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Origin and evolution of the Sebes Lotru terrane, South Carpathians (Romania)

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Abstract: The Sebes Lotru terrane (SLT) is the largest basement unit of the South Carpathians and of the Dacia superterrane. It is also one of the largest basement terranes in Alpine Europe. It represents the metamorphosed basement of the Alpine Getic thrust sheet and is covered in places by unmetamorphosed Alpine rocks. Its relationships with most of the other basement units in the South Carpathians is tectonic and is related to the assembly of a Mesozoic fold–thrust belt. Only its juxtaposition against greenschist facies rocks to the north and east in a small area of the Cibin and Lotru mountains is documented to be Permian, possibly early Triassic. The SLT was metamorphosed to amphibolite facies during the Variscan orogeny. Previous regional zircon (detrital and igneous) U–Pb studies have shown a continuous Ediacaran–early Silurian magmatic arc, with some additional inherited ages at 1 Ga and older than 2 Ga. A major 470–460 Ma zircon age peak dwarfs all other ages in the zircon archive and reflects a flare-up event at that time. However useful, these ages are insufficient in unravelling the full origin of these rocks without a petrological context and there are few constraints on the timing of their metamorphism. This paper provides new whole-rock geochemical and radiogenic isotopic ($^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$) data from the SLT basement ortho-rocks of the Cibin, Sebes and Lotru mountains in the central South Carpathians. New Sm–Nd garnet ages are also reported for the spatially extensive Negovanu mica schist and U–Pb zircon ages for pegmatitic granites, most of which cross-cut the metamorphic fabric. Most of the rocks are mafic and intermediate with calc-alkaline compositions and trace element patterns typical of subduction-related magmatic rocks. The isotopic ratios are relatively non-radiogenic at the time of igneous crystallization. Overall, the trace elements and isotopes of the magmatic rocks are consistent with a transitional island arc origin. The presence of various inherited Precambrian age peaks in the volcano-sedimentary detrital record demonstrates proximity to the larger Gondwana mass. The Negovanu Mare schist is probably a cover sequence that rests unconformably over the island arc assemblages. They were metamorphosed together at *c.* 340–323 Ma in the area of the Cibin Mountains. The pegmatitic granites were emplaced at *c.* 323–317 Ma based on new zircon U–Pb age dates on three of the samples presented here. The SLT is similar to other basement terranes identified elsewhere in Europe and has a peri-Gondwanan origin. Its arcs are probably related to the development and closure of the Rheic Ocean. The location of the terrane at the time of its major pulse of magmatism was close to modern-day North Africa. The SLT was juxtaposed against another Cambro-Ordovician terrane free of Variscan metamorphism during the latest Permian. The exact evolution and history of docking to larger continental masses during the Paleozoic remains unresolved for the SLT and nearby terranes.

Supplementary material: Analytical techniques, sample petrographic description, major and trace elemental analysis data, isotope and geochronology data are available at https://doi.org/10.6084/m9.figshare.c.8184414

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Dedicated to the memory of my former undergraduate classmate and lifelong friend Elena Negulescu, the best all-time metamorphic petrologist of Romania, who recently passed away prematurely after a long battle with a merciless evil disease.

Most of the basement terranes in Europe are peri-Gondwanan arc and back-arc domains of latest Precambrian to Silurian age (Dalziel 1997; Neubauer 2002; von Raumer *et al.* 2013) and are related to the evolution of island arc magmatism within the Rheic Ocean. They are typically metamorphosed, some during the Alpine orogeny, but many have unmetamorphosed covers that are late Paleozoic–Mesozoic (Stampfli and Borel 2002). The terranes that were metamorphosed during the Paleozoic are generally Variscan, a well-documented collisional orogen responsible for regional high-grade metamorphism (Franke *et al.* 2017). Metamorphic terranes of Paleozoic age are well documented in the western Balkans and the Serbian Carpatho-Balkanides (Jovanovic *et al.* 2019). Some of the least studied basement terranes of Europe are located in the Carpathian Mountains in Romania, where modern investigations of basement rocks did not begin until well into the twenty-first century (for a review, see Balintoni *et al.* 2014) and are primarily geochronological in nature. New results are rendering the majority of the older models regarding the age and cause of basement metamorphism and magmatism obsolete and, for the most part, demonstrably erroneous (for a review, see Kräutner 1997).

This paper presents new geochemical and petrological data and geochronological constraints on basement rocks from the Cibin, Sebes and Lotru mountains in the South Carpathians (Romania). These mountains are part of the Sebes Lotru terrane (SLT), the largest individual basement terrane in the Romanian Carpathians, which makes up the bulk of a basement-dominated Alpine thrust sheet, the Getic nappe (Iancu *et al.* 2005), which is part of the Dacia superterrane (Maţenco 2017).

Balintoni *et al.* (2010), Stoica *et al.* (2016) and Ducea *et al.* (2016) used igneous and detrital U–Pb zircon geochronology to determine that the SLT is a peri-Gondwanan terrane with a classic early Phanerozoic (Mid-Ordovician) peak in magmatism, but also with a slightly older Ediacaran signature. These age peaks are taken to represent a signature for the Dacia superterrane (or Median Dacides; Săndulescu 1984) because they are also seen as prominent peaks in the sedimentary record derived from this basement (Stoica *et al.* 2016; Ducea *et al.* 2018; Roban *et al.* 2023). Metamorphism of the SLT is generally accepted to have been Variscan (350–325 Ma) based on limited data (Iancu *et al.* 1998; Drăguşanu and Tanaka 1999; Medaris *et al.* 2003). Although the metamorphic grade varies from one area to another, it is mostly amphibolite facies.

Little is known of the origin of the SLT beyond these ages and some limited information on the metamorphic conditions (Săbău and Massonne 2003; Negulescu *et al.* 2014). Previous studies of the origin of the terrane (Balintoni *et al.* 2009, 2010, 2014) have mostly been concerned with identifying the place of origin of the terrane within Gondwana in the early Paleozoic using the distribution of inherited Precambrian zircons. This paper complements these results with data pertinent to the magmatic origin of these rocks. Their chemistry and isotopes, as well as their overall map distribution, are consistent with an island-arc-like origin, the build-up of which started in the Ediacaran and lasted throughout the earliest Silurian. This long-lived arc straddling the Precambrian–Phanerozoic boundary was a segment of a large-scale, continent-forming, peri-Gondwanan subduction environment that is recognizable as a distinctive peak in arc magmatism globally (Ducea *et al.* 2015*c*; Balica *et al.* 2020) and represents new crust added to the continental masses in the latest Precambrian and Phanerozoic.

Geological background

Figure 1 shows the extent of the basement rocks in the Carpathians and the wider Balkans region. The South Carpathians are dominated by basement rocks representing pre-Alpine (pre-Jurassic) rocks that are mostly metamorphic rocks and unmetamorphosed plutons. The assembly of the modern South Carpathians as a fold–thrust belt is a result of the closure of a small oceanic basin, the Severin Ocean, most commonly attributed to the Alpine Tethys (Săndulescu 1984; Iancu *et al.* 2005; Schmid *et al.* 2020; van Hinsbergen *et al.* 2020). This is now preserved as a thrust sheet, the Arjana–Severin nappe, which consists of a tectonic mélange of serpentinites, metamorphosed mafic rocks, calc-silicate rocks, meta-carbonate rocks and various flyschoid sedimentary rocks. These formerly oceanic rocks have been metamorphosed to the prehnite–pumpellyite facies (Ciulavu *et al.* 2008), a low-grade form of subduction metamorphism.

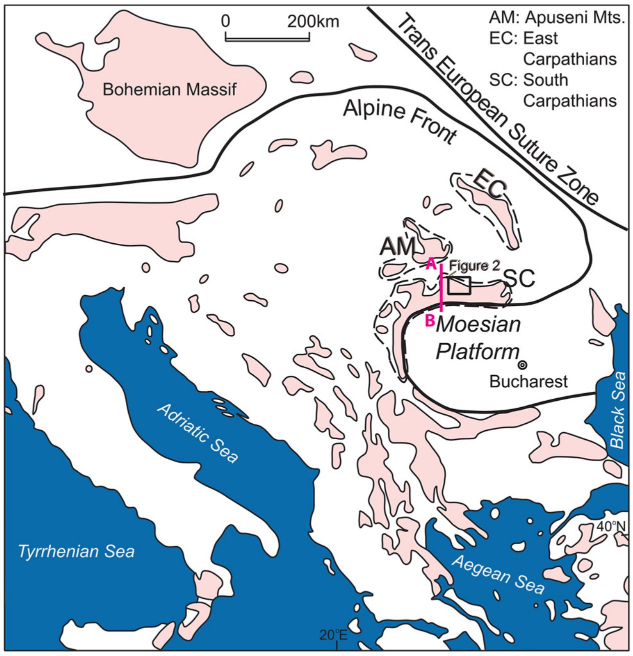

Fig. 1. Location of the main exposures of basement rocks (pink) in central Europe. The approximate locations of the detailed geological map and cross-section are also shown. All the units shown in pink as basement rocks are Ediacaran–Silurian in age and contain various proportions of rocks metamorphosed as Barrovian sequences during the Variscan Orogen (Carboniferous–Permian). Source: from Ducea et al. (2016).

