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**Special Section:**
Tectonic evolution of West-Central Tethysides

**Key Points:**
- The Persani volcanic field shows clear temporal geochemical and temperature patterns
- These patterns are indicative of two components: one lithospheric and one asthenospheric present in the magmas
- These results are consistent with the slab rollback and/or delamination hypothesis under the SE Carpathians

**Supporting Information:**
- Supporting Information S1

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# Temporal-Geochemical Evolution of the Persani Volcanic Field, Eastern Transylvanian Basin (Romania): Implications for Slab Rollback Beneath the SE Carpathians

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**Abstract** The Quaternary Persani volcanic field (PVF) consists of alkali basalts formed in an extensional basin at the SE end of the Transylvanian basin, near an important anomaly in the European mantle, the Vrancea slab, a seismically active near-vertical lithospheric fragment of debated origin. The PVF is the only basaltic field regionally, has been studied geochemically in the past, and is also known for the presence of abundant mantle xenoliths. Here, we describe new geochemical data on rocks recently dated by Ar-Ar chronometry and show that while we can reproduce virtually all previous results, there is a clear temporal evolution of the magmatic system. There is an increase of over 80°C in temperatures determined by the Si activity thermometer, from 1,300°C to 1,380°C during the ~0.5-Myr duration of volcanic activity, which is accompanied by several coherent trends in geochemistry, among which the decrease of Zn/Fe and $^{87}Sr/^{86}Sr$ ratios over time. Earlier, higher Zn/Fe ratios are indicative of a pyroxenite/eclogite-dominated source, which gradually changed to a peridotite-dominated source. These characteristics are typical of a dynamic mantle in which vertical mantle lithosphere tectonics, either due to slab rollback or mantle dripping plays a role and are not consistent with simple decompression melting of asthenosphere. Synchronous adakitic rocks found about 25–30 km east of PVF are presumed to be slab melts and are consistent with the Vrancea slab rollback as the trigger for mantle melting responsible for the PVF.

## 1. Introduction

The southeastern Carpathians highly curved oroclinal bend in Romania has a distinctive surface geometry which is also accompanied by the presence of a descending slab at 100–500 km beneath the surface, under the Vrancea region (Martin et al., 2006; Oncescu et al., 1984). This slab has a limited extent horizontally (~60 km) and generates the largest present day strain concentration and highest seismicity in Europe today (Ismail-Zadeh et al., 2012; Wenzel et al., 1999). Crustal earthquakes are also present, but there is a clear gap of seismicity in the mantle documenting that whatever its origin, this fragment inferred to be lithospheric in origin is now detached from the lithosphere. There is uncertainty with regard to what are the plausible mechanisms for bringing this lithospheric slab/drip in near vertical position (Figure 1). The leading hypotheses for the origin of this slab/drip are that it is (a) the remnant of a slab subducted from the foreland side to the east, which was initially shallowly subducted under Transylvania and Pannonia but underwent slab rollback and eventual detachment when nearly vertical (Horváth et al., 2006; Royden et al., 1983; Wortel & Spakman, 2000), or (b) a fragment of delaminated lithosphere confined to the narrow corner of the oroclinal bend (Knapp et al., 2005) which presumably underwent high magnitude shortening and unusual crustal thickening. A mix of the two end member ideas is the trap-door delamination hypothesis (Fillerup et al., 2010; Gîrbacea & Frisch, 1998) in which a continental lithospheric fragment possibly containing eclogitic lower crust, initially flat under Transylvania, underwent delamination sensu Bird (1979). It has become clearer in recent years that the thickness of the Vrancea slab (>100 km and possibly over 150 km) makes it most likely a fragment of the foreland continental lithosphere subducted under the Carpathians (Şengül-Uluocak et al., 2019), while any leading oceanic fragment is not detectable today in the geophysical data. Therefore, whenever we refer to the "Vrancea slab" in this paper, we envision a piece of continental lithosphere containing a sizable portion of crust being subducted and undergoing ultrahigh pressure

