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The Late Cretaceous Klepa basalts in Macedonia (FYROM)—Constraints on the final stage of Tethys closure in the Balkans

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Abstract

The waning stage(s) of the Tethyan ocean(s) in the Balkans are not well understood. Controversy centres on the origin and life-span of the Cretaceous Sava Zone, which is allegedly a remnant of the last oceanic domain in the Balkan Peninsula, defining the youngest suture between Eurasia- and Adria-derived plates. In order to investigate to what extent Late-Cretaceous volcanism within the Sava Zone is consistent with this model we present new age data together with trace-element and Sr–Nd–Pb isotope data for the Klepa basaltic lavas from the central Balkan Peninsula. Our new geochemical data show marked differences between the Cretaceous Klepa basalts (Sava Zone) and the rocks of other volcanic sequences from the Jurassic ophiolites of the Balkans. The Klepa basalts mostly have Sr–Nd–Pb isotopic and trace-element signatures that resemble enriched within-plate basalts substantially different from Jurassic ophiolite basalts with MORB, BAB and IAV affinities. Trace-element modelling of the Klepa rocks indicates 2%–20% polybaric melting of a relatively homogeneously metasomatised mantle source that ranges in composition from garnet lherzolite to ilmenite+apatite bearing spinel–amphibole lherzolite. Thus, the residual mineralogy is characteristic of a continental rather than oceanic lithospheric mantle source, suggesting an intracontinental within-plate origin for the Klepa basalts. Two alternative geodynamic models are internally consistent with our new findings: (1) if the Sava Zone represents remnants of the youngest Neotethyan Ocean, magmatism along this zone would be situated within the forearc region and triggered by ridge subduction; (2) if the Sava Zone delimits a diffuse tectonic boundary between Adria and Europe which had already collided in the Late Jurassic, the Klepa basalts together with a number of other magmatic centres represent volcanism related to transtensional tectonics.

1 | INTRODUCTION AND SETTING

The Balkan region occupies an important segment of the Alpine–Himalayan collisional orogenic belt and consists of several Phanerozoic mobile belts (e.g., Cvetković, Prelević, & Schmid, 2016; Schmid et al., 2008) (Figure 1). The dominant geological structure crossing the Balkan Peninsula is an axial belt originally named "Vardar Zone" by Kossmat (1924) who characterised this zone as "a steep belt made up of a large variety of intercalated continental and ophiolitic slivers that, in Macedonia, separate the culmination of the Pelagonian Massif in the west from the culmination of the Serbo-Macedonian Massif and the Rhodope in the east" (Figure 1). In modern

