360547 | 0.034517009 | 0.7118267 | 0.00002 | 0.706007615 | 27.01236996 |
| Gs-5 | 335 | 169 | 75 | 1.284651164 | 0.036335422 | 0.7128951 | 0.00002 | 0.706769456 | 37.8323506 |
| Sp-107 | 335 | 144 | 75 | 1.507784604 | 0.042646589 | 0.7135987 | 0.00002 | 0.706409082 | 32.7141638 |

*Depositional age.

$^{146}Nd/^{144}Nd = 0.7219$ (O'Nions *et al.* 1979) in order to correct procedural and instrumental mass fractionation; and deviations from the La Jolla reference value (Lugmair *et al.* 1983) were corrected by analysing the standard along with the samples, yielding an average value of $^{143}Nd/^{144}Nd = 0.511851$ for six replicas, with an internal accuracy rate of ± 0.00002 ($2\sigma$). Analytical errors in the $^{147}Sm/^{144}Nd$ and $^{143}Nd/^{144}Nd$ ratios were estimated at less than 0.1 and 0.006%, respectively. The results are given in Table 3, and are plotted in Figures 3 and 4.

Multi-dimensional scaling (MDS) was used to analyse a compilation of U–Pb detrital zircon ages from SW Iberia (SPZ, PLZ and OMZ) and Nova Scotia (West Avalonia and Meguma terranes) to test whether there was any influence of Gondwanan-type (OMZ) sources on the Mira and Brejeira formations (Fig. 5). MDS is a statistical technique that provides a means for the correlation of samples, based on quantified pairwise comparisons of their detrital zircon ages, and is useful for visualizing the degree of similarity/dissimilarity between samples in a 2D space (Vermeesch 2013; Spencer *et al.* 2016). This mathematical approach transformed a matrix of pairwise similarities between detrital zircon age populations into Cartesian coordinates in a 2D space, where greater distances between samples represent a greater degree of dissimilarity between points on the MDS diagrams (Wissink *et al.* 2018). MDS diagrams (Fig. 6) were produced using IsoplotR (Vermeesch 2018).

## Whole-rock geochemistry

### *Whole-rock geochemistry results*

The new geochemical data are shown for the purpose of comparison in diagrams, together with data previously published by Pereira *et al.* (2014) (Fig. 3). The whole-rock geochemical features, together with the Sm–Nd and Rb–Sr isotopic data (presented below), were used to discuss the chemical discrimination of provenance for SPZ Carboniferous turbidites.

In the chemical classification diagram of Herron (1988), the two new analysed samples of the Mértola Formation (Sp-107 and Mr-1) are plotted in the shalefield, while the other six samples of the Mira and Brejeira formations are included in the Fe-sand, shale and litharenite fields (Fig. 3a). These differences are mainly related to: (i) the $SiO_2/Al_2O_3$ ratio that expresses detrital quartz enrichment and clay depletion over time (Mértola Formation: 4–4.1; Mira Formation: 5.6–9.4; Brejeira Formation: 4.7–9.6); and (ii) the higher $K_2O$ content of the Mértola and Mira turbidites compared to those of the Mira Formation, which contain a lesser amount of detrital mica and K-feldspar.

**Table 3.** *Whole-rock Sm–Nd isotope data of SPZ siliciclastic rocks*

| | Age* (Ma) | Sm | Nd | $^{147}Sm/^{144}Nd$ | $^{143}Nd/^{144}Nd$ | $\pm$ SE ($\times 10^{-6}$) | $\varepsilon_{Nd}(0)$ | $\varepsilon_{Nd}(t)$ | $T_{DM}$[†] |
|---|---|---|---|---|---|---|---|---|---|
| Gs-15 | 315 | 3.27 | 20 | 0.0988 | 0.511968 | 13 | −13.1 | −9.1 | 1426 |
| Am-3 | 315 | 3.6 | 21.3 | 0.1022 | 0.512043 | 17 | −11.6 | −7.8 | 1365 |
| Th-5 | 315 | 4.3 | 20 | 0.1300 | 0.512089 | 16 | −10.7 | −8.0 | 1734 |
| Gs-13 | 315 | 7.24 | 35.6 | 0.1229 | 0.512095 | 18 | −10.6 | −7.6 | 1588 |
| Sp-201 | 315 | 5.5 | 26.4 | 0.1259 | 0.512087 | 21 | −10.7 | −7.9 | 1657 |
| Cpt-1 | 315 | 4.31 | 20.72 | 0.1256 | 0.512076 | 1 | −11.0 | −8.1 | 1671 |
| Tel-1 | 315 | 4.87 | 22.13 | 0.1331 | 0.512168 | 1 | −9.2 | −6.6 | 1652 |
| Pru-1 | 315 | 5.65 | 26.88 | 0.1271 | 0.512121 | 1 | −10.1 | −7.3 | 1621 |
| Gs-7 | 325 | 3.57 | 18.5 | 0.1166 | 0.512035 | 17 | −11.8 | −8.5 | 1581 |
| Gs-9 | 325 | 3.82 | 18.4 | 0.1255 | 0.512295 | 17 | −6.7 | −3.7 | 1292 |
| Gs-11 | 325 | 3.28 | 15.2 | 0.1304 | 0.512143 | 12 | −9.7 | −6.9 | 1644 |
| Sc-6 | 325 | 4 | 18.1 | 0.1336 | 0.512258 | 16 | −7.4 | −4.8 | 1490 |
| Al-3 | 325 | 2.39 | 11.69 | 0.1234 | 0.512356 | 1 | −5.5 | −2.5 | 1160 |
| Sbm-5 | 325 | 2.91 | 13.03 | 0.1351 | 0.512258 | 1 | −7.4 | −4.9 | 1518 |
| Gs-1 | 335 | 4.98 | 23.7 | 0.1270 | 0.512354 | 14 | −5.5 | −2.6 | 1212 |
| Gs-3 | 335 | 4.58 | 22.9 | 0.1209 | 0.512297 | 14 | −6.7 | −3.4 | 1226 |
| Gs-5 | 335 | 4.94 | 23.6 | 0.1265 | 0.512302 | 19 | −6.5 | −3.5 | 1294 |
| Sp-107 | 335 | 5 | 26 | 0.1163 | 0.512351 | 15 | −5.6 | −2.2 | 1085 |
| Mr-1 | 335 | 5.11 | 27.32 | 0.1131 | 0.512250 | 1 | −7.6 | −4.0 | 1202 |

*Depositional age.
[†] Nd model age calculated by DePaolo (1981).

Chondrite-normalized REE plots of the newly analysed samples (Fig. 3b) show decreasing amounts of REE from the Mértola Formation (ΣREE = 129.5–161.5 ppm) as we move towards the Mira Formation (ΣREE = 74.3–80.8 ppm), and increasing amounts in the Brejeira Formation (ΣREE = 123–174.1 ppm). These changes are also significant when looking at the fluctuations in their fractionation patterns and linked ratios (Mértola Formation: $La/Lu_N = 8.3–10.9$, $La/Sm_N = 3.2–4$; Mira Formation: $La/Lu_N = 5.6–9.1$, $La/Sm_N = 2.9–4.4$; Brejeira Formation: $La/Lu_N = 7.3–9.2$, $La/Sm_N = 3.1–5.4$), which confirm previous data (Fig. 3b). Taking into account their chondrite-normalized REE patterns, SPZ Carboniferous siliciclastic rocks display a composition similar to that of the upper continental crust (Taylor and McLennan 1985).