Structurally above the South Carpathians (to the north) lie the Getic and Supragetic nappes, and below (to the south) are the Danubian nappes, which, in turn, override the Moesian foreland (Fig. 2). All these nappes have various post-tectonic cover units overlying the thrust belt architecture. The closure of the Severin basin is believed to be early to Mid-Cretaceous in age, although its Alpine metamorphism (Ciulavu *et al.* 2008) has never been dated in detail. However, there is ample evidence that the Severin basin was closed much earlier than its sibling, the Ceahlau basin, to the east (Schmid *et al.* 2020 and references cited therein), probably because the basin was segmented and separated by a large transform fault during the Cretaceous (Ducea and Roban 2016). Both sides of the Severin basin are covered by large carbonate platforms of Mesozoic age (Burchfiel 1980).

The Getic and Supragetic nappes are part of the Dacia superterrane, which is found not only in the South Carpathians, but also represents the basement of the East Carpathians and is also presumably buried under the Transylvanian basin and the basement part of the East Carpathians. The Danubian nappes, also mostly basement rocks, are linked to western Moesia in origin (Iancu *et al.* 2005). The Danubian units are distinct from the Getic–Supragetic domain (nappes) in that they contain large, unmetamorphosed late Precambrian granitic bodies (600–570 Ma), as well as unmetamorphosed post-Variscan plutons (300–290 Ma) (Liegeois *et al.* 1996; Balintoni *et al.* 2011). The crystallization age of the Dragsan Series, the oldest metamorphic suite in the Danubian, is *c.* 800–780 Ma based on zircon U–Pb dating (Balintoni *et al.* 2011), making it the oldest unit in the Carpathians. Overall, although the Danubian basement rocks display a similar latest Precambrian–Paleozoic history, they are distinct from the Getic–Supragetic basement in their zircon U–Pb age distribution and metamorphic history (Ducea *et al.* 2018). The upper nappes (Getic and Supragetic) do not contain unmetamorphosed Precambrian plutons (Balintoni *et al.* 2014).

The SLT (Balintoni *et al.* 2009), also known locally as the Lotru Unit (or Metamorphic Suite) in the area presented here (Ducea *et al.* 2016 and references cited therein), makes up a large fraction of the Getic nappe and is the largest single mega-unit mapped in the Romanian Carpathians. Mapping of these rocks has been attempted during several iterations by the Romanian Geologic Survey (also known as the Romanian Geologic Institute), with outcomes leading to different map patterns (Codarcea-Dessila 1965; Codarcea-Dessila and Iliescu 1967; Gheorghian *et al.* 1975; Săbău 1994, 1998; Dinică 1996, 1998; Gheuca 1998; Stelea 1999).

The SLT is not properly defined in space with it's original pre-Alpine boundaries because it is considered that most of its modern limits are Alpine (Mesozoic and Cenozoic) faults (Balintoni *et al.* 2014). The exception is the contact with low-grade units near Rasinari and along the western part of the Olt Gorge along a ductile shear zone (Hann 1995; Ducea *et al.* 2016), where hints of the original pre-Mesozoic juxtaposition are preserved locally, even though the structure was reactivated in the Cretaceous and again in the Cenozoic (Hann 1995; Ducea and Roban 2016).

The Sebes and Cibin mountains are located in the central part of the South Carpathians and are almost exclusively composed of SLT rocks. To the south, the SLT is bounded in this area by the Getic–Severin thrust fault and to the east by the Cretaceous Transcarpathian strike-slip fault (Ducea and Roban 2016), which reactivates an older, ductile fault system, the Sibisel shear zone

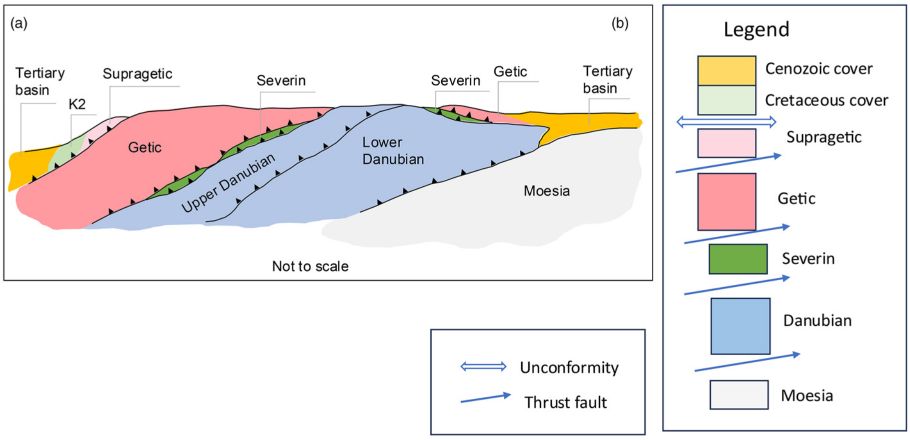

Fig. 2. Schematic north–south cross-section through the South Carpathians showing the main thrust sheets and their geometry. The Sebes Lotru terrane is the largest basement unit of the Getic unit and the largest unit of all the basement domains of the Romanian Carpathians. Source: modified after Stoica *et al.* (2016).

(Ducea *et al.* 2016). To the north of these ranges, the SLT boundary is partly a Permian shear zone (the Sibisel shear zone, Pană and Erdmer 1994; Ducea *et al.* 2016) and partly the Supragetic–Getic thrust fault (Iancu *et al.* 2005). To the west, the SLT continues in the Parang Mountains and to the western end of the South Carpathians (Fig. 1), outside the area of this field study.

Figure 3 is a simplified geological map of the field area built on work originally reported by Săbău (1994) and shows the main mappable units. The basement units shown on the map are, from the structurally lower to upper positions: (1) the Saracinu Unit made primarily of Ediacaran amphibolite facies meta-granitoids and amphibolites, although more exotic assemblages such as meta-peridotites and eclogites are present out of context; (2) the Paltinis gneisses, made primarily of amphibolite facies two-mica orthogneisses with minor screens of quartzites; and (3) the Negovanu Mare mica schists, which are garnet- and staurolite-rich two-mica metasediments.

There may be some stratigraphic significance to these units because the Negovanu Mare mica schists appear to lie unconformably on top of the other units based on the field relationships.