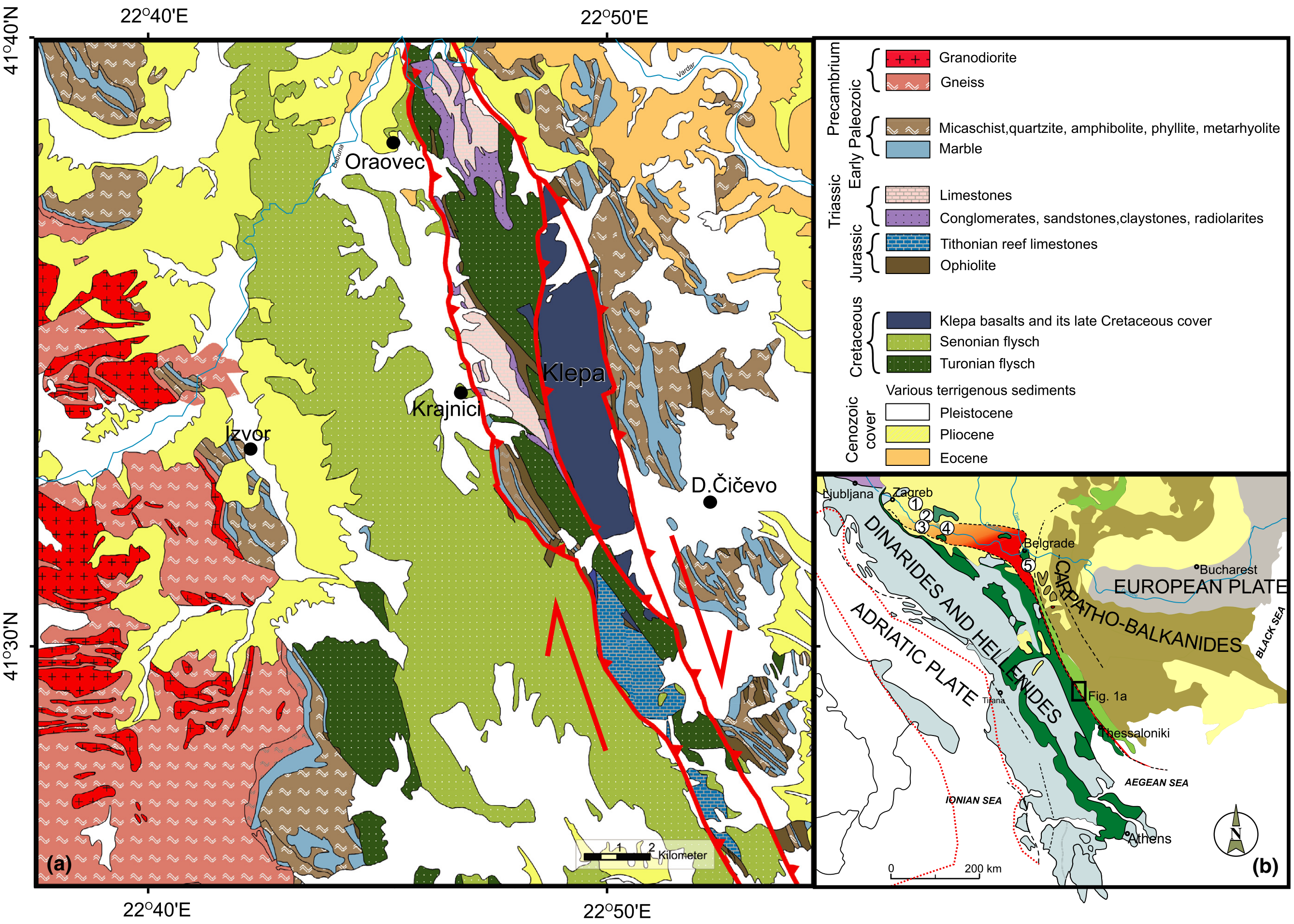

FIGURE 1 (a) Simplified geological map of the Klepa block and surrounding areas within the Sava Zone of Macedonia (FYROM), based on the Geological Map of Yugoslavia 1:100,000 (sheet Prilep) with the modifications of Robertson et al. (2013). Red lines indicate tectonic contacts formed in a dextrally transgressional environment. (b) Simplified tectonic map of the Balkan Peninsula after Schmid et al. (2008), depicting from west to east Adria-related units (pale blue) and W Vardar ophiolites (dark green), Sava suture (red), European units (brown and grey), E-Vardar ophiolites (pale green) and Cenozoic cover (yellow). Numbered circles indicate discrete Cretaceous magmatic centres along the Sava Zone mentioned in the text (1: Moslovačka Gora; 2: Prosara; 3: Kozara; 4: Požeška Gora; 5: Tešića Majdan) [Colour figure can be viewed at wileyonlinelibrary.com]

terms this belt separates a younger SW-verging nappe stack of the Dinarides derived from the Adriatic continental margin (Gondwana) in the west from an older and dominantly NE-facing nappe stack of the Carpatho-Balkan orogen derived from the European margin (Laurasia) in the east (Figure 1 inset). The Adriatic and European margins had developed in the Mesozoic, forming the northern branch of the Neotethys (e.g., Sengör & Yilmaz 1981), which was closed in the Late Cretaceous to Early Cenozoic (e.g. Cvetković et al., 2016 and references therein). The loosely defined Vardar Zone in the sense of Kossmat (1924), therefore, must represent an important suture between the Adriatic and European margins.

The origin and the emplacement mechanisms of the Balkan ophiolites have been subject to vigorous debate particularly around the question of whether the different ophiolites were derived from a single or from several oceans (for discussions, see Schmid et al., 2008). In terms of geographical distribution, at least two subparallel ophiolite belts can be distinguished in the Balkans: an eastern one (Eastern Vardar ophiolite belt) and a western one (Western Vardar ophiolite belt) (Cvetković et al., 2016; Schmid et al., 2008 and references therein). There is emerging consensus about the geodynamics and origin of the two Vardar belts: the Eastern Vardar belt is interpreted as a Jurassic back-arc basin that closed shortly after its opening (e.g., Božović et al., 2013; Gallhofer, von Quadt, Peytcheva, Schmid, & Heinrich, 2015) and obducted towards the east (Schmid et al., 2008); the Western Vardar ophiolite belt is regarded as part of a huge piece of the Neotethys oceanic lithosphere, which was more or less uniformly obducted towards the west, that is, onto the passive margin of northern Gondwana (Schmid et al., 2008). After their emplacement, both ophiolitic belts underwent weathering and erosion in the Late Jurassic/Early Cretaceous (Cvetković et al., 2016 and references therein).

