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Key Points:

- Major ductile shear zone delimitates two arc terranes in the Carpathians
- Terrane accretion extended until well after the Variscan (Carboniferous age) mega collision in eastern Europe
- The shear zone is a paleosuture

Supporting Information:

- Supporting Information S1

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Evolution of the Sibișel Shear Zone (South Carpathians): A study of its type locality near Rășinari (Romania) and tectonic implications

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Abstract The Sibișel Shear Zone is a 1–3 km wide, ductile shear zone located in the South Carpathian Mountains, Romania. In the Rășinari area, the ductile shear zone juxtaposes amphibolite facies rocks of the Lotru Metamorphic Suite against greenschist facies rocks of the Râușorul Cislădioarei Formation. The first represents the eroded remnants of Peri-Gondwanan arcs formed between the Neoproterozoic–Silurian (650–430 Ma), regionally metamorphosed to amphibolite facies during the Variscan orogeny (350–320 Ma). The second is composed of metasedimentary and metavolcanic Neoproterozoic–Ordovician (700–497 Ma) assemblages of mafic to intermediate bulk composition also resembling an island arc metamorphosed during the Ordovician (prior to ~463 Ma). Between these lie the epidote amphibolite facies mylonitic and ultramylonitic rocks of the Sibișel Formation, a tectonic mélange dominated by mafic actinolite schists attenuated into a high strain ductile shear zone. Mineral Rb–Sr isochrons document the time of juxtaposition of the three domains during the Permian to Early Triassic (~290–240 Ma). Ductile shear sense indicators suggest a right lateral transpressive mechanism of juxtaposition; the Sibișel shear zone is a remnant Permo-Triassic suture between two Early Paleozoic Gondwanan terranes. A zircon and apatite U–Th/He age transect across the shear zone yields Alpine ages (54–90 Ma apatite and 98–122 Ma zircon); these data demonstrate that the exposed rocks were not subjected to Alpine ductile deformation. Our results have significant implications for the assembly of Gondwanan terranes and their docking to Baltica during Pangea's formation. Arc terranes free of Variscan metamorphism existed until the Early Triassic, emphasizing the complex tectonics of terrane amalgamation during the closure of Paleotethys.

1. Introduction

The variably metamorphosed basement exposures of the Carpathians record the long-term evolution of a Peri-Gondwanan convergent margin from the Neoproterozoic to the Early Paleozoic [Balintoni *et al.*, 2014], followed by a continental assembly period during the Variscan orogeny [Drăgușanu and Tanaka, 1999; Medaris *et al.*, 2003], the extensional collapse of the Variscan collisional orogen [Dallmeyer *et al.*, 1998], and its subsequent dismemberment and incorporation into Alpine structures [Burchfiel, 1980; Săndulescu, 1984; Schmid *et al.*, 2008]. Within each basement unit, there is an archive of magmatism, sedimentation, and metamorphism predating Alpine orogenic events that to a first order represent the building blocks of the central-eastern European crust, which is a relatively young block of Earth's continental mass.

There are several well-defined, large-scale, mostly steeply dipping, pre-Alpine ductile shear zones mapped within the Romanian Carpathians basement terranes [Pană and Erdmer, 1994]. These structures bounding various basement domains have received little attention in modern geologic research beyond the description of their location and origin [Pană and Erdmer, 1994]. Regardless of their origin, these shear zones are comparable in magnitude (widths of several kilometers) to midcrustal exposures of other large strike-slip systems around the world, and some could represent former sutures or other types of exhumed paleoplate boundaries.

Our study includes microstructural, geochronologic/thermochronologic, geochemical, and isotopic data from the Sibișel Shear Zone. We show that the Sibișel Shear Zone accommodated Permo-Triassic dextral oblique deformation and that this structure is the boundary between two Cambro-Ordovician basement domains of similar origin that evolved independently through the Variscan orogeny (Silurian–Carboniferous) until being juxtaposed by the shear zone near the end of the Permian. One of these

Figure 1. Regional map of Carpathians in central-eastern Europe showing the principal areas of exposure of pre-Alpine basement in pink [after Kounov et al., 2012]; the three main segments of the Romanian Carpathians are also identified, as well as the location of Figure 2.

within the Sibişel Shear Zone near the village of Răşinari in the northern part of the South Carpathians (Romania) (Figure 1), and to characterize the geologic history of the units exhumed by the Sibişel Shear Zone. The assembly of basement terranes in the Carpathians and nearby orogens is difficult to sort out because most of the pre-Alpine (pre-Jurassic) contacts have been significantly reactivated by Mesozoic and younger tectonism that are ultimately responsible for the development of the modern mountain ranges in Europe. The Răşinari segment of the Sibişel Shear Zone is a rare and thus important regional basement contact not dismembered by younger faults and contains three distinctive units, including a mafic core [Codarcea-Dessila, 1965]. This observation is based on the fact that a major Alpine structure which reactivates much of the Sibişel Shear Zone elsewhere does not extend into the Răşinari area (Geologic Map of Romania, Sheet L-35-73-C, Sibiu, 1:50,000, Geologic Institute of Romania, 1975). Therefore, the major aim of this study is to contribute geologic and geochronologic data capable of sorting out the pre-Alpine deformational history of this important area of central-eastern European peri-Gondwanan geology.

2. Geologic Background

The Romanian segment of the Carpathian Mountain belt is a fold and thrust belt that was assembled during the Alpine Orogeny (mid-Jurassic to late Cenozoic) and extends along the East and South Carpathians. It includes cover units and basement blocks [Schmid et al., 2008] that were formed and metamorphosed during the Cadomian (Late Precambrian), Caledonian (Cambro-Devonian), and Variscan (Late Paleozoic) orogenic cycles [Schmid et al. [2008], Săndulescu [1984], and Balintoni et al. [2014] for regional review papers). Many of the thrust sheets of the Romanian Carpathians contain basement (metamorphosed, pre-Triassic rocks); most thrust sheets in the South Carpathians are dominated by basement units. Figure 1 shows the distribution of the major basement units in central and eastern Europe, with the location of the study area. Large-scale rotations in the Cenozoic [e.g., Balla, 1987; Pătraşcu et al., 1994; Dupont-Nivet et al., 2005] and various strike-slip faults [e.g., Ratschbacher et al., 1993; Ducea and Roban, 2016] led to the extreme modern oroclinal bending of various strands of the Carpathians and to the fragmentation of various basement blocks, making difficult their correlation and study in a pre-Alpine configuration. Most contacts between basement units in the Carpathians are tectonic and Mesozoic or younger in age, although in many cases they reactivate earlier structures.

domains was a Latest Precambrian–Lower Paleozoic arc [Balintoni et al., 2010a] regionally metamorphosed during a Himalayan-style Variscan collisional event, while the other consists of low-grade metasedimentary and meta-volcanic rocks, intruded by Ordovician granitoid lenses. We also show that mafic rocks with geochemical affinities and isotopic ratios indicative of an island arc or back-arc origin are located between the two crustal blocks and have been deformed and metamorphosed to epidote amphibolite facies [Codarcea-Dessila, 1965, Codarcea-Dessila et al., 1968]. The fault zone was reactivated as a minor brittle oblique strike-slip fault during the mid-Cretaceous. These results have significant implications for the tectonic evolution of metamorphic terrains in the Carpathians.

The main objective of this study is to establish the age and kinematics of the ductile deformation that took place

The South Carpathians Mesozoic thrust sheets contain large proportions of metamorphosed basement and lesser amounts of Late Paleozoic cover rocks. Approximately 80% of the exposed geology [Codarcea-Dessila *et al.*, 1968] (several 1:200,000 geologic map sheets published during the 1960s and 1970s by the Geological Institute of Romania) comprises such rocks; this observation combined with outstanding exposures in the glaciated high parts of the range make this segment of the Carpathians the most obvious choice for the study of regional pre-Alpine geology. Alpine regional metamorphism has not been identified in Romania, except for low-grade subduction-type prehnite-pumpellyite domains in the South Carpathians which occurred during the closure of the Ceahlău-Severin Ocean and collision of Dacia (upper plate) with Moesia (lower plate) in the mid-Cretaceous [Ciulavu *et al.*, 2008]. In the South Carpathians, Dacia continental rocks make up the *Getic-Supragetic nappes* (thrust sheets), whereas Moesia is exposed as the lower plate of this Cretaceous subduction system represented in the South Carpathians by the *Danubian nappes*. The Supragetic nappe system was thrust over the Getic nappe system during the mid-Cretaceous [Streckeisen, 1934; Iancu *et al.*, 2005]. The suture marking the mid-Cretaceous closure of the above mentioned Ceahlău-Severin Ocean and the ensuing continental collision between Dacia and Moesia is marked by the discontinuous presence throughout the western part of the South Carpathians of an ophiolitic mélange locally named the Severin nappe [Iancu *et al.* [2005] for a review].

The N-S trending (present day coordinates) Sibișel shear zone in a broad sense is located close to the boundary between the Alpine Getic and Supragetic nappes (Figure 2). Historically, the Cretaceous Getic-Supragetic structural boundary is broadly defined “fault zone” located within the N-S trending units immediately west of the Olt River. The Sibișel Shear zone’s main strand runs along the western side of the river Olt (Figure 2) [Codarcea-Dessila, 1965; Hann, 1995], which primarily comprises a mylonitic and ultramylonitic mafic (amphibole-bearing) complex interpreted as metamorphosed ophiolites [Codarcea-Dessila, 1965]. Along with amphibole-rich mafic rocks, the Sibișel Formation also contains mylonitic metacarbonate rocks (marbles), epidote-grade quartzo-feldspathic metamorphic rocks, and graphite schists. Most of these nonmafic lithologies are discontinuous along strike (Figure 2).

The Rășinari segment of the Sibișel Shear Zone is close to the northern edge of the central South Carpathians and appears to be left laterally offset from the main path of the shear zone by a recent brittle fault; the fault is not mapped in Figure 2 (Ducea, unpublished mapping). This is the area where the Sibișel Formation was first described as a mylonitic unit [Codarcea-Dessila, 1965]. A west-east oriented strand of ductile shear zone west of Sibiu has been interpreted as part of the Sibișel shear zone, giving an arcuate shape for its total exposure within the South Carpathians [Pană and Erdmer, 1994]. That segment has received far less attention, and it is difficult to evaluate whether it is or not part of the same structure.

The Sibișel Shear Zone is defined in this paper as the tract of ductile deformation along the western side of Olt River and its continuation to the north at Rășinari (Figure 2). Mafic assemblages are common but are not found everywhere along the structure. Overall, the area west of the Olt River is more complex due to numerous brittle faults that juxtaposed several long slivers of metamorphic basement rocks (Figure 2) [Hann, 1995] in a structural style indicative of a flower structure formed along a transpressive strike-slip fault [Ducea and Roban, 2016]. The temperatures of deformation are most likely at 400–500°C, based on the fact that these rocks are dominated by feldspar and have ductile fabrics, yet they do not contain high temperature metamorphic assemblages [Codarcea-Dessila, 1965]. Brittle deformation is loosely constrained to be mid-Cretaceous to Late Cretaceous and has been classically interpreted as the Getic-Supragetic thrust contact, in Carpathian geology [Streckeisen 1934] and many researchers after). More recently, it has been reinterpreted as the location of a mid-Cretaceous STEP (subduction transform edge propagator fault) related to the closure of the Ceahlău-Severin Ocean [Ducea and Roban, 2016]. The brittle structures have been reactivated during the Cenozoic [Mațenco *et al.*, 1997] albeit as secondary features and some segments of the fault system continue to be active today [Onicescu *et al.*, 1999; Romanian National Institute for Earth Physics, real-time earthquake archives, <http://www1.infp.ro/realtime-archive>].

The spatial relationships between the ductile and brittle structures prompted Pană and Erdmer [1994] to suggest that perhaps the mylonitic deformation was Alpine, but very little quantitative thermochronologic data exist to resolve that. Dallmeyer *et al.* [1998] reported a Permian (288 Ma) Ar-Ar mica age from the Sibișel shear zone near Rășinari. Low-temperature thermochronologic ages, while not exactly targeting the fault systems west of Olt, suggest that regionally, the Getic/Supragetic blocks have not been exhumed more than a few

Figure 2. Simplified geological map of the Râșinari-Olt River Gorge area (modified and compiled after Codarcea-Dessila [1965], Dinică [1996, 1998], Gheorghian *et al.* [1975], Geologic Map of Romania, Sheet L-35-73-C, Sibiu, 1:50,000, Geologic Institute of Romania, 1975, Gheuca [1998], Hann [1995], and Săbău [1998]), showing the study area. The location of "Figure 4" is also showed in the map.

kilometers (~6 km) since the Cretaceous [e.g., *Merten et al.*, 2010]. These data suggest that the Cretaceous and younger structures are merely reactivating some sizable ductile pre-Alpine structures.

Figure 2 is a compilation geologic map of the Olt Valley area showing several metamorphic units affected by the Olt Valley fault system: the Lotru Metamorphic Suite, the Sibișel, Sadu, and the Râușorul Cislăcioarei Formations, and the Tălmăcel, Călinești, and the Moldoveanu and Argeș Units. The ages of these basement units are poorly constrained and are not ordered chronologically in the legend of Figure 2; limited regional data suggest that most metamorphic units of the Romanian Carpathians are late Precambrian-Silurian arc/back-arc terranes [*Balintoni et al.*, 2014]. The Lotru Metamorphic Suite (Sebeș-Lotru terrane, as defined by *Balintoni et al.* [2009], or the Sebeș-Lotru Formation of *Iancu et al.* [2005], among other names in the local literature) is the single largest basement block of the Getic-Supragetic nappe system in the South Carpathians. To the east of the Olt Valley corridor, the Moldoveanu and Argeș Units make up the bulk of the basement of the Făgăraș Mountains that is assigned tectonically to the Supragetic nappe [*Săndulescu*, 1988]. The Tălmăcel, Sadu, and Călinești Units crop out between these large basement domains forming a mosaic of basement slivers which we interpret to have been dragged along the right lateral Trans-Carpathian Fault System during the mid-Cretaceous [*Ducea and Roban*, 2016].

The Lotru Metamorphic Suite [*Săbău and Massonne*, 2003] was studied petrologically (including quantitative thermobarometry), and some ideas exist to explain its origin and tectonomagmatic evolution during the Paleozoic. The other units are not very extensive, and although their importance has been highlighted over the past 50 years in the local Romanian literature, there are no modern studies on them. Available igneous and detrital zircon U-Pb geochronology data for the Lotru Metamorphic Suite [*Balintoni et al.*, 2009, 2010a, 2014] suggest that it was a predominantly Ordovician arc possibly emplaced in an older (latest Proterozoic to Early Cambrian) basement also representing an arc. Detrital zircons from the Lotru Metamorphic Suite suggest a Peri-Gondwanan origin [*Balintoni et al.* [2014], for a review], like many terranes making up the basement of mobile Europe [*von Raumer et al.*, 2013]. The Lotru Metamorphic Suite includes Ordovician to Silurian island arc lithologies mixed with two mica schist representing cover units of the arc all of whom were unconformably covered by a metasedimentary unit of staurolite and garnet micaschists (locally known as the Negovanu schists) (M. N. Ducea et al., unpublished data, 2016). More than 70% of the zircons recovered from various Lotru Metamorphic Suite lithologies are 460–470 Ma old, an age concentration that is reflected also in detrital Cretaceous and younger sedimentary units from nearby basins [*Stoica et al.*, 2016]. A second main population of zircons from the Lotru Metamorphic Suite yielded ages around the Precambrian-Cambrian boundary (570–550 Ma). Since only very few metagneous assemblages may have crystallized at that time, most zircons of that age are likely inherited in younger plutons or detrital; consequently, it is still unclear if the mid-Ordovician arc developed on a Proterozoic-Cambrian basement or if those zircons were transported from a nearby continental region. The entire sequence was metamorphosed to amphibolite facies and locally granulite and eclogite facies (up to 1.5 GPa and 650°C) at 350–320 Ma [*Săbău and Massonne*, 2003; *Medaris et al.*, 2003] during the peak of Variscan collisional processes in central Europe. Based on mineral assemblages present in more common metapelitic rocks of this terrane, metamorphic conditions probably did not exceed 7–8 kbar and ~700°C [*Săbău and Massonne*, 2003]. Lotru rocks contain Variscan monazites [*Negulescu et al.*, 2014]. A garnet peridotite tectonically emplaced into the Lotru Metamorphic Suite not far from our study area at 316 Ma [*Medaris et al.*, 2003] was interpreted to signify the beginning of tectonic collapse and post-Variscan extension in this block and the incorporation of the lithospheric mantle block into the Lotru crust.