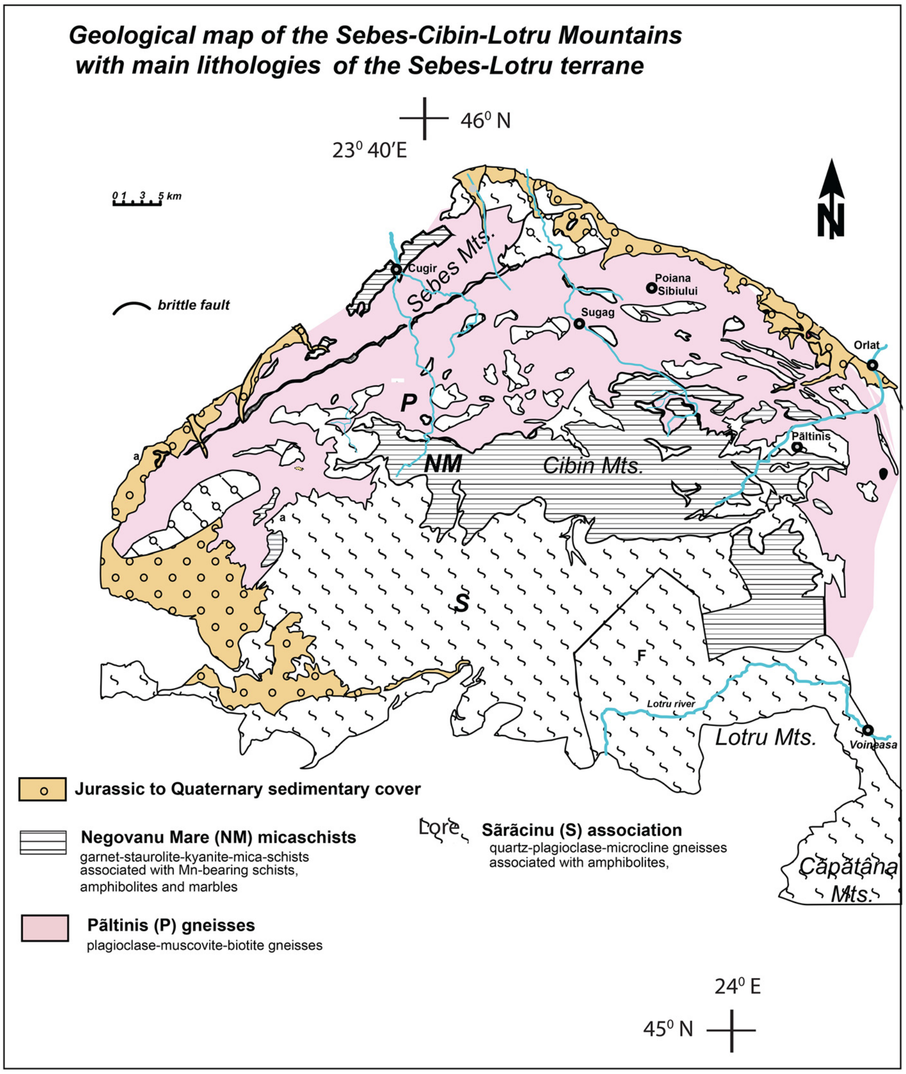

Fig. 3. Simplified geological map of the Sebes Lotru terrane in the Cibin and Lotru mountains. The blue lines show the main rivers in the area and the small circles denote local towns. The brittle fault shown in the northern part of the map is the Alpine reactivation of the Sibisel shear zone (Ducea *et al.* 2016). Source: compilation using a variety of sources shown on the map; the primary sources are Stelea (1994), later modified by Săbău and Massonne (2003).

Table 1. Sebes Lotru Units

	Association	Lithology	Depth (km)	Age (Ma)	Date of metamorphism (Ma)
	Negovanu Mare	Garnet–staurolite–kyanite mica schist	1.5–2	Post-440 and pre-340	335
	Paltinis	Plagioclase–muscovite–biotite gneiss/schist, amphibolites, ultramafic rocks	3–4	535–440	350–320
	Saracinu	Amphibolites, some ultramafic rocks, quartz–plagioclase–muscovite gneiss	1.5–2	588–535	350–320

Although the Saracinu and Paltinis units interfinger in a relatively complex pattern, at least as far as can be deduced this from this relatively poorly exposed and forested area, it is becoming clear from the emerging geochronology that the Saracinu Unit (also identified as the Lotru Unit of the SLT) is the Ediacaran basement of the Paltinis units, which is Ordovician–Silurian in age. These two distinct arcs may, in fact, have formed a continuous arc. The Negovanu Mare meta-sediments lie unconformably on top of this mostly igneous package (Table 1). Presumably all the units were metamorphosed together during the Variscan (Medaris *et al.* 2003), although this has not previously been resolved. About 3% of the Sebes Lotru rock units (as a large-scale average) consist of various pegmatitic granitois dykes and veins that are typically 1–10 m wide (Manecan 1985; Hann 1987). They are syn- to post-tectonic because most of them cross-cut the metamorphic fabric. They were dated for the first time in this study and are late Variscan. An exception is the Cataracte pegmatite, a leucogranite that is pegmatitic in appearance and crops out along the River Lotru. The Cataracte leucogranite is a large (2 km × 3 km in map view; Hann 1987) undeformed igneous body in the SLT with a late Permian age (258 Ma; Ducea *et al.* 2022), much younger than the pegmatites described here. The metamorphic fabrics are, for the most part, sealed by the older pegmatites and are clearly older than the Cataracte body.

The late Jurassic–Quaternary cover consists mainly of Mesozoic marine platform limestones and is overlain by marine clastic units that grade into continental sediments in the second half of the Cenozoic (Iancu *et al.* 2005). The unmetamorphosed sedimentary cover is volumetrically insignificant and appears to be mostly post-tectonic in nature with respect to the Alpine orogeny. There is no indication of Alpine metamorphism, either here or elsewhere in the Getic–Supragetic units. There is a series of small-volume adakitic intrusions of Mid-Cretaceous age (110–100 Ma) within the Sebes Mountains (Dobrescu *et al.* 2010). These are not shown on the map (Fig. 3) because they are too small at the map scale; their origin is unclear and they are not discussed further here.

Figure 4 is a probability density plot of all the published and some unpublished U–Pb ages obtained for the SLT within the past 18 years, mostly at the Arizona Laserchron Laboratory at the University of Arizona (Ducea *et al.* 2016) and subsequently at the Petrochron Laboratory of the University of Bucharest (modified after Roban *et al.* 2023). The shapes of the peaks (i.e. the abundance of zircons of certain ages) may be biased because certain rock types yield more zircons than others. However, this diagram gives an unambiguous timeline of the development of this terrane as an Ediacaran–Silurian series of magmatic arcs (possibly formed in continuity) with few inherited older zircons. This suggests an origin as an island arc formed in the proximity of an old *c.* 2 Ga continental mass (Balintoni *et al.* 2009; Stoica *et al.* 2016; Ducea *et al.* 2018). Together with its post-tectonic cover, the arc was metamorphosed to amphibolite facies during a collisional event in the Variscan. Some zircons were produced as metamorphic overgrowths during this event, whereas other zircons are from the pegmatitic leucogranites that formed during the late stages of this collisional event.

Samples and methods

Forty samples were collected from the SLT for petrographic, geochemical and geochronological analyses. Fifteen fresh samples from all three groups were selected based on their key locations with respect to the shear zone for geochemical (whole-rock major and trace element analyses) and isotopic work. The locations, assigned metamorphic units and brief petrographic descriptions of these samples are given Supplementary Data Table 1.

Initially determined commercially at ACME Laboratories (Canada), the major element concentrations reported here were re-determined by X-ray fluorescence spectrometry following lithium borate fusion at the Petrochron Laboratory (University of Bucharest) (see Supplementary material for techniques). The sample aliquots for trace element analyses were dissolved in a mixture of concentrated hydrofluoric and nitric acids for four days, followed by dissolution in concentrated hydrochloric acid for one day at 175°C. The evaporated samples were re-dissolved in 2% nitric acid

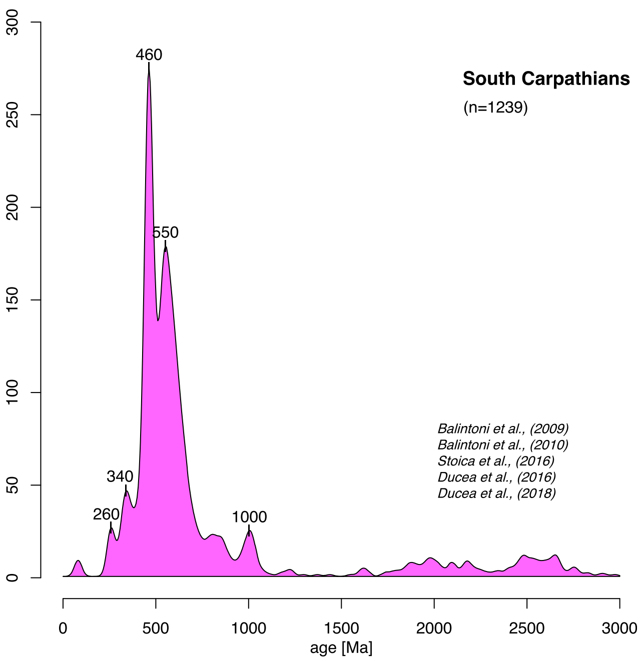

Fig. 4. Summary probability density plot of zircons from the Getic nappe (or thrust sheet). This plot combines detrital and igneous zircon ages measured directly on Getic rocks or indirectly on sedimentary materials derived demonstrably from only a Getic basement source. Source: modified after Roban *et al.* (2023).

before analysis on a Thermo-Scientific X-Series 2 quadrupole inductively coupled plasma mass spectrometer at the University of Arizona. The sample runs were calibrated with the BCR-2, BHVO-1 and G2 reference standards distributed by the US Geological Survey; the procedures in this laboratory were described previously by Rossel *et al.* (2013).