In the discriminant function diagram produced by Roser and Korsch (1988), all the siliciclastic rocks of the Brejeira Formation and one sample of the Mira Formation are plotted in field P4 (recycled), while the other samples of the Mira and Mértola formations are plotted in fields P2 (intermediate) and P1 (mafic) (Fig. 3c).

In the La/Th v. Hf binary diagram developed for the source and compositional discrimination of turbiditic sandstones (Floyd and Leveridge 1987), most SPZ Carboniferous turbidites are plotted in the acidic arc source field. A slighty higher Hf content in some samples from the Brejeira and Mira formations points to the increasing influence of old continental crustal sources, associated with a greater input of recycled material (Fig. 3d).

The increase in the importance of recycling from the Visean to the Moscovian is also evidenced by Th/Sc ratios (Fig. 4a). Most samples from the Mértola (Th/Sc = 0.65–0.84; average 0.63) and Mira (Th/Sc = 0.36–1.02; average 0.69) formations show smaller Th/Sc ratios than those of Brejeira Formation rocks (Th/Sc = 0.74–1.35; average 0.83). The Th/Sc ratio above the upper continental crustal (UCC) (Th/Sc = 0.75: Rudnick and Gao 2003) of Brejeira turbidites suggests an increased input from felsic igneous and/or sedimentary (i.e. old crust) sources, while the older Mértola and Mira formations which are richer in Sc may have been derived from a more intermediate–mafic source (Fig. 4a). The higher enrichment of Th in the Brejeira turbidites could also indicate a greater degree of weathering of their source rocks.

## Whole-rock geochemistry interpretations

Data plots of the major elements (Fig. 3a, c, d) of SPZ Carboniferous turbidites show, from the Visean to the Moscovian, the increasingly significant contribution over time of an old recycled crustal source. This tendency is evidenced by the presence of significant numbers of grains of quartz, sedimentary and metasedimentary rocks in the Brejeira Formation, contrasting with the even larger numbers of feldspar grains and volcanic fragments in the Mira and

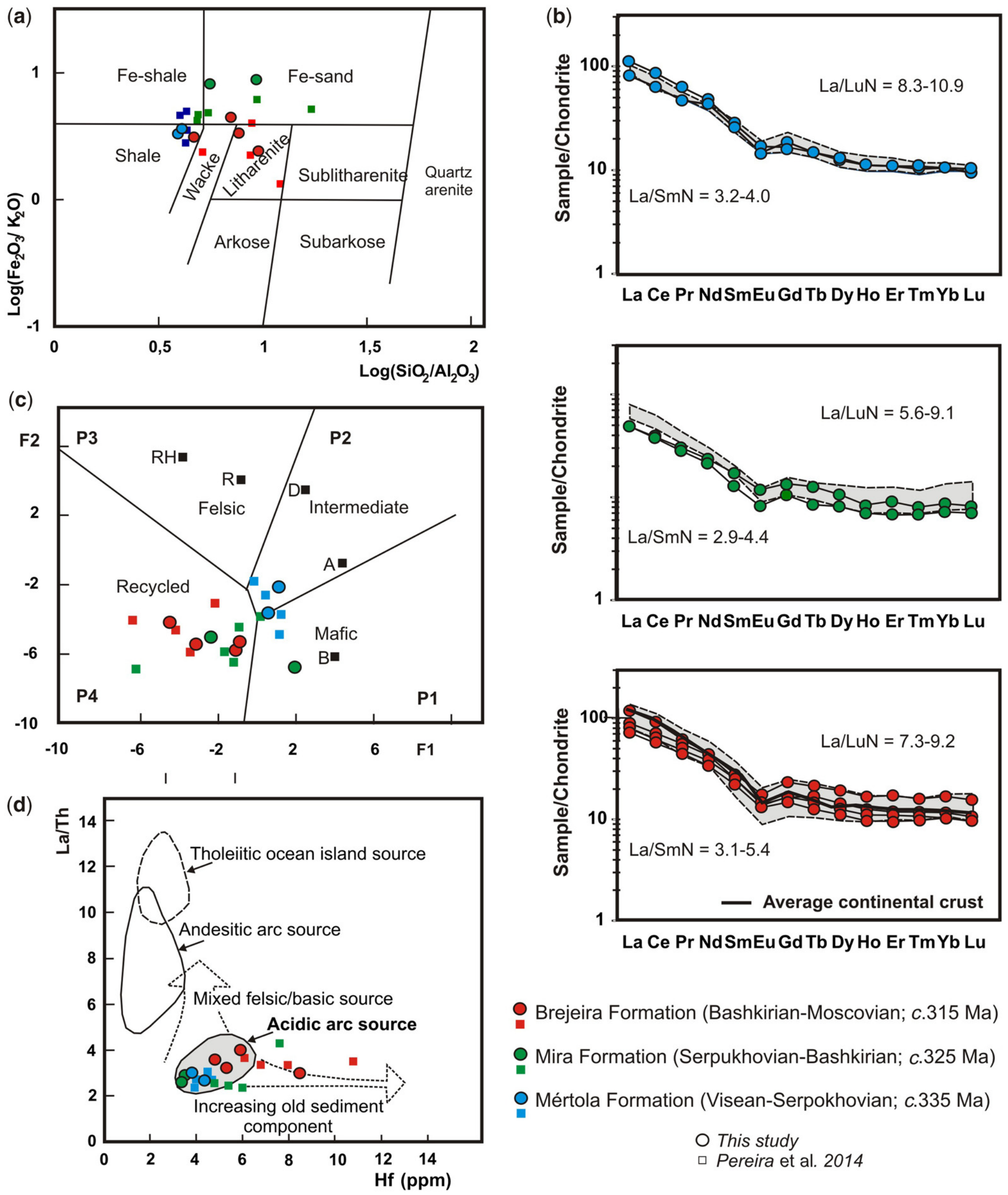


**Fig. 3.** Chemical diagrams for SPZ siliciclastic rocks (SW Iberia): (**a**) chemical classification scheme for siliciclastic sediments (Herron 1988); (**b**) chondrite-normalized REE plots (upper continental crust (UCC) values from Taylor and McLennan 1985); (**c**) discriminant function diagram F1 v. F2 for provenance of turbiditic sandstones (Roser and Korsch 1988); and (**d**) binary diagram La/Th v. Hf for the source and compositional discrimination of turbiditic sandstones (Floyd and Leveridge 1987).

Mértola formations. In the QtFL ternary diagram, the Mira and Brejeira formations plot in the recycled orogenic field, while the Mértola samples plot in both the same field and the dissected arc field (Jorge *et al.* 2013).

REE patterns of SPZ Carboniferous turbidites are not significantly different from various estimates of UCC composition (Rudnick and Gao 2003 and references therein) and active margin-related sedimentary basins (McLennan *et al.* 1990). They show a small