Metamorphosed mafic-ultramafic rocks of the Sibișel Formation have been interpreted as ophiolitic in origin [*Codârcea-Dessila*, 1965]; however, the lack of geochemical data precludes an unequivocal interpretation of the origin of these rocks. Its age and metamorphic history are unresolved. These mafic rocks are associated with a variety of metasedimentary rocks including marbles and graphitic schists. Although originally mapped by *Codârcea-Dessila* [1965] as a metamorphosed sequence with a resolvable stratigraphy, these lithologies are more likely mixed in a tectonic mélange dominated by mafic schists.

The low-grade Râușorul Cislăcioarei Formation to the east of the Sibișel Formation predominantly consists of chlorite and albite schists. Based on controversial palynological evidence, this unit has been interpreted as a Cambro-Ordovician volcanosedimentary sequence similar to other low-grade terrains in the Carpathians [*Codârcea-Dessila and Iliescu*, 1967; *Dimitrescu et al.*, 1990]. Although original interpretations (best

summarized in the Geologic Map of Romania, Sheet L-35-73-C, Sibiu, 1:50,000, Geologic Institute of Romania, 1975) favored peak metamorphic conditions at greenschist facies conditions in these rocks, more recent investigations interpret this low-grade metamorphism as retrograde. To our knowledge, there are no published quantitative data to constrain the origin of the Râușorul Cislădioarei Formation, although detrital zircon studies carried out on similar low-grade units (e.g., Tulgheș, in the East Carpathians) in other parts of the Carpathians have so far confirmed a Cambrian to Early Ordovician maximum depositional age [Balintoni *et al.*, 2010b], consistent with palynologic data. There are no geochronologic constraints onto the metamorphic ages of these low-grade units except that they cannot be Alpine—since Late Paleozoic sedimentary cover rocks sit unconformably over these rocks in some locations [Săndulescu, 1984].

The Sibișel Shear Zone affects the Sibișel Formation and extends a few hundred meters west and east into adjacent areas of the Lotru Metamorphic Suite and the Râușorul Cislădioarei Formation (Figure 2) [Codarcea-Dessila, 1965]. The Sibișel Shear Zone is the ductile structure “stitching” these three units. The Cretaceous and younger Trans-Carpathian Fault System [Ducea and Roban, 2016] dismembered some of the original contacts between the units. The Sibișel Shear Zone affecting the Sibișel Formation in a strict sense and its two adjacent units is best exposed immediately south of Rășinari.

3. The Rășinari Section

South of Rășinari (Figure 2), the Sibișel Shear Zone is exposed along the Sibișel valley and neighboring ridges in its type locality. From west to east, the Lotru Metamorphic Suite, Sibișel Formation, and Râușorul Cislădioarei Formation are all sheared and mylonitized. The Lotru Metamorphic Suite is the most extensive unit; it is affected by a steeply dipping ($\sim 70^\circ$ NE) foliation in the shear zone that continues westward into the Lotru Metamorphic Suite rocks proper for up to 800 m that changes into more gently dipping foliations ($\sim 30^\circ$ NE) that characterize the domal structure of the Lotru Metamorphic Suite (not pictured). At its contact with the Râușorul Cislădioarei Formation, the Sibișel shear zone exhibits similar pattern of transition from highly sheared ultramylonite to less deformed rocks. Our studied section is confined to the areas between Steaza Valley and the area just north of Râul Sadului. Some structural complexities shown on the compiled geologic map (Figure 2) are likely due to Alpine reactivations of faults that have not been addressed in this study.

The Lotru Metamorphic Suite consists mostly of orthogneisses and amphibolites with lesser amounts of paragneisses and two mica schists, although the metasedimentary assemblages (paragneisses especially) dominate near the shear zone. Staurolite, sillimanite, and/or kyanite and garnet indicate upper amphibolite facies metamorphic conditions with very limited evidence for retrogression. The alternation of several of these lithologies within a single outcrop is suggestive of a metamorphic volcanosedimentary sequence. Several distinctive horizons of banded and/or augen gneisses run subparallel to the strike of the foliation. Coarser grained lenses of less deformed pegmatites are also common in the Lotru Metamorphic Suite in this area, none of which was well exposed near the contact with the Sibișel shear zone.

The Sibișel Formation is predominantly mafic and also contains metacarbonates, epidote, sericite, and albite schists and graphitic schists in what appears to be a succession without any stratigraphic order. The mafic assemblages are mostly actinolite schists and amphibolites. Various metasedimentary units appear to pinch and swell in a mafic matrix. The entire sequence was subject to epidote amphibolite facies peak conditions, and no garnet is present in the mafic rocks. Chlorite and albite are common. The entire formation is highly attenuated (thickness reduced by shearing) and is overprinted by mylonitic to ultramylonitic fabrics. We interpret this unit to be a tectonic mélange. The best exposures of the Sibișel Formation in the shear zone come from a large quarry near the mouth of Valea Muntelui, a small Sibișel River tributary; most of the samples were collected from that quarry or its immediate neighboring area (Figure 3).

The Râușorul Cislădioarei Formation is a distinctive greenschist facies sequence made predominantly of chlorite and albite schists, with a monotonous dark grey appearance. The formation is best exposed in the Râușorul Cislădioarei Creek (hence its name). Small (50–200 m long) leucocratic granitic lenses with no apparent metamorphic fabrics cross cut the greenschist rocks. These igneous lenses were inferred based on their lack of metamorphism to be Mesozoic [Codarcea-Dessila, 1965]; we sampled these granitoid lenses in order to determine their emplacement age.

Figure 3. Structures and microstructures from the Sibişel Shear Zone. Steeply dipping foliations in (a) chlorite and albite schist, (b) actinolite schist, and (c) quartz-rich paragneiss; (d) shear sense indicator in mafic ultramylonite (sample C4); (e and f) photomicrographs (cross polars) of kinematic indicators showing dextral ductile deformation in samples VC02 and VC17.

Although the contacts between the three units are not exposed, they can be reasonably inferred. Various brittle reverse and normal faults that are offsetting the three lithologic units described here have been mapped on our compilation map (Figure 2). We only some of these brittle faults mapped by us or determined previously (Geologic Map of Romania, Sheet L-35-73-C, Sibiu, 1:50,000, Geologic Institute of Romania, 1975) in order to keep the map legible. Small outcrops of Albian-Aptian conglomeratic and carbonaceous overlaying the Răușorul Cislădioarei Formation appear to be fault bounded. Some crosscutting faults are clearly minor and are probably young range-bounding normal faults. There is no reason for us to infer that significant reverse or thrust faults are displacing the Sibişel shear architecture at this particular location.

4. Samples and Methods

A total of 45 samples were collected from all lithologies within the shear zone as well as from outside of the highly deformed corridor, for petrographic, geochemical, and geochronological analyses. We measured the orientation of foliations and stretching lineations, and we analyzed shear sense indicators in the field. Eighteen fresh samples from all three groups were selected based on their key location with respect to the shear zone for geochemical (whole rock major and trace element analyses) and isotopic work. Location, assigned metamorphic units, and a brief petrographic description of these samples are given Table 1. A more detailed description of these samples including their mineral modes and the presence of secondary features is given in supporting information Table S1.

U-Pb zircon dating was carried out for three samples from the Lotru Metamorphic Suite, two samples from the Răușorul Cislădioarei Formation, and one igneous sample from a granitoid found in the Răușorul Cislădioarei Formation. Measurements were carried out at the Laserchron facility at the University of Arizona [Gehrels *et al.*, 2008] following routine separation procedures. Whole rock major and trace elemental analyses were performed on 11 samples, principally focusing on the Sibişel Formation mafic rocks, at the University of Arizona following the procedures in Rossel *et al.* [2013]. Whole rock Sr and Nd isotopes were measured on 16 samples at the Arizona TIMS laboratory. The analytical procedures followed Otamendi *et al.* [2009] and Drew *et al.* [2009]. A subset of five samples was further selected for mineral Rb-Sr thermochronology; analytical procedures are as in Toljić *et al.* [2013]. Three of these samples are from the Lotru

Table 1. Sample Locations and Brief Description^a

Unit and Sample Name	Mineralogy	Latitude	Longitude
<i>Sibişel Formation</i>			
Mafic unit	Chl-Ep-Tr-Qtz-Ab-Ms		
C2		45°41'09.5000"	024°03'04.5000"
C3		45°41'10.0000"	024°03'05.1800"
C4		45°41'09.2100"	024°03'03.4300"
VC16		45°41'30.7800"	024°03'04.8000"
Metasedimentary	Chl-Ab-Qtz-Ms		
VC01		45°41'40.6799"	024°03'26.5201"
C1		45°41'09.8400"	024°03'07.3800"
	Qtz-Kfs-Ms-Chl-Zo		
VC08		45°41'35.4001"	024°03'12.4200"
VC11		45°41'33.3600"	024°03'08.5201"
VC19		45°41'16.9800"	024°03'05.0400"
<i>Ausorul Cisanadioarei Formation</i>			
Metagreywacke	Qtz-Ab-Chl-Ep		
P05-1		45°41'07.0800"	024°04'20.7000"
P05-2		45°41'11.1000"	024°04'22.3200"
Leucogranite	Qtz-Kfs-Plg-Bi		
MMO1		45°40'45.4764"	024°04'21.7992"
<i>Lotru Metamorphic Suite</i>			
Two mica gneiss	Qtz-Kfs-Bt-Ms-Tur		
VP09		45°41'06.4200"	024°03'03.4800"
VP04		45°41'05.3401"	024°02'26.5200"
VS01		45°42'16.2000"	024°01'27.1200"
VS03		45°42'24.0001"	024°01'16.0799"
C5		45°41'08.4600"	024°03'02.5100"

^aMineral abbreviations after *Whitney and Evans* [2010].

Metamorphic Suite and two from the Sibişel Formation. Minerals that were believed to yield a good spread on two point Rb-Sr isochrons with the whole rocks were separated using a Dremmel milling tool and using a Micromill instrument [see *Ducea et al.*, 2003]; both of these were equipped with Brassler burrs.

Eight samples were also collected for zircon and apatite U-Th/He chronometry along a vertical profile cutting across the Sibişel Shear Zone at Răşinari (location of these samples and geochronological data are given in

Figure 4. Geologic map of the Răşinari section of the Sibişel Shear zone showing sample locations, mineral foliation, and lineation trends within the shear zone and their lower hemisphere stereographic projection showing Fisher Mean Vector and contours using Stereonet [Allmendinger et al., 2013]. About 40 individual measurements are plotted on the Stereonet.