The sample aliquots for isotope analysis were spiked and then dissolved in a mixture of concentrated hydrofluoric and nitric acids, followed by dissolution in concentrated hydrochloric acid for one day at 175°C. The dissolved samples were run through a series of cation-exchange procedures to isolate Nd, Sm, Sr, Rb and Pb elutates. The isotope ratios and concentrations of Nd, Sm and Sr were determined by isotope dilution on a VG54 multi-collector thermal ionization mass spectrometer at the Radiogenic Isotope Laboratory, University of Arizona. The samples were spiked with mixed spikes of Sm–Nd, as well as separate Rb and Sr spikes. The analytical procedures have been described previously by Otamendi *et al.* (2009). The Nd isotopic ratios were normalized to $^{146}Nd/^{144}Nd = 0.7219$. The Rb isotopic ratios were determined on a Thermo-Scientific X-Series 2 quadrupole inductively coupled plasma mass spectrometer at the University of Arizona.

Two samples of the Negovanu Mare mica schist were selected for Sm–Nd geochronology. The garnets were separated in a Frantz magnetic separator, washed in dilute nitric acid, crushed to a third of their size and then optically picked to obtain a concentrate that lacked inclusions. The garnets were then crushed further in a shatterbox and spiked according to the described techniques. Sm–Nd isotopes were also measured in whole-rock samples free of garnet to construct isochrons. All the measurements were performed on a VG Sector 54 mass spectrometer at the University of Arizona following the procedures of Ducea *et al.* (2003) and Otamendi *et al.* (2009).

U–Pb zircon dating was carried out for three pegmatitic samples from the SLT. Zircons were extracted using conventional techniques (crushing, sieving, heavy liquid separation and magnetic separation). Measurements were carried out at the Laserchron facility at the University of Arizona (Gehrels *et al.* 2008) and the Petrochron Laboratory at the University of Bucharest (see Supplementary material) following routine mineral separation procedures.

The whole-rock chemistry results are given in Supplementary Data Table 2 and the whole-rock radiogenic isotopic results are given in Supplementary Data Table 3. Supplementary Data Table 4 contains the U–Pb data on pegmatites and Supplementary Data Table 5 contains the Sm–Nd geochronology data.

Results

Petrography

The sample petrography is summarized in Supplementary Data Table 1. Figure 5 shows the typical appearance of the major rock units in hand specimen. The two most common assemblages are (1) amphibolites and gneisses representing a variety of ortho-rocks ranging from ultramafic and meta-mafic to dacitic and rhyolitic in composition and (2) an intermediate mica schist with kyanite, garnet and staurolite (the Negovanu Mare Unit). The gneisses with quartz, K-feldspar, plagioclase and mica(s), which are intermediate in composition based on the relative proportion of felsic to mafic minerals, are more often members of the Paltinis Unit, although similar rocks are also found in the Saracinu Unit. The meta-granitoids of the Saracinu Unit tend to be coarser grained and distinct from those in the Paltinis Unit and commonly contain K-feldspar mega-crysts and amphibole in their assemblages.

All the described rocks have been metamorphosed to garnet amphibolite facies. According to Medaris *et al.* (2003) and Săbău and Massonne (2003), their peak metamorphism was at *c.* 0.7–0.9 GPa and >650–700°C. Note that both these studies are heavily biased towards the highest grade rocks in these suite (the rare eclogitic and granulitic facies rocks) and that no P–T study has been published for the more common rocks. These rocks are also intensely deformed, with >70% of the outcrops investigated here showing these three main types of rocks with highly deformed, commonly mylonitic textures. Retromorphic reactions are present in the rocks, but are not predominant.

Leucogranitic pegmatites represent the third rock type present and investigated here. They are ubiquitous in many outcrops and are either concordant with the foliation or, more commonly, cross-cut the main foliation (Hann 1987; the author's own field observations). The three pegmatites analysed for U–Pb geochronology here contain two different micas and black tourmaline, in addition to quartz and microcline with various amounts of plagioclase. This pegmatitic province is generally not known to be rich in rare minerals, although spodumene and beryl have been reported as rare accessory minerals in few outcrops; black tourmaline (schörl) is ubiquitous (Hann 1987).

Whole-rock geochemistry

The meta-magmatic rocks range in composition from ultramafic to granitic, covering an entire spectrum of intermediate compositions, as is commonly the case with subduction-related arc rocks (Fig. 6). The rocks are calc-alkaline and average *c.* 60% SiO_2 for the Lotru Unit and 55–56% SiO_2 for the Sebes rocks. They are normal arc rocks without any tendency towards hyperalkalinity and are not adakitic. The average Saracinu chemistry suggests a crustal thickness of 25 km, whereas the Paltinis chemistry is indicative of a slightly shallower (20 km) depth to the Moho (Luffi and Ducea 2022). The Negovanu Mare schists are also intermediate in composition. They stand out in terms of their radiogenic isotope data, but not, somewhat surprisingly, in their major element chemistry.

The trace element analyses plotted as spider diagrams show that all the Saracinu and Paltinis rocks are arc-like – that is, they show the negative anomalies in Nb–Ta and Ti typical of subduction-related arc rocks (Fig. 7). The rare earth element spider diagrams show moderate enrichment in the light rare earth elements and, most commonly, negative Eu anomalies, indicating a medium-thick crust at the time of igneous genesis. A variety of Pearce-type diagrams (not shown) all indicate a subduction-related origin for the Saracinu and Paltinis rocks and the Negovanu Mare meta-sedimentary schists, which appear to be derived from arc materials based on the major and trace elemental patterns, although their ultimate source rocks are unknown.

Whole-rock isotope geochemistry

The whole-rock Sr and Nd isotopic ratios, corrected for age, show a range of values for both Saracinu and Paltinis assemblages (Fig. 8). The author does not overinterpret these initial values because these rocks have subsequently been affected by high-grade metamorphism and various forms of fluid flow and the original isotopic signature may have been modified at a later time. However, it is important to point out that the initial isotopes for most of the ortho-rocks are fairly non-radiogenic, but are not in the depleted mantle range. The initial $^{87}Sr/^{86}Sr$ range of 0.704–0.706, for example, is fairly typical of a suite of calc-alkaline rocks that formed in a transitional island arc environment. The older Saracinu and the younger Paltinis rocks appear to be similar in their isotopic characteristics. These rocks did not form on a mature continental crust as the other lines of evidence presented here suggest. There is little correlation between how radiogenic a rock is and the amount of silica, suggesting that crustal contamination had a limited role in shaping the isotopic ratios measured here (Fig. 9).

The Nd model ages relative to the depleted mantle are in the range 0.8–1 Ga, which is indicative of the extraction of these rocks from a