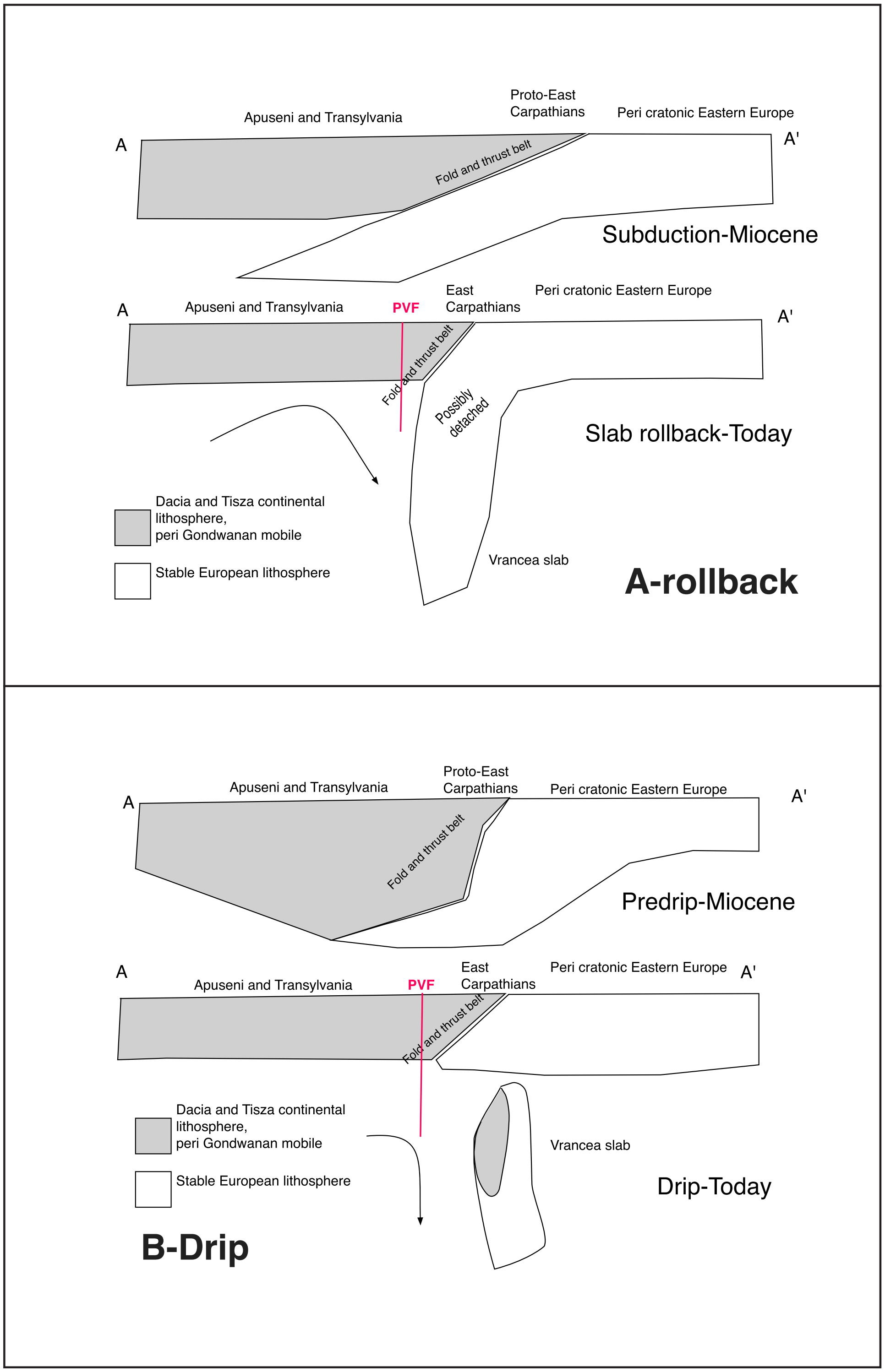


**Figure 1.** (a) Rollback hypothesis: a low angle European continental lithosphere subducting under the Carpathians during the Miocene rolls back to near vertical position during the Quaternary and attains the modern day position of the Vrancea slab; (b) Drip/RT instability hypothesis: a thickened crust/lithosphere of the Carpathians due to continental collision and formation of the East Carpathians during the Miocene–Pliocene leads to density driven foundering of the lower lithosphere during the Quaternary and the current Vrancea drip. A-A′ are the locations of these schematic cross sections on the simplified geologic map of Figure 2a. The two hypotheses are detailed in the introduction and throughout the geodynamic implications section of the text. These schematic diagrams are no to vertical scale.

metamorphism, similar to the Pamirs (Ducea et al., 2003). The Vrancea slab is arguably the best continental example of active vertical tectonics in which a lithospheric piece is unquestionably descending into the asthenospheric mantle. The entire region is characterized by relatively thin crust, and topography is in part dynamically supported from the uppermost mantle (Şengül-Uluocak et al., 2019).

The Quaternary alkali basaltic Persani volcanic field (PVF) (Seghedi et al., 2016, Downes et al., 1995 and some older regional references therein) is located about 75 km west of the Vrancea slab and comprises the only direct mantle-derived material that can shed some light into the nature of dripping. The presence of numerous mantle xenoliths (Falus et al., 2008; Vaselli et al., 1995) in many of the PVF basalts makes the "archive" of mantle material at PVF even more appealing. A recent high precision Ar-Ar study (Panaiotu et al., 2013) resolved the chronology of various basalts in the PVF in great detail. Earlier geochemical-petrologic studies of the PVF (Downes et al., 1995; Harangi et al., 2013) report high-quality data but are difficult to place in the temporal progression established by Panaiotu et al. (2013). On the other hand, basalt petrology and especially those studies targeting dynamic processes in the mantle require understanding of the temporal evolution at the scale of the volcanic field (Blondes et al., 2008). Delamination-related magmatism in particular is expected to produce basalts that are progressively hotter and change from a lithospheric drip-dominated to an asthenosphere-dominated signature (Elkins-Tanton, 2007, Ducea et al., 2013). Continental extension-driven basaltic magmatism forms due to adiabatic upwelling of asthenospheric mantle (Wang et al., 2002) filling up space vacated by the extending and thinning lithosphere; magmas of that origin will show similar temperatures throughout the lifetime of volcanism, since an upwelling adiabat does not change much in temperature within the range of plausible depths of continental extension-related basaltic magmatism.

Here, we present new geochemical and isotopic data on samples collected from the locations of the Panaiotu et al. (2013) chronologic study of the PVF. We show that while our data are perfectly consistent with the data trends from earlier studies of the PVF, they also do show distinctive temporal trends that are consistent with some form of convective removal or slab rollback and not just with continental extension. We then place these results in a regional perspective and speculate that the rolling back Vrancea continental slab may be responsible for the generation of PVF as well as nearby synchronous adakitic volcanism.

## 2. Geologic Background

The regional geology of the Carpathians consists of units assembled during the Alpine orogeny (Balintoni et al., 2014, Figure 2a). The south Carpathians were formed during the early Cretaceous by the closure of a thin Jurassic ocean and are dominated by Paleozoic basement rocks. The East Carpathians represent a fold a thrust belt riding over the European platform to the east; they comprise primarily Cretaceous to Pliocene marine sedimentary units that were part of the Alpine Tethys and later the Paratethys and that were assembled during compression during the latter parts (Miocene–Pliocene) of the Cenozoic. Uplift near the oroclinal bend is the youngest in the Carpathians (Matenco et al., 2010). The Transylvanian basin is filled with Cretaceous to young sediments and should perhaps contain the high heat flow of the Panonnian basin the west given its thin crust and mantle lithosphere (Demetrescu & Andreescu, 1994) but instead is cold; this was taken as an indication of a very young thinning of the lithosphere, possibly related to delamination or slab rollback of the Vrancea slab/drip.

The PVF is located in the southeastern part of the Transylvanian basin near the southern end of the East Carpathians (Figure 2a) and is Quaternary in age. It contains flows, maars, and cinder cones with Ar-Ar ages of 1.2–0.68 Ma (Panaiotu et al., 2013). Ages indicate six volcanic events (Seghedi et al., 2016) with the one at 1.06 Ma, dwarfing the other ones by volume. More than 90% of the effusive products were formed at 1.06 Ma, which happens to be the third eruptive moment in the life of PVF. There is no spatial migration of volcanism over that time period. The total volume of effusive products is estimated based on outcrop coverage and thicknesses of flows/cinder cones to be no more than 1 km$^3$. Errors reported on those ages by Panaiotu et al. (2013) are typically around 0.03 Ma or less; consequently, the age distinction in separate events is well resolved.

Volcanism is located in a small unnamed sub-basin of the Brasov basin near the villages of Racos and Bogata (Figure 2b), which is one of the several extensional basins formed immediately west of the East Carpathians in SE Transylvania (Ciulavu et al., 2000; Gîrbacea et al., 1998). These basins are