Table 2. U-Pb Geochronologic Analyses

Analysis	U	206Pb	U/Th	206Pb*	±	Isotope Ratios				Apparent Ages (Ma)				Best age	±	Conc
						207Pb*	±	206Pb*	±	error	206Pb*	±	207Pb*	±		
T-Grain Tip, C-Grain Core	(ppm)	204Pb		207Pb*	(%)	235U*	(%)	238U	(%)	corr.	238U*	(Ma)	235U	(Ma)	(Ma)	(%)
<i>Sample VS01</i>																
LP-VS01-20C	194	7016	11.8	17.5330	2.4	0.5425	2.6	0.0690	1.0	0.40	430.0	4.3	440.1	9.4	492.9	87.2
LP-VS01-22C	196	49144	9.1	17.5216	2.4	0.5557	3.2	0.0706	2.2	0.67	439.9	9.2	448.8	11.7	494.3	89.0
LP-VS01-21 T	235	76141	5.0	18.0913	2.0	0.5575	2.8	0.0732	2.0	0.71	455.1	8.9	449.9	10.3	423.4	107.5
LP-VS01-13 T	387	77009	84.6	17.6838	1.7	0.5704	2.6	0.0732	1.9	0.75	455.2	8.6	458.3	9.6	474.0	96.0
LP-VS01-1 T	720	187505	141.7	17.7966	1.1	0.5669	1.6	0.0732	1.2	0.74	455.3	5.3	456.0	5.9	459.9	99.0
LP-VS01-22 T	267	59074	9.6	17.5722	1.4	0.5779	1.8	0.0737	1.2	0.65	458.1	5.2	463.1	6.7	487.9	93.9
LP-VS01-10 T	383	57389	56.5	17.7512	1.1	0.5761	1.8	0.0742	1.4	0.79	461.3	6.2	462.0	6.5	465.6	99.1
LP-VS01-6C	215	48786	3.3	17.9550	2.6	0.5707	2.9	0.0743	1.3	0.43	462.1	5.6	458.5	10.8	440.2	105.0
LP-VS01-20 T	490	14394	33.2	17.4662	0.9	0.5908	1.4	0.0748	1.0	0.76	465.3	4.6	471.4	5.1	491.3	92.8
LP-VS01-21C	98	28587	4.4	18.9473	7.3	0.5466	7.5	0.0751	1.8	0.24	466.9	8.0	442.8	27.0	319.2	146.2
LP-VS01-19C	780	200643	9.3	17.7403	0.7	0.5854	1.1	0.0753	0.8	0.79	468.2	3.8	467.9	4.0	466.9	100.3
LP-VS01-7 T	409	3163	8.4	17.4615	4.5	0.5949	4.8	0.0753	1.4	0.30	468.3	6.4	474.0	18.0	501.9	93.3
LP-VS01-4C	153	29742	4.2	17.3769	3.4	0.5980	5.0	0.0754	3.6	0.73	468.4	16.3	475.9	18.9	512.6	91.4
LP-VS01-12C	688	37748	2.0	17.6977	0.8	0.5895	2.4	0.0757	2.3	0.95	470.2	10.5	470.5	9.2	472.2	99.6
LP-VS01-11 T	345	98955	9.3	17.6183	1.7	0.5938	2.0	0.0759	1.1	0.54	471.4	4.9	473.3	7.7	482.2	97.8
LP-VS01-6 T	370	206780	6.8	17.4343	0.8	0.6072	1.8	0.0768	1.6	0.88	476.9	7.3	481.8	6.9	505.3	94.4
LP-VS01-3 T	317	116099	2.3	17.2654	2.1	0.6313	3.1	0.0790	2.2	0.73	490.4	10.5	496.9	12.0	526.7	93.1
LP-VS01-7C	107	3446	2.2	16.4921	6.7	0.6613	7.4	0.0791	3.3	0.45	490.7	15.7	515.4	30.1	626.3	78.4
LP-VS01-23 T	596	70075	121.5	17.6460	0.4	0.6214	2.2	0.0795	2.2	0.98	493.3	10.4	490.7	8.7	478.7	103.1
LP-VS01-4 T	128	193619	2.4	17.3271	3.9	0.6415	4.2	0.0806	1.6	0.39	499.8	7.9	503.3	16.8	518.9	96.3
LP-VS01-24C	758	6843	1.6	16.4988	1.5	0.6950	5.6	0.0832	5.4	0.96	515.0	26.7	535.8	23.3	625.4	82.3
LP-VS01-19 T	566	4987	17.3	17.1459	5.4	0.6718	6.2	0.0835	3.1	0.50	517.2	15.5	521.8	25.5	541.9	95.4
LP-VS01-15 T	231	47263	7.6	16.5781	1.6	0.7118	3.1	0.0856	2.6	0.85	529.4	13.4	545.8	13.0	615.1	86.1
LP-VS01-8 T	317	101188	8.3	17.1446	1.6	0.6969	4.1	0.0867	3.8	0.92	535.8	19.5	537.0	17.2	542.1	98.8
LP-VS01-23C	386	21174	2.6	16.7003	1.8	0.7272	2.7	0.0881	2.0	0.75	544.2	10.5	554.9	11.5	599.2	90.8
LP-VS01-11C	871	51456	1.9	16.5940	0.7	0.7498	2.0	0.0902	1.9	0.93	556.9	9.9	568.1	8.7	613.0	90.9
LP-VS01-9 T	966	62129	14.6	16.7622	0.4	0.7450	1.3	0.0906	1.3	0.95	558.9	6.8	565.3	5.8	591.2	94.5
LP-VS01-24 T	543	133404	2.7	16.7783	1.2	0.7612	3.4	0.0926	3.1	0.93	571.1	17.0	574.7	14.7	589.1	96.9
LP-VS01-16 T	461	191585	32.5	15.4436	3.2	0.8364	4.5	0.0937	3.1	0.70	577.3	17.3	617.1	20.6	766.3	75.3
LP-VS01-5 T	410	130196	1.0	16.5934	1.0	0.7809	3.0	0.0940	2.8	0.94	579.0	15.6	586.0	13.3	613.1	94.4
LP-VS01-17 T	549	179628	100.4	16.5620	1.2	0.7861	2.5	0.0944	2.2	0.88	581.6	12.2	589.0	11.2	617.2	94.2
LP-VS01-3C	208	67232	0.8	16.4203	2.1	0.7960	2.6	0.0948	1.4	0.56	583.9	8.0	594.6	11.5	635.7	91.8
LP-VS01-9C	862	653009	13.9	16.5297	0.7	0.7996	2.8	0.0959	2.8	0.97	590.1	15.5	596.6	12.8	621.4	95.0
LP-VS01-8C	205	96655	4.6	16.5145	2.4	0.8099	3.1	0.0970	2.0	0.65	596.9	11.6	602.4	14.2	623.4	95.7
LP-VS01-5C	770	422218	1.1	16.4547	0.7	0.8239	2.0	0.0983	1.9	0.94	604.6	10.9	610.2	9.2	631.2	95.8
LP-VS01-2C	608	52992	3.7	16.3732	0.9	0.8489	2.7	0.1008	2.5	0.94	619.2	15.0	624.1	12.6	641.9	96.5
LP-VS01-10C	73	14093	0.7	16.5645	5.4	0.8551	6.4	0.1027	3.5	0.55	630.4	21.0	627.5	30.0	616.8	102.2
LP-VS01-2 T	557	311591	6.0	16.1775	0.5	0.8880	1.6	0.1042	1.5	0.95	638.9	9.1	645.3	7.5	667.7	95.7
LP-VS01-13C	381	103339	1.1	16.2204	1.3	0.8961	3.8	0.1054	3.5	0.94	646.1	21.7	649.6	18.1	662.0	97.6
LP-VS01-1C	527	187764	5.3	15.5974	1.5	0.9334	4.0	0.1056	3.7	0.92	647.1	22.6	669.4	19.5	745.3	86.8
LP-VS01-17C	915	62770	2.2	16.1165	0.4	0.9133	1.9	0.1068	1.9	0.98	653.9	11.7	658.8	9.4	675.8	96.8
LP-VS01-18 T	353	120740	6.6	15.8313	1.1	0.9666	2.2	0.1110	1.9	0.87	678.5	12.4	686.7	11.1	713.8	95.0
LP-VS01-14C	1222	307111	4.1	15.0319	2.9	1.0292	8.5	0.1122	7.9	0.94	685.5	51.7	718.5	43.5	823.0	83.3
LP-VS01-15C	139	64849	3.4	15.5175	2.6	1.0591	3.2	0.1192	1.9	0.60	725.9	13.2	733.4	16.8	756.2	96.0

Table 2. (continued)

Analysis	U	206Pb	U/Th	206Pb*	±	207Pb*	±	238U	206Pb*	±	error	206Pb*	±	207Pb*	±	206Pb*	±	Best age	±	Conc
T-Grain Tip, C-Grain Core																				
		204Pb				235U*		(%)			(%)	238U		(%)		235U		(Ma)		(%)
Sample P05-01																				
LP-VS01-18C	302	137140	4.5	15.2250	0.9	1.1682	1.8	0.1290	1.6	0.88	782.1	11.8	785.8	10.0	796.2	18.0	782.1	11.8	98.2	
LP-VS01-14T	577	303950	3.2	14.8889	1.1	1.2449	5.0	0.1344	4.8	0.97	813.1	36.8	821.1	27.9	842.9	23.2	813.1	36.8	96.5	
LP-VS01-16C	507	529974	2.6	13.7551	0.5	1.5996	1.4	0.1596	1.3	0.93	954.4	11.3	970.1	8.5	1005.6	9.8	1005.6	9.8	94.9	
Sample P05-01																				
LP-PO5-1-3C	104	39556	2.5	17.2623	5.3	0.6639	6.2	0.0831	3.1	0.50	514.7	15.2	517.0	25.0	527.1	117.2	514.7	15.2	97.6	
LP-PO5-1-2T	271	78893	4.0	17.0804	1.6	0.6715	1.8	0.0832	0.8	0.46	515.1	4.2	521.6	7.5	550.3	35.7	515.1	4.2	93.6	
LP-PO5-1-7T	328	35230	5.6	16.8933	1.2	0.6838	7.7	0.0838	7.6	0.99	518.6	37.8	529.0	31.7	574.3	25.0	518.6	37.8	90.3	
LP-PO5-1-2C	77	18628	3.2	17.0502	5.9	0.6807	6.1	0.0842	1.5	0.25	521.0	7.7	527.2	25.2	554.2	129.4	521.0	7.7	94.0	
LP-PO5-1-12	143	84572	1.7	17.4623	2.4	0.6676	3.3	0.0846	2.2	0.66	523.2	10.9	519.3	13.3	501.8	53.9	523.2	10.9	104.3	
LP-PO5-1-1C	193	50370	2.6	17.4781	3.3	0.6675	5.3	0.0846	4.1	0.77	523.6	20.4	519.2	21.3	499.8	73.4	523.6	20.4	104.8	
LP-PO5-1-15	379	65660	1.8	17.0871	1.6	0.6830	2.1	0.0846	1.4	0.67	523.8	7.2	528.6	8.7	549.4	34.1	523.8	7.2	95.3	
LP-PO5-1-16	176	49640	1.6	17.3272	2.0	0.6736	2.2	0.0847	0.9	0.42	523.9	4.5	522.9	8.8	518.9	43.2	523.9	4.5	101.0	
LP-PO5-1-20	184	43189	1.8	17.1192	2.3	0.6848	2.8	0.0850	1.6	0.56	526.1	7.9	529.7	11.5	545.3	50.6	526.1	7.9	96.5	
LP-PO5-1-24	234	17594	3.2	16.8608	3.1	0.6986	4.0	0.0854	2.5	0.63	528.4	12.8	537.9	16.8	578.5	68.0	528.4	12.8	91.3	
LP-PO5-1-3T	136	50479	2.3	17.0435	2.5	0.6912	3.0	0.0854	1.6	0.55	528.5	8.2	533.5	12.3	555.0	54.1	528.5	8.2	95.2	
LP-PO5-1-1T	93	36203	2.9	16.5303	3.4	0.7154	4.3	0.0858	2.7	0.62	530.5	13.7	548.0	18.4	621.3	73.6	530.5	13.7	85.4	
LP-PO5-1-6C	108	25341	2.6	17.4016	3.3	0.6848	4.1	0.0864	2.4	0.59	534.4	12.3	529.7	16.8	509.4	72.5	534.4	12.3	104.9	
LP-PO5-1-6T	142	33628	2.8	17.1608	3.2	0.6947	3.9	0.0865	2.1	0.55	534.6	10.9	535.6	16.1	540.0	70.7	534.6	10.9	99.0	
LP-PO5-1-26	162	52217	2.2	17.3988	2.7	0.6882	3.5	0.0868	2.2	0.64	536.9	11.5	531.7	14.5	509.8	59.0	536.9	11.5	105.3	
LP-PO5-1-14	179	13949	2.2	17.3349	3.0	0.6922	3.4	0.0870	1.5	0.45	537.9	7.9	534.1	14.1	517.9	66.4	537.9	7.9	103.9	
LP-PO5-1-10	433	122057	4.1	17.2646	0.9	0.7013	1.5	0.0878	1.2	0.82	542.6	6.5	539.6	6.3	526.8	18.8	542.6	6.5	103.0	
LP-PO5-1-9	296	144821	2.1	17.2281	1.3	0.7028	2.2	0.0878	1.7	0.81	542.6	9.1	540.5	9.1	531.5	27.9	542.6	9.1	102.1	
LP-PO5-1-25	266	119655	3.7	17.0827	1.1	0.7127	2.3	0.0883	2.0	0.87	545.5	10.4	546.4	9.7	550.0	25.0	545.5	10.4	99.2	
LP-PO5-1-4T	135	38607	1.8	16.8368	1.9	0.7759	5.3	0.0947	4.9	0.93	583.5	27.3	583.1	23.3	581.5	42.2	583.5	27.3	100.3	
LP-PO5-1-22	218	114946	1.1	16.7294	1.9	0.7876	2.1	0.0956	0.9	0.44	588.3	5.3	589.8	9.6	595.4	41.8	588.3	5.3	98.8	
LP-PO5-1-17	288	47924	1.1	16.7674	1.5	0.7930	2.0	0.0964	1.3	0.64	593.5	7.3	592.9	9.0	590.5	33.5	593.5	7.3	100.5	
LP-PO5-1-23	208	109643	53.2	16.5774	1.5	0.8025	2.5	0.0965	2.0	0.81	593.8	11.3	598.2	11.2	615.2	31.6	593.8	11.3	96.5	
LP-PO5-1-8	137	35327	1.3	16.6902	2.9	0.8189	3.1	0.0991	1.2	0.37	609.3	6.7	607.4	14.2	600.5	62.5	609.3	6.7	101.5	
LP-PO5-1-7C	296	56285	35.1	16.7925	1.4	0.8152	2.0	0.0993	1.5	0.74	610.2	8.7	605.3	9.2	587.3	29.5	610.2	8.7	103.9	
LP-PO5-1-11	51	35239	2.5	16.6477	5.5	0.8386	6.0	0.1012	2.3	0.39	621.7	13.8	618.4	27.8	606.0	119.5	621.7	13.8	102.6	
LP-PO5-1-5C	96	54625	3.2	16.2018	3.7	0.8806	4.2	0.1035	2.1	0.49	634.8	12.4	641.3	20.1	664.5	79.1	634.8	12.4	95.5	
LP-PO5-1-5T	488	105104	1.9	16.5023	0.9	0.8657	2.1	0.1036	1.9	0.91	635.6	11.7	633.2	10.0	625.0	18.8	635.6	11.7	101.7	
Sample P05-02																				
LP-PO5-2-3T	551	1556	3.6	16.6832	2.5	0.5741	4.6	0.0695	3.9	0.84	432.9	16.2	460.7	17.1	601.4	54.7	432.9	16.2	72.0	
LP-PO5-2-10	353	27920	2.2	17.5688	1.9	0.6296	2.8	0.0802	2.2	0.76	497.4	10.3	495.8	11.2	488.4	40.9	497.4	10.3	101.9	
LP-PO5-2-6	201	63524	2.7	17.1379	2.2	0.6558	3.6	0.0815	2.9	0.80	505.2	14.1	512.1	14.5	542.9	47.1	505.2	14.1	93.0	
LP-PO5-2-4T	397	6127	4.9	16.9265	4.1	0.6642	6.0	0.0815	4.4	0.73	505.3	21.3	517.2	24.4	570.0	89.6	505.3	21.3	88.6	
LP-PO5-2-2C	168	79272	2.9	17.3615	2.8	0.6589	3.2	0.0830	1.6	0.50	513.8	7.9	513.9	13.0	514.5	61.6	513.8	7.9	99.9	
LP-PO5-2-1C	107	29133	1.6	17.6461	4.7	0.6486	5.2	0.0830	2.2	0.43	514.0	11.0	507.6	20.6	478.7	102.9	514.0	11.0	107.4	
LP-PO5-2-2T	134	60994	4.7	17.0849	3.5	0.6802	4.2	0.0843	2.3	0.55	521.6	11.5	526.9	17.1	549.7	75.8	521.6	11.5	94.9	
LP-PO5-2-1T	288	9913	0.9	17.1218	1.8	0.6802	2.4	0.0845	1.6	0.65	522.7	7.8	526.9	9.8	545.0	39.7	522.7	7.8	95.9	
LP-PO5-2-7	247	71991	3.9	17.2793	2.0	0.6969	2.4	0.0873	1.4	0.56	539.7	7.1	536.9	10.1	524.9	43.8	539.7	7.1	102.8	
LP-PO5-2-11	417	80189	1.1	16.7619	1.0	0.8010	2.2	0.0974	2.0	0.88	599.0	11.3	597.4	10.1	591.2	22.7	599.0	11.3	101.3	
LP-PO5-2-4	715	457519	2.3	16.2515	0.4	0.9020	1.2	0.1063	1.2	0.95	651.3	7.3	652.8	6.0	657.9	8.4	651.3	7.3	99.0	

Table 2. (continued)