In recent years the controversy regarding the waning stage(s) of the life of the Tethyan ocean(s) has slowly overshadowed any debate over the origin of the ophiolites and their emplacement mechanisms. Some authors consider Europe–Adria collision to have occurred in the Late Jurassic (e.g., Csontos & Vörös, 2004), whereas others envisage that the final closure of the last Tethyan ocean happened at the end of the Cretaceous (Karamata, 2006; Robertson, Karamata, & Šarić, 2009; Schmid et al., 2008; Ustaszewski et al., 2009) along the Sava Zone (or Sava suture zone) as mapped by Schmid et al. (2008). The discussion now centres on the existence, origin and life-span of this Cretaceous Sava Ocean (Ustaszewski et al., 2010), considered by many to contain a relic of the youngest Tethyan oceanic realm left behind after the major convergence in the Jurassic (e.g., Karamata, 2006; Robertson et al., 2009; Schmid et al., 2008). In this context the Sava suture may possibly host remnants of a wider Late Cretaceous oceanic domain whose eastern continuation may be found in, for example, the Cyclades Islands (Fu et al., 2012), in Crete (Langosch et al., 2000) and in Turkey (inset of Figure 1).

In this study we focus on the geochemistry, petrology and age data of basaltic lavas from newly discovered "ophiolitic" outcrops in Macedonia called the Klepa block for which our new age data reveal a Late Cretaceous age, meaning that it potentially may represent a piece of oceanic lithosphere belonging to the alleged Sava Ocean. Our aim is to compare this occurrence with ophiolitic counterparts in Macedonia and further north in Serbia and Bosnia and to discuss their petrogenesis in the light of viable geodynamic scenarios.

2 | GEOLOGY OF THE KLEPA BLOCK

The Klepa block is a 10 km long (NNW–SSE) 1–2 km wide (WSW–ENE) and 1150 m high inselberg, which is dominantly composed of basaltic rocks occasionally covered by a thin veneer of sedimentary rocks not mappable at conventional scales (Figure 1). The bulk of the basaltic sequence consists of pillows, sheet flows, dikes and cumulates (Appendix S1, Figure 1). Due to the low aspect ratio of the lavas the volcanic structure may be interpreted as a relict shield volcano. Along the eastern margin the volcanic rocks are locally transgressed by slightly sheared conglomerates containing sub-angular to subrounded quartzite, schist and limestone clasts, as well as by fine-grained marlstones and sandstones. To the north along the eastern and western margins the basaltic sequence is overlain by sheared reddish clay-rich *Scaglia Rossa* hemipelagic limestones (presumably Campanian, by analogy with the North Kozara Mts., Ustaszewski et al., 2009, 2010) that are covered by sandy (possibly Maastrichtian) conglomerates.

In the east the basaltic sequence is in subvertical tectonic contact with formations made up of a series of deformed and mylonitised (most probably Jurassic) ophiolitic mélange sequence, including serpentinite, gabbro and limestone blocks (Appendix S1, Figure 2), interlayered with a sequence of dominantly mylonitic marbles and mylonitic sericite schists with biotite and chlorite. The latter lithologies are interpreted as a part of the Palaeozoic Veles Series (Antić et al., 2016; Grubić & Ercegovac, 1974) and represent the Palaeozoic part of the Circum-Rhodope belt (van Hinsbergen & Schmid, 2012). The intensity of deformation within the Veles Series increases considerably towards the contact with the Klepa block where lineations become subhorizontal and shear indicators suggest dextral strike slip. The formations west of the Klepa block are evidently also in tectonic contact with the adjacent units (Figure 1), which include Triassic–Jurassic cover, Turonian conglomerates and flysch, and slivers of serpentinites. These units may be attributed to the Jadar-Kopaonik thrust sheet (sensu Schmid et al., 2008) and involve the Mesozoic basement and cover of the Adriatic margin. Further west the Jadar-Kopaonik thrust sheet is emplaced on top of Senonian flysch, which, together with Turonian conglomerates at its base, rests in stratigraphic contact directly on the basement of the Pelagonian Massif. All these sequences are strongly mylonitised and sheared, especially near the contact with the Klepa basaltic sequences.

3 | ANALYTICAL TECHNIQUES

We studied 29 samples from the Klepa volcanic rocks (Appendix S2) for major and trace elements and 12 samples for Sr, Nd and Pb isotope analysis following the procedures described in Božović et al. (2013), including a thorough leaching procedure specially designed for ophiolitic basalts. Moreover, amphibole and feldspars from two samples were dated using the ^{40}Ar/^{39}Ar method following the procedure described by Božović et al. (2013). Reproducibility of the trace elements, internal and external standards and the quality of the isotopic analyses are shown in detail in Božović et al. (2013).