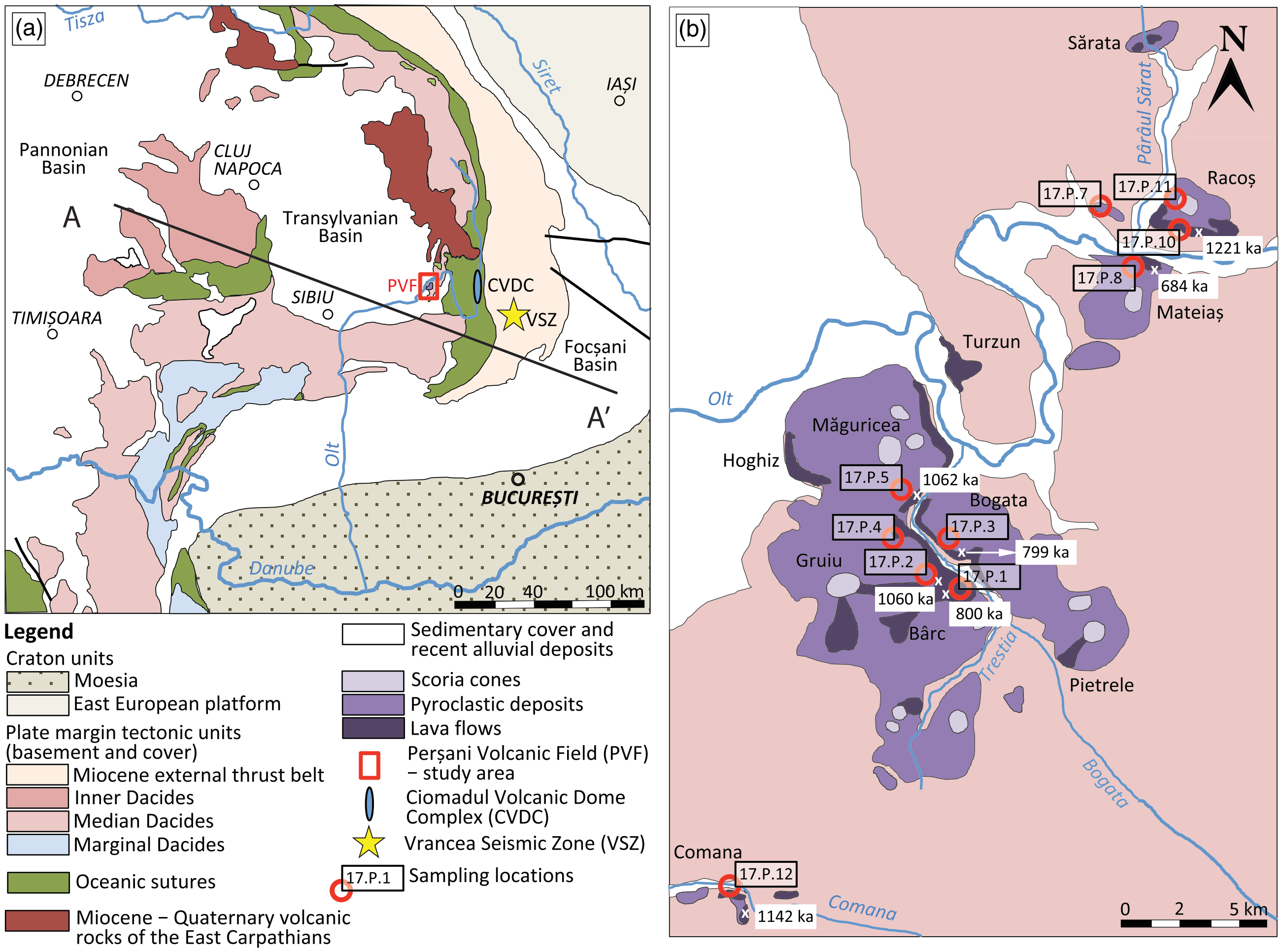


**Figure 2.** (a) Schematic map showing the studied area within the context of major Alpine tectonic features of the Romanian Carpathians. Modified after Săndulescu (1984) and Balintoni et al. (2014); line A-A′ represents the transect along which schematic cross sections of Figure 1 were depicted to intersect the surface. (b) Map of Perani Mountains volcanic field showing sampling locations for this study. Modified after Panaiotu et al. (2013).

morphologically obvious on satellite maps and several normal faults are visible in outcrops of the PVF; they cut some of the earlier lava flows (Ciulavu et al., 2000), and therefore, deformation was at least in part synchronous with magmatism. Ciulavu et al. (2000) document that volcanic centers are found along NE-SW trending normal faults. The association with continental extension is therefore clear despite the lack of a good local-scale geologic map.

Basaltic volcanic rocks rest on a variety of rock formations, most commonly on Triassic and Jurassic limestones, on Cretaceous flyschoid sandstones and shales, and on poorly dated Miocene rhyolitic tuffs (Seghedi et al., 2016). When exposed in quarries, stratigraphic (vertical) relationships generally reveal several volcanic products at any given location (scoria, tuffs, flows) separated by lacustrine or fluvial deposits.

Volcanism is alkali-basaltic at PVF (Downes et al., 1995; Harangi et al., 2013; Seghedi et al., 2011) with most lava and scoria cones displaying primitive compositions (MgO >8%, Mg# >60, and silica around 48%). Harangi et al. (2013) used the classic Langmuir et al. (1992) algorithm to determine pressures of 2–2.5 GPa of magma origin and normal mantle adiabatic temperatures in the 1,350–1420°C range. These data all agree that PVF volcanic rocks are to a first-order Ocean Island Basalts (OIB)-like (as referred to by Downes et al., 1995) in the sense that they are true asthenospheric melts with little evidence for subduction-related pollution. Harangi et al. (2013) allow for possible contributions from the mantle lithosphere and document the fast ascent of most PVF magmas. There are no obvious high field strength elements (HFSE) depletions in these lavas, and they are overall enriched relative to the depleted mantle. In detail, however, when compared to the other basaltic fields from the Pannonian region (Lustrino & Wilson, 2007), they are similar in most respects (isotopically, trace elements) but have a subtle subduction component (Downes et al., 1995).

The primitive nature of these rocks is supported by the presence of ultramafic xenoliths (predominantly spinel peridotites, rare garnet-free pyroxenites) in about 10 of the flows and scoria cones spanning the entire age range of the field. They represent fragments of the subcontinental mantle lithosphere (Vaselli et al., 1995), have radiogenic (Sr, Nd, and Pb) isotopic compositions that are distinct from the host basalts and Pannonian basalts in general (Vaselli et al., 1995). The highly depleted isotopic compositions of most of these spinel peridotites (with $\varepsilon_{Nd}$ as high as +18), differentiates them from the host basalts. Otherwise, these mantle xenoliths carry plenty of evidence for some subduction-related modal metasomatic enrichment, in the form of amphibole megacrysts (Vaselli et al., 1995) and various cross cutting veins including those of carbonates (Chalot-Prat & Girbacea, 2000). It is unclear at this time which subduction event do these features belong, the youngest compressive events making up the modern Carpathians or some older event; no data are available to put constrains on the timing of metasomatism.

The other important regional aspect of volcanism in the PVF is the distribution of other volcanic fields nearby. As it stands, the PVF is the only young basaltic field in all of the SE Transylvanian extensional (or intermontane as sometimes referred to as) basins. The closest similar basaltic field is Lucaret, an early Quaternary outpouring of basalts located about 350 km to the west at SE end of the Pannonian basin (Seghedi, Downes, Szakacs, et al., 2004). Far more important regionally is the chain of Miocene-Quaternary calk-alkaline volcanoes migrating from northern (Calimani/Gurghiu) to southern (Harghita) locations, along a NW-SE line that is offset about 30 km from the PVF (Seghedi et al., 2019). The southernmost, youngest (and active) volcano of that chain, Ciomadul, is located about 35 km from PVF. The closest volcanic products (31 km in a straight line east of PVF) are a series of intermediate volcanic and subvolcanic bodies (e.g., Malnas, Bixad, Balvanyos, Puturosul, and Baba Lapos) which are contemporaneous with, or even younger (e.g., Turnu Lapor) than the PVF (Molnár et al., 2018). They all have adakitic and shoshonitic characteristics and are all interpreted to be Ciomadul-related (Molnár et al., 2018). All of the volcanic products of the Miocene-Quaternary calk-alkaline arc (which extends to the north into Ukraine and beyond, Seghedi, Downes, Vaselli, et al., 2004 and references therein) are more siliceous (andesites, dacites, and more silicic rocks) and are very similar to subduction magmatism; the origin of the East Carpathians young magmatism (Mason et al., 1995; Seghedi & Downes, 2011; Seghedi, Downes, Szakacs, et al., 2004; Seghedi, Downes, Vaselli, et al., 2004) remains puzzling and highly debated since there is certainly no ongoing oceanic subduction today or since the Miocene, although various speculative tectonic and magmatic models abound (Maţenco et al., 2007; Seghedi et al., 2011; Wortel & Spakman, 2000). Yet intermediate volcanism regionally must bear some relevance to the PVF given their proximity and overlap in age.