Analysis	U	206Pb	U/Th	206Pb*	±	207Pb*	±	206Pb*	±	error	238U*	238U	±	207Pb*	±	Best age	±	Conc
T-Grain Tip, C-Grain Core																		
		204Pb		207Pb*	(%)	235U*	(%)	238U	(%)	corr.	238U*	(Ma)	±	235U	(Ma)	207Pb*	(Ma)	(%)
Sample VP09																		
LP-P05-2-9	365	22436	8.1	16.0327	1.2	0.9339	2.3	0.1086	1.9	0.85	664.6	12.2	669.7	11.2	686.9	25.8	664.6	12.2
LP-P05-2-35	466	51663	2.6	15.6768	1.1	0.9990	2.0	0.1136	1.7	0.84	693.5	11.2	703.3	10.3	734.6	23.7	693.5	11.2
LP-P05-2-3C	372	189745	1.9	15.4964	1.0	1.0673	1.7	0.1200	1.4	0.80	730.3	9.4	737.4	8.9	759.1	21.3	730.3	9.4
Sample VP04																		
LP-VP09-1-11T	2284	59675	81.0	18.5249	0.5	0.4132	2.3	0.0555	2.3	0.97	348.3	7.7	351.2	7.0	370.2	11.9	348.3	7.7
LP-VP09-1-12T	380	89498	212.6	18.3725	2.4	0.4188	2.6	0.0558	1.0	0.39	350.0	3.5	355.2	7.8	388.8	54.0	350.0	3.5
LP-VP09-1-8T	919	147386	61.9	18.4314	1.2	0.4245	2.3	0.0568	2.0	0.86	355.8	6.9	359.3	7.0	381.6	26.7	355.8	6.9
LP-VP09-1-9T	236	61055	11.3	17.6559	3.6	0.5620	5.9	0.0720	4.7	0.79	448.0	20.3	452.9	21.6	477.5	79.4	448.0	20.3
LP-VP09-1-7T	674	246466	2.8	17.7373	0.7	0.5599	1.9	0.0720	1.8	0.93	448.4	7.7	451.5	7.0	467.3	16.1	448.4	7.7
LP-VP09-1-6T	325	8419	7.8	17.7408	1.8	0.5676	3.5	0.0730	3.0	0.85	454.4	13.2	456.4	13.0	466.8	40.9	454.4	13.2
LP-VP09-1-11C	1380	5186	1.4	16.8818	2.7	0.6045	8.9	0.0740	8.5	0.95	460.3	37.8	480.1	34.2	575.8	59.6	460.3	37.8
LP-VP09-1-5C	556	182439	0.7	17.5876	0.6	0.6086	2.3	0.0776	2.2	0.97	481.9	10.4	482.7	8.9	486.0	12.8	481.9	10.4
LP-VP09-1-9C	336	56695	1.2	17.4586	1.4	0.6131	2.1	0.0776	1.6	0.76	482.0	7.4	485.5	8.2	502.3	30.4	482.0	7.4
LP-VP09-1-10T	409	7629	9.1	17.1504	2.2	0.6269	2.7	0.0780	1.6	0.58	484.1	7.4	494.2	10.7	541.3	48.7	484.1	7.4
LP-VP09-1-5T	514	82144	0.9	17.6430	1.4	0.6109	2.7	0.0782	2.3	0.85	485.2	10.7	484.1	10.4	479.1	31.9	485.2	10.7
LP-VP09-1-7C	890	13394	0.7	17.4725	1.9	0.6171	4.1	0.0782	3.7	0.89	485.4	17.2	488.0	16.0	500.5	41.6	485.4	17.2
LP-VP09-1-1C	1183	16783	6.8	13.0576	7.3	0.8297	8.9	0.0786	5.1	0.57	487.6	23.7	613.5	40.9	1110.4	146.0	487.6	23.7
LP-VP09-1-12C	332	82695	9.1	17.6602	1.8	0.6227	2.8	0.0798	2.1	0.75	494.7	9.8	491.6	10.7	476.9	40.5	494.7	9.8
LP-VP09-1-4T	678	39675	1.2	17.0381	1.3	0.7256	2.2	0.0897	1.7	0.81	553.5	9.3	554.0	9.2	555.7	27.4	553.5	9.3
LP-VP09-1-4C	807	276094	1.0	16.7951	0.4	0.7648	1.6	0.0932	1.5	0.96	574.2	8.3	576.8	6.9	586.9	9.6	574.2	8.3
LP-VP09-1-8C	245	122487	1.8	16.4053	2.3	0.8453	3.1	0.1006	2.0	0.67	617.8	12.0	622.1	14.3	637.7	49.2	617.8	12.0
LP-VP09-1-6C	192	41777	1.0	16.4526	2.9	0.8780	3.3	0.1048	1.6	0.49	642.3	10.0	639.9	15.8	631.5	62.4	642.3	10.0
LP-VP09-1-10C	1209	5721	3.9	15.3912	1.5	0.9774	4.2	0.1091	3.9	0.93	667.5	24.8	692.3	21.1	773.4	32.6	667.5	24.8
LP-VP09-1-2C	118	22900	1.0	8.4607	1.2	3.9506	2.8	0.2424	2.5	0.91	1399.3	31.5	1624.1	22.4	1929.1	21.0	1929.1	21.0
Sample VP04																		
LP-VP04-16T	423	1358	29.5	18.1934	5.0	0.3870	5.1	0.0511	1.1	0.22	321.1	3.6	332.2	14.4	410.8	110.8	321.1	3.6
LP-VP04-12T	221	32615	1226.4	19.2480	4.1	0.3801	4.7	0.0531	2.2	0.47	333.3	7.2	327.1	13.1	283.4	94.1	333.3	7.2
LP-VP04-2C	179	49239	4.4	17.6610	2.5	0.4951	3.3	0.0634	2.2	0.65	396.4	8.4	408.4	11.2	476.8	55.9	396.4	8.4
LP-VP04-4C	395	28586	1.7	17.8756	2.5	0.5298	4.2	0.0687	3.4	0.81	428.2	14.2	431.7	14.9	450.0	55.1	428.2	14.2
LP-VP04-7T	794	32537	38.4	17.6423	1.1	0.5471	1.7	0.0700	1.3	0.77	436.2	5.5	443.1	6.1	479.2	23.9	436.2	5.5
LP-VP04-8C	408	99682	2.7	17.6349	0.9	0.5572	2.0	0.0713	1.8	0.90	443.8	7.7	449.7	7.3	480.1	19.4	443.8	7.7
LP-VP04-8T	513	308416	8.1	17.6741	1.0	0.5590	1.5	0.0717	1.1	0.74	446.1	4.8	450.9	5.4	475.2	22.1	446.1	4.8
LP-VP04-14C	248	9338	2.9	17.2191	4.3	0.5802	5.0	0.0725	2.6	0.52	451.0	11.5	464.6	18.8	532.6	94.1	451.0	11.5
LP-VP04-1T	898	150457	14.4	17.6936	0.9	0.5661	1.9	0.0726	1.7	0.88	452.0	7.4	455.5	7.1	472.8	20.4	452.0	7.4
LP-VP04-11T	101	13856	4.2	18.3771	5.4	0.5480	5.7	0.0730	1.8	0.32	454.5	7.9	443.7	20.5	388.3	121.3	454.5	7.9
LP-VP04-11C	130	3583	4.0	17.1798	7.3	0.5879	7.7	0.0733	2.6	0.34	455.7	11.6	469.5	29.1	537.6	159.1	455.7	11.6
LP-VP04-14T	357	48245	4.6	17.7418	1.9	0.5704	2.2	0.0734	1.1	0.50	456.6	4.9	458.3	8.2	466.7	42.9	456.6	4.9
LP-VP04-13T	898	18245	32.3	17.5900	2.8	0.5787	2.2	0.0738	2.0	0.89	459.2	8.8	463.7	8.3	485.8	22.7	459.2	8.8
LP-VP04-19T	315	15339	3.6	17.5037	1.0	0.5821	3.3	0.0739	1.7	0.51	459.6	7.4	465.8	12.3	496.6	62.7	459.6	7.4
LP-VP04-12C	300	62006	3.7	17.5543	2.1	0.5812	2.4	0.0740	1.2	0.48	460.1	5.1	465.2	9.0	490.2	46.9	460.1	5.1
LP-VP04-15C	354	83966	6.3	17.9133	1.5	0.5712	2.7	0.0742	2.2	0.83	461.4	10.0	458.8	10.0	445.4	33.3	461.4	10.0
LP-VP04-3C	148	44091	2.5	17.4824	3.4	0.5855	3.6	0.0742	1.1	0.32	461.6	5.1	468.0	13.4	499.2	74.6	461.6	5.1
LP-VP04-6C	502	240837	3.4	17.7659	1.3	0.5777	2.0	0.0744	1.5	0.76	462.9	6.9	463.0	7.6	463.8	29.8	462.9	6.9
LP-VP04-18T	468	58886	9.6	17.5932	1.2	0.5846	2.4	0.0746	2.0	0.86	463.8	9.1	467.4	8.9	485.3	26.7	463.8	9.1
LP-VP04-13C	675	11931	1.3	17.7347	1.3	0.5818	1.6	0.0748	1.0	0.61	465.2	4.4	465.6	6.0	467.6	28.1	465.2	4.4

Table 2. (continued)

Analysis	U	206Pb	U/Th	206Pb*	±	207Pb*	±	235U*	(%)	238U	206Pb*	±	error	206Pb*	±	207Pb*	±	235U	(Ma)	207Pb*	(Ma)	±	Best age	±	Conc
T-Grain Tip, C-Grain Core	(ppm)	204Pb		207Pb*	(%)	235U*	(%)	238U	(%)	corr.	238U*	(Ma)		238U*	(Ma)	235U	(Ma)	207Pb*	(Ma)	±	(Ma)			(%)	
Sample MM01																									
G-6	275	39650	1.7	17.5352	3.3	0.5671	4.4	0.0721	2.9	0.66	448.9	12.8	456.1	16.3	492.6	73.7	448.9	12.8	91.1						
G-28	532	242855	7.7	17.6734	0.7	0.5628	3.1	0.0721	3.0	0.97	449.0	12.9	453.3	11.2	475.3	15.1	449.0	12.9	94.5						
G-7	367	70778	3.7	17.6972	2.8	0.5689	3.0	0.0730	1.1	0.35	454.4	4.6	457.3	11.0	472.3	62.0	454.4	4.6	96.2						
G-5	407	112192	1.5	17.8094	1.0	0.5678	2.9	0.0733	2.7	0.94	456.2	12.0	456.6	10.6	458.3	21.3	456.2	12.0	99.5						
G-10	256	57577	5.8	17.7662	3.0	0.5696	3.4	0.0734	1.6	0.46	456.6	6.9	457.8	12.5	463.7	66.7	456.6	6.9	98.5						
G-14	183	52785	2.1	17.7709	3.4	0.5707	3.7	0.0736	1.6	0.43	457.6	7.0	458.5	13.8	463.1	75.0	457.6	7.0	98.8						
G-3	291	197297	7.7	18.1542	2.9	0.5591	3.2	0.0736	1.4	0.44	457.9	6.3	450.9	11.7	415.6	64.3	457.9	6.3	110.2						
G-2	161	37401	4.0	17.6081	3.7	0.5787	5.2	0.0739	3.6	0.70	459.6	16.0	463.6	19.3	483.5	82.5	459.6	16.0	95.1						
G-9	273	130241	7.0	17.9309	2.0	0.5693	2.7	0.0740	1.8	0.65	460.4	7.8	457.5	9.9	443.2	45.5	460.4	7.8	103.9						
G-20	187	179837	2.6	17.8606	6.2	0.5719	6.2	0.0741	0.7	0.11	460.7	3.0	459.2	22.9	451.9	136.9	460.7	3.0	101.9						
G-13	581	17560	3.4	17.9891	2.3	0.5690	5.0	0.0742	4.5	0.89	461.6	19.8	457.4	18.4	436.0	50.7	461.6	19.8	105.9						
G-12	270	72500	8.1	17.8070	2.4	0.5757	2.5	0.0743	0.6	0.26	462.3	2.9	461.7	9.3	458.6	54.0	462.3	2.9	100.8						
G-1	95	21454	0.7	17.7063	8.7	0.5796	8.9	0.0744	1.9	0.21	462.8	8.3	464.2	33.1	471.2	192.4	462.8	8.3	98.2						
G-11	230	37476	8.1	17.5645	2.2	0.5845	2.3	0.0745	0.7	0.28	462.9	2.9	467.3	8.7	488.9	49.1	462.9	2.9	94.7						
G-32	276	60226	4.8	17.7215	2.0	0.5798	2.4	0.0745	1.3	0.55	463.3	5.8	464.3	8.9	469.3	44.2	463.3	5.8	98.7						
G-21	259	71286	5.3	17.7042	3.8	0.5807	4.8	0.0746	2.9	0.61	463.6	13.1	464.9	18.0	471.4	85.2	463.6	13.1	98.3						
G-27	205	45571	8.8	18.1889	5.1	0.5698	5.5	0.0752	2.1	0.38	467.2	9.6	457.9	20.3	411.3	113.9	467.2	9.6	113.6						
G-16	133	33205	1.4	17.6118	5.1	0.5899	5.5	0.0753	2.0	0.37	468.3	9.0	470.8	20.6	483.0	112.2	468.3	9.0	96.9						
G-24	422	123473	7.5	17.6111	1.8	0.5921	3.2	0.0756	2.6	0.82	470.0	11.9	472.2	12.1	483.1	40.6	470.0	11.9	97.3						
G-31	124	38087	1.1	18.5699	6.2	0.5637	6.3	0.0759	1.0	0.16	471.7	4.6	453.9	22.9	364.8	139.3	471.7	4.6	129.3						
G-35	123	50911	2.3	17.4948	3.0	0.6002	3.4	0.0762	1.7	0.49	473.1	7.6	477.4	13.0	497.7	65.8	473.1	7.6	95.1						
G-29	155	35170	2.4	17.6969	4.6	0.5940	5.1	0.0762	2.3	0.44	473.4	10.8	473.4	19.3	472.3	101.3	473.4	10.8	100.3						
G-38	87	14310	0.7	17.3409	8.0	0.6074	8.5	0.0764	2.8	0.33	474.5	12.3	481.9	32.7	517.1	177.0	474.5	12.8	91.8						
G-30	202	61537	2.8	17.4386	2.4	0.6052	2.9	0.0765	1.5	0.54	475.5	7.1	480.5	11.0	504.8	52.9	475.5	7.1	94.2						
G-34	479	135076	7.3	17.5614	1.2	0.6026	4.7	0.0767	4.6	0.97	476.7	21.0	478.9	18.0	489.3	26.4	476.7	21.0	97.4						
G-36	319	150402	3.3	17.7964	2.8	0.6017	3.8	0.0777	2.5	0.67	482.2	11.8	478.3	14.4	459.9	61.9	482.2	11.8	104.8						
G-40	162	73562	6.5	17.8210	5.4	0.6089	6.9	0.0787	4.3	0.62	488.4	20.0	482.9	26.5	456.9	120.2	488.4	20.0	106.9						
G-17	808	247508	5.0	17.1831	1.4	0.6707	1.8	0.0836	1.2	0.64	517.5	5.8	521.1	7.4	537.2	30.6	517.5	5.8	96.3						
G-23	280	125347	4.8	16.2127	1.6	0.7877	2.2	0.0926	1.6	0.72	571.0	8.8	589.9	10.0	663.0	33.2	571.0	8.8	86.1						

Table 2. (continued)

Analysis	U	206Pb	U/Th	Isotope Ratios				Apparent Ages (Ma)						Conc					
				206Pb*	±	207Pb*	±	206Pb*	±	207Pb*	±	206Pb*	±		Best age	±			
T-Grain Tip, C-Grain Core	(ppm)	204Pb		207Pb*	(%)	235U*	(%)	238U	(%)	corr.	238U*	(Ma)	235U	(Ma)	207Pb*	(Ma)	(Ma)	(%)	
G-25	127	42620	0.7	16.8166	3.9	0.7639	4.2	0.0932	1.5	0.36	574.2	8.3	576.2	18.3	584.1	84.1	574.2	8.3	98.3
G-39	555	191149	5.3	16.1870	1.2	0.9108	4.5	0.1069	4.4	0.96	654.9	27.1	657.5	21.9	666.4	26.1	654.9	27.1	98.3
G-33	271	105697	1.9	15.1702	2.0	1.2532	5.7	0.1379	5.3	0.94	832.7	41.6	824.9	32.2	803.8	42.2	832.7	41.6	103.6

Table 6). All samples are metamorphic and are from the Sibişel Formation (the two samples from lower elevations) and from the Lotru Metamorphic Suite (the remainder). Zircons and apatites were separated and analyzed for U-Th/He ages (AZr and AHe) at the University of Arizona Helium laboratory, following the analytical protocol in *Reiners et al.* [2004]. Three individual crystals of apatite and zircon were determined for each sample. Their reproducibility is within about 30% of the reported ages (Table 6), which are averages of the individual measurements. Analytical uncertainty of zircon and apatite He ages measurements is around 1% of the reported values. Standard alpha ejection corrections were performed to account for alpha particle emission of U and Th particles. This correction assumes a homogenous distribution of parent nuclei and negligible implantation of 4He from outside the grain.