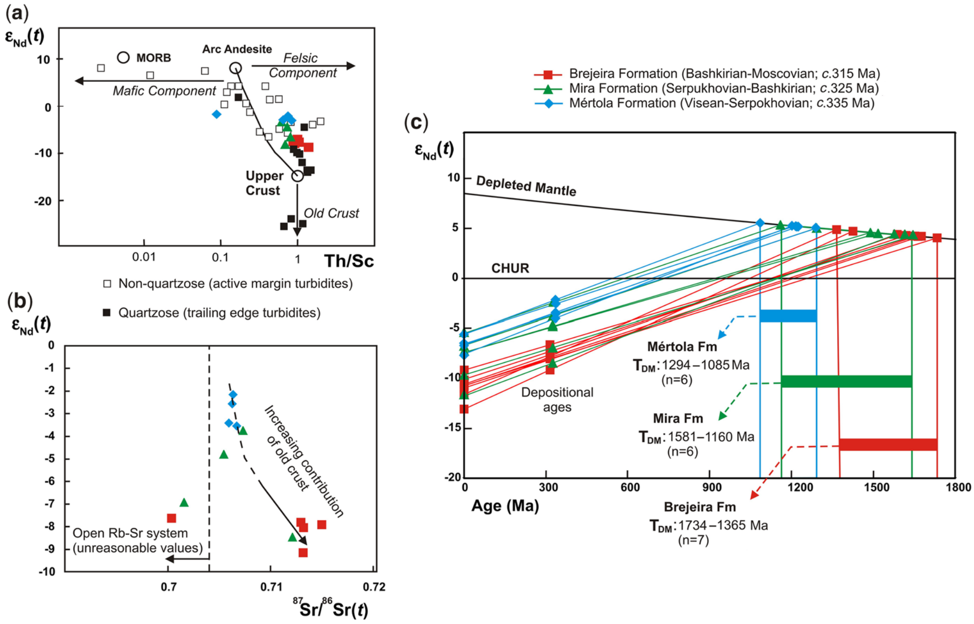


**Fig. 4.** Isotope chemistry plots for SPZ siliciclastic rocks (SW Iberia): (**a**) $\varepsilon_{Nd}(t)$ v. Th/Sc diagram for the provenance of modern sediments (McLennan *et al.* 1993); (**b**) $\varepsilon_{Nd}(t)$ v. $^{87}Sr/^{86}Sr(t)$ diagram showing the changing contribution of old crustal sources; and (**c**) Nd $T_{DM}$ model ages (DePaolo 1981) for SPZ Carboniferous siliciclastic rocks (SW Iberia). CHUR, Chondritic uniform reservoir.

Eu negative anomaly, fractionation from La to Sm, and an almost flat HREE profile (Fig. 3b).

Further, $La/Lu_N$ values for the SPZ Carboniferous turbidites ($La/Lu_N = 5.6$–10.9) occur in the lower part of the range defined by sediments derived from silicic rocks ($La/Lu_N = 3$–27: Cullers *et al.* 1997), suggesting a mixed or intermediate composition of the source regions. In addition, the Th/Sc ratio values (Fig. 4a) of most of the Mértola, Mira and Brejeira formations also indicate felsic sources (Th/Sc = 1.1–7: Cullers *et al.* 1997). Nevertheless, Visean samples show Th/Sc ratios typical of sources with an intermediate composition, in some cases reaching the upper range of sediments derived from basic rocks (Th/Sc = 0.05–0.4: Cullers *et al.* 1997).

Uniformly low La/Th ratios (ranging from 2.4 to 4.4) and a Hf average content of 6 ppm give a distribution for the SPZ Carboniferous turbidites that falls in the field of sediments derived from acid-dominated arc sources, as defined by Floyd and Leveridge (1987) (Fig. 3d). In the discrimination diagram, the deviation of the Brejeira samples to the right, as well as some of the Mira Formation samples having a Hf content up to 10.8 ppm (Fig. 3d), could indicate the progressive dissection of the magmatic arc. The erosion of the plutonic roots of the arc and the older host continental basement rocks could explain the increase in Hf content over time via the release of zircon, its main host mineral phase (Floyd and Leveridge 1987).

## Sm–Nd and Rb–Sr isotope geochemistry

### *Sm–Nd and Rb–Sr isotope geochemistry results*

The Mértola and Brejeira turbidites define two narrow ranges in the $\varepsilon_{Nd}(t)$ values (Fig. 4). Mértola siliciclastic rocks (−3.5 to −2.1) show less negative $\varepsilon_{Nd}(t)$ values than the Brejeira samples (−9.1 to −7.6). The Mira Formation presents a wider range of $\varepsilon_{Nd}(t)$ values, from −8.5 to −3.7, which is in between the Mértola and Brejeira values (Fig. 4).

Combining Nd isotope data and Th/Sc ratios in the diagram developed by McLennan *et al.* (1993) (Fig. 4a), negative $\varepsilon_{Nd}$ values and high Th/Sc values of SPZ Carboniferous siliciclastic rocks plot in the quartzose field, which indicates the likelihood of an older provenance. At the same time, Brejeira Formation rocks plot closer to the composition of the upper crust, while the samples from the Mértola Formation show a tendency to approach the arc andesite field (i.e. juvenile source).

$^{87}Sr/^{86}Sr(t)$ ratios are distinct but quite homogeneous for the Mértola (0.706–0.707) and Brejeira (0.713–0.715) formations. In addition, Mira