### 2.1. Samples and Analytical Techniques

Ten basalt samples from various eruptive sites within PVF (Figure 2) were collected and analyzed in this study from the sites previously sampled by Panaiotu et al. (2013) for their geochronologic study. They were selected to be among the most representative locations in PVF and obviously to span the entire life of the volcanic field. Whole-rock major and trace elements compositions were determined at ActLabs (Canada; http://www.actlabs.com/). Whole-rock samples were analyzed by X-ray fluorescence (XRF) for major elements following a lithium tetraborate fusion and inductively coupled plasma mass spectrometer (ICP/MS) for trace elements following acid digestion (Longerich et al., 1990). Duplicate and standard samples analysis results were used to ensure data reliability. Major elemental uncertainty is around 0.5% or less, and ICP-MS uncertainties are less than 5% and typically around 2%. This means that virtually all geochemical plots in this paper containing elemental concentrations or ratios of elements have errors smaller than the size of symbols.

All isotopic work was performed in the Arizona Radiogenic Isotope Facility at the University of Arizona. Isotopic separation was carried out in chromatographic columns via HCl elution. Conventional cation columns filled with AG50W-X4 resin were used for Sr and REEs separation and anion columns with LN Spec resin for Nd separation (Drew et al., 2009; Otamendi et al., 2009). Subsequently, Sr cuts were loaded onto Ta single filaments and Nd cuts onto Re filaments. Isotopic analyses were performed using a VG Sector 54 thermal ionization mass spectrometer instrument fitted with adjustable $10^{11}$ Ω Faraday collectors and Daly photomultipliers. NBS SRM 987 Sr standard and La Jolla Nd standard were analyzed during the sample run in order to ensure the stability of the instrument. All whole rock geochemistry results (elemental and isotopic) are presented in Table S1 in the supporting information. Errors on isotopic ratios are around 10 ppm for Sr isotopes and 12 ppm for Nd isotopes.

Determination of rock-forming minerals textural and chemical features was performed at the University of Arizona Electron Microprobe Laboratory. Combined microscopic and backscattered electron images were used for textural characterization of the mineral phases. Chemical composition of these phases was determined using CAMECA SX100 Ultra electron probe micro analyzer equipped with five wavelength dispersive spectrometer (WDS) spectrometers and one Energy dispersive spectrometer (EDS) detector. The instrument was calibrated using natural and synthetic standards. Analyses were performed using the following operating conditions: 15-keV accelerating voltage, 20-nA beam current, 20-s counting time in peak position for major elements, and 15 keV, 100 nA, and 30 s for minor elements. Olivine and clinopyroxene crystals were analyzed, together with adjacent glass for subsequent thermobaric computation. Results are given in Table S2.

## 3. Results

### 3.1. Petrography

Our rocks are basaltic with aphanitic to weakly porphyritic textures (Figure 3). All samples are massive, with the exception of one Racos sample, which is scoriaceous (up to 40 vol.% vesicles). Barc, Bogata, and Mateias localities contain abundant mantle-derived xenolith inclusions. The phenocryst assemblage is dominated by olivine and, more rarely, clinopyroxene, set in a microcrystalline groundmass consisting of plagioclase, clinopyroxene, olivine, Fe-Ti oxides, nepheline, and minor glass. Phenocryst contents are slightly variable but generally show low modal proportions (less than 10% by volume), ranging from 0.4 to 1.7 mm in size for olivine and <1 mm for clinopyroxene grains, respectively.

Olivine grains occur mostly as euhedral to subhedral phenocrysts with rounded spinel inclusions and as fine-grained, subrounded crystals and glomerophyric aggregates in the groundmass. In addition, rare olivine xenocrysts have been identified. Most olivines lack any visible alteration products, except for three samples (Barc samples 17P01 and 17P02 and Bogata sample 17P05) in which most olivines display thin (10–30 μm), reddish-brown iddingsite alteration coronas along cracks and at mineral margins, which were avoided during microprobe data acquisition. The forsterite content of olivine grains varies significantly between phenocrysts and groundmass crystals. Xenocryst olivines were not analyzed in this study; however, previous published data on mantle xenolith-hosted olivines from Persani region (Falus et al., 2008; Vaselli et al., 1995) show marked compositional differences compared to our results. Olivine phenocrysts have high-Mg compositions and show a wide core-rim variation ($Fo_{84–88}$ at core, and $Fo_{70–74}$ at rims). They display high core-to-rim concentration gradients in their major elements with Mn and Ca enrichments toward the margins, coupled with core-to-rim Ni depletion. Nickel values range between 0.15 and 0.28 wt.% NiO at cores, and 0.06 and 0.15 wt.% at rims; CaO values are 0.07–0.23 wt.% at cores, and 0.31–0.48 wt.% at rims, while MnO values are 0.14–0.25 wt.% at cores and 0.27–0.83 wt.% at rims. In contrast, groundmass olivines are significantly less magnesian, with core and rim compositions of $Fo_{63–76}$ and $Fo_{56–71}$, respectively. Groundmass olivines are largely similar in their major element content, with limited ranging NiO (0.06–0.12 wt.%), MnO (0.49–0.66 wt.%), and CaO (0.22–0.47 wt.%) core values. They preserve similar, but much attenuated, major element zonation trends as olivine phenocrysts.

### 3.2. Major Element Chemistry and Thermometry

Rocks studied here are basalts and trachybasalts according to the TAS classification scheme (not pictured), as also previously determined by Downes et al. (1995). All but one studied rock have MgO in excess of 8 wt.% suggesting they are relatively primitive rocks. The presence of mantle xenoliths in six of the analyzed materials further indicates that these magmas did not experience much crustal contamination or fractionation along the way. Mg#'s are with one exception, > 0.62.