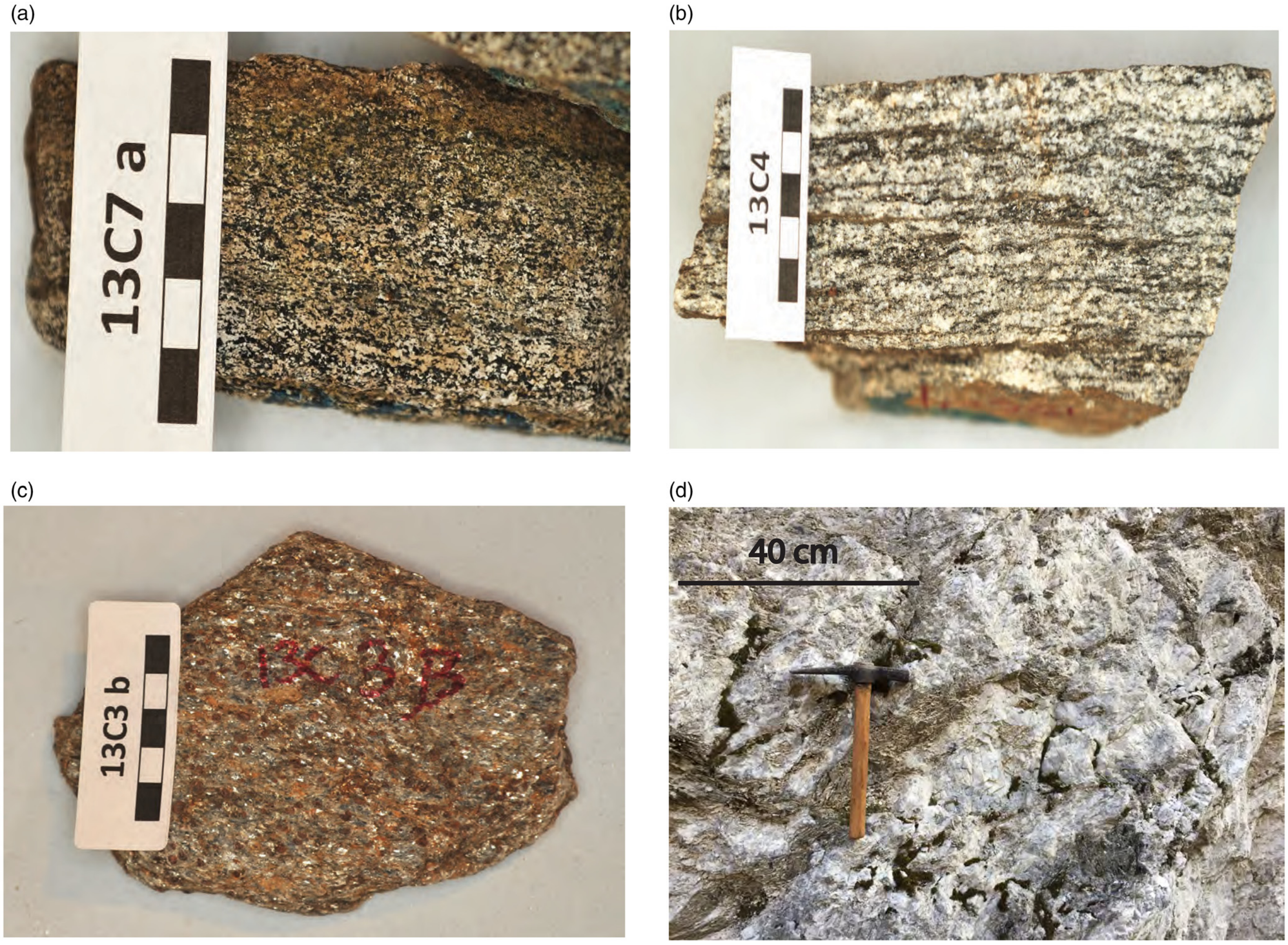

Fig. 5. Hand specimen photographs of the main assemblages of the Sebes Lotru terrane. (**a**) Intermediate gneiss from the Saracinu Unit. (**b**) Ortho-gneiss of the Paltinis Unit. (**c**) Kyanite and staurolite mica schist of the Negovanu Mare units. (**d**) Leucogranitic pegmatite.

fairly young reservoir in the mantle (Fig. 9). This is similar to other peri-Gondwanan Ediacaran–Ordovician arcs worldwide. They are not as primitive as the most primitive modern island arcs, but they seem to have been formed on what may have been an overly extended continental margin with some contributions from older materials (e.g. Walker *et al.* 2015).

The isotopic discrepancy between the ortho-rocks and the cover Negovanu Mare schists is also evident in Figure 9. Similar whole-rock Nd model ages have been obtained on a variety of metamorphic rocks from the Romanian Carpathians, including the Getic unit rocks (Balintoni *et al.* 2001), presumably mostly on meta-sedimentary rocks (Balintoni 1997). At almost twice the Nd model age of the arc rocks, these cover sequences could not have been derived from the arcs themselves, but from a more inboard continental source. They mark the arrival of these arcs closer to a continental mass. The fact that whole-rock ε_{Nd} values define a

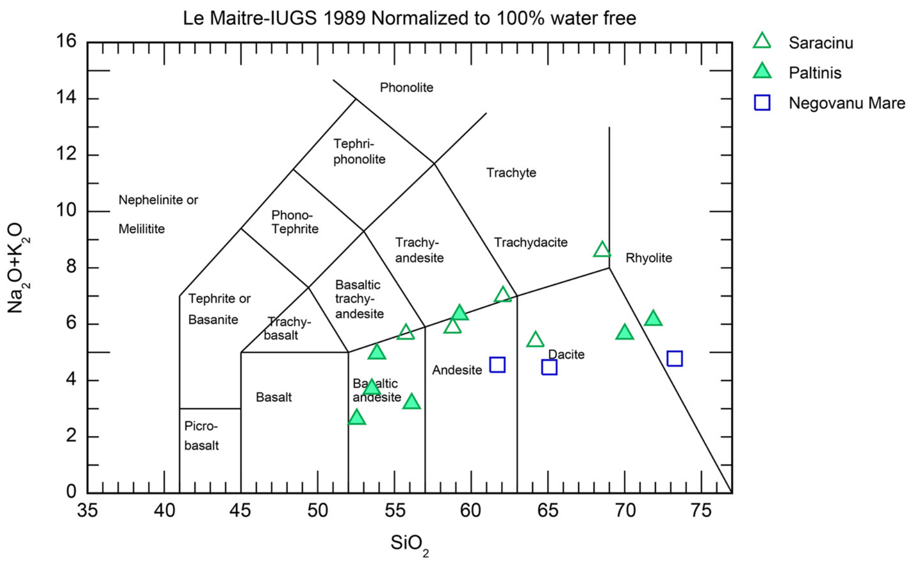

Fig. 6. Total alkalis–silica diagram showing the petrographic composition of the analysed rocks expressed in volcanic equivalents. All the rocks are typical of the calc-alkaline suites found in subduction zones.

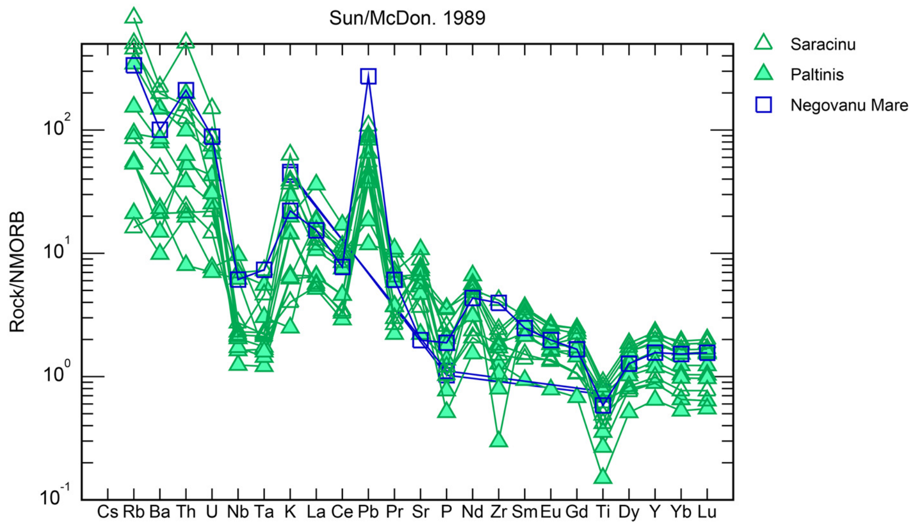

Fig. 7. Trace element spider diagram of the Sebes Lotru terrane rocks normalized to the normal-type mid-ocean ridge basalt of Sun and McDonough (1989).

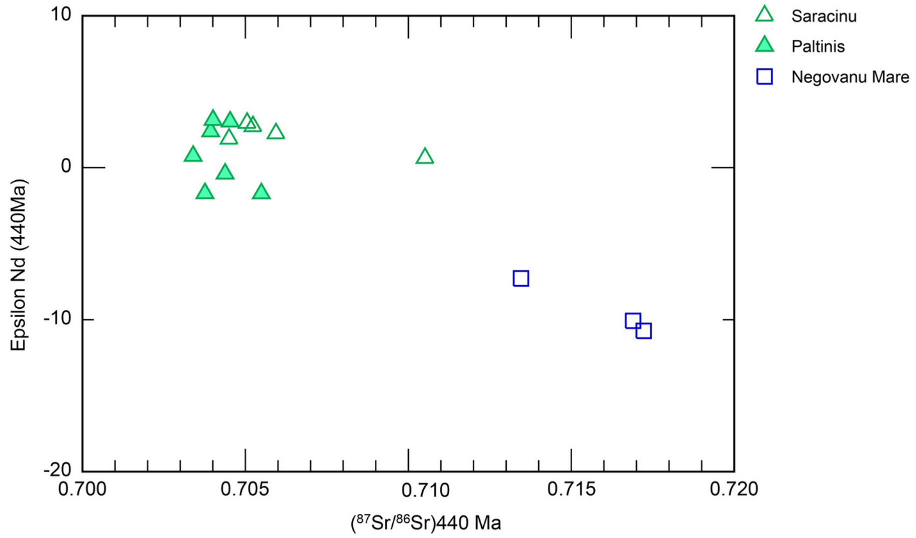

Fig. 8. $^{143}Nd/^{144}Nd$ v. $^{87}Sr/^{86}Sr$ whole-rock values calculated at 440 Ma, the youngest permissible crystallization age for arc rocks in the Sebes Lotru Terrane.