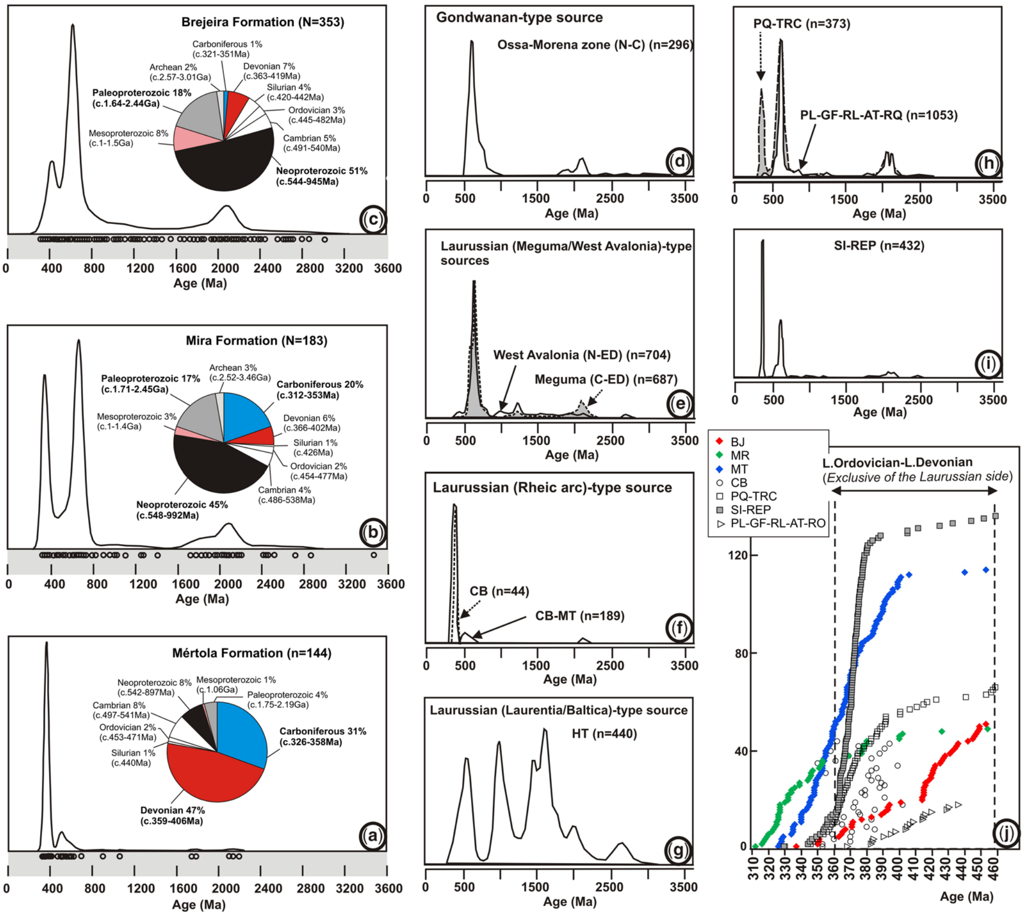


**Fig. 5.** Pie diagrams and kernel density estimation (KDE) with U–Pb detrital-zircon ages of the SPZ siliciclastic rocks (SW Iberia): (**a**) the Mértola Formation; (**b**) the Mira Formation; and (**c**) the Brejeira Formation. Detrital zircon U–Pb ages from Braid *et al.* (2011), Pereira *et al.* (2012*a*, 2014) and Rodrigues *et al.* (2014). Kernel plots of different potential sources for SPZ siliciclastic rocks: (**d**) Ossa-Morena Zone N-C: Linnemann *et al.* (2008) and Pereira *et al.* (2012*b*); (**e**) West Avalonia N-D: Henderson (2016) and Henderson *et al.* (2016); and Meguma C-ED: Murphy *et al.* (2004), Waldron *et al.* (2009) and White *et al.* (2018); (**f**) Pereira *et al.* (2012*a*, 2014) and Rodrigues *et al.* (2014); (**g**) Pérez-Cáceres *et al.* (2017); (**h**) PQ-TRC: Braid *et al.* (2011), Pereira *et al.* (2012*a*) and Pérez-Cáceres *et al.* (2017); and PL-GF-RL-AT-RO: Pereira *et al.* (2017) and Pérez-Cáceres *et al.* (2017); (**i**) Pereira *et al.* (2017) and Pérez-Cáceres *et al.* (2017); and (**j**) detrital zircon ages cumulative frequency plots (U–Pb ages younger than 460 Ma). Abbreviations: N-C, Neoproterozoic–Cambrian; N-D, Neoproterozoic–Devonian; N-ED, Neoproterozoic–Early Devonian; C-ED, Cambrian–Early Devonian; PL-GF-RL-AT-RO, Pulo do Lobo–Gafo–Ribeira de Limas–Atalaia–Ronquilho formations; SI-REP, Santa Iria–Represa formations; PQ-TRC, Phyllite–Quartzite–Tercenas formations; HT, Horta da Torre Formation; CB, Cabrela Formation; MT, Mértola Formation; MR, Mira Formation; BJ, Brejeira Formation.

turbidites display a wider range of Sr isotope compositions (0.706–0.712), partly overlapping previous compositions (Fig. 4b). The smaller $^{87}Sr/^{86}Sr(t)$ ratios of the Mértola samples indicate a smaller contribution of the old crust component compared with younger turbidites. Two samples (GS-11 and GS-13) show geologically unexpected low values of $^{87}Sr/^{86}Sr(t) < 0.704$, indicating Rb gain or Sr loss.

Nd $T_{DM}$ model ages for these formations are remarkably different (Fig. 4c). Brejeira siliciclastic rocks present $T_{DM}$ model ages ranging from 1.73 to 1.37 Ga, which are much older than those of the Mértola turbidites, which range from 1.29 to 1.09 Ga (Fig. 4c). The other samples from the Mira Formation show $T_{DM}$ model ages ranging from 1.58 to 1. 16 Ga, which overlap the calculated Nd

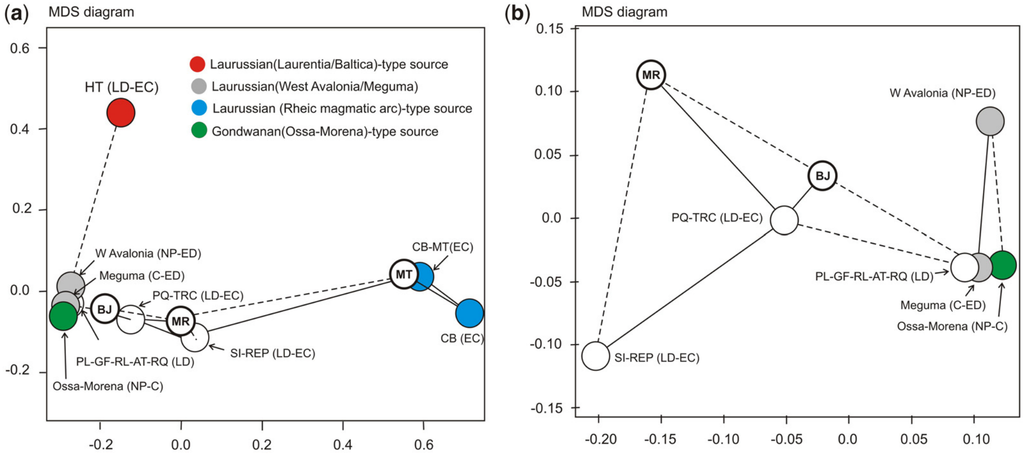


**Fig. 6.** Multi-dimensional scaling diagrams (Vermeesch 2018): (**a**) for SPZ siliciclastic rocks (SW Iberia) and different potential sources; and (**b**) detail of (a). Detrital zircon ages (U–Pb data sources): OMZ, Ossa-Morena Zone (Linnemann *et al.* 2008; Pereira *et al.* 2008, 2012*c*); PL, Pulo do Lobo Formation (Pereira *et al.* 2017; Pérez-Cáceres *et al.* 2017); SPZ, South Portuguese Zone (Braid *et al.* 2011; Pereira *et al.* 2012*a*, 2014; Rodrigues *et al.* 2014), West Avalonia/Meguma terrane (Krogh and Keppie 1990; Murphy *et al.* 2004; Waldron *et al.* 2009; Henderson 2016; Henderson *et al.* 2016; White *et al.* 2018). Abbreviations: NP-C, Neoproterozoic–Cambrian; NP-ED, Neoproterozoic–Early Devonian; C-ED, Cambrian–Early Devonian; PL-GF-RL-AT-RQ, Pulo do Lobo, Gafo, Ribeira de Lima and Atalaia formations (PLZ: LD, Late Devonian) and Ronquillo formation (SPZ: LD, Late Devonian); PQ-TRC, Phyllite–Quartzite and Tercenas formations (SPZ: LD-EC, Late Devonian– Early Carboniferous); SI-REP, Santa Iria and Represa formations (PLZ: LD-EC); HT, Horta da Torre Formation (PLZ: LD-EC); MT, Mertola Formation (SPZ: EC); CB, Cabrela Formation (OMZ: EC); CB-MT, Cabrela and Mertola formations; MR, Mira Formation (SPZ: Early–Late Carboniferous); BJ, Brejeira Formation (SPZ: Late Carboniferous).

model ages of the Mértola and Brejeira formations (Fig. 4c). The compositional variations found are indicative of changes in provenance over time, with increasing contributions from old continental crustal sources.

### *Sm–Nd and Rb–Sr isotope geochemistry interpretations*

The Mértola, Mira and Brejeira samples show negative $\varepsilon_{\mathrm{Nd}}(t)$ values ($-9.1$ to $-2.2$: Fig. 4a) and plot in the upper range of the quartzose field defined by trailing edge turbidites in the discriminant diagram devised by McLennan *et al.* (1993), indicating the average composition of provenance for the modern turbidites. In this discrimination diagram, the Mértola Formation overlaps the lower range of the non-quartzose field defined by active margin turbidites (Fig. 4a), which might indicate a mixture of young arc-derived detritus (of highly variable composition) and old UCC sources (McLennan *et al.* 1990). The significant differences in terms of Sm–Nd and Rb–Sr isotope composition between the Mértola samples ($\varepsilon_{\mathrm{Nd}}(t) = -3.5$ to $-2.2$; $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}(t) = 0.706$–$0.707$) and those of the Brejeira Formation ($\varepsilon_{\mathrm{Nd}}(t) = -9.1$ to $-7.6$; $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}(t) = 0.713$–$0.715$) suggest the increasingly important contribution of old crust from the Visean to the Moscovian (Fig. 4b), as might be expected during the denudation of a continental magmatic arc after continental collision.