4 | RESULTS

Based on the petrography, mineralogy and geochemistry of the lavas four rock types were identified: subalkaline transitional basalts, alkaline basalts, Ti-amphibole-bearing microgabbros and trachyandesites/trachytes (Figure 3 and 4 in Appendix S1). The rocks are porphyritic with phenocrystic subhedral olivine pseudomorphs, augite, plagioclase and in some samples amphibole (for mineral chemistry, including BSE images, major- and trace-element analyses, see Appendix S3). The groundmass is composed of tabular and acicular plagioclase (partly albitised), amphibole and in most cases completely altered glass. Secondary minerals include chlorite, calcite, epidote, sericite, albite and clays.

The Klepa basalts have a HFSE and REE signature that resembles trace-element enriched within-plate basalts with low Zr/Nb (4–8), high Zr/Hf (>40), Nb/Yb (up to 60) and Nb/Ta (up to 20) and variable La/Yb (Appendix S2). In a Th/Yb vs. Nb/Yb diagram (Figure 2b), the Klepa samples fall in the mantle array and are displaced from MORB towards OIB compositions (Pearce, 2008). Despite variable trace-element ratios the lavas show relatively uniform Nd and Pb isotopic compositions with a limited range of ^{143}Nd/^{144}Nd$_i$ (0.51287–0.51289) plotting outside the MORB array (Figure 2c). The Pb isotope compositions of the Klepa lavas are also invariable with ^{206}Pb/^{204}Pb ~ 19.6 and high ^{207}Pb/^{204}Pb ratios that range between

15.60 and 15.65 and fall within the OIB field (Figure 2d). Only Sr isotopes show slight variations, which are interpreted below as having been produced by alteration of the groundmass glass present in most of the investigated samples (Figure 2c).

$^{40}Ar/^{39}Ar$ incremental heating experiments were conducted on two samples of separated amphibole and feldspar phenocrysts. The results are presented in Appendix S4. The measurements yielded plateau ages at 80.4 ± 0.9 and 80.7 ± 0.5 Ma, respectively, based on more than 50% Ar released.

5 | DISCUSSION

5.1 | No evidence for MORB/BAB or IA affinity of the Klepa volcanics

Our new geochemical data show marked differences between the Klepa basalts and the volcanic rocks of other Balkan (Jurassic) ophiolites in Serbia and Macedonia (FYROM) (Figure 2a,b). In general the Klepa basalts have HFSE signatures that resemble those shown by trace-element enriched within-plate basalts, which, in turn, substantially differ from ophiolite samples of MORB and BAB affinity. In addition, no arc signature is seen in the geochemistry of the Klepa lavas. In contrast, the bulk of the oceanic crust of Vardar Tethys has petrological and geochemical compositions characteristic of rocks of mid-ocean ridge or back-arc origin (MORB and BAB) (Božović et al., 2013; Robertson & Karamata, 1994). These lavas have variously depleted LREEs relative to HREEs and radiogenic $^{143}Nd/^{144}Nd$ values similar to those of a BAB/MORB source. Some of the ophiolites of the Eastern Vardar subordinately contain lavas that show a pronounced subduction-related geochemical signature (Marroni et al., 2004; Saccani et al., 2008; Božović et al., 2013) and contain boninites, adakites and keratophyres that formed in the fore-arc region of an island-arc system. Most of these arc lavas are interpreted to have been generated during subduction initiation within a back-arc basin (Božović et al., 2013). If we exclude the subordinate occurrences of OIB-like lavas in the Greek eastern Vardar (Saccani et al., 2008) and in the Dinarides (Popević, Memović, Zakariadze, Milovanović, & Karamata, 2005), none of the Jurassic ophiolites of the Balkans have geochemical and petrological associations similar to those of the Late-Cretaceous volcanic rocks of the Sava zone.

5.2 | Source mineralogy of the Klepa basalts and its significance

The variable composition of the Klepa magmas seen in simple bivariate diagrams (e.g. SiO_2 and TiO_2 vs. MgO) clearly demonstrates that more evolved Klepa lavas underwent Ol–Cpx–Pl–Ti mineral fractionation (Appendix S5). However, the most primitive samples (screened for >3% MgO) show significant geochemical variation that is related to the mantle-melting processes. For instance, distinct fractionation of LREE and MREE from HREE is largely related to melting of the mantle source as fractional crystallization of typical basalt phases does not modify the REE pattern significantly (e.g., Ellam, 1992; McKenzie & O'Nions, 1991). Klepa basalts show a considerable fractionation of La/Yb and La/Nd when plotted against a strongly incompatible element, for example Th (Appendix S5), indicating a decrease in the degree of melting or a variation in the metasomatic enrichment of LREE (McKenzie & O'Nions, 1991).