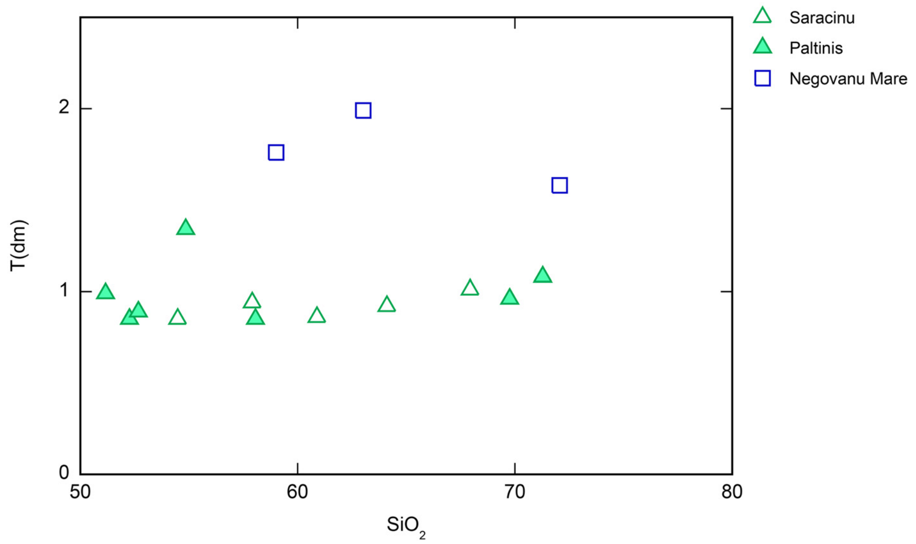

Fig. 9. T_{DM} v. silica for the analysed samples The Negovanu Mare rocks have distinctively older model ages than the other rocks. The depleted mantle model age is calculated according to DePaolo (1988).

model age of *c.* 2 Ga cannot in itself determine the origin of the continental mass, but, together with the intermediate, arc-like bulk chemistry of these rocks, it is an indication of a mass that underwent arc magmatism in the Proterozoic and does not, at first glance, bear an Archean component. The author speculates that this is more likely to be a Gondwanan signature, similar to the overall origin of the Romanian metamorphic terranes (Balintoni *et al.* 2014) and not a Baltica signature.

U–Pb geochronology

Three pegmatites were sampled from the Cibin Mountains. Sample 23MC, which is a muscovite pegmatitic leucogranite, is concordant with the foliation in the main metamorphic fabric (Fig. 10a) and has an age of 322 ± 7 Ma (Fig. 11), a high error attributed to the fact that only four of the entire population of zircons are not inherited. The great majority of zircons in this sample are inherited from the Ordovician and earlier magmatic peaks.

Sample 28MC and sample 19ML, which are petrographically similar to the sample 23MC, are dykes cross-cutting the main fabric of the SLT (Fig. 10b). Sample 28MC yields an age of 317 ± 4.1 Ma and sample 19ML yields an age of 317.6 ± 2.1 Ma (Fig. 11). Some grains are inherited from the Ediacaran–Ordovician arcs. Both samples contain mostly discordant grains and therefore it is perhaps better to calculate the lower intercepts of a discordant age after clearly inherited grains have been removed from consideration. When that analysis was performed (not shown), the lower intercept ages were within the errors reported here. The pegmatites were emplaced at the end of the Variscan metamorphic event, just prior to the extensional collapse that started in the area at *c.* 316–310 Ma (Medaris *et al.* 2003).

Sm–Nd garnet–whole-rock isochron geochronology

Two samples of the Negovanu Mare schist (samples 13C3 and 13C7) were analysed for garnet–whole-rock isochron geochronology. Garnet fractions and whole rocks free of garnet were analysed from each sample. Inclusion-free garnets were picked optically to better constrain the isochrons. Figure 12 shows ages of 334.9 ± 2.7 Ma (sample 13C7) and 336.8 ± 3.3 Ma (sample 13C3). Both of these ages are consistent with previous Sm–Nd ages of the South Carpathians basement (Drăgușanu and Tanaka 1999; Medaris *et al.* 2003). They demonstrate that the Negovanu Mare unit experienced amphibolite metamorphism at the same time as the underlying units of the SLT and therefore that the entire SLT package was experiencing a common history by the time of the Varsican Orogeny.

Discussion

Temporal evolution

Re-interpretation of the geological maps with our new knowledge of the ages and petrology confirms that the Sebes and Cibin mountains SLT is built from two distinct segments: an older Ediacaran magmatic arc basement and a younger Cambro-Silurian, mainly Mid-Ordovician, arc (Fig. 13). More complex map unit patterns (Iancu *et al.* 1998) are not helpful at the scale of this study. The outcrop and map patterns suggest that the younger arc was emplaced into the older arc and may even have been active continuously between *c.* 600 and 440 Ma. There is nothing to indicate that the two arcs were in tectonic contact, although the outcrops in the area are not sufficient to completely rule out some structural juxtaposition between the Sebes and Lotru rocks. The younger arc rocks contain inherited zircons from the earlier basement. The youngest magmatic arc rocks of the terrane are augen gneisses found in the Sebes Unit, which are known in the study area as the Paltinis gneisses, whereas elsewhere to the east they are better known as the Cozia gneisses (Drăgușanu and Tanaka 1999).

Both of these units are covered by a post-tectonic metasedimentary sequence (the Negovanu mica schist), which is significantly more evolved isotopically than both the Sebes and Lotru arc rocks and thus probably formed when the Sebes and Lotru arcs were starting to accrete to a larger continental mass. All three units were metamorphosed to upper amphibolite facies during a Variscan (350–320 Ma) collisional event, as documented in previous studies (Drăgușanu and Tanaka 1999; Ducea 1999; Medaris *et al.* 2003).

The ductile deformation and high-grade metamorphism is sealed by ubiquitous pegmatitic and leucogranitic veins in all three units (323–320 Ma). The last notable activity in the basement was the emplacement of late Permian leucogranites in response to the nearby closure of the Palaeotethys Ocean. The only pre-Alpine contact preserved in the SLT is the Sibisel shear zone, a Permo-Triassic ductile shear zone that bounds the SLT to the east and north

Fig. 10. (**a**) Field photograph of concordant pegmatitic vein. (**b**) Field photograph of discordant pegmatitic dyke.