Despite some controversies regarding the geological significance of Nd $\mathrm{T_{DM}}$ model ages for a given suite of rocks, they can be used to constrain the isotopic signature of the source region (Murphy and Nance 2002). SPZ Carboniferous turbidites present a wide range of Nd $\mathrm{T_{DM}}$ model ages, varying from 1.29–1.09 Ga in the Mértola Formation to 1.73–1.36 Ga in the Brejeira Formation. The Sm–Nd and Rb–Sr isotope data evidence presented in this paper indicate that the SPZ Carboniferous sedimentary succession records the inverted stratigraphy of its source, suggesting a change in provenance that is likely to be marked by the increment over time of a contribution from old continental basement rocks (Fig. 4c).

## Multi-dimensional scaling (MDS)

### *MDS results*

An analysis of the MDS diagram shows that the SPZ Carboniferous formations studied are widely scattered and associated with different potential sources

(Fig. 6a). In Figure 6a, the Mértola Formation is adjacent to the Cabrela Formation, indicating a common source. These two formations contain abundant Middle–Late Devonian zircon and fewer pre-Devonian detrital grains than the other Late Devonian–Early Carboniferous formations of SW Iberia (Fig. 5f, h, i).

In Figure 6a, it should be noted that the Mira Formation is closely related to the Santa Iria and Represa formations, which in turn have a tenuous association with the Mértola and Cabrela formations. This affinity is mainly associated with the significant amount of Middle–Late Devonian zircon (Fig. 5a, f, i). The increasing number of pre-Devonian grains included in the Mira, Santa Iria and Represa siliciclastic rocks means that they are close together in the MDS diagram, and nowhere near the Mértola and Cabrela turbidites (Fig. 6a). In Figure 6a, the Mira turbidites occur near the Brejeira turbidites and the Phyllite–Quartzite and Tercenas formations, which closely approximate to a cluster formed by the Pulo do Lobo, Gafo, Ribeira de Limas, Atalaia and Ronquillo formations, and Gondwanan (Ossa-Morena)- and Laurussian (West Avalonia/Meguma)-type sources. In the MDS diagram, Ediacaran–Early Devonian West Avalonia siliciclastic rocks that contain a larger number of Mesoproterozoic and Paleoproterozoic ages are located far from the Meguma- and the Ossa-Morena-type sources (Fig. 5e).

Besides this, the Frasnian Pulo do Lobo, Gafo, Ribeira de Limas, Atalaia and Ronquillo formations are superimposed on Cambrian–early Devonian Meguma siliciclastic rocks, leading us to consider the latter as their source (Fig. 6b).

Another finding is that both the Mira and Brejeira formations present a greater degree of affinity with the Phyllite–Quartzite and Tercenas formations than with the other sources shown in the MDS diagram (Fig. 6b).

The MDS diagram enables us to confirm the existence in the Late Paleozoic siliciclastic rocks of SW Iberia of a distinctive source, resembling those from Laurentia and Baltica, characterized by a population of detrital zircon in the age range *c.* 1.9–1.1 Ga (Fig. 5g). The Late Devonian–Early Carboniferous Horta da Torre siliciclastic rocks of the PLZ plot at a great distance from the other samples (Fig. 6a).

### *MDS interpretations*

The degree of proximity between the Mértola and Cabrela turbidites probably results from the fact that they were derived from the denudation of a Middle–Late Devonian magmatic arc, with little influence from old cratonic sources, and both sequences were deposited coevally with synorogenic Early Carboniferous volcanism. These two formations are interpreted as being directly linked to the denudation of a Devonian arc that was built on a Meguma/Avalonia-type basement (Pereira *et al.* 2017). Thus, the Mértola and Cabrela formations were most likely to have been derived from a Laurussian (Rheic magmatic arc)-type source (Fig. 6a). The preservation of Middle–Late Devonian detrital zircon in Late Devonian–Early Carboniferous siliciclastic rocks of SW Iberia, rather than in arc-related igneous rocks, indicates that the arc system built on the Laurussian margin as a result of the Rheic Ocean subduction may have been largely and progressively destroyed by erosion (Pereira *et al.* 2017). In addition, the Mértola and Cabrela formations also contain Early Carboniferous detrital zircon (Fig. 5j), inferred as having resulted from synorogenic volcanism occurring on both sides of the Rheic suture zone (Pereira *et al.* 2012*b*).

The increasing number of pre-Devonian grains included in the Phyllite–Quartzite, Tercenas, Mira and Brejeira siliciclastic rocks (SPZ) and in the Santa Iria and Represa turbidites (PLZ) means that they were probably sharing a common source, and distinct from the Laurussian (Rheic magmatic arc)-type source (Fig. 6a). They closely approximate to a cluster formed by the Pulo do Lobo, Gafo, Ribeira de Limas, Atalaia and Ronquillo formations, and Gondwanan (Ossa-Morena)- and Laurussian (West Avalonia/Meguma)-type sources (Fig. 6). However, as shown in Figure 6b, the Ediacaran–Early Devonian West Avalonia siliciclastic rocks that contain a larger number of Mesoproterozoic and Paleoproterozoic ages are not overlapping the Meguma- and the Ossa-Morena-type sources (Fig. 5d, e). This difference is explained as follows: initially, Cambrian Meguma siliciclastic rocks shared common sources with Ediacaran–Cambrian Ossa-Morena siliciclastic rocks but later, in the Silurian–Early Devonian, they were derived from the same sources as West Avalonian siliciclastic rocks. The Frasnian PLZ and SPZ formations were most probably derived from Cambrian–early Devonian Meguma siliciclastic rocks, and not from a Gondwanan (Ossa-Morena)-type source, because they include Late Ordovician–Silurian and Mesoproterozoic detrital zircon grains. The great degree of affinity of the Mira and Brejeira formations with the Phyllite–Quartzite and Tercenas formations indicate that zircon age populations occur in intermediate sediment repositories as result of sediment recycling during the Late Paleozoic. The presence of Late Ordovician–Silurian and Mesoproterozoic detrital zircon in the Mira and Brejeira formations (Fig. 5b, c) seems to indicate a Laurussian (West Avalonia/Meguma)-type as the most likely source. However, a contribution from a Gondwanan (Ossa-Morena)-type source whose population of detrital zircon grains overlaps and, therefore, may be confused with previous sources cannot be ruled out. This is supported by the fact that the abundant Bashkirian detrital zircon in Mira turbidites (Fig. 5b) seems to point to provenance from magmatism recorded on the Gondwanan side (Pereira *et al.* 2015; Dias da Silva *et al.* 2018), which is not the case on the Laurussian side.

The MDS diagram also enables us to confirm the existence in Late Paleozoic siliciclastic rocks of SW Iberia of a distinctive source, resembling those from Laurentia and Baltica, characterized by a population of detrital zircon in the age range *c.* 1.9–1.1 Ga (Fig. 5g). The Late Devonian–Early Carboniferous Horta da Torre siliciclastic rocks of the PLZ plot at a great distance from the other samples (Fig. 6a). The Horta da Torre Formation is regarded as an intermediate sediment repository that was derived from a Laurussian (Laurentia/Baltica)-type source (Fig. 6a), which is unknown in SW Iberia (Pereira *et al.* 2019).