The primitive Klepa magmas show invariably radiogenic $^{206}Pb/^{204}Pb$ at relatively high $^{207}Pb/^{204}Pb$ and high $^{143}Nd/^{144}Nd$ (Figure 2c,d). Together with trace-element patterns showing regular variations of HFSE, this indicates that variable degrees of partial melting of a relatively homogeneously enriched mantle source rather than a variably metasomatised mantle played a crucial role in the petrogenesis of these rocks (Cebria & Lopez Ruiz, 1996; Cebria et al., 2000). We modelled mantle melting using the inverse method (Cebria & Lopez Ruiz, 1996; Class & Goldstein, 1997; Treuil & Joron, 1975) to estimate major melting parameters and to model variable degrees of melting of different types of homogeneous mantle based on the mineralogical constraints obtained from the melting model. Below is a brief summary of the modelling method and results we obtained. A detailed description of the method is included in Appendix S6.

In general, the concentration of trace elements in the melt becomes effectively buffered by the residual mineral assemblages. This buffering effect is seen in the relatively low and uniform concentrations of the elements that are highly concentrated in some residual phases. In contrast, the most incompatible elements, which are not buffered by the residual minerals, will show the largest compositional range. By plotting the most incompatible element against the elements buffered by some residual phases and comparing the slopes of the regression lines, we can broadly estimate the extent of depletion and indirectly determine the composition of the residual phases (Appendix S6).

The variation in the geochemical data implies that Th is the most incompatible element in the mantle source of the Klepa lavas. The relative degree of incompatibility of other elements (Figure 3a; see Appendix S6 for details) shows that U and La behave similarly and that incompatibility decreases in the order Nb, Ta, Ba, Dy, Yb, P to Ti. (Figure 3a inset), which suggests the presence of several residual minerals in the mantle source: amphibole will retain Ba (and Rb), P will be held by apatite, and Nb, Ta and Ti will be kept by some Ti phase, most probably ilmenite. By using the extents of element incompatibility quantified by their enrichment ratios (E) (Figure 3a), we obtained negative anomalies for Rb, Ba, Nb, Ta, P and Ti, confirming the presence of residual amphibole, apatite and a Ti phase (ilmenite?). The most important outcome of this modelling is the recognition of several residual metasomatic minerals typically reported from the continental lithospheric mantle (e.g. Cvetković, Downes, Prelević, Jovanovic, & Lazarov, 2004; Ionov, Bodinier, Mukasa, & Zanetti, 2002; Ionov, Gregoire, & Prikhodko, 1999; O'Reilly & Griffin, 2000) but not usually found in the oceanic lithospheric mantle.

Fractionation of LREE/HREE may additionally indicate the presence of melts that formed in the garnet stability field (Ellam, 1992).