We calculated temperatures for individual eruptions with the magnesium and silica-activity thermometer, which uses bulk rock chemistry (Lee et al., 2009) and assumes that mafic melts, whatever their ultramafic source, ultimately equilibrated with an olivine-rich mantle before leaving the mantle. Errors on temperatures are estimated to be around 10°C. Temperatures range from 1,309°C to 1,387°C (Table S1). We also used the clinopyroxene-glass thermometer (Putirka, 2008), as an independent check of temperatures, which

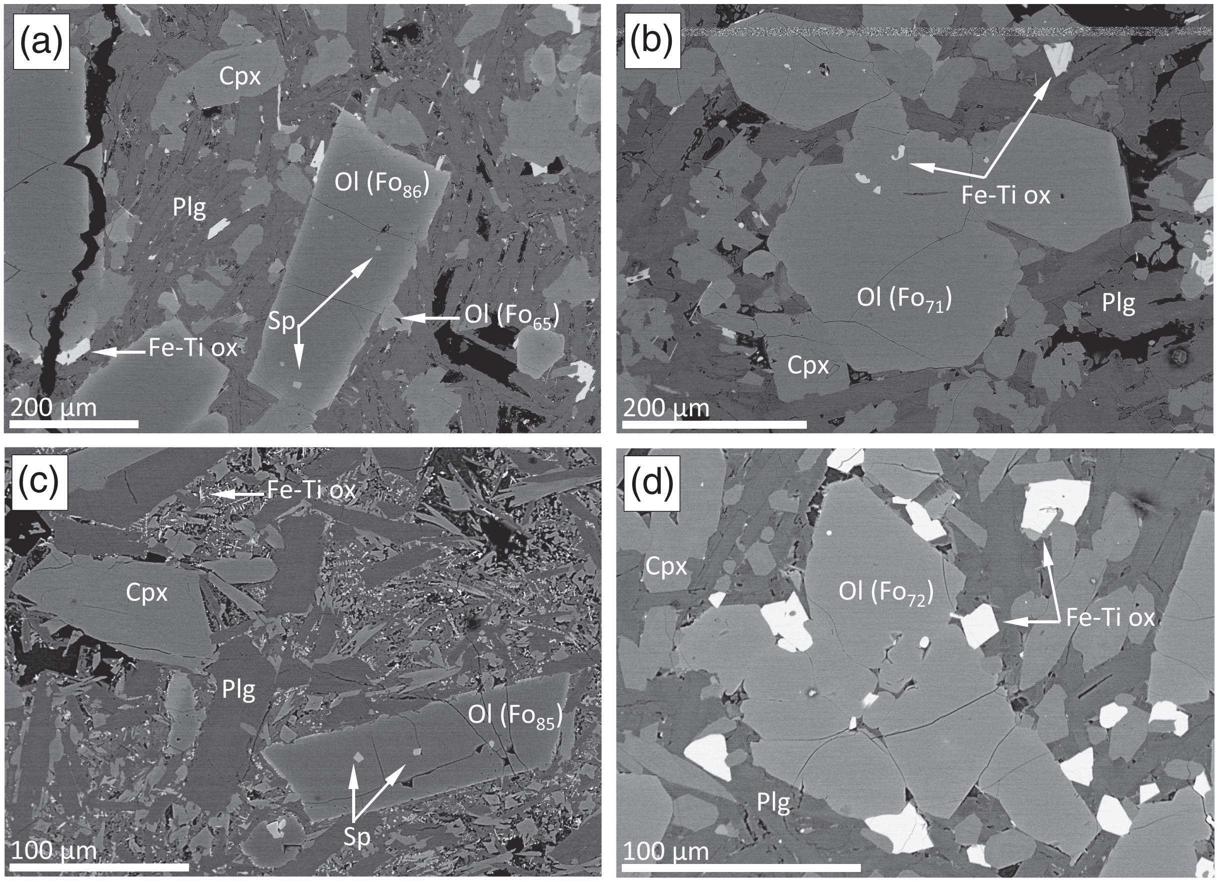


**Figure 3.** Petrographic features of Persani rocks, shown in SEM backscatter images: (a) zoned, euhedral microphenocrysts of Mg-rich olivine with rounded spinel inclusions and smaller clinopyroxene, Fe-rich olivine, plagioclase laths, and Fe-Ti oxides (sample 17.P.5, Bogata); (b) homogeneous, euhedral olivine microphenocryst with Fe-Ti oxide inclusions in a groundmass of plagioclase, glomerophyric aggregates of clinopyroxenes and Fe-Ti oxides (17.P.7, Mateias); (c) microphenocrysts of clinopyroxene, plagioclase, and high-Mg, zoned olivine with euhedral and subhedral spinel inclusions in a groundmass of olivine, plagioclase, clinopyroxene, and skeletal Fe-Ti oxides (17.P.11, Racos); (d) subhedral olivine showing incipient reabsorption texture and smaller clinopyroxene, plagiclase, and euhedral to subhedral Fe-Ti oxides (17.P.12, Comana). Ol: olivine; Sp: spinel; Cpx: clinopyroxene; Plg: plagioclase; Fe-Ti ox: Fe-Ti oxide.

yielded results within the error of the silica activity temperature calculations. These calculations assume dry melting and thereby represent maximum temperatures.

### 3.3. Trace Elements

Trace elemental patterns in spider-diagrams show an enriched light REE pattern relative to a chondrite source (Figure 4a) as well as a similar trend (previously labeled as OIB-like by Downes et al., 1995) in a spider-diagram including a larger array of incompatible trace elements (Figure 4b). Rare earth elements are most consistent with a small degree of partial melting in the spinel stability field of peridotites given the relatively flat concentrations of MREE and HREEs. However, garnet is likely to have been present in a pyroxenite/eclogite component (see below) given the steep LREE/HREE patterns. What stands out on Figure 4b is that there is no strong evidence for cryptic a “subduction” imprint in these rocks and their sources (as evidence by the lack of high filed strength element anomalies, e.g., Nb or Ta). Downes et al. (1995) indicated that compared to other Pannonian basin recent basaltic fields, some of these rocks do have a “small subduction” component.

Transition metals and their ratios (Le Roux et al., 2010) show good correlations among themselves (Figure 5) as well as with age (see below). The great majority of samples fall within a dominantly peridotite source with regard to Zn/Fe ratios (and equivalents Mn/Fe, etc.), but there is a correlation pointing toward pyroxenite-present melting (higher Zn/Fe) in the earlier melts. Overall, we interpret this to represent a peridotite-dominated melting environment with an eclogite or pyroxenite dominated in the