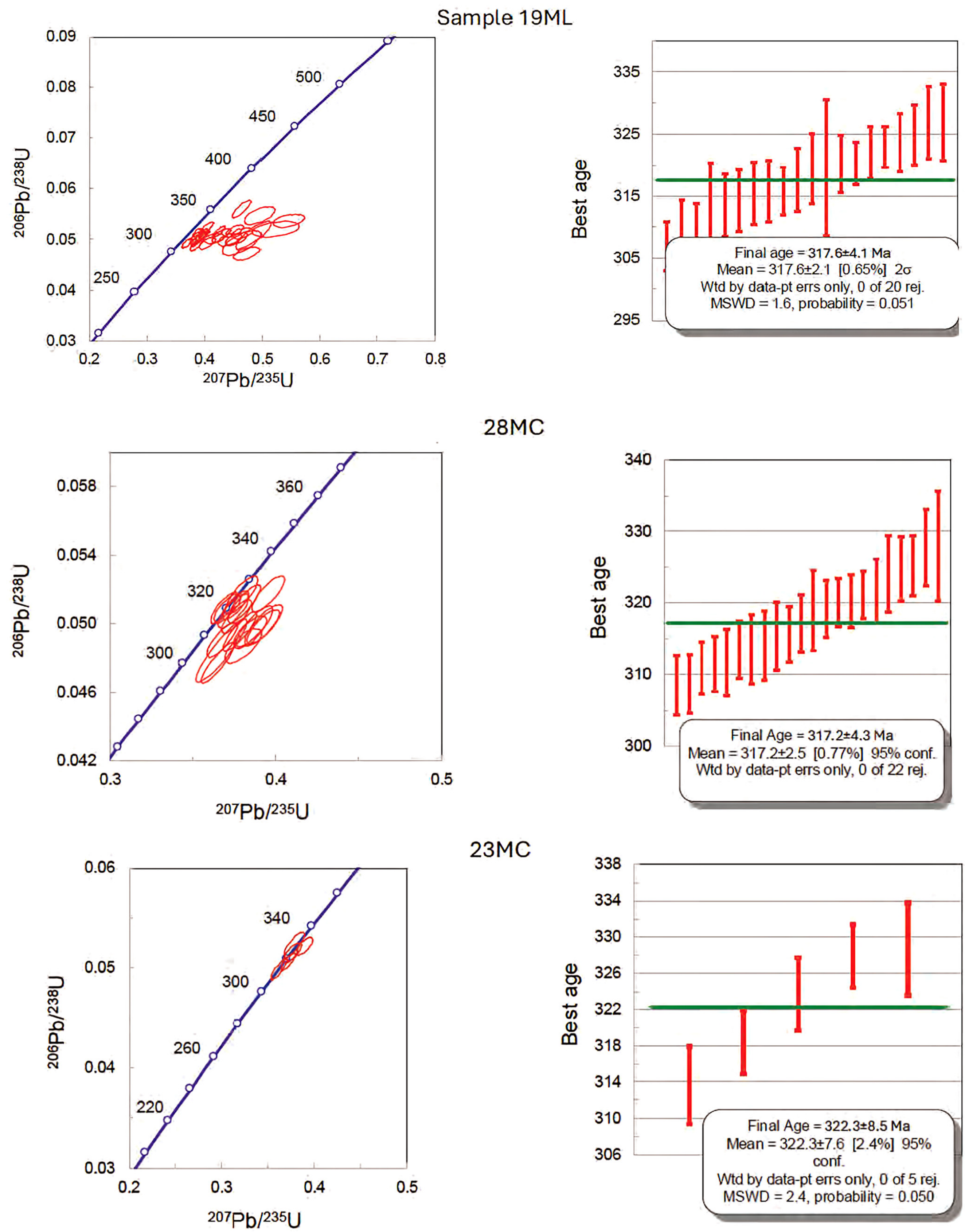

Fig. 11. Crystallization age zircon U–Pb concordia and best-age diagrams for the three pegmatitic leucogranites analysed in this study plotted using ISOPLOT-R (Vermeesch 2018).

and separates it from a low-grade Ordovician series that did not experience Variscan metamorphism (Ducea *et al.* 2016). The Sibisel shear zone was reactivated as an Alpine strike-slip fault along the River Olt (Ducea and Roban 2016).

Origin of the SLT

The SLT is primarily made of meta-igneous rocks ranging from basalt to rhyolite and averaging andesite. The calc-alkaline nature of

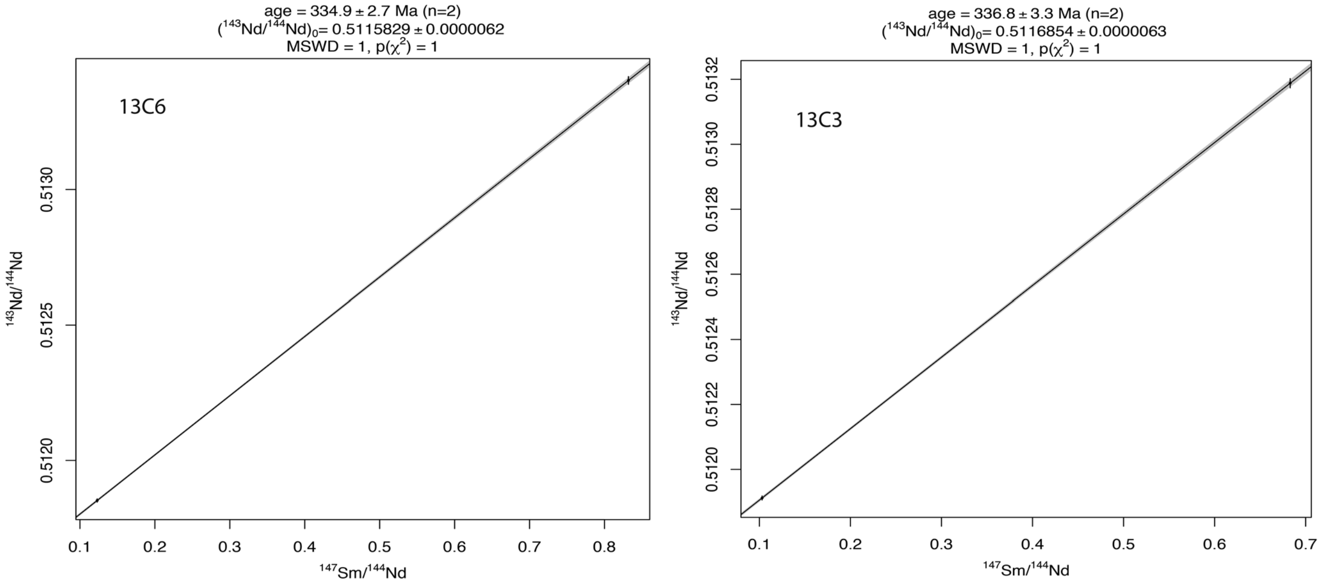

Fig. 12. Garnet–whole-rock Sm–Nd isochrons for the Negovanu Mare schists.

these rocks and the range in silica leave little doubt that they were part of a subduction-related arc from the Ediacaran to the earliest Silurian, with a major high-flux event at 470–460 Ma. The arc was relatively thin throughout its evolution and there is no evidence that its demise is related to a collisional event. Instead, it is capped by a sedimentary cover of passive margin affinity. Metamorphism took place >100 Myr after the arc stopped producing magma. The predominant juvenile isotopic signature of the arc is consistent with its origin as an island arc or perhaps a transitional arc. The presence of many small ultramafic slivers within SLT is also consistent with a more juvenile origin of the arc; they probably represent former mélange rocks or other types of serpentinites commonly found in oceanic terranes.

Although this study focused on the Sebes and Cibin mountains, all the other segments of the Getic basement units elsewhere in the South Carpathians also have a similar meta-igneous basalt unit covered by meta-sediments.

Similarities with young accreted arcs

The SLT is a classic post-800 Ma arc terrane and represents close to 100% new crustal growth at a former subduction margin (Stern 1994; Ducea *et al.* 2015*a*). The complexities of a non-metamorphosed island arc are well known on geological maps of young arcs because they mainly form underwater. Perhaps the best-mapped example is the Cretaceous Alisitos arc of western Baja California

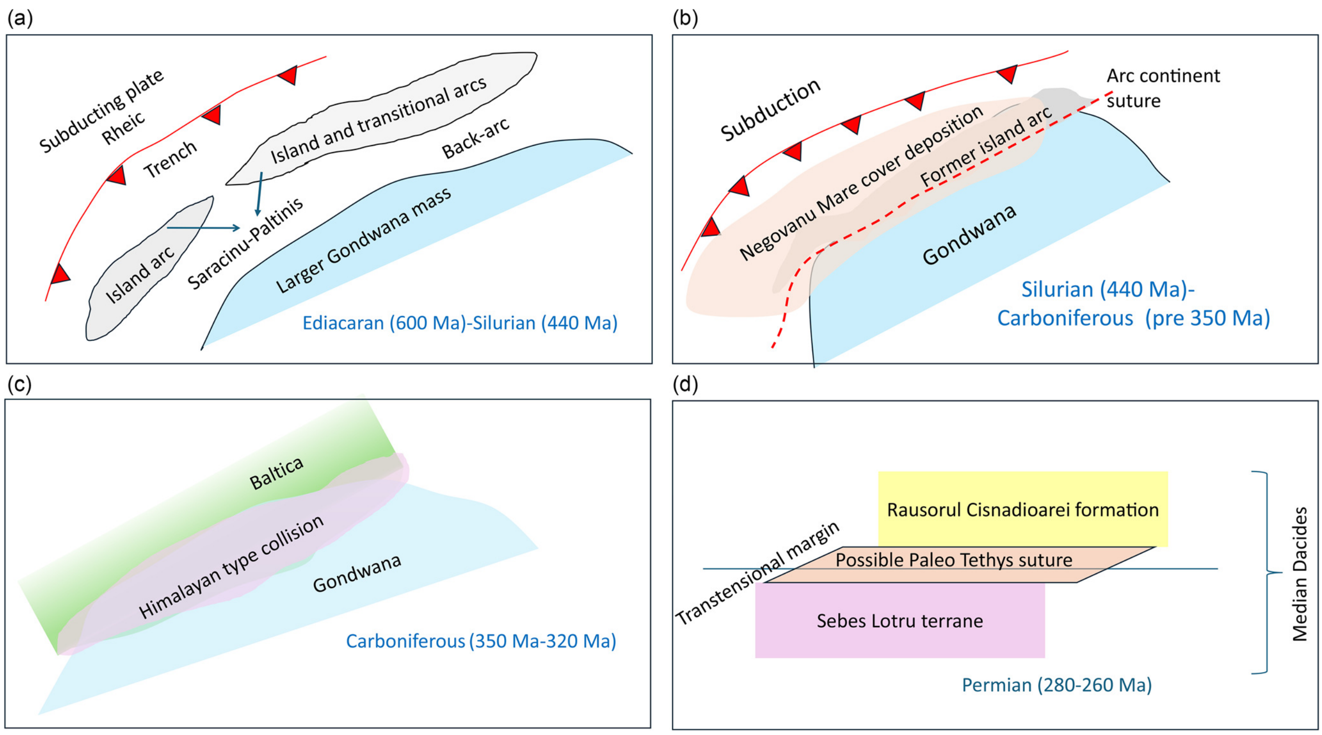

Fig. 13. Schematic diagram of the evolution of the Sebes Lotru terrane in four temporal steps. (**a**) Formation of the Ediacaran–Silurian arc. (**b**) Deposition of the Negovanu Mare Unit from a Gondwana source. (**c**) Collision with the continent during the Variscan. (**d**) Further collision or transpresssional margin marking the closure of the Palaeotethys Ocean in the late Permian or possibly early Triassic.