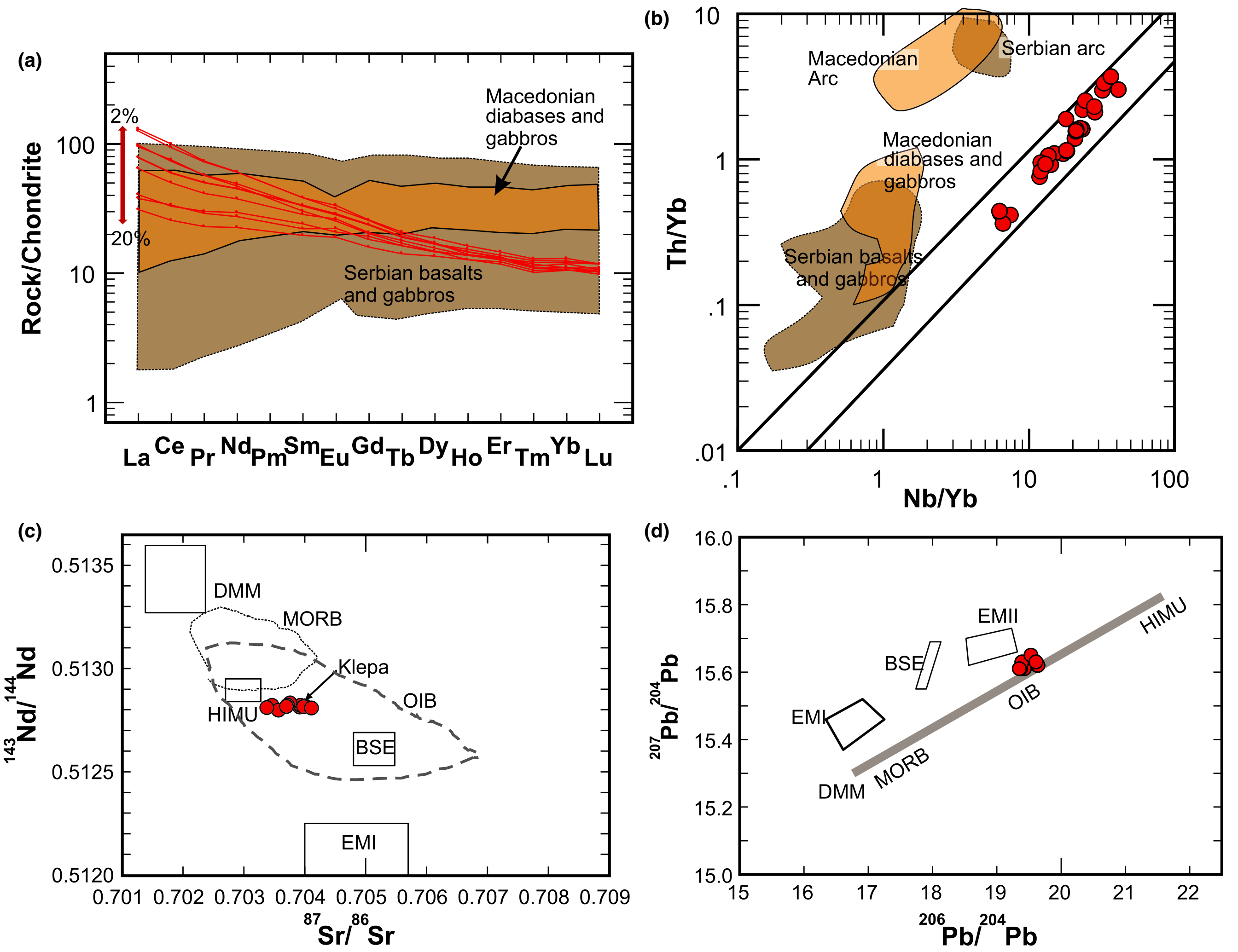

FIGURE 2 (a) Chondrite-normalised (Sun & McDonough, 1989) concentrations of REE for selected samples from the Klepa basalts (red lines). Only samples with MgO >3wt% are shown to demonstrate the mantle control on the range of REE pattern. For comparison, we plot the arrays for Serbian Jurassic ophiolitic basalts and gabbros and Jurassic diabase and gabbro from the East Vardar ophiolites in Macedonia (FYROM) (Božović et al., 2013 and references therein; Prelević unpublished). The red double arrow indicates the variation in LREE due to different extents of partial melting of a geochemically homogeneous mantle source. A rough estimation of the extent of partial melting is 2%–20%. This estimate is based on, Cebria & Lopez Ruiz (1996) and Maaløe & Pedersen (2003), who proposed that for highly incompatible elements whose partition index is close to zero ($D^i \approx 0$), the simple batch melting equation can be approximated with $C^i_m = C^i_o/F$ (C^i_m – concentration of the highly incompatible element *i* in the melt; C^i_o – concentration of the highly incompatible element *i* in the source; F – melting degree). Hence, the highest and lowest concentrations of the highly incompatible element are produced by the lowest (F_{low}) and highest (F_{high}) melting degrees, respectively. As has been shown by Cebria & Lopez Ruiz (1996) and Maaløe & Pedersen (2003) for highly incompatible elements, we can approximate the relation formula, which enables us to estimate the relative range of the degree of melting (F_{high}/F_{low}). Using this assumption and the Th and La variations, we estimate the relative range of the degree of melting for the Klepa rocks to be $F_{high}/F_{low} \approx 10$. (b) Nb/Yb vs. Th/Yb (Pearce & Peate, 1995) for the Klepa basalts, with reference fields for Serbian Jurassic ophiolitic basalts and gabbros and Macedonian Jurassic ophiolitic diabases and gabbros (Božović et al., 2013 and references therein; Prelević unpublished). (c) and (d) Sr–Nd and Pb isotopic variations in the igneous rocks of the Klepa basalts, respectively. Geochemical mantle components are based on Zindler and Hart (1986): DMM – depleted MORB mantle, HIMU – high μ; BSE – bulk silicate earth; EM I – enriched mantle 1; EM II – enriched mantle 2 [Colour figure can be viewed at wileyonlinelibrary.com]