## Discussion

Taken together, petrography and whole-rock geochemistry (Jorge *et al.* 2013; Pereira *et al.* 2014; this study), U–Pb geochronology of detrital zircon (Pereira *et al.* 2012*a*, 2014; Rodrigues *et al.* 2014), and Sm–Nd and Rb–Sr isotope chemistry (this study), the data as a whole seem to suggest that SPZ Carboniferous turbidites were derived from different sources, whose contribution varied over time. However, it is noteworthy that there is no consensus as yet as to the probable location of these sources, considering the range of different Paleozoic terranes involved in the collision between Gondwana and Laurussia (Pereira *et al.* 2012*a*, 2014; Jorge *et al.* 2013; Rodrigues *et al.* 2014). The findings obtained in the present study provide a valuable contribution towards furthering our knowledge of the provenance of SPZ Carboniferous turbidites.

### *A dissected continental magmatic arc built on the Laurussian margin*

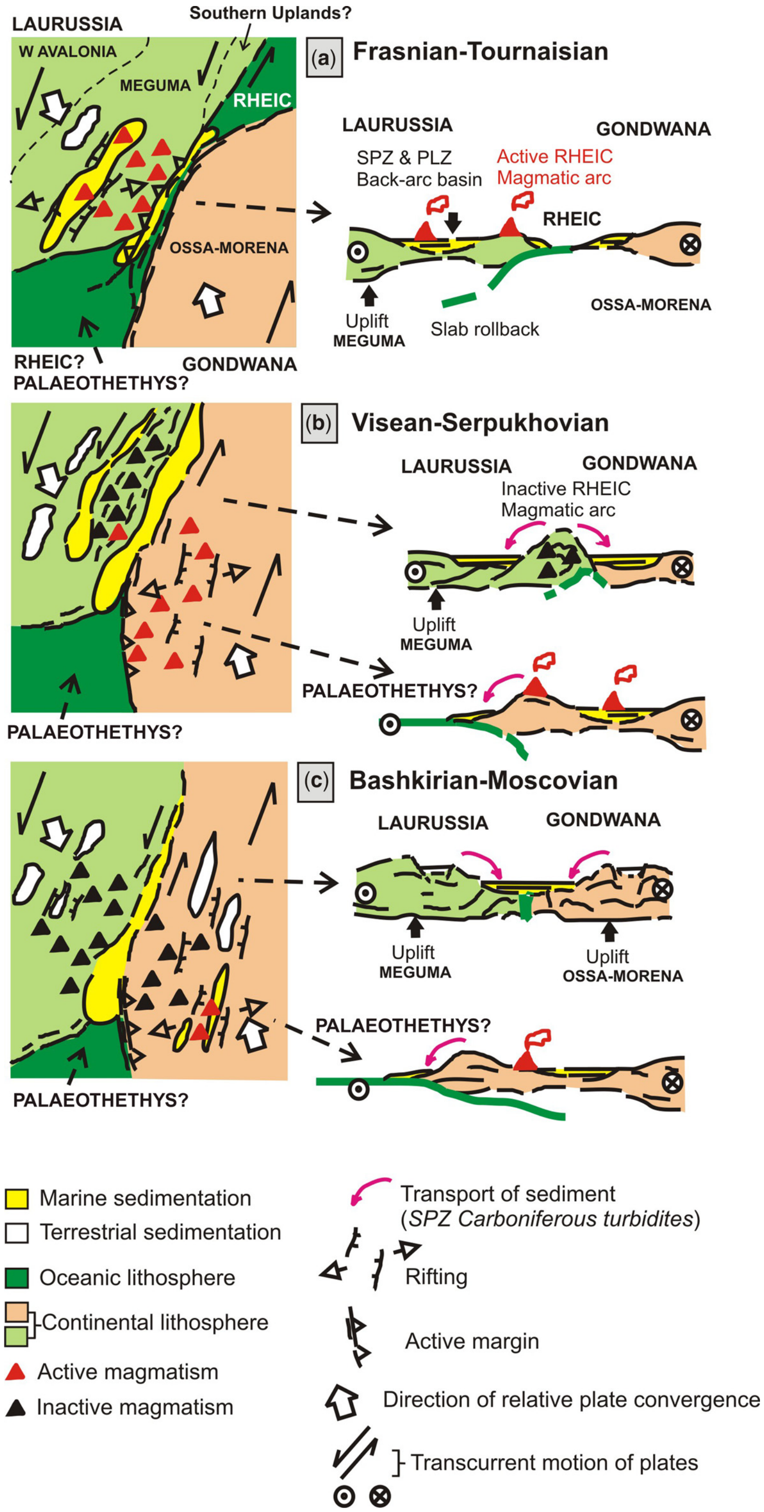
A notable change in the sources of SPZ Carboniferous turbidites is supported by whole-rock geochemistry (Jorge *et al.* 2013; Pereira *et al.* 2014; this study), by U–Pb dating of detrital zircon grains (Pereira *et al.* 2012*a*, 2014; Rodrigues *et al.* 2014), and by Sm–Nd and Rb–Sr isotope chemistry (this study). The Mértola samples were influenced less by sedimentary recycling of old continental crust, as indicated by the smaller amount of pre-Devonian zircon grains (22%: Fig. 5a) compared with those found in the siliciclastic rocks of the Mira (74%: Fig. 5b) and Brejeira (92%: Fig. 5c) formations.

Other relevant geochronological information regarding the provenance of Mértola turbidites concerns the large group of Middle–Late Devonian detrital zircon ages found which do not correlate with OMZ (on the Gondwanan side) sources, since Middle–Late Devonian magmatic rocks are absent from the OMZ.

Nd $T_{DM}$ model ages for the Mértola samples are younger than most of the Ediacaran–Early Devonian siliciclastic rocks of the OMZ (Fig. 2a). However, there is Early–Middle Cambrian Early Rift Volcanism (ER)–Main Rift Volcanism (RR) sedimentary and volcanic rocks (OMZ) presenting $T_{DM}$ model ages that approach those of the Mértola samples (Fig. 2a). Nevertheless, we consider it unlikely that Early–Middle Cambrian ER–RR sedimentary and volcanic rocks are the source of Mértola turbidites because they are spatially related to Ediacaran and Cambrian siliciclastic and felsic–intermediate volcanic rocks displaying much higher $T_{DM}$ values (Fig. 2) and containing a distinct population of zircon grains (Fig. 5).

At the same time, by assuming the absence of a Devonian magmatic arc on the Gondwana margin, it was initially proposed that the Mértola Formation was derived from the denudation of an intra-oceanic arc located far from the influence of old continental sources (Pereira *et al.* 2012*a*). More recently, it has been suggested that the Devonian magmatic arc was built on the Laurussia margin, which is inferred from Devonian detrital zircon Hf isotope compositions (Pereira *et al.* 2017). The Hf model ages of the majority of the Devonian zircon grains of the Mértola Formation reported by Pereira *et al.* (2017) range from 1.13 to 0.67 Ga, leading to the proposition that the basement on which the Devonian arc was built is younger (Laurussian side Meguma/West Avalonia-type) than the more evolved basement of the OMZ (Gondwanan side). Therefore, an entirely intra-oceanic arc provenance for the Mértola turbidites seems unlikely.