5. Results and Interpretations

5.1. Field Observations

The shear zone consists of rocks ranging from slightly deformed to protomylonites to mylonites from the margins to the center of the highly deformed zone. In several areas within the core of the shear zone the rocks are ultramylonitic (Figure 3). Most common ultramylonites are petrographically actinolite schists. All rocks have clearly defined penetrative foliations and mineral lineations defined primarily by the orientation of amphibole crystals.

Foliations in the shear zone are steeply dipping which is in strong contrast to foliations of metamorphic rocks of the Lotru Metamorphic Suite away from the shear zone—those define a broad anticlinal or domal shape to the south of the shear zone. The general strike of the foliations is NW paralleling the boundaries between the three main units as seen at map scale in Figure 2. Foliation in the shear zone are parallel to the strike of the ultramylonites (Figures 3 and 4). The foliation dips are steep, typically more than 60° toward both the NE and SW, but there is no spatial pattern to variations in foliation dip (e.g., such as them defining and anticlinal shape).

Mineral lineations are fairly uniform throughout the shear zone. Based on lineation trends, a domain of consistent deformation was observed oriented NW-SE (mean Fisher vector 142°, Figure 4). Lineation dips are moderately plunging to the SE, consistent with an updip component to the deformation. Outside the boundaries of the shear zone, lineation directions show approximately E-W orientation (mean Fisher vector 274°, not pictured).

Kinematic indicators (e.g., S-C fabrics) WEERE MEASURED in an area adjacent to the highly strained ultramylonitic rocks of the Sibişel Formation. We used oriented thin sections that were cut perpendicular as well as parallel to the foliation planes. Shear sense indicators were obtained both at outcrop and oriented thin section scales. Most S-C fabrics are indicative of dextral shear and were determined from amphibole and feldspar δ and σ clasts (Figure 3b). In thin sections cut parallel to the SE plunging lineations (the majority of analyzed samples) kinematic indicators are consistent with a top to the south-east reverse sense of shearing. We interpret this to represent indications of thrusting during the fabric generation.

Figure 5. Kernel density estimation plots for detrital zircon U-Pb ages analyzed from the Lotru Metamorphic Suite in this study: (a) sample VS01, (b), sample VP04, and (c) sample VP09.

with no Precambrian-inherited zircon grains. The maximum depositional age of this rock is also ~430 Ma. A few grains (<5%) show distinctive rims visible in CL images that correspond to areas with metamorphic U/Th ratios (>10) and Variscan ages (330–350 Ma). We interpret them to represent the product of the Variscan metamorphism.

5.2. U-Pb Geochronology

Zircon U-Pb ages were determined on three samples from the Lotru Metamorphic Suite (VS01, VP09, and VP04) and one igneous sample with no metamorphic fabrics (MM101) from the Râușorul Cisnădioarei Formation. Additionally, two greenschist facies rocks (epidote-albite-calcite schists) from the Râușorul Cisnădioarei Formation of unclear (metasedimentary or metavolcanic) origin were also selected for zircon U-Pb geochronology (P05-1 and P05-2); they were sampled in close proximity to each other from minuscule outcrops and will be treated below as one sample. Data are presented in Table 2. We did not sample for U-Pb geochronology from the predominantly mafic Sibișel Formation, suspecting that these rocks do not contain zircon.

5.2.1. Samples From the Lotru Metamorphic Suite

Sample VS01 is a highly deformed quartz-rich paragneiss with augen gneissic textures in hand specimen. Instead, it is a two mica gneissic rock whose augen plagioclase crystals give the false impression of an orthogneiss. The distribution of concordant U-Pb ages (Figure 5a) is a feature typical of many of the Lotru Metamorphic Suite rocks and Alpine sedimentary rocks derived from them [Balintoni *et al.*, 2009; Stoica *et al.*, 2016]. Overall the zircon age distribution in this rock shows a peak in the mid-Ordovician; the presence of a number of zircon with latest Proterozoic ages is typical of many rocks previously analyzed from the Lotru Metamorphic Suite (see review paper by Balintoni *et al.* [2014]). The maximum depositional age is constrained by the youngest zircons as early Silurian (~430 Ma).

Biotite and muscovite gneiss sample VP04 (Figure 5b) contains ages that cluster in the Ordovician (500–430 Ma)

Figure 6. $^{206}\text{Pb}/^{238}\text{U}$ crystallization zircon age of igneous sample MM01 (a few inherited Precambrian grains were excluded from the calculation).

is 462.8 ± 2.3 Ma (mean square weighted deviation = 3.4) by pooling 24 individual $^{238}\text{U}/^{206}\text{Pb}$ ages (all concordant but with less precise $^{235}\text{U}/^{207}\text{Pb}$ ages) (Figure 6). Two Cambrian and one Neoproterozoic inherited ages were not included in the age determination.

Samples P05-1 and P05-2 are chlorite/calcite and albite schists sampled from the same rock, at two nearby small outcrops. Zircons from both samples were combined to produce one zircon age distribution. The distribution of ages is consistent with a detrital pattern with ages ranging from Neoproterozoic to latest Cambrian (490 Ma) (Figure 7) and several Neoproterozoic and Cambrian peaks extending to about 700 Ma ages. Only two zircons have ages older than 700 Ma out of a total of 40 individual ages (5%). We tentatively interpret these rocks to be volcanosedimentary in origin based on their mafic-intermediate bulk chemistry and to have a maximum depositional age of ~ 497 Ma. Their main sources of material are intermediate volcanic rocks of late Cambrian age (520–500 Ma).

5.3. Mineral Rb-Sr Geochronology

We targeted the shear zone proper in order to determine the age of ductile deformation. We determined mineral-whole rock Rb-Sr isochrons for six assemblages (Table 3 includes the ages, whereas the isotope data

Figure 7. Zircon U-Pb age kernel density estimation plot for combined detrital samples P05 (1 and 2) from the Răușorul Cîsnădioarei Formation. The sample has a maximum depositional age of ~ 490 Ma.

Sample VP09 (Figure 5c) is a gneiss with similar zircon patterns to sample VP04, except that it contains about 25% Neoproterozoic-Cambrian inherited zircons, and one grain of ~ 2 Ga. The maximum depositional age is 448 ± 20 Ma. The sample also displays rim resetting (high U/Th domains) at Variscan peaks (348–355 Ma), which is typical for the Lotru Metamorphic Suite.

5.2.2. Samples From the Răușorul Cîsnădioarei Formation

Sample MM01 is a leucogranite lens, one of several that is crosscutting the Răușorul Cîsnădioarei Formation south of Rășinari (Figure 2). These granitoid bodies are not metamorphosed and therefore can constrain the age of metamorphism. The U-Pb age of this sample

are shown in Table 5). Three samples were ultramylonites, two mylonites, and one protomylonite. We micro-sampled biotite, fine-grained white mica (sericite), epidote, actinolite, and plagioclase to be paired with their corresponding whole rock samples. Three of these phases (biotite, sericite, and actinolite) have higher Rb/Sr ratios than the corresponding whole rock, whereas the other two (epidote and plagioclase) have much lower Rb/Sr than the whole rock values. One sample (VC11) did not yield a realistic Rb-Sr, mainly because of lack of spread for Rb/Sr ratios, so it will not be discussed further.

The other five samples yielded two-point isochron Rb-Sr ages between 293 and 234 Ma, with the ultramylonitic

Table 3. Rb-Sr Isochron Ages

Sample	Deformation	Rb (ppm)	Sr (ppm)	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$	2 σ Standard Error	Initial $^{87}\text{Sr}/^{86}\text{Sr}$	Isochron Age (Ma)
<i>Lotru Metamorphic Suite</i>								
VS03	WR	Mylonite	124.82	165.61	2.1710	0.725776	0.0012	0.717451(25)
	Biotite		364.64	40.55	26.1386	0.817677	0.0010	
C5	WR	Ultramylonite	143.04	123.24	3.3454	0.732242	0.0042	0.720810(53)
	White mica		192.59	228.51	2.4286	0.729109	0.0010	240.2 $\pm$ 1.3
<i>Sibişel Formation</i>								
VC01	WR	Protomylonite	17.00	133.45	0.3663	0.709299	0.0013	0.707771(11)
	Epidote		0.09	1293.57	0.0002	0.707772	0.0008	
VC08	WR	Mylonite	159.62	78.59	2.4133	0.749409	0.0029	0.740089(44)
	Actinolite		52.58	62.99	5.8646	0.762737	0.0021	
C4	WR	Ultramylonite	4.70	163.20	0.0828	0.704105	0.0035	0.703829(06)
	Plagioclase		1.24	229.55	0.0156	0.703881	0.0007	234.2 $\pm$ 7.1

rocks from the center of the shear zone (C4 and C5) being the youngest (234 $\pm$ 7 Ma and 240 $\pm$ 1.3 Ma) and the least deformed rock (VC01) being the oldest (Figure 8).

Closure temperature is difficult to assess in the case of Rb-Sr system (see Müller [2003], for discussion) for many minerals specially micas, with few reliable diffusion data. In general, amphibole, feldspars, epidote, and white micas close around 500–600°C [Cherniak, 2010], whereas biotite has a much lower closure temperature, 250–300°C [Dodson, 1973], although closure depends significantly on grain size and cooling rate. The degree of recrystallization during ductile deformation may reset the system more than classic closure temperatures in highly deformed rocks that experienced ductile shear in the mid temperature range (300–500°C) [Villa, 2016]. In our data, the inverse correlation between the degree of mylonitization and ages support this assertion.

Taken together, and given the uncertainty surrounding the significance of Rb-Sr ages in highly deformed rocks, we interpret that the high strain ductile deformation took place somewhere between the Permian and Early Triassic (290–240 Ma), with the ultramylonitic rocks showing the youngest ages in that range. To the south, along the Olt River, Sibişel Formation exposes garnet amphibolite facies rocks equivalent to our actinolite-rich rocks; those were subjected to peak metamorphism in the earliest Triassic (~247 Ma [Negulescu et al., 2014]). Those ages are better constrained through garnet Sm-Nd and monazite U-Th-Pb geochronology. Even farther to the south, unmetamorphosed Permo-Triassic sediments are trapped as thin, near-vertical slivers in the Sibişel Shear zone [Udubaşa and Hann, 1988]. Overall, there is evidence that the major deformation event of the Sibişel shear zone is Late Permian to Early Triassic.

5.4. Major and Trace Element Geochemistry

Whole rock major and trace elemental geochemistry (Table 4) obtained from a limited set of samples shows that the Sibişel Formation mafic rocks are basaltic andesites and andesites. Their trace elemental concentrations suggest an arc/back-arc origin. They are slightly higher in silica (52–55% SiO₂) than basalts, have moderate MgO (4–5 wt %) and compatible trace element (Ni = 50–70 ppm, Cr = 100–400 ppm) concentrations and Mg# ~55–60. None of those values are indicative of primitive mantle melts. Since our samples are metamorphosed and highly deformed, we use only the most immobile geochemical tracers in our interpretation [e.g., Rollinson, 1993]. For example, the Sibişel Formation has distinctive light rare earth elements enrichment patterns and high field strength element (Nb, Zr) depletions on chondrite-normalized spider diagrams (Figure 9). On Ti/Mn/P major element and La/Nb/Y ternary tectonic discrimination diagrams for basaltic rocks (not pictured), the Sibişel Formation mafic rocks mostly fall within island arcs or back-arc fields. Only in a few tectonic discrimination diagrams the samples plot on mid-ocean ridge basalt (MORB) fields. The pronounced Ce anomaly in most mafic rocks is possibly an indication of seawater interaction with magmatic rocks during or soon after their formation [Rollinson, 1993].

The Răuşorul Cislădioarei Formation rocks are distinct from the Sibişel Formation in trace elemental abundances but are also typical of arcs, when viewed in chondrite-normalized rare earth element (REE) and spider diagram plots. The overall geochemical trends and ratios for these rocks are important instead of absolute concentrations, in part because they are sedimentary rocks (derived from an arc source instead of being

Figure 8. Two-point mineral-whole rock Rb-Sr ages on the five samples (protomylonite, mylonite, and ultramylonites) from the Sibișel Shear Zone—see text for details.

magmatic products) and also because of the potential mobility of some elements during metamorphism. The Sr/Y and La/Yb ratios (used to infer crustal thickness in arc rocks) [Profeta *et al.*, 2015] are suggestive of thin crust (<30 km) for all of the measured samples.

5.5. Whole Rock Nd and Sr Isotopes

Whole rock Sr and Nd isotopic ratios, as well as supporting elemental concentration data for Rb, Sr, Sm, and Nd determined by isotope dilution are given in Table 5. When plotted on a $^{87}\text{Sr}/^{86}\text{Sr}$ – $^{143}\text{Nd}/^{144}\text{Nd}$ isotopic diagram (ratios corrected to 250 Ma, the average age of ductile deformation) the Râușorul Cisnădioarei,

Table 4. Major and Trace Element Data

	Sibişel Formation								Rausorul Cisnadioarei Formation	
	VC08	VC11	VC01	VC16	C1	C2	C3	C4	P05-1	P05-2
<i>Major Elements (wt %)</i>										
SiO ₂	65.45	52.32	55.61	52.73	53.12	54.51	52.07	62.61	61.59	64.27
TiO ₂		2.10	0.66	1.36	1.60	0.92	1.51	0.29	0.77	0.17
Al ₂ O ₃	11.17	11.56	13.22	11.04	12.57	12.21	12.54	12.67	11.94	11.93
MgO	1.55	4.05	5.04	4.45	5.46	4.92	5.07	5.01	1.86	1.54
FeO	5.22	11.56	7.96	10.19	11.29	8.59	8.59	6.11	5.032	5.22
MnO	0.03	0.19	0.19	0.18	0.21	0.17	0.21	0.13	0.09	0.05
K ₂ O	6.37	0.87	0.45	0.42	0.43	0.50	0.46	0.22	3.08	3.72
CaO	0.60	8.76	8.10	8.37	9.73	9.61	9.29	7.65	3.58	3.90
Na ₂ O	2.05	2.93	4.70	3.17	4.16	2.80	3.63	4.14	1.28	1.03
P ₂ O ₅	0.19	0.30	0.05	0.22	0.23	0.11	0.22	0.05	0.08	0.10
LOI	7.37	5.36	4.02	7.86	1.18	5.67	6.41	1.13	10.70	8.15
<i>Trace Elements (ppm)</i>										
Sc	9.5	30.0	bdl	30.0	26.6	bdl	28.2	bdl	bdl	bdl
V	bdl	369.7	209.2	294.4	297.1	284.0	342.9	160.2	153.7	23.4
Cr	396.1	379.5	869.1	319.2	195.2	347.4	134.9	161.4	199.7	191.3
Co	bdl	60.4	49.9	56.3	59.0	51.1	62.4	32.3	17.0	6.2
Ni	6.0	16.2	63.1	66.1	56.2	70.3	65.8	31.7	25.3	11.8
Cu	31.1	172.6	25.1	62.9	19.7	29.8	54.4	66.7	11.4	22.2
Zn	30.8	55.2	130.3	89.9	105.1	79.3	102.1	77.3	67.9	35.4
Ga	15.5	24.8	22.9	21.8	20.9	19.5	22.8	14.5	22.1	21.4
Ge	7.4	bdl	6.3	bdl	4.9	3.9	2.4	2.6	bdl	bdl
As	bdl	1.5	bdl	bdl	3.7	2.8	4.2	1.1	bdl	bdl
Se	bdl	6.0	2.4	bdl	1.8	2.2	2.8	4.6	3.2	bdl
Br	bdl	bdl	bdl	bdl	bdl	bdl	bdl	1.3	bdl	bdl
Rb	110.5	30.1	23.0	23.1	21.4	21.1	22.9	17.1	80.6	92.6
Sr	67.2	176.7	174.2	205.7	186.4	172.5	199.6	162.2	65.5	64.6
Y	7.3	39.9	21.4	27.9	28.9	25.9	33.6	13.6	28.1	56.5
Zr	143.3	145.8	87.6	110.1	115.2	113.0	120.1	90.6	173.7	300.3
Nb	8.6	7.7	6.5	6.7	8.1	6.6	6.8	6.2	12.1	13.2
Mo	1.4	7.3	2.4	2.0	1.7	2.0	2.7	1.9	bdl	bdl
Ag	9.6	bdl	bdl	bdl	bdl	6.0	bdl	bdl	bdl	15.7
Cd	bdl	5.3	3.7	bdl	3.3	bdl	3.5	bdl	3.2	bdl
In	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl
Sn	3.9	7.4	9.0	7.2	5.7	6.1	5.9	5.1	6.3	3.8
Sb	5.7	8.8	bdl	19.8	13.7	bdl	bdl	34.3	9.6	9.2
I	4.1	211.3	33.5	133.3	186.4	72.7	183.2	50.4	4.4	bdl
Cs	2.1	bdl	bdl	bdl	2.4	1.4	bdl	bdl	2.8	bdl
Ba	448.3	247.0	373.0	283.3	204.7	168.3	198.0	195.3	495.7	588.0
La	32.3	33.7	72.3	50.3	42.7	74.7	54.7	80.0	50.0	42.2
Ce	34.3	59.2	45.5	57.5	49.3	25.6	51.4	27.6	68.8	122.2
Pr	bdl	14.6	21.9	13.8	13.1	15.2	11.1	10.3	11.2	5.2
Nd	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	3.5
Sm	5.4	8.2	8.8	bdl	7.9	6.8	8.4	7.2	6.5	5.8
Eu	0.9	1.5	bdl	1.2	2.1	bdl	1.6	bdl	bdl	bdl
Gd	bdl	12.2	13.9	10.9	10.2	12.2	10.1	10.9	5.9	2.5
Tb	0.7	2.6	2.4	2.7	2.8	2.1	2.8	1.5	1.2	0.9
Dy	0.7	3.7	8.3	5.6	5.3	7.2	5.7	8.0	4.6	2.4
Ho	0.9	0.9	1.0	0.9	0.9	0.9	0.9	0.9	0.9	0.8
Er	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl
Tm	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl
Yb	2.2	2.2	2.2	2.1	2.1	2.2	2.2	2.2	2.4	2.6
Lu	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl
Hf	5.4	bdl	7.8	bdl	3.0	3.2	1.6	1.4	5.0	5.1
Ta	3.8	bdl	2.3	bdl	bdl	1.2	bdl	1.4	1.5	2.5
W	42.1	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl
Hg	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl
Tl	1.1	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl
Pb	58.0	3.7	4.2	3.1	1.9	3.2	2.9	bdl	2.8	6.1