Figure 3b displays La/Yb and Dy/Yb ratios and confirms that the Klepa basalts may dominantly have originated from 2%–20% partial melting of an amphibole–apatite–ilmenite-bearing metasomatised mantle source within the spinel stability field. The restricted stability field of hydrous minerals in peridotite (Frost, 2006) limits this assemblage to the lithospheric mantle. However, the spreading of the data towards the garnet stability field in Figure 3b may be interpreted as the result of two-component mantle melting–mixing: one component tapped the (metasomatised lithospheric) mantle situated in the spinel stability field, and the second component is derived from the mantle located within the garnet stability field. In other words, we may propose a continuum between low-degree melting in the garnet stability field and high-degree melting of the metasomatised mantle in the spinel stability field. The invariable Nd and Pb isotopic signatures

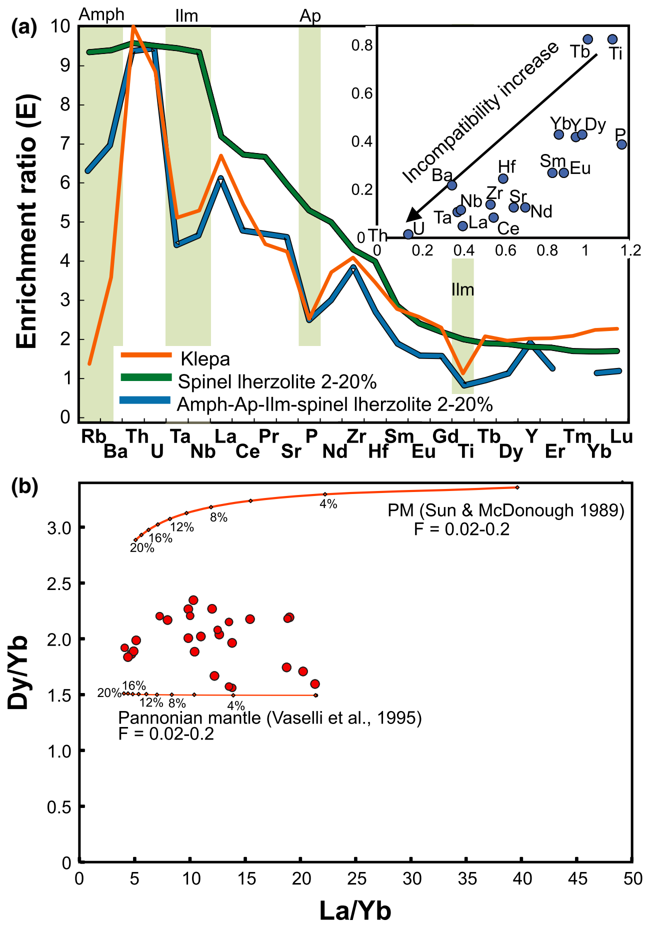

FIGURE 3 (a) Magma source mineralogy of the Klepa basalts (for details of the estimation of *E* values refer to Appendix S6). The enrichment ratio (*E*) pattern uses estimated *E* values from Appendix S6. We also recalculated *E* values for 2%–20% non-modal batch melting of spinel-lherzolite and amphibole–apatite–ilmenite–spinel-lherzolite sources with the composition shown in the diagram; note that four troughs with low E values (pale green arrays) cannot be reproduced without residual amphibole (Amph), apatite (Ap) and Ti-phase (ilmenite – Ilm) in the source. Modelling details including partition coefficients and modal contributions of different phases are presented in Appendix S6. Inset: Relative degree of incompatibility of trace elements relative to the Klepa mantle source mineralogy. For details, see Appendix S6; b) Results of trace-element modelling of primitive samples of Klepa basalts: La/Yb vs. Dy/Yb. Modelled trajectories are for non-modal, batch partial melts (Shaw, 1970) of garnet-facies lherzolite ($Ol_{0.60}Opx_{0.25}Cpx_{0.09}Grt_{0.06}$) that melts in the proportions ($Ol_{0.12}Opx_{0.25}Cpx_{0.30}Grt_{0.33}$) and amphibole–apatite–ilmenite-lherzolite from spinel-facies mantle (Appendix S6). Tick marks on the curves represent percentage of melt extracted (20, 18, 16, 14, 12, 10, 8, 6, 4, 2%). Source compositions: Primitive Mantle (PM) of McDonough (1990) and Pannonian metasomatised mantle of Vaselli et al. (1995) were chosen for partial melting scenarios. The partition coefficients used are presented in Appendix S6 [Colour figure can be viewed at wileyonlinelibrary.com]

may reflect the fact that melting of depleted mantle does not significantly contribute to the Nd and Pb budgets, which are dominated by the metasomatised mantle source. Note, mantle heterogeneities and/or melt mixing within the asthenospheric mantle source (Beier, Stracke, & Haase, 2007), which are typical in plume-related mantle melting, would result in a broader range of Nd and Pb isotopic compositions of the rocks.