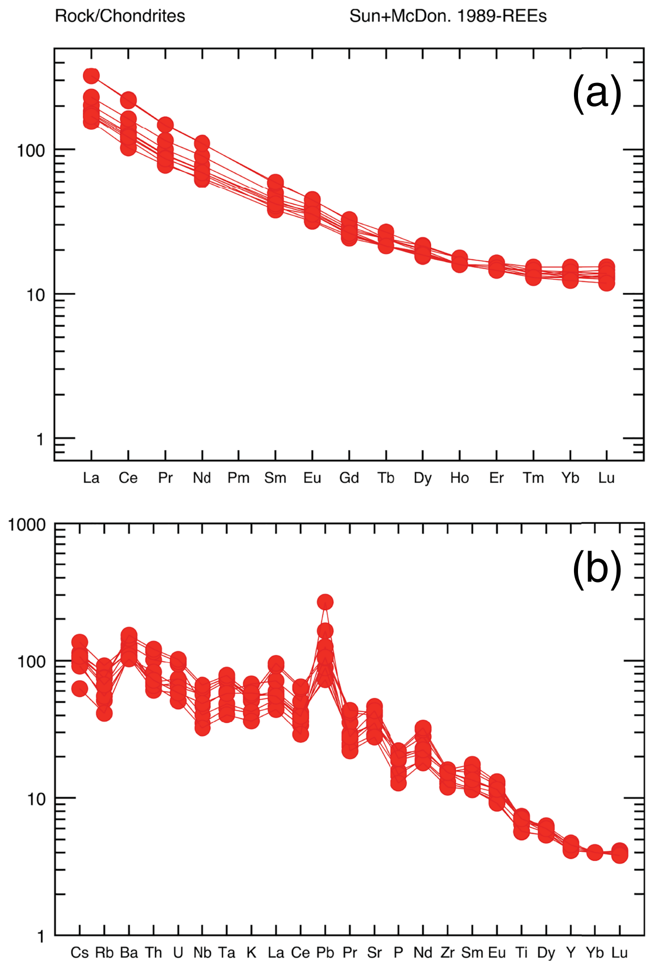


**Figure 4.** (a) Normalized rare earth element and (b) extended trace element patterns for Persani Mountains volcanic field samples. Normalizing values are from Sun and McDonough (1989) and represent primitive mantle.

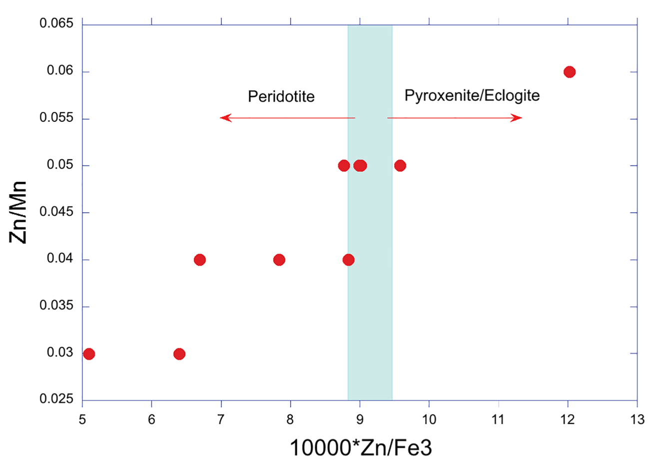


**Figure 5.** Transition metal correlations in the database: $10^4 \times$ Zn/Fe versus Zn/Mn (see also Figure 7).

earliest phase of melting, a signal subdued in later, exclusively peridotite-derived melts. A weaker correlation also exists between Zn/Fe and MgO (not pictured), where MgO is taken to represent how primitive the basaltic rock is. More primitive rocks contain less of the pyroxenite component. The correlation of age with Zn/Fe and other pyroxenite/peridotite discriminant diagrams suggests that pyroxenite sources were present in all melts but had a diminished preponderance in younger melts (Ducea et al., 2013).

### 3.4. Radiogenic Isotopes

Sr and Nd isotopes span the classic mantle array of Zindler and Hart (1986) (Figure 6) and occupy some of the most depleted (in Sr isotopes) space of the Pannonian basaltic field (Downes et al., 1995). These isotopes are fully consistent with a mix of lithospheric and asthenospheric compositions of these magmatic rocks in which the asthenospheric component was dominant. Isotopes correlate with relevant chemical parameters (Zn/Fe or Mn/Fe) indicating that the most evolved isotopic rations (higher $^{87}$Sr/$^{86}$Sr and lower $^{143}$Nd/$^{144}$Nd) correspond to the more eclogite or pyroxenite-sourced melts.

### 3.5. Temporal Changes in Chemistry

High precision Ar-Ar ages (Panaiotu et al., 2013) correlate positively with Sr isotopes and Zn/Fe and inversely with temperature (Figure 7). Other significant correlations (not pictured) are with La/Yb, Zn/Mn, Nd isotopes as well as several trace elements. Mg# does not correlate well with age. The decrease in Zn/Fe and increase in temperature toward young ages are signature features of a dynamic mantle with colder eclogite/pyroxenite-melting products (possibly mixed with peridotite melts) earlier in the life of the volcanic field, followed by hotter, peridotite-derived melts (Ducea et al., 2013).

## 4. Discussion

The salient results of this study is that our data show clear chemical temporal patterns in the PVF. Notably, the parameters indicating pyroxenite/peridotite sources in the melt (Le Roux et al., 2010) such as Zn/Fe are decreasing with time, suggesting an eclogite or pyroxenite-dominated source in the early stages of volcanism, leading way to higher proportions of peridotite source in the melt (although the proportions are impossible to quantify since we do not know the exact compositions of the end members). Second, the temperatures of magma increased about 80°C over the course of magmatism, which is outside of the error of estimating these values. Isotopes also vary with time from more depleted to slightly more enriched radiogenic Nd isotopes (and the opposite for Sr isotopes). These signatures represent positive tests for a dynamic mantle source in which early eclogite or pyroxenite-derived melts of the mantle lithosphere give way to hotter asthenospheric melts sourced primarily by peridotites. This scenario is consistent with a either a Rayleigh Taylor instability or some other form of lithospheric delamination (Elkins-Tanton, 2007; Ducea et al., 2013) or multicomponent melting during slab rollback and not with the simple mechanism of decompression-related melting in response to continental extension; any of the models shown schematically in Figure 1 would allow for such a pattern. The primary trace elements signature of the youngest rocks in the PVF, those also characterized by higher temperatures, are OIB-like

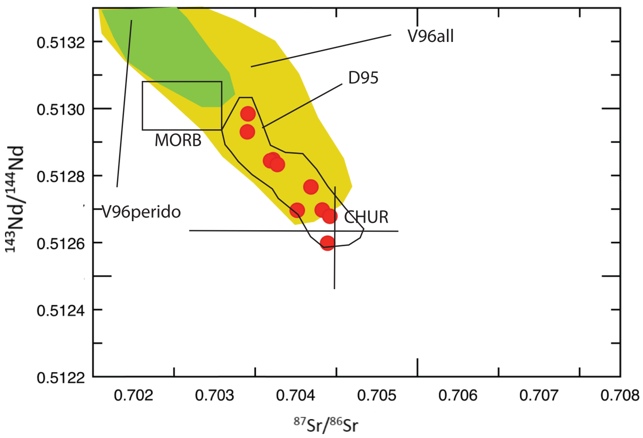


**Figure 6.** $^{143}Nd/^{144}Nd$ vs. $^{87}Sr/^{86}Sr$ diagram for Persani volcanic field samples. Mantle reservoirs are from Zindler and Hart (1986). Shown for comparison are volcanic data from Downes et al. (1995) as D96 and Persani xenolith isotopes from Vaselli et al. (1995); all data (V96all) and dominant-depleted peridotite (V96perido). Reference reservoirs: MORB: depleted MORB mantle; CHUR = chondritic uniform reservoir.