In previous studies, a number of different arguments based on Sm–Nd isotopic data were used to support the hypothesis that the unknown pre-Frasnian basement rocks of the SPZ have Laurussian (West Avalonia/Meguma) affinity. de la Rosa *et al.* (2002) argued that the Nd $T_{DM}$ model ages of the Late Devonian–Carboniferous felsic magmatism from the SPZ and the West Avalonia and Meguma terranes (Nova Scotia) are quite similar, suggesting a common source. In fact, the Nd $T_{DM}$ model ages of the Gil Marquez granitic rocks (1.1–0.9 Ga: Castro *et al.* 1995), intrusive in the Late Devonian–Early Carboniferous siliciclastic strata of the SPZ, overlap the isotopic composition of the granulite xenoliths of the Late Devonian Tangier lamprophyre (1.1–1 Ga: Eberz *et al.* 1991), deriving from a basement with an isotopic composition distinct from the overlying Meguma terrane and the Cambrian–Devonian volcanic rocks of West Avalonia (1–0.7 Ga: Keppie *et al.*


LAURUSSIA
Southern Uplands?
W AVALONIA
MEGUMA
RHEIC
(a)
Frasnian-Tournaisian
LAURUSSIA
GONDWANA
SPZ & PLZ
Back-arc basin
Active RHEIC
Magmatic arc
RHEIC
OSSA-MORENA
OSSA-MORENA
Uplift
MEGUMA
Slab rollback
RHEIC?
PALAEOTHETHYS?
GONDWANA
(b)
Visean-Serpukhovian
LAURUSSIA
GONDWANA
Inactive RHEIC
Magmatic arc
Uplift
MEGUMA
PALAEOTHETHYS?
PALAEOTHETHYS?
(c)
Bashkirian-Moscovian
LAURUSSIA
GONDWANA
Uplift
MEGUMA
Uplift
OSSA-MORENA
PALAEOTHETHYS?
PALAEOTHETHYS?
🟨 Marine sedimentation
☐ Terrestrial sedimentation
🟩 Oceanic lithosphere
Continental lithosphere
▲ Active magmatism
▲ Inactive magmatism
Transport of sediment
(*SPZ Carboniferous turbidites*)
Rifting
Active margin
Direction of relative plate convergence
Transcurrent motion of plates

1997) (Fig. 2b). Moreover, the Ediacaran–Early Devonian siliciclastic rocks and most of the crustal-derived felsic igneous rocks of the OMZ (Gondwanan side) present much more pronounced $\varepsilon_{Nd}(t)$ negative values and older Nd $T_{DM}$ model ages (Fig. 2a) than basement rocks from Nova Scotia. At the same time, the few *c.* 1.2–0.8 Ga inherited cores found in the Gil Marquez granitic rocks and other plutons of the Sierra del Norte Batholith have been interpreted as having been derived from unexposed SPZ basement rocks with Laurussian affinity, since they include Stenian–Tonian ages which are lacking in OMZ sources (de la Rosa *et al.* 2002; Braid *et al.* 2012; Gladney *et al.* 2014). The main implications of this are: (i) the granulite xenoliths found in late Devonian lamprophyres of the Meguma terrane come from a basement indistinguishable from West Avalonia sources; this suggests that the Avalon terrane is the structural basement for the Meguma terrane (Shellnutt *et al.* 2019); and (ii) West Avalonia sources demonstrate a high degree of affinity with the basement rocks from which SPZ magmatic rocks are derived (Braid *et al.* 2012). The Mértola turbidites seem to derive largely from erosion of a magmatic arc built on the Meguma terrane (representing the unexposed basement of the SPZ).

## *Evidence for Laurussian-type sources of SPZ Carboniferous turbidites*

The Sm–Nd isotope composition of Ediacaran–Early Devonian siliciclastic rocks and most of the crustal-derived felsic igneous rocks of the OMZ is very similar to that of the Cambrian and Ordovician sedimentary and Silurian felsic volcanic rocks of the Meguma terrane (Fig. 2), suggesting an isotopically identical source. Conversely, the Neoproterozoic–Devonian sedimentary and volcanic rocks of West Avalonia are mostly characterized by their distinct $\varepsilon_{Nd}(t)$ values and younger $T_{DM}$ model ages (Fig. 2). The Ediacaran–Silurian crustal-derived felsic suites of West Avalonia (1.2–0.9 Ga: Fig. 2b) place isotopic constraints on the underlying Avalonian-type basement source (Murphy *et al.* 1996, 2018; Murphy and Nance 2002) and are distinct from the Gondwanan-type source related to the OMZ. Additionally, in West Avalonia, the Silurian siliciclastic rocks of the Beechill Cove Formation and some Neoproterozoic siliciclastic rocks of the Gamble Brook Formation (Nd $T_{DM}$ ages ages ranging from 1.8 to 1.4 Ga: Murphy 2002; Murphy and Nance 2002) (Fig. 2b) render the provenance study of sediments resulting from the denudation of West Avalonia more complex. The Mértola samples show Nd $T_{DM}$ model ages ranging from 1.3 to 1.1 Ga, overlapping the $T_{DM}$ model age interval of 1.6–0.6 Ga of: (i) Tournaisian–Visean Pyrite Belt Volcanic–Sedimentary Complex intermediate–mafic and felsic (1.6–1 Ga volcanic rocks: Mitjavila *et al.* 1997) (Fig. 2a); (ii) the Ediacaran–Silurian bimodal volcanic suites of West Avalonia (Keppie *et al.* 1997; Murphy and Nance 2002; Murphy *et al.* 2018) (Fig. 2b); (iii) the Late Ordovician–Silurian White Rock mafic volcanic rocks of the Meguma terrane (Keppie *et al.* 1997) (Fig. 2b); and (iv) the Late Devonian McAras Brook siliciclastic and volcanic rocks of Nova Scotia (Keppie *et al.* 1997) (Fig. 2b).

Detrital zircon grains presented in the Mértola samples include mainly Devonian and Carboniferous ages (78%: Fig. 5a), followed by a cluster of Ediacaran–Cambrian ages (16%), and a few Paleoproterozoic (4%), Ordovician (2%), Silurian (1%) and Mesoproterozoic (1%) grains. The volumetrically insignificant contribution of old cratonic sources to the basin fill confirms that: (i) Mértola turbidites were mainly derived from the erosion of a nearby middle–late Devonian volcanic arc (probably represented by the Cercal porphyries of SW Iberia, the South Mountain Batholith and the McAras Brook rocks of Nova Scotia), and the Tournaisian–Visean Pyrite Belt, Cabrela Formation and Toca da Moura volcanic–sedimentary complexes (Fig. 2a); and (ii) basement denudation

**Fig. 7.** Idealized diagrams showing inferred tectonic evolution and sedimentation recorded in SW Iberia Late Devonian–Carboniferous stratigraphy, associated with the Laurussia–Gondwana oblique collision. (**a**) Devonian active magmatic arc developed on the Laurussian margin associated with the Rheic Ocean subduction; Tournaisian slab rollback, Meguma terrane rapid uplift and terrestrial sedimentation in the Laurussian margin, and marine sedimentation at the back-arc basin (PLZ and SPZ). (**b**) Visean–Serpukhovian back-arc basin inversion and rapid denudation of the inactive magmatic arc and Meguma terrane; terrestrial sedimentation in the Laurussian margin: SPZ (Mértola and Mira formations) and OMZ (Cabrela and Toca da Moura volcanic–sedimentary complexes) turbiditic sedimentation with increasing contributions from old continental crustal sources; alleged subduction of Palaeothethys? oceanic lithosphere under the Gondwanan margin and a contribution from Carboniferous magmatic sources. (**c**) Bashkirian–Moscovian continuous continental convergence, increasing uplift of the Meguma terrane and the OMZ; opening of OMZ terrestrial basins (Santa Susana Formation) and SPZ turbiditic sedimentation (Brejeira Formation) associated with Laurussian-type and Gondwanan-type sources; continuing alleged subduction of Palaeothethys oceanic lithosphere under Gondwana; sinistral transcurrent motion responsible for the spatial distribution of distinctive source terranes along the SW Iberia reworked suture zone that juxtaposed the Laurussian and Gondwanan margins during the Bashkirian–Moscovian.

would not have been very significant, as is clearly evident in the population of detrital zircon grains of Tournaisian–Visean Cabrela turbidites (Fig. 5f).