5.3 | Unlocking the geodynamic significance: intracontinental rifting vs. a seamount ophiolitic origin for the Klepa basalts

The identification of amphibole, apatite, ilmenite and potentially garnet in the source region of the Klepa lavas puts important constraints on the melting depth and indirectly on the type of mantle involved in the melting process. We interpret the crystallization of a number of metasomatic minerals in the mantle as a result of metasomatising effects of alkaline basaltic precursor melts (Pilet, 2015). Their presence is instrumental in lowering melting temperatures and indicates that the source region is dominantly situated within the lithospheric mantle (Frost, 2006). Furthermore, the data indicating the presence of garnet in the mantle source roughly constrain the depth of partial melting to reach the garnet stability field at 25–30 kbars (Klemme, 2004 and references therein).

The following two geodynamic settings may account for the geochemical variation observed in the Klepa basalts:

1. The Klepa basalts show some geochemical characteristics of seamount basaltic magmas, similar to the origin recently proposed for the Cretaceous bimodal association in Kozara Mt. (Cvetković, Šarić, Grubić, Cvijić, & Milošević, 2014) (Figure 1, inset). Unmetamorphosed (Yang, Li, Xiao, & Tong, 2015) and metamorphosed (John et al., 2010) seamount-derived material comprising dismembered and mixed MORB- and OIB-type basalts and radiolarites has been found in ophiolites. However, seamounts typically demonstrate linear trends in multi-isotope plots as well as in isotopes vs. canonical trace-element ratios, resulting from a multicomponent mixing process involving some of the typical mantle end-members (e.g. EM-I, EM-II or HIMU). This type of isotopic variation is not observed in the Klepa basalts, in spite of variable trace-element ratios (Figure 2). Moreover, the identification of amphibole, apatite, ilmenite and garnet in the source implies the involvement of metasomatised lithospheric mantle with a thickness of >90 km. Oceanic lithosphere of this thickness would be typical of an old oceanic domain (Class & Goldstein, 1997) but is not viable for the alleged Sava oceanic lithosphere, which is supposed to be younger than 160 Ma.
2. Our preferred model is that the continental mantle has played a major role in the origin of the Klepa basalts. In this model Klepa magma is generated by extension-driven partial melting at the asthenosphere–lithosphere boundary. This model can explain geochemical variations that result from polybaric melting of the relatively homogeneously metasomatised continental lithospheric mantle by migration of the locus of magma generation from the garnet to the spinel stability field. These melting paths are consistent with adiabatically ascending normal-temperature asthenosphere beneath an extensively thinned and metasomatised

continental lithosphere: heat supply from the asthenosphere will induce partial melting in the most fertile parts of the lithospheric mantle, resulting in the basaltic magmatism (e.g. Pilet, 2015 and references therein).

5.4 | Geodynamic implications

Our preferred model implies that the Klepa basalts formed by intracontinental volcanism triggered by extension and elevated heat flow, which tapped the continental rather than the oceanic mantle lithosphere. In other words, the Klepa block does not represent ophiolite remnants of an alleged Late Cretaceous oceanic domain. In the following, we outline possible scenarios for the origin of the Klepa magmatism, taking into account two substantially different views on the Cretaceous large-scale regional development for two end-member-type settings:

I. The Sava Zone comprises the remnants of the youngest Neotethyan ocean, which remained open until the latest Cretaceous (Gallhofer et al. 2015; Schmid et al., 2008; Ustaszewski et al., 2009, 2010). In this scenario, the Sava zone is part of an accretionary wedge whose northern segment is present in N Bosnia (see Figure 1, locality 1 of inset map) and which underwent amphibolite-grade metamorphism at around 65 Ma. The strongest argument for this model is the existence of the Late Cretaceous Apuseni-Banat–Timok–Srednjegorje magmatic and metallogenic belt further eastward (Berza, Constantinescu, & Vlad, 1998; Ciobanu, Cook, & Stein, 2002; Gallhofer et al., 2015; von Quadt, Moritz, Peytcheva, & Heinrich, 2005). In view of the subduction-type geochemistry shown by these rocks and their association with typical porphyry copper deposits, many authors interpret this belt as a magmatic arc installed onto the European continent during the north-eastward subduction of oceanic lithosphere, that is, the Sava Ocean, in an