(Downes et al., 1995) or perhaps better referred to as asthenospheric melts without much influence of subduction, whereas the earlier melts contain a lithosphere-influenced pyroxenite or eclogite source.

The mantle lithosphere beneath PVF is known from the abundant xenoliths of the region (Vaselli et al., 1995; Chalot-Prat & Girbacea, 2000; Falus et al., 2008). They are significantly colder than the temperature of PVF products (~1,000°C, using data from Vaselli et al., 1995) which together with their depleted isotopic characteristics, identifies them clearly as subcontinental lithospheric mantle. There are no barometric determinations on these rocks, which are predominantly represented by spinel peridotites, but these xenoliths are sampled from shallow depths immediately below the Moho (35–50 km). They do not appear to be the lithospheric source in the PVF basalts. The standout feature of these rocks is the highly unradiogenic Sr isotopic ratios in some of the xenoliths (as little as 0.7019, Vaselli et al., 1995), which is corroborated with extremely high $\varepsilon_{Nd}$ ratios (as high as +18). A whole rock Sm-Nd errorchron of about 650 ± 150 Ma calculated by us based on data from Vaselli et al. (1995) using the most depleted 14 samples in that data set argues against an ancient age for these xenoliths. Instead, despite the extreme depleted isotopic signatures, this mantle could well be the lower lithospheric parts complementing Dacia, the surface terrane representing a collage of island arcs of Cambro-Ordovician peri-Gondwana terranes (Balintoni et al., 2014) with a subsequent Alpine geology but with no indication of any kind of a Precambrian history beyond possibly the latest Precambrian (Ediacaran). These xenoliths demonstrate that not all mantle lithosphere was removed by 0.68 Ma, and some native sub-Dacia lithospheric mantles still exist beneath the orogen. Unraveling the timing of the subduction related metasomatism described in these rocks (e.g., Chalot-Prat & Girbacea, 2000) is a critical next step in understanding mantle dynamics regionally. Instead, the lithospheric and eclogitic signature in the basalts is a deeper one originating in the descending Vrancea slab.

## 5. Geodynamic Implications

The persistence of volcanism at essentially the same location is somewhat perplexing to a first order. One would expect that magmatism, if formed in response to dripping, would somehow migrate toward the edge of the Vrancea slab. The fixed location of the locus of magmatism over a cca. 0.5-Myr period reflects either a stationary drip relative to the upper plate or some form of focusing of magmas toward the same point in the lithosphere and surface. However, since the volumetrically predominant event at 1.06-Ma event dwarfs the other eruptive volumes (Seghedi et al., 2016), this implies that any geodynamically relevant process took place at that point under Persani. More complex models envisioning focused flow of asthenosphere and of magmas toward a unique discharge can be entertained but are beyond the scope of this paper.

Emplacement of several adakitic intermediate volcanic bodies nearby (Molnár et al., 2018) essentially synchronous with the PVF and just slightly younger than the 1.06-Ma event is intriguing. The Malnas and Bixad domes located only some 30 km east of PVF formed at 0.96–0.91 Ma (Molnár et al., 2018) are shoshonitic intermediate rocks with extreme adakitic signatures strongly suggesting a continental eclogitic source. These are crustal-derived melts with Mg# of 0.6 or higher that traveled through the uppermost mantle and which formed only some 50,000 years after the main burst of basalts at PVF. These adakitic intermediate rock may be the products of direct partial melting of the crustal (mafic not ultramafic) parts of the downgoing slab/drip. It is otherwise difficult to explain the extreme adakitic signatures during the Quaternary since the crust is known to be less than 35 km thick regionally (Ivan, 2011; Laske et al., 2013). Limited published trace elemental data on these rocks (Roşu et al., 2004, Molnár et al., 2018) show extreme enrichment or light REE over the heavy REE ($La/Yb_n$ ~ 100) and lack of Eu anomalies, consistent with a garnet rich and plagioclase and amphibole-poor crustal residue. These ratios (La/Yb and Sr/Y) are well in excess of those characterizing the spectrum of moderate to thick crustal intermediate rock sources (Profeta et al., 2015), so they are not characteristic of the in situ lower crust of Dacia. Moreover, they contain ample evidence at

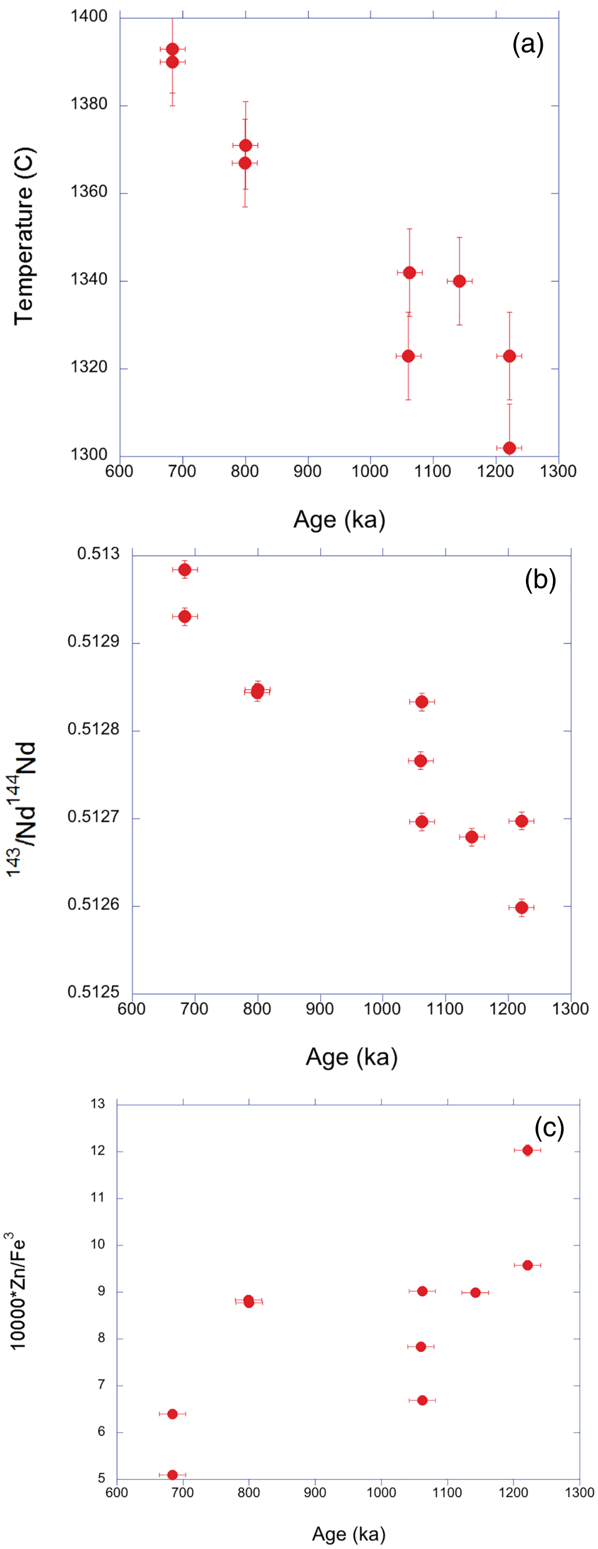


**Figure 7.** (a) Correlation between age (Panaiotu et al., 2013) and temperature (this study) for the 10 analyzed basalt samples from PVF; temperatures were calculated using Lee et al. (2009); (b) age (Panaiotu et al., 2013) versus $^{143}Nd/^{144}Nd$ (this study); and (c) age (Panaiotu et al., 2013) versus Zn/Fe ratios (this study). 2$\sigma$ errors are shown where larger than symbols.