Table 4. (continued)

	Sibişel Formation								Răuşorul Cisnădioarei Formation	
	VC08	VC11	VC01	VC16	C1	C2	C3	C4	P05-1	P05-2
	<i>Major Elements (wt %)</i>									
Bi	42.5	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	15.1
Th	3.1	bdl	bdl	bdl	bdl	bdl	bdl	bdl	7.9	11.4
U	5.6	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	1.6

^abdl = below detection limit. Typical major element errors are 1%. Trace elemental errors are 3–5%.

Sibişel mafic rocks, and Sibişel Formation metasedimentary rock VC01 are significantly more unradiogenic in Sr isotopes and radiogenic in Nd isotopes than the samples from the Lotru Metamorphic Suite and three metasedimentary samples from within the Sibişel Formation (Figure 10). The depleted Nd isotopes of

Figure 9. Trace element spider diagrams for mafic rocks from the Sibişel Formation. (a) Rare earth element chondrite-normalized diagrams showing light REE enrichment and Ce negative anomalies (suggesting possible involvement of seawater). Some samples show negative Eu anomalies. (b) Spider diagram of various incompatible elements (also normalized to chondritic values) showing negative anomalies of high field strength elements such as Nb and Ti—these features are also indicative of an arc origin for these rocks. Chondrite-normalizing values are from Sun and McDonough [1989].

the Sibişel and Răuşorul Cisnădioarei Formations are not as depleted as normal MORB values (they are 2–3 ϵ_{Nd} units lower than the depleted MORB ϵ_{Nd} at 250 Ma as well as at 490 Ma, which is the likely sedimentary age of the Răuşorul Cisnădioarei rocks analyzed here). The isotopic ratios are similar to metamorphosed mafic rocks from the Lotru Metamorphic Suite farther to the south and west of our field area (M. N. Ducea et al., unpublished data, 2016) and are overall characteristic of the Early Paleozoic island arc input into various Carpathian terranes [Balintoni et al., 2001]. All metasedimentary rocks of the Lotru Metamorphic Suite are significantly more enriched isotopically (higher $^{87}Sr/^{86}Sr$ and lower $^{143}Nd/^{144}Nd$ —this study as well as M. N. Ducea et al., unpublished data, 2016).

Sample C5 is an ultramylonite of the Sibişel Shear Zone that has Lotru Metamorphic Suite isotopic characteristics; we infer that the boundary between the Sibişel Formation and the Lotru is located between the locations of samples C4 and C5. Based on isotopic ratios, sample VC01, likely is part of the Răuşorul Cisnădioarei Formation. The similarities of the isotopic ratios of samples VC08 and VC11 and the Lotru Metamorphic Suite rocks is puzzling as they are sampled from within the mafic zone and they are petrographically amphibole schist. Sample VC19 also has Lotru isotopic ratios, but it is a metasedimentary rock (muscovite-quartz-plagioclase). We interpret these results to be indicative of a mechanical mixing

Table 5. Whole Rock Sr and Nd Isotope Data and Mineral Rb-Sr Data

Sample	Rb (ppm)	Sr (ppm)	$^{87}\text{Rb}/^{86}\text{Sr}$ (0)	$^{87}\text{Sr}/^{86}\text{Sr}$ (0)	std err%	$^{87}\text{Sr}/^{86}\text{Sr}$ (250)	Sm (ppm)	Nd (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$ (0)	$^{143}\text{Nd}/^{144}\text{Nd}$ (0)	std err%	$^{143}\text{Nd}/^{144}\text{Nd}$ (250)	ε_{Nd} (0)	ε_{Nd} (250)
<i>Sibişel Formation</i>														
C3	12.54	189.59	0.190157	0.704708	0.0025	0.703978	4.67	13.98	0.334153	0.513017	0.0018	0.512660	7.39	7.21
C2	10.08	169.26	0.171224	0.705532	0.0010	0.704874	2.65	7.51	0.353220	0.512984	0.0010	0.512607	6.75	6.17
C4	4.70	163.20	0.082791	0.704105	0.0035	0.703787	1.85	5.07	0.365403	0.512996	0.0029	0.512606	6.98	6.15
VC16	12.44	218.39	0.178964	0.704451	0.0017	0.703764	4.09	13.21	0.309902	0.512923	0.0021	0.512592	5.56	5.88
VC01	17.00	133.45	0.366309	0.709299	0.0013	0.707892	1.32	3.81	0.347269	0.512962	0.0011	0.512591	6.32	5.86
C1	12.24	247.40	0.14227	0.705485	0.0114	0.704938	6.21	13.33	0.465759	0.512914	0.0022	0.512416	5.38	2.46
VC19	129.51	40.61	9.226047	0.770281	0.0026	0.734840	1.33	3.47	0.231763	0.512184	0.0028	0.511774	-8.86	-10.08
VC08	159.62	78.59	2.413336	0.749409	0.0029	0.740139	0.43	1.52	0.170762	0.512162	0.0020	0.511860	-9.29	-8.40
VC11	77.63	211.43	1.056372	0.713682	0.0039	0.709624	5.44	24.49	0.134272	0.512168	0.0008	0.511931	-9.17	-7.02
<i>Răşorul Cisnădioarei Formation</i>														
P05-1	90.10	47.11	5.512092	0.729489	0.0012	0.708315	3.90	18.91	0.124805	0.512597	0.0012	0.512376	-0.80	1.68
P05-2	53.70	342.87	0.450458	0.710086	0.0008	0.708356	8.20	30.81	0.160937	0.512591	0.0012	0.512307	-0.92	0.31
<i>Lotru Metamorphic Suite</i>														
VP09-1	122.96	68.85	5.155093	0.746836	0.001	0.727033	2.32	9.74	0.143919	0.51227	0.0008	0.512016	-7.18	-5.37
C5	143.04	123.24	3.345435	0.732242	0.0042	0.719391	5.89	22.57	0.157853	0.512213	0.0031	0.511934	-8.29	-6.96
V501	133.23	138.09	2.779604	0.726986	0.0037	0.716309	0.88	3.29	0.161645	0.512174	0.0023	0.511888	-9.05	-7.85
VP04	16.13	121.55	0.382389	0.730837	0.0025	0.729368	2.46	10.32	0.143928	0.512125	0.0010	0.511871	-10.01	-8.20
V503	124.82	165.61	2.171042	0.725776	0.0012	0.717436	2.33	8.09	0.173850	0.512113	0.0019	0.511806	-10.24	-9.46
<i>Mineral Data</i>														
C4 plagioclase	1.24	229.55	0.0156	0.703881	0.0007									
C5 muscovite	192.59	228.51	2.4286	0.729109	0.0010									
VC01 epidote	0.09	1293.57	0.0002	0.707772	0.0008									
VC08 actinolite	52.58	62.99	5.8646	0.762737	0.0021									
V503 biotite	364.64	40.55	26.1386	0.817677	0.0010

Figure 10. Whole rock Sr and Nd isotopic data (corrected at 250 Ma) plotted for the rocks from the three units analyzed here: Lotru Metamorphic Suite, Sibișel Formation, and Râșorul Cisnădioarei Formation. SF mafic = Sibișel Formation mafic rocks, SF other = metasedimentary rocks from within the Sibișel Formation, LMS = Lotru Metamorphic Suite, and RC = rocks from the Râșorul Cisnădioarei Formation. CHUR = Chondritic Uniform Reservoir at 250 Ma.

of Lotru and Sibișel rocks in the highest deformation domain of the shear zone as a result of juxtaposition of rocks from both domains in the ultramylonite zone. Alternatively, it is possible that the rocks covering the mafic assemblages of the Sibișel Formation are similar to/derived from the Lotru domain.

Overall, the Sibișel Formation mafic rocks are isotopically similar to the Râșorul Cisnădioarei Formation, whereas meta-sedimentary rocks found within the Sibișel Formation are similar to the Lotru Metamorphic Suite. For that reason, we cannot rule out connections between the Sibișel Formation and its two bounding blocks. However, our preferred interpretation is that the Sibișel Formation has a distinct origin from its

two neighboring blocks and that the ductile shear zone led to mechanical mixing between formations to a sub outcrop scale.

5.6. Uranium-Thorium/Helium Zircon (ZHe) and Apatite (AHe) Ages

Eight helium ages of apatite (AHe) range from 59 to 90 Ma, whereas the zircon (ZHe) ages are between 98 and 122 Ma (Table 6). The reproducibility of data within a single sample is somewhat poor. This is common for small and anhedral apatite and zircon grains found in metamorphic rocks such as those studied here, but our overall results are consistent. A correlation exists between ZHe and AHe, and they both correlate with elevation (Figure 11). There is an increase in age with modern elevation from low elevations in the Râșinari area (within the Sibișel Shear Zone) to higher elevations to the southwest. Samples from the highest elevations show a decrease in ages. If the slope of the lower six samples is considered for the AHe and we assume no block rotations since the locking of the apatite ages, one can infer a relief of as much as 2000 m during Late Cretaceous, assuming that the contact between basement and the Transylvanian basin was at sea level most part of the mid-Cretaceous to Late Cretaceous [Ciulavu and Bertotti, 1994].

Assuming a thermal gradient of 30°C/km, and a closure temperature of 200°C for AZr, a little over 6 km of rock unroofing took place locally since the mid-Cretaceous. This is consistent with other regional studies in the central part of the South Carpathians [Merten et al., 2010].

6. Discussion

6.1. Origin and Age of the Lotru Metamorphic Suite

The Lotru Metamorphic Suite is the largest metamorphic unit in the South Carpathians and has a rather complex lithology and tectonic evolution. It is dominated by latest Precambrian to Early Silurian zircon ages

Table 6. U-Th-He Apatite and Zircon Data, Location, and Brief Description of Samples

Sample	Latitude	Longitude	Elevation (m)	Petrographic Features	Apatite Age (Ma)	Zircon Age (Ma)
210808P1	N45° 42.314	E24° 02.286	613	Augen gneiss	58.9 ± 1.9	106.4 ± 2.3
210808P2	N45° 42.795	E24° 00.970	729	Biotite bearing gneiss	54.9 ± 1.6	117.7 ± 2.6
210808P3	N45° 42.577	E24° 00.412	855	Muscovite bearing pegmatite	73.1 ± 1.7	121.4 ± 4.6
210808P4	N45° 42.093	E24° 00.100	931	Pegmatite	89.3 ± 2.4	115.7 ± 4.3
210808P5	N45° 41.562	E24° 00.026	1050	Pegmatite	85.1 ± 2.4	125.2 ± 5.1
210808P6	N45° 40.963	E23° 57.570	1257	Muscovites schist	90.6 ± 2.0	122 ± 4.6
210808P7	N45° 39.009	E23° 56.655	1450	Pegmatite and gneiss	61.9 ± 2.2	119.6 ± 5.2
210808P8	N45° 39.591	E23° 57.635	1370	Two mica gneiss	56.5 ± 2.2	98.5 ± 2.3

Figure 11. (a) Apatite (AHe) U-Th-He ages (million years) plotted against sample elevation and (b) zircon (ZHe) U-Th-He ages plotted against sample elevation of eight samples from a transect crossing the Sibişel Shear Zone showing that ZHe ages are mid-Cretaceous, whereas all AHe ages are Late Cretaceous consistent with about 3–6 km of unroofing during the main Alpine orogenic phases in the South Carpathians. The younger ages of the highest elevation samples probably were affected by intra basement brittle faults outside of the main area of interest in this paper; they are not interpreted further here.

with a single large mid-Ordovician age peak at 460–470 Ma, likely reflecting a subduction-related flare-up event which probably makes up more than 70% of the exposed basement [Balintoni *et al.*, 2009; Stoica *et al.*, 2016]. That age peak is in fact a global zircon magmatic arc flare-up event, perhaps the largest in the Phanerozoic [Ducea *et al.*, 2015] and is certainly reflected in many basement terranes of the Alpine-Carpathian domain [von Raumer *et al.*, 2013]. The most abundant rocks of the Lotru Metamorphic Suite exposed in the Cibin Mountains are garnet amphibolites and orthogneisses of andesitic bulk composition; they are interlayered with two-mica rich rocks that are more silicic and are probably volcanosedimentary assemblages derived from the same arc but with input from nearby older arc rocks and an array of inherited Precambrian zircons with Peri-Gondwana affinities [Balintoni *et al.*, 2014]. A latest Precambrian-Cambrian basement may have existed in the southern part of the Lotru Metamorphic Suite but has not been positively identified from the limited data available. A younger unconformable sedimentary sequence (now garnet micaschists) overlays the arc sequence. They were metamorphosed during a Variscan Barrovian collisional event documented by Sm-Nd garnet [Medaris *et al.*, 2003] and U-Th/Pb monazite [Stoica *et al.*, 2016] ages. The consistent presence of the inherited age peaks is taken to indicate the proximity of a continental

mass. Its exact continental match within Gondwana is debatable [Balintoni *et al.*, 2014], but its derivation from a subduction-related island or transitional arc close to Gondwana is unquestionable and consistent with the overall origin of basement terrains of the Alps and Carpathians [von Raumer *et al.*, 2013].