(Busby *et al.* 2006). Although all rocks in that terrane are arc-related and have ages between 125 and 100 Ma, the terrane represents a complex mix of ignimbrites, mafic to felsic flows, rocks with a submarine volcano-sedimentary origin *sensu lato*, and slightly younger intrusive rocks of quartz diorite to tonalite compositions that intrude into an earlier volcanic sequence of rocks. If that package were to be plastically deformed and metamorphosed to amphibolite grade, it probably would look like the SLT.

As a former island arc or transitional arc, as suggested by the lack of an older basement, the SLT has geochemical characteristics typical of thinner arcs, such as relatively low La/Yb and Eu anomalies (Ducea *et al.* 2015*a*). When these characteristics are entered into modern chemical mohometry calculators (Luffi and Ducea 2022), the SLT has a crustal thickness ≤25 km. The primitive nature of the isotopes is consistent with the juvenile origin of the arc. Countless similar Ediacaran–Ordovician arc segments are known around the peri-Gondwana margins (Stern 1994; Dalziel 1997) and are exposed today in much of the basement of Europe (von Raumer *et al.* 2013), South America (the Famatinian arc; Ducea *et al.* 2015*b*), North America, and Asia as far east as the Himalaya (Ducea *et al.* 2015*c*). The largest pulse of magmatism in the SLT and globally appears to have been the Mid-Ordovician (470–455 Ma), although a good review and quantification of this large-scale flare-up 'event' on a global scale is still missing from the literature.

Summary and tectonic implications. The SLT consists primarily of a Mid-Ordovician island arc or a transitional magmatic arc and is dominated by andesitic calc-alkaline compositions. It is a fairly primitive arc petrographically, although isotopically it is more evolved than an arc with a mafic component derived from a depleted mantle. This arc was at least partially built on an earlier Ediacaran thin continental basement (Balintoni *et al.* 2014). The proximity to Gondwana is established by the presence of pre-latest Precambrian inherited and detrital zircons of the SLT previously studied by Balintoni *et al.* (2010). The exposed palaeo-arc consists primarily of volcanic and volcaniclastic sequences with some shallow plutons intruded into them, similar to the current exposures of many well-exposed younger accreted arcs, such as the Mesozoic Alisitos arc in Baja California (Busby *et al.* 2006), although in that example there is no thin continental crustal basement.

A sizable post-tectonic cover of the SLT is the Negovanu Unit, a large meta-sedimentary unit that lies unconformably above the Ordovician arc and is distinctly more mature isotopically, suggesting that the Ordovician arc was closer to a continental mass after its formation. Both the calc-alkaline arc and its sedimentary cover were metamorphosed to amphibolite facies during the Variscan orogeny (330–325 Ma) based on newly obtained garnet–whole-rock Sm–Nd ages, consistent with previously reported work (Medaris *et al.* 2003). Regionally extensive pegmatitic leucogranitic dykes with a syn-collisional, syn- to late tectonic origin were emplaced immediately after that metamorphic event (323–318 Ma). Some magmatism may be syn-collisional and may have led to the addition of granitic material concordant with the metamorphic fabric (Balintoni *et al.* 2009). There are a few larger plutons in the SLT that are synchronous with the Variscan metamorphism, but they are all located in ranges west of the Cibin and Lotru mountains (at Poniasca and Sichevita; Ducea, unpublished data). Variscan-age, Himalayan-type metamorphism is common throughout basement terranes of the Alps and Carpathians (von Raumer *et al.* 2013; Franke *et al.* 2017). However, we do not know from the South Carpathians perspective which larger continental mass the SLT arc collided with in the Variscan because no other block of that metamorphic age is preserved due to the Alpine fragmentation of these terranes.

The SLT collapsed extensionally between *c.* 320 and 280 Ma, as evidenced by coal-bearing Carboniferous continental cover rocks mixed with the rhyolitic volcanic rocks overlying its basement. It is part of the larger Basin and Range-like continental extension that affected many of the Variscan basement fragments elsewhere in Europe (Ménard and Molnar 1988). The SLT was not been buried to >6–7 km after the Permian (Merten *et al.* 2010; Ducea *et al.* 2016 and all references cited therein to young fission track and U–Th/He ages in the South Carpathians).

The SLT was further stitched with the Sibisel terrane, the location of which in present-day coordinates is to the north and east, during the Permian, as indicated by the Rb–Sr ages of the shear zone between the two terranes (290–240 Ma, poorly constrained age interval due to large errors; Ducea *et al.* 2016) and by one Ar–Ar age within the same shear zone (285 Ma; Dallmeyer *et al.* 1998). The long-known presence of late Permian, highly deformed sedimentary rocks in the shear zone at Valea lui Stan (Hann 1995 and references cited therein) is also consistent with a latest Paleozoic age (or younger) age for that shear zone.

The Sibisel terrane has a similar origin to the SLT, representing an island arc of latest Precambrian–Ordovician age, but has a different metamorphic history. The Sibisel terrane was metamorphosed to greenschist facies prior to the emplacement of undeformed granitoids at 466 Ma (Ducea *et al.* 2016). This metamorphic event was most likely synchronous with the development of an island arc. The Permian collisional suture known as Sibisel shear zone is only locally preserved (Pană and Erdmer 1994) because it was reactivated in most places by brittle Alpine faults. This was a soft collisional event producing no additional high-grade metamorphism in the SLT. The SLT was the upper plate of that system, but was characterized by a thick zone (1–3 km) of compressional and lateral ductile deformation affecting both units (Hann 1995; Ducea *et al.* 2016). At the time of collision, the currently exposed levels of the SLT were probably above (more shallow than) the brittle–ductile transition in the crust, as evidenced by the hornblende–muscovite and biotite Ar–Ar spectra of the rocks of the SLT (Dallmeyer *et al.* 1998). However, it was not at the surface because no Permian sedimentary rocks are known to cover the SLT in the Cibin or Lotru mountains.

The Sibisel SLT soft collisional event is the latest terrane docking/assembly event known in the pre-Alpine (pre-Jurassic) Carpathians and could possibly locally represent the closure of the Palaeotethys Ocean. The Cataracte leucrogranite (258.3 ± 2.5 Ma; Ducea *et al.* 2022) is synchronous with this latest pre-Alpine collisional event and the author suggests that there may be a link between the two. There are *c.* 30 km in a straight line between Cataracte and the type locality of the Sibisel shear zone at Rasinari, with the leucogranite being located in the upper plate. The age of the Cataracte leucogranite provides a tighter constraint for this latest terrane assembly event than previous data (Rb–Sr and Ar–Ar dates and the age of unmetamorphosed sedimentary rocks in the shear zone), which were subject to larger errors (Dallmeyer *et al.* 1998; Ducea *et al.* 2016).

In conclusion, the SLT is a juvenile arc terrane built over *c.* 150 Myr along the long-lived subduction margin of Gondwana (Stampfli *et al.* 2011). There is no basement older than Ediacaran in the SLT, but inherited zircon ages suggest that the SLT was close to the modern-day NE African part of Gondwana. The SLT has an average andesitic composition and is covered by a post-tectonic sequence of continentally derived passive margin sediments, probably from Gondwana. Docking to a larger continental mass took place *c.* 100 Myr after peri-Gondwana subduction ended and resulted in Variscan amphibolite facies metamorphism of the entire sequence between 345 and 320 Ma. The sedimentary cover of these arcs suggests that the docking was between these juvenile arcs and NE Africa, not with Baltica, as may be hypothesized by analogy with similar European terranes (von Raumer *et al.* 2013). Syn-collisional magmatism is represented by small, but ubiquitous, leucogranitic ('pegmatitic') veins. Juxtaposition against the Sibisel assemblage, a terrane with a similar peri-Gondwanan origin, but only pre-Variscan, low-grade metamorphism (Ducea *et al.* 2016), took place during the latest Permian, possibly marking the closure of the Palaeotethys Ocean.

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

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