crystal scale for interaction with mantle assemblages (Molnár et al., 2018). We propose that these are clear petrologic indicators of a slab/drip scenario and the distances and timing are consistent with them representing a one million-year phase of retreat and descent of the Vrancea slab/drip. The nature of that slab is still unresolved, but the most direct clues to its origin lie with the adakitic rocks east of PVF. The eclogitic/pyroxenitic component in the PVF may be the same as the one dominating in the adakitic rocks of Malnas and Bixad, and it is overpowered by the peridotite-derived melt volume or may represent part of the ultramafic component of the Vrancea slab.

Regardless, data presented here as well as other recent studies provide evidence for multisource melting in the uppermost mantle at ca. 1 Ma which is consistent with delamination or some form of a Rayleigh-Taylor instability (Houseman & Gemmer, 2007) of a rolled back slab inferred to be Vrancea. The overall distribution in time of volcanism in and around the Transylvanian basin (including the Apuseni Mts and beyond) (Seghedi & Downes, 2011) is clearly more consistent with a slab rollback hypothesis, whereas the thickening of the local crust to the point of generating a Rayleigh Taylor instability during the Late Cenozoic is a less likely scenario (Maţenco et al., 2007) or possibly quite impossible given the regional geology in the late Cenozoic. The eastward migration of magmatism with an eclogitic source from the southern Apuseni area (1.5 Ma at Uroi, Roşu et al., 2004) to the PVF (1.06 Ma, Panaiotu et al., 2013 and this study) and eastward (Malnas and equivalents <1 Ma and as young as 0.3 Ma, Molnár et al., 2018) is fully consistent with the slab rollback hypothesis. Figure 8 is a schematic E-W-oriented cartoon style cross section in which we outline the location of Uroi, Persani, and Malnas as they mark the proposed path of partial melting of a steepening slab (adakites and the pyroxenitic component in PVF) and the convecting mantle filling in the space (the peridotitic component in PVF). The three-dimensionality of the Transylvanian orocline and various possible tearing mechanisms that could have led to the rollback are not captured in this cartoon and are for future seismic images and geodynamic models to establish. We suggest that pyroxenite-derived lithospheric melts of the early PVF were part of the retreating Vrancea slab and were replaced by later peridotite-dominated melts with upwelling asthenospheric signatures typical of most basaltic fields of the Pannonian/Transylvanian region. As the Vrancea slab steepened, slab-derived eclogite-derived crustal melts emerged at the surface immediately after the main burst of PVF magmatism. They make up the 0.9-Ma Malnas-Bixad and other smaller volume adakitic rocks of the composite Ciomadul volcanic suite and represent the most direct evidence (although themselves somewhat polluted by their passage though mantle assemblages) of the nature of the Vrancea slab. The eclogite/pyroxenite component in the PVF is overpowered by the asthenospheric mantle-derived component but is isotopically evolved, thus clearly not MORB mantle, suggesting a continental nature of that lithospheric component, which we interpret to be the Vrancea slab.

The duration of the steepening (less than or similar to 1 Myr) as constrained by this model is within the sinking rate of a large dense body containing eclogite (and presumably peridotite-dominated foreland lithospheric mantle) into hotter asthenosphere. It is well established that bodies of 100 km thickness and length or more can sink toward the mantle transition zone in $10^4$–$10^5$ years (Houseman et al., 1982).

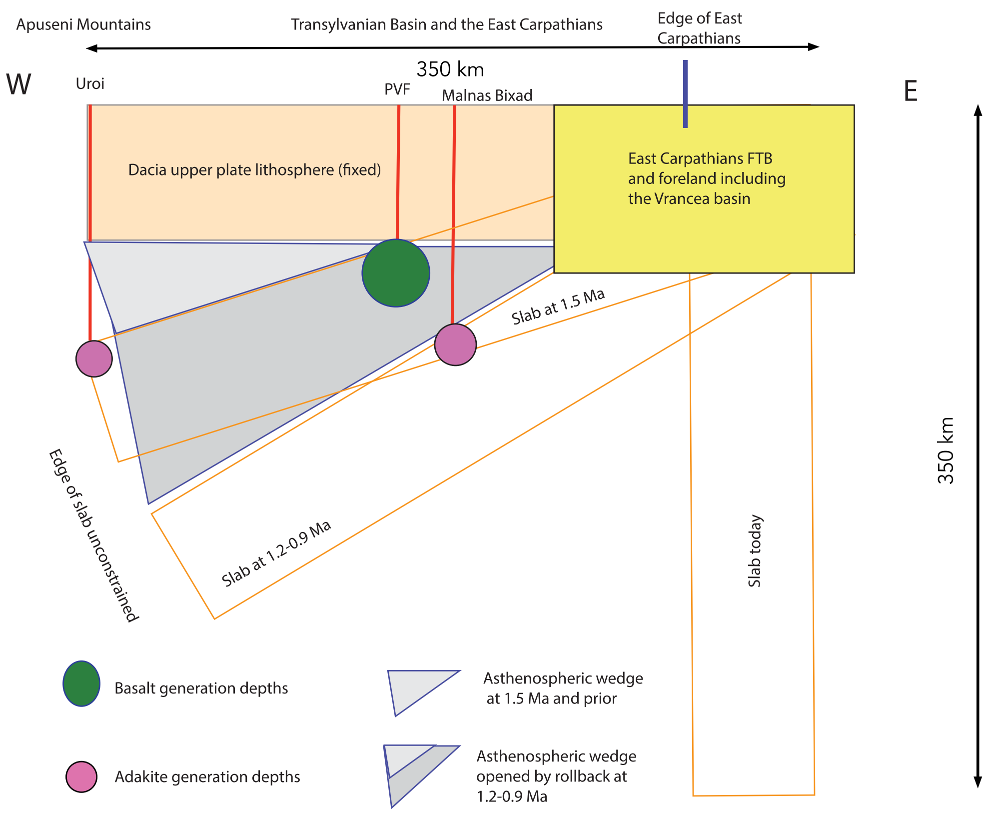


**Figure 8.** Cross-sectional cartoon showing the proposed evolution of the Vrancea slab from shallow in the earlier Quaternary to today's vertical position. There is no vertical exaggeration in the figure, and the horizontal distances between the features of interest (Uroi, PVF, Malnas, Vrancea basin today) are projected onto this E-W transect based on the real distances in the field. Lithospheric thicknesses of the upper and lower plates are inspired by existing geophysical data. However, the exact angles of the slab and depths of melt generation are interpreted.


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