Our new data add some information to this picture and are fully consistent with previously published results. Based on our observations, Lotru Metamorphic Suite rocks cropping out near Răşinari are mostly metasedimentary; however, they are not part of the Negovanu cover but rather belong to the main Paleozoic arc section; they appear to form a consistent metasedimentary sequence, although orthogneisses and amphibolites have been observed outside of the research area. The detrital U-Pb zircon age distribution is consistent with a primary mid-Ordovician source and the typical latest Precambrian-Ordovician tract of ages; the youngest zircons are Silurian, suggesting that magmatism continued into that period. The metasediments that we analyzed have maximum depositional ages of around 420–430 Ma. Zircon rims with metamorphic U/Th ratios of 340–350 Ma suggest that these rocks underwent Variscan metamorphism.

6.2. Origin and Age of the Răușorul Cisnădioarei Formation

The Răușorul Cisnădioarei Formation, in contrast to the Lotru Metamorphic Suite, has a rather limited extent in the South Carpathians, and there are no modern data available in the literature pertinent to its age and origin. It has been described as a chlorite facies metamorphic unit and interpreted as (see references in *Pană and Erdmer* [1994]) a retrograde series formed over the Lotru Metamorphic Suite following high-grade metamorphism. In contrast, *Codarcea-Dessila* [1965] suggests that differences in metamorphic grade between Lotru Suite and Răușorul Cisnădioarei Formation are due to the fact that they experienced different orogenic cycles.

Our mapping and analytical data suggest that the bulk of the Răușorul Cisnădioarei Formation is made of andesitic/basaltic andesitic metavolcanic rocks that most likely represent a calc-alkaline arc. Combined sample PS01-PS02 is a volcanosedimentary material whose deposition age is as old as 490 Ma based on the youngest detrital age peak. The detrital distribution of ages is consistent with a peak magmatic event at around 520 Ma, which corresponds to a subtle gap in magmatism in all other peri-Gondwanan Carpathian terranes [*Balintoni et al.*, 2014]. These rocks are crosscut by an unmetamorphosed leucogranite at 463 Ma suggesting that the low-grade albite-chlorite metamorphism took place during the Ordovician between deposition and intrusion. We suspect that since the Răușorul Cisnădioarei Formation resembles an island arc, metamorphism was probably near synchronous with volcanism and sedimentation in the basin.

Unlike the Lotru Metamorphic Suite, the Răușorul Cisnădioarei Formation did not undergo Variscan metamorphism and had a common history with the Lotru Suite and Sibișel Formation only after their juxtaposition during the Permian or Triassic. Rocks included in the Răușorul Cisnădioarei Formation and the Lotru Metamorphic Suite, as well as most metamorphic basement sequences from the Alps and Carpathians in central and eastern Europe were forming part of island arcs and back arcs of Cambro-Ordovician age located proximally to a main Gondwana landmass. Further work on Răușorul Cisnădioarei rocks is necessary in order to resolve its Cambro-Ordovician history, but for now and based on our present data, we conclude that Răușorul Cisnădioarei Formation had a very different geologic evolution during the Variscan compared to the Lotru Metamorphic Suite.

6.3. Origin and Age of the Sibișel Formation

The Sibișel Formation is dominated by a mafic sequence of actinolite schists mixed with metasedimentary rocks of unknown origin, probably a tectonic mélange. The highly chaotic distribution of different lithologies at ~100 m scale in the field is suggestive of the mélange origin. There is no indication of retrograde reactions at outcrop and/or thin section scale. Instead, we interpret that epidote amphibolite facies metamorphism of the Sibișel Formation was a direct result of ductile shearing and the precursor rocks were not metamorphosed before the Permo-Triassic. The highly attenuated nature of the Sibișel Formation due to high strain makes it difficult to sort out details preductile shearing. Some of the metasedimentary rocks from Sibișel Formation have petrographic characteristics of the Lotru Metamorphic Suite nearby—they were probably slivers from that unit caught in the ductile shear zone, but that cannot be uniquely resolved. We cannot rule out the possibility of the Sibișel Formation being related to the Lotru Suite. The mafic units in the Sibișel Formation, on the other hand, are significantly more depleted isotopically suggesting a different origin. The mafic units have island arc geochemical characteristics, with depletions of high field strength elements. Overall trace elements are more consistent with an island arc or back-arc origin than a MORB-like ophiolite. We do not have any age constraints on the unit other than the Rb-Sr mineral ages that constrain the ductile deformation to be Permo-Triassic.

While it remains unresolved as to whether the Sibișel Formation was attached to either Răușorul Cisnădioarei or the Lotru Metamorphic Suite, or neither for the second part of the Paleozoic, we favor an interpretation in which the three have evolved separately until their juxtaposition in the Permian.

6.4. Age and Significance of the Sibișel Shear Zone

We show that the Sibișel ductile shear zone includes parts of the Lotru Metamorphic Suite and Răușorul Cisnădioarei Formation, as well as the entire Sibișel Formation was active between the Permian and Early Triassic. Our Rb-Sr results are consistent with a previously published Ar-Ar age on micas from the Sibișel Shear Zone at Rășinari (288 ± 1 Ma [*Dallmeyer et al.*, 1998]). Some of the earlier ages (290 Ma) may be partially reset Rb-Sr ages and thus incorrectly suggest a prolonged deformation starting in the early Permian.

However, the ultramylonitic part of this major structure appears to have been developed the latest (~240 Ma), synchronous with error with the Sm-Nd and monazite ages determined on the Sibişel Shear Zone to the south [Negulescu *et al.*, 2014] in an area where the ductile zone developed under higher-grade metamorphism. This is also consistent with the presence of latest Permian and earliest Triassic unmetamorphosed sedimentary rocks even further to the south along the Sibişel Shear Zone (Figure 2). All these geochronologic indications point to an Early Triassic deformation possibly extending into the Permian. The top to the southwest deformation is suggesting that ductile deformation was compressional with a dextral component—there is no information on the magnitude of lateral shear. The timing of deformation is surprising: regional Carpathian tectonic activity time line was rather quiescent in the Triassic [Săndulescu, 1984]. The opening and evolution of the Meliata Ocean [Schmid *et al.*, 2008], an early version of the Neotethys [Ionescu *et al.*, 2009], whose remnants are found in the east Carpathians, is the closest tectonic event of that age but was extensional and started somewhat later (220 Ma [Schmid *et al.*, 2008]). The Sibişel Formation may be a product of the final closing of the Paleotethys, perhaps marking the accretion of a last Peri-Gondwanan terrane (Răuşorul Cislădioarei Formation) to the Lotru Metamorphic Suite, which had been metamorphosed during its Variscan collision with Baltica. Future work on the age, metamorphic history, and origin of all assemblages caught in the shear zone and of the Sibişel Formation in particular may shed additional light on the regional significance of this remarkable structure.

6.5. Regional Significance

Our results demonstrate that assembly of the Carpathian basement terranes took place as late as the Triassic and was not completed with the main Variscan barrovian tectonometamorphic events [Medaris *et al.*, 2003]. We also present data that document for the first time that at least some of the metamorphic units of the South Carpathians were metamorphosed during the Ordovician. Similar patterns may be sought after in correlative terranes in the Apuseni Mountains and the Eastern Carpathians [Balintoni *et al.*, 2014]. The Sibişel Shear Zone is one of the few regional structures now resolved in terms of its age of deformation. The pre-Alpine component of this structure is clearly different from the younger, Alpine brittle reactivation [Ducea and Roban, 2016], at least along the segment south of Răşinari. Although it has been suggested that some ductile deformation along this and the other six major ductile shear zones in various locations of the Romanian Carpathians basement [Pană and Erdmer, 1994] could be Alpine (Mesozoic), we show that at least in the Sibişel Shear Zone, this was not the case.

6.6. Alpine Reactivation of the Shear Zone

Our U-Th/He thermochronologic data show that the Răşinari area was not above the closure temperature of ZHe (~200°C) since the mid-Cretaceous, which combined with the Permo-Triassic Rb-Sr ages indicate that the last ductile deformation was pre-Alpine. Pervasive brittle deformation exist in the area, perhaps less intense than along the southern continuation of the Sibişel Shear Zone along the Olt River, but nevertheless, high-angle brittle faults with evidence for dextral shear are quite common in our field area. We interpret them to represent strands of the Trans-Carpathian Fault System [Ducea and Roban, 2016] a STEP fault accommodating the closure of the Severin oceanic basin in the Cretaceous—today marked by an ophiolitic suture west and south of our field area. That fault system probably was transpressive during the Cretaceous and was responsible for the Late Cretaceous exhumation patterns that seem to correlate with modern elevation. Our data also suggest the existence of significant topography (>2000 m) during the latest Cretaceous. Overall, the average exhumed thickness from the northern parts of the South Carpathians since the Late Cretaceous is in the range of 5–7 km (based on data from Merten *et al.* [2010]), which is consistent with our U-Th/He data. This is also in agreement with the idea that the crust presently exposed in our field area was not buried close to or beneath the brittle ductile transition during the main regional Alpine compressional events (mid-Cretaceous to Late Cretaceous [Săndulescu, 1984; Schmid *et al.*, 2008]).

6.7. Significance for Arc Terrane Amalgamation in Europe

Most paleotectonic reconstructions of Europe [e.g., Stampfli *et al.*, 2011; von Raumer *et al.*, 2011, 2013] (NefteX Geodynamic Earth Model) indicate that the Rheohercynian Ocean [Nance *et al.*, 2010] was for the most part consumed by the early Permian and the bulk of Gondwanan terrane had docked to the large Caledonia-Avalonia-Baltica large continent. Moreover, western and central European terranes had already experienced collision with proto-Africa by that time. The Variscan orogen [Neubauer and Handler, 1999], which was

completed by Permian time, is fundamentally the product of collision and amalgamation of Gondwanan terranes into Baltica's cratonal margin.

The Paleotethys Ocean, which underwent "zipper tectonics" during the Late Paleozoic closing of oceans separating Baltica from the remnants of Gondwana, was still an oceanic realm in Permo-Triassic times east of the main European continent, where most of the eastern European terrane presumably evolved. The unusual geometry of closing the Paleotethys [Schmid *et al.*, 2008] was conducive to oblique accretion of late errand Early Paleozoic peri-Gondwanan arcs that were not docked to Baltica by the Variscan orogeny—as we suggest it was the case for the terrane from which the Râușorul Cislădioarei Formation is derived. The oblique and soft docking of such masses to a larger microcontinent previously attached to Baltica during the main Variscan orogen was perhaps responsible for development of the Sibișel Shear Zone and similar shear zones (transpressional sutures with oceanic-like materials in their core). In fact, the plate boundary extending from the Paleotethys into the collisional zone of Gondwana with Baltica during the Permian from east to west in modern coordinates has been interpreted as a major strike-slip boundary [e.g., McCann *et al.*, 2006]. We propose that the Sibișel Shear Zone was a part of this paleoplate boundary during the Late Permian and earliest Triassic.

7. Conclusions

The Sibișel Shear Zone near Rășinari juxtaposes two distinct metamorphic terranes of the South Carpathians: the spatially extensive Lotru Metamorphic Suite characterized by a sequence of Cambro-Silurian magmatic arc rocks and their eroded sedimentary equivalents that were metamorphosed to amphibolite facies conditions (and locally at higher metamorphic grade) during a Carboniferous Variscan collisional event and the Râușorul Cislădioarei Formation, a Cambrian arc terrain that was metamorphosed to greenschist facies immediately after its formation and is crosscut by mid-Ordovician unmetamorphosed granitoids. The two arc terrains were juxtaposed during the Permian and Early Triassic along a major transpressional ductile shear zone. The core of this highly deformed area is represented by a third, distinctive metamorphic unit, the Sibișel Formation. The Sibișel Formation contains primarily mafic assemblages with chemical and isotopic characteristics of an island arc or a back arc; these were metamorphosed to epidote amphibolite facies probably during Permo-Triassic ductile shearing. The original age of the Sibișel Formation is not resolved. The results are consistent with age and other geologic constraints from other segments along the Sibișel Shear Zone. Our data have several potential implications for understanding the basement evolution of the Carpathians:

1. There is a clear distinction in metamorphic evolution between low-grade and high-grade terrains. Low-grade (greenschist facies) rocks of the Râușorul Cislădioarei Formation did not evolve with the higher-grade rocks of the Lotru Metamorphic Suite until after the Variscan orogeny. This may apply to other low-grade domain-high-grade domain boundaries regionally.
2. The shear zone is a mylonite-ultramylonite domain comprising a distinct unit that is mostly mafic in origin (Sibișel Formation) and appears to have geochemical characteristics of island arc or back-arc basalts and basaltic andesites. We tentatively interpret the Sibișel Formation to represent a unit marking an oceanic suture (perhaps reflecting the closure of a small back-arc basin).
3. Terrane docking/juxtaposition during the latest Permian to Triassic is unexpected given known regional geologic events [Săndulescu, 1984] and is indicative of convergent/transform tectonic activity related to the closure of the Paleotethys.

Additional data from similar shear zones from the South and East Carpathians, as well as the Apuseni Mountains, will be required to test a regional tectonic model and put our results into a regional European tectonic context.

References

- Allmendinger, R. W., N. C. Cardozo, and D. Fisher (2013), *Structural Geology Algorithms: Vectors and Tensors*, 289 pp., Cambridge Univ. Press, Cambridge, England.
- Balintoni, I., D. I. Pană, R. A. Creaser, and I. A. Heaman (2001), The impact of recent Sm-Nd and U-Pb data on previous classifications of basement rocks in the Carpathians-Romania, *Gondwana Res.*, 4, 144–146, doi:10.1016/S1342-937X(05)70668-7.
- Balintoni, I., C. Balica, M. Ducea, F. Chen, H. Hann, and V. Sabliovschi (2009), Late Cambrian-Early Ordovician Gondwanan terranes in the Romanian Carpathians: A zircon U-Pb provenance study, *Gondwana Res.*, 16, 119–133, doi:10.1016/j.gr.2009.01.007.