In the Mira and Brejeira formations, an increase in Nd $T_{DM}$ model ages from 1.6–1.2 Ga (Fig. 2: Serpukhovian–Bashkirian) to 1.7–1.4 Ga (Fig. 2: Bashkirian–Moscovian) is notable, evidenced by a significant increase in the number of pre-Devonian detrital zircon grains (74–92%: Fig. 5b, c). In this group of detrital zircon grains, the presence of Late Ordovician–Silurian and Mesoproterozoic ages is salient, accounting for 7 and 8%, respectively, of ages in Brejeira turbidites whose sources are absent in the OMZ (Gondwanan side: Fig. 5d). The Late Ordovician–Silurian and Mesoproterozoic detrital zircon grains can be found in several potential sources on the Laurussian side: (i) the Phyllite–Quartzite and Tercenas formation (Fig. 5h), the Pulo do Lobo, Gafo, Ribeira de Limas, Atalaia and Ronquillo formation (Fig. 5h), and the Santa Iria and Represa formation (Fig. 5i) siliciclastic rocks of the SPZ and PLZ; (ii) the Cambrian–early Devonian siliciclastic rocks of the Meguma terrane (Fig. 5e); and (iii) the Neoproterozoic–Early Devonian siliciclastic rocks of West Avalonia (Fig. 5e). Taking into account the geochronological information described above and the Nd $T_{DM}$ model ages of the Mira and Brejeira formations, several hypotheses for the provenance of these SPZ turbidites may be advanced, involving the evolution of mixed provenance from: (i) more juvenile Late Devonian–Early Carboniferous Pyrite Belt bimodal volcanic rocks (Nd $T_{DM} = 1.6$–$0.9$ Ga) and Late Devonian–Early Carboniferous Phyllite–Quartzite siliciclastic rocks (Nd $T_{DM} = 2.5$–$1.5$ Ga), both from the SPZ (Fig. 2a); (ii) Cambrian–Ordovician Meguma Group (Goldenville and Halifax groups) and siliciclastic rocks (Nd $T_{DM} = 1.7$ Ga), and Late Ordovician–Silurian White Rock felsic volcanic rocks (Nd $T_{DM} = 1.8$–$1.2$ Ga), both from the Meguma terrane (Fig. 2b); (iii) Neoproterozoic Gamble Brook (Nd $T_{DM} = 1.9$–$0.9$ Ga) and Silurian Arisaig (Nd $T_{DM} = 1.7$–$1.4$ Ga) siliciclastic rocks, with Cambrian McDonalds Brook (Nd $T_{DM} = 1$–$0.7$ Ga) and Dunn Point (Nd $T_{DM} = 1$–$0.9$ Ga) siliciclastic rocks, and Ediacaran Georgeville (Nd $T_{DM} = 1.2$–$0.9$ Ga), Cambrian McDonalds Brook (Nd $T_{DM} = 1.2$–$0.9$ Ga), Ordovician McGillivray Brook (Nd $T_{DM} = 1.1$–$0.9$ Ga) felsic volcanic rocks and Silurian Arisaig bimodal volcanic rocks (Nd $T_{DM} = 1$–$0.7$ Ga); and (iv) Middle–Late Devonian McAras Brook siliciclastic (Nd $T_{DM} = 0.9$–$0.8$ Ga) and bimodal volcanic (Nd $T_{DM} = 0.9$–$0.7$ Ga) rocks. The Late Ordovician, Silurian and Devonian magmatism that is recorded in Nova Scotia stratigraphy (Fig. 2) plays an important role as an exclusive source for the Laurussian side (Fig. 5j). Thus, the available isotopic data from the SPZ unequivocally demonstrate a close association with Laurussian-type sources.

## Conclusions and evolutionary model

In conclusion, important changes were observed in the sources from which SPZ Carboniferous turbidites were derived, as might be expected during the denudation of a continental magmatic arc after oblique continental collision, as occurred during Pangea amalgamation (Fig. 7). In this convergence model between Laurussia and Gondwana, two oceans were involved: the Rheic Ocean that closed by the end of the Devonian; and the Palaeotethys Ocean that was subducted under the Gondwanan margin during the Carboniferous. PLZ and SPZ Frasnian–Tournaisian sedimentation occurred through the opening of a back-arc basin formed along the Laurussian active margin during Rheic Ocean subduction (Fig. 7a), simultaneously with the rapid uplift of the Meguma terrane between *c.* 370 and 365 Ma (Murphy and Hamilton 2000; Archibald *et al.* 2018). Amalgamation of Pangea was oblique and complex, possibly involving the long-distance tectonic transport of distinct provenance crustal fragments to the collision zone. Recycling of Laurentia/Baltica-type sources from the Southern Uplands terrane into the Horta da Torre Formation is pausible in such a geodynamic model (Braid *et al.* 2011). Mértola Formation rocks (Visean–Serpukhovian: Fig. 7b), that do not reveal Laurentia/Baltica-type sources, mostly inherited their geochemical and isotopic characteristics from an adjacent uplifted Devonian continental magmatic arc with an intermediate–felsic composition (i.e. Cercal porphyries of SW Iberia, the South Mountain Batholith and/or the McAras Brook rocks of Nova Scotia). As result of the back-arc inversion, the progressive dissection of the inactive Devonian magmatic arc and the erosion of its plutonic roots and the Meguma terrane basement rocks are evidenced in the Mira (Serpukhovian–Bashkirian: Fig. 7b) and Brejeira (Bashkirian–Moscovian: Fig. 7c) formations by the increasing contribution from recycled old continental crust. This interpretation is corroborated by the new Sm–Nd and Rb–Sr isotope data presented here: (i) $^{87}Sr/^{86}Sr(t)$ ratio increasing from the Mértola (0.706–0.707), Mira (0.706–0.712) to Brejeira (0.713–0.715) formations; and (ii) Nd $T_{DM}$ model ages recording an inverted stratigraphy of its source: Mértola (1.29–1.09 Ga), Mira (1.58–1.16 Ga) and Brejeira (1.73–1.37 Ga). Isotope geochemical data, together with detrital zircon information, also constrain the relationship between the SPZ Carboniferous basin formation and the adjacent Paleozoic terranes.

In addition to Nd $T_{DM}$ model ages, detrital zircon age populations were used employing the MDS technique to compare SPZ Carboniferous turbidites with potential terrane sources from SW Iberia (SPZ, PLZ and OMZ) and Nova Scotia (West Avalonia and Meguma terranes). The Mértola and Cabrela formations were most likely to have been derived from a Laurussian (Rheic magmatic arc)-type source with a limited contribution from old crustal rocks. Both the Mira and Brejeira formations have a greater affinity with the Phyllite–Quartzite and Tercenas formations, indicating that zircon age populations were reproduced faithfully in intermediate sediment repositories due to recycling. The presence of Late Ordovician–Silurian and Mesoproterozoic detrital zircon in the Mira and Brejeira formations suggests Laurussian (West Avalonia/Meguma)-type sources but a contribution from Gondwanan (Ossa-Morena)-type sources cannot be discarded. The increasing proportion of detritus derived from the older basement from the base to the top of the SPZ Carboniferous stratigraphy is consistent with the progressive uplift of the Appalachian–Variscan orogenic chain during the Laurussia–Gondwana collision. The pronounced similarity between the Nd $T_{DM}$ model ages and the detrital zircon populations of the Mira and Brejeira formations (SW Iberia) and of the Horton Group (Fig. 2) suggests that they share a common source (i.e. Meguma terrane) that experienced noteworthy uplift during the Late Devonian–Carboniferous.

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**Data availability statement** All data generated or analysed during this study are included in this published article (and its supplementary information files).

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