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- Balintoni, I., C. Balica, M. Ducea, H. Hann, and V. Sabliovschi (2010a), The anatomy of a Gondwanan terrane: The Neoproterozoic-Ordovician basement of the pre-Alpine Sebeş-Lotru composite terrane (South Carpathians, Romania), *Gondwana Res.*, **17**, 561–572, doi:10.1016/j.gr.2009.08.003.
- Balintoni, I., C. Balica, M. N. Ducea, L. Zaharia, F. Chen, M. Cliveti, H. P. Hann, L.-Q. Li, and L. Ghergari (2010b), Late Cambrian-Ordovician northeastern Gondwanan terranes in the basement of the Apuseni Mountains, Romania, *J. Geol. Soc.*, **167**, 1131–1145, doi:10.1144/0016-76492009-156.
- Balintoni, I., C. Balica, M. N. Ducea, and H. P. Hann (2014), Peri-Gondwanan terranes in the Romanian Carpathians: A review of their spatial distribution, origin, provenance and evolution, *Geosci. Front.*, **5**, 395–411, doi:10.1016/j.gsf.2013.09.002.
- Balla, Z. (1987), Tertiary paleomagnetic data for the Carpatho-Pannonian region in light of Miocene rotation kinematics, *Tectonophysics*, **139**, 67–98, doi:10.1016/0040-1951(87)90198-3.
- Burchfiel, B. C. (1980), Eastern European Alpine system and the Carpathian orocline as an example of collision tectonics, *Tectonophysics*, **63**, 31–61, doi:10.1016/0040-1951(80)90106-7.
- Cherniak, D. J. (2010), Cation diffusion in feldspars, *Rev. Mineral. Geochem.*, **72**, 691–734, doi:10.2138/rmg.2010.72.15.
- Ciulavu, D., and G. Bertotti (1994), The Transylvanian Basin and its Upper Cretaceous substratum, *Rom. J. Tectonics*, **75**(2), 59–64.
- Ciulavu, M., R. F. Mahlmann, S. M. Schmid, H. Hofmann, A. Seghedi, and M. Frey (2008), Metamorphic evolution of a very low-to low-grade metamorphic core complex (Danubian window) in the South Carpathians, in *Tectonic Aspects of the Alpine-Dinaride-Carpathian System*, edited by S. Siegesmund, B. Fugenschuh, and N. Froitzheim, Geol. Soc., London, Spec. Publ., **298**, 281–315.
- Codârcea-Dessila, M. (1965), *Studiul Geologic și Petrografic al Regiunii Râșinari-Cisnădioara-Sadu*, Mem. Com. Geol., vol. 6, 96 pp., Inst. Geol. Rom., București.
- Codârcea-Dessila, M., and V. Iliescu (1967), Asupra prezenței depozitelor metamorfizate ale paleozoicului inferior în Carpații Meridionali Centrali (regiunea Râșinari-Cisnădioara-Sadu), *Stud. Cercet. Geol., Geofiz., Geogr.: Geol.*, **12**(2), 311–319.
- Codârcea-Dessila, M., R. Dimitrescu, and I. Stancu (1968), Sheet 27 Sibiu, Geological map of Romania, scale 1:200,000, State Comm. for Geol., Geol. Inst. of Romania.
- Dallmeyer, R. D., F. Neubauer, H. Fritz, and V. Mocanu (1998), Variscan vs. Alpine tectonothermal evolution of the Southern Carpathian orogen: Constraints from $^{40}\text{Ar}/^{39}\text{Ar}$ ages, *Tectonophysics*, **290**(1–2), 111–135, doi:10.1016/S0040-1951(98)00006-7.
- Dimitrescu, R., L. Olaru, and L. Ilnativ (1990), Contributions à la détermination de l'âge des formations cristallines du massif lezer-Păpușa, Dări de Seamă ale Ședințelor, *Inst. Geol. Geofiz.*, **74**(4), 5–11.
- Dinică, I. (1996), Structural evolution of the metamorphics in the Cibin Mountains, *Anu. Inst. Geol. Geofiz.*, **69**, 204–206.
- Dinică, I. (1998), Structure of the metamorphic rocks of the Olt Defile, between Sadu and Robești, *Anu. Inst. Geol. Geofiz.*, **70**, 172–176.
- Dodson, M. H. (1973), Closure temperature in cooling geo-chronological and petrological systems, *Contrib. Mineral. Petrol.*, **40**, 259–274.
- Drăgușanu, C., and T. Tanaka (1999), 1.57-Ga magmatism in the South Carpathians: Implications for the pre-Alpine basement and evolution of the mantle under the European continent, *J. Geol.*, **107**(2), 237–248.
- Drew, S. T., M. N. Ducea, and L. M. Schoenbohm (2009), Mafic volcanism on the Puna Plateau, NW Argentina: Implications for lithospheric composition and evolution with an emphasis on lithospheric foundering, *Lithosphere*, **1**, 305–318, doi:10.1130/L54.1.
- Ducea, M. N., and R. D. Roban (2016), The role of strike slip structures in the development of highly curved orogens: The Transcarpathian fault system, South Carpathians, *J. Geol.*, **124**, 519–527.
- Ducea, M. N., J. Ganguly, E. J. Rosenberg, P. J. Patchett, W. Cheng, and C. Isachsen (2003), Sm-Nd dating of spatially controlled domains of garnet single crystals: A new method of high-temperature chronology, *Earth Planet. Sci. Lett.*, **213**, 31–42, doi:10.1016/S0012-821X(03)00298-X.
- Ducea, M. N., J. B. Saleeby, and G. Bergantz (2015), The architecture, chemistry, and evolution of continental magmatic arcs, *Annu. Rev. Earth Planet. Sci.*, **43**, 299–331, doi:10.1146/annurev-earth-060614-105049.
- Dupont-Nivet, G., I. Vasiliev, C. G. Langereis, W. Krijgsman, and C. Panaiotu (2005), Neogene tectonic evolution of the southern and eastern Carpathians constrained by paleomagnetism, *Earth Planet. Sci. Lett.*, **236**(1), 374–387, doi:10.1016/j.epsl.2005.04.030.
- Gehrels, G. E., V. A. Valencia, and J. Ruiz (2008), Enhanced precision, accuracy, efficiency, and spatial resolution of U-Pb ages by laser ablation-multicollector-inductively coupled plasma-mass spectrometry, *Geochim. Geophys. Geosyst.*, **9**, Q03017, doi:10.1029/2007GC001805.
- Gheorghian, M., D. Gheorghian, and A. Schuster (1975), Sheet 92c Sibiu, Geologic Map of Romania, scale 1:50,000, Geol. Inst. of Romania.
- Gheuca, I. (1998), Lithostratigraphic and tectonic structure of the Lotru Group metamorphics, *Dări Seama Sedintelor Inst. Geol. Geofiz.*, **70**, 159–161.
- Hann, H. P. (1995), Central South Carpathians: Petrologic and structural investigations, *Rom. J. Petrol.*, **76**, 13–19.
- Iancu, V., T. Berza, A. Seghedi, I. Gheuca, and H. P. Hann (2005), Alpine polyphase tectono-metamorphic evolution of the South Carpathians: A new overview, *Tectonophysics*, **410**, 337–365, doi:10.1016/j.tecto.2004.12.038.
- Ionescu, C., V. Hoeck, C. Tomek, F. Koller, I. Balintoni, and L. Besuțiu (2009), New insights into the basement of the Transylvanian depression (Romania), *Lithos*, **108**, 172–191.
- Kounov, A., J. Graf, A. von Quadt, D. Bernoulli, J.-P. Burg, D. Seward, Z. Ivanov, and M. Fanning (2012), Evidence for a “Cadomian” ophiolite and magmatic-arc complex in SW Bulgaria, *Precambrian Res.*, **212–213**, 275–295, doi:10.1016/j.precamres.2012.06.003.
- Mațenco, L., G. Bertotti, C. Dinu, and S. Cloetingh (1997), Tertiary tectonic evolution of the external South Carpathians and the adjacent Moesian platform (Romania), *Tectonics*, **16**, 896–911, doi:10.1029/97TC01238.
- McCann, T., M. J. Timmerman, P. Krzywiec, J. Lopez-Gomez, A. Wetzel, C. M. Krawczyk, H. Rieke, and J. Lamarche (2006), Post-Variscan (end Carboniferous-Early Permian) basin evolution in western and central Europe, in *European Lithosphere Dynamics, Mem.*, vol. 32, edited by D. G. Gee and R. A. Stephenson, pp. 355–388, Geol. Soc. of London, London.
- Medaris, G., M. Ducea, E. Ghent, and V. Iancu (2003), Timing of high-pressure metamorphism in the Getic-Supragetic basement nappes of the South-Carpathian mountains fold-thrust belt, *Lithos*, **70**, 141–161, doi:10.1016/S0024-4937(03)00096-3.
- Merten, S., L. Mațenco, J. P. T. Foeken, F. M. Stuart, and P. A. M. Andriessen (2010), From nappe stacking to out-of-sequence postcollisional deformations: Cretaceous to Quaternary exhumation history of the SE Carpathians assessed by low-temperature thermochronology, *Tectonics*, **29**, TC3013, doi:10.1029/2009TC002550.
- Müller, W. (2003), Strengthening the link between geochronology, textures and petrology, *Earth Planet. Sci. Lett.*, **206**(3–4), 237–251, doi:10.1016/S0012-821X(02)01007-5.
- Nance, R. D., G. Gutiérrez-Alonso, J. D. Keppie, U. Linnemann, J. B. Murphy, C. Quesada, R. A. Strachan, and N. H. Woodcock (2010), Evolution of the Rheic Ocean, *Gondwana Res.*, **17**, 194–222, doi:10.1016/j.gr.2009.08.001.
- Negulescu, E., G. Săbău, M. N. Ducea, and H.-J. Massonne (2014), Sm-Nd garnet and U-Th-Pb, monazite ages in basement units of the South Carpathians: New data and a consistency check, in *Proceedings of the 20th Congress of the Carpathian-Balkan Geological Association September 24–26, 2014 Tirana, Albania, Bul. i Shkencave Gjeol.*, vol. 1(special issue), pp. 212–215, Balkan Geological Association, Tirana.
- Neubauer, F., and R. Handler (1999), Variscan orogeny in the eastern Alps and Bohemian Massif: How do these units correlate, *Mitt. Österreichischen Geol. Ges.*, **92**, 35–59.

- Oncescu, M., V. Mârza, M. Rîzescu, and M. Popa (1999), The Romanian earthquake catalogue between 1984–1997, in *Vrancea Earthquakes: Tectonics, Hazard and Risk Mitigation*, edited by F. Wenzel, D. Lungu, and O. Novak, pp. 43–47, Kluwer Acad., Dordrecht.
- Otamendi, J., M. Ducea, A. Tibaldi, G. Bergantz, J. de la Rosa, and G. Vujovich (2009), Generation of tonalitic and dioritic magmas by coupled partial melting of gabbroic and metasedimentary rocks within the deep crust of the Famatinian Magmatic Arc, Argentina, *J. Petrol.*, *50*(5), 841–873, doi:10.1093/petrology/egp022.
- Pană, D., and P. Erdmer (1994), Alpine crustal shear zone and pre-Alpine basement terranes in the Romanian Carpathians and Apuseni Mountains, *Geology*, *22*, 807–810.
- Pătrașcu, S., C. Panaiotu, M. Șeclăman, and C. E. Panaiotu (1994), Timing of rotational motion of Apuseni Mountains—Paleomagnetic data from Tertiary magmatic rocks, *Tectonophysics*, *223*, 163–176, doi:10.1016/0040-1951(94)90239-9.
- Profeta, L., M. N. Ducea, J. B. Chapman, S. R. Paterson, S. M. Henriquez Gonzales, M. Kirsch, L. Petrescu, and P. G. DeCelles (2015), Quantifying crustal thickness over time in magmatic arcs, *Sci. Rep.*, *5*, 17786, doi:10.1038/srep17786.
- Ratschbacher, L., H. G. Linzer, F. Moser, R.-O. Strusievcz, H. Bedelea, N. Har, and P.-A. Mogoș (1993), Cretaceous to Miocene thrusting and wrenching along the Central South Carpathians due to a corner effect during collision and orocline formation, *Tectonics*, *12*, 855–873, doi:10.1029/93TC00232.
- Reiners, P. W., T. L. Spell, S. Nicolescu, and K. A. Zanetti (2004), Zircon (U-Th)/He thermochronometry: He diffusion and comparisons with ⁴⁰Ar/³⁹Ar dating, *Geochim. Cosmochim. Acta*, *68*(8), 1857–1887, doi:10.1016/j.gca.2003.10.021.
- Rollinson, H. (1993), *Using Geochemical Data: Evaluation, Presentation, Interpretation*, 352 pp., Longman Group Ltd., England.
- Rossel, P., V. Oliveros, M. Ducea, R. Charrier, S. Scaillet, L. Retamal, and O. Figueroa (2013), The Early Andean subduction system as an analogue to island arcs: Evidence from across-arc geochemical variations in northern Chile, *Lithos*, *179*(2), 211–230, doi:10.1016/j.lithos.2013.08.014.
- Săbău, G. (1998), The manganese-silicate rocks in the Lotru Metamorphic Suite: An example of mineral concentration driven by metamorphic processes, *Dari Seama Sedintelor-Inst. Geol. Geofiz.*, *70*, 162–167.
- Săbău, G., and H.-J. Massonne (2003), Relationships among eclogite bodies and host rocks in the Lotru Metamorphic Suite (South Carpathians, Romania): Petrological evidence for multistage tectonic emplacement of eclogites in a medium-pressure terrain, *Int. Geol. Rev.*, *45*(3), 225–262, doi:10.2747/0020-6814.45.3.225.
- Săndulescu, M. (1984), *Geotectonica României*, 336 pp., Editura Tehnică, București.
- Săndulescu, M. (1988), Cenozoic tectonic history of the Carpathians, in *The Pannonian Basin: A Study in Basin Evolution, Mem.*, vol. 45, edited by L. H. Royden and F. Horváth, pp. 17–25, AAPG, Houston, Tex.
- Schmid, S., D. Bernoulli, B. Fügenschuh, L. Mañenco, S. Schefer, R. Schuster, M. Tischler, and K. Ustaszewski (2008), The Alpine-Carpathian-Dinaridic orogenic system: Correlation and evolution of tectonic units, *Swiss J. Geosci.*, *101*, 139–183, doi:10.1007/s00015-008-1247-3.
- Stampfli, G. M., and G. D. Borel (2002), A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrones, *Earth Planet. Sci. Lett.*, *196*, 17–33, doi:10.1016/S0012-821X(01)00588-X.
- Stampfli, G. M., J. von Raumer, and C. Wilhem (2011), The distribution of Gondwana derived terranes in the early Paleozoic, in *The Ordovician of the World, Cuad. del Mus. Geomin.*, vol. 14, edited by J. C. Gutiérrez-Marco, I. Rábano, and D. García-Bellido, pp. 567–574, Inst. Geol. y Min. de España, Madrid.
- Stoica, A. M., M. N. Ducea, R. D. Roban, and D. Jianu (2016), Origin and evolution of the South Carpathians basement (Romania): A zircon and monazite geochronologic study of its Alpine sedimentary cover, *Int. Geol. Rev.*, *58*(4), 510–524, doi:10.1080/00206814.2015.1092097.
- Streckeisen, A. (1934), Sur la tectonique des Carpathes Méridionales, *Anu. Inst. Geol. Rom.*, *16*, 327–417.
- Sun, S.-S., and W. F. McDonough (1989), Chemical and isotopic systematics of oceanic basalts: Implications for mantle composition and processes, in *Magmatism in the Ocean Basins, Spec. Publ.*, vol. 42, edited by A. D. Saunders, and M. J. Norry, Geol. Soc., London, Spec. Publ., *42*, 313–345, doi:10.1144/GSL.SP.1989.042.01.19.
- Toljić, M., L. Mañenco, M. N. Ducea, U. Stojadinovic, and J. Milivojenic (2013), The evolution of a key segment in the Europe-Adria collision: The Fruska Gora of northern Serbia, *Global Planet. Change*, *103*(1), 39–62, doi:10.1016/j.gloplacha.2012.10.009.
- Udubașă, G., and H. P. Hann (1988), A shear-zone related Cu-Au ore occurrence: Valea lui Stan, South Carpathians, *Dări de Seamă ale Ședințelor, Inst. Geol. Geofiz.*, *72–73*(2), 259–282.
- Villa, I. M. (2016), Diffusion in mineral geochronometers: Present and absent, *Chem. Geol.*, *420*, 1–10, doi:10.1016/j.chemgeo.2015.11.001.
- von Raumer, J., F. Bussy, and G. M. Stampfli (2011), Les Alpes paléozoïques—De la marge de Gondwana à la collision varisque, *Géochronique*, *137*, 34–37.
- von Raumer, J. F., F. Bussy, U. Schaltegger, B. Schulz, and G. M. Stampfli (2013), Pre-Mesozoic Alpine basements—Their place in the European Paleozoic framework, *Geol. Soc. Am. Bull.*, *125*, 89–108, doi:10.1130/B30654.1.
- Whitney, D. L., and B. W. Evans (2010), Abbreviations for names of rock-forming minerals, *Am. Mineral.*, *95*, 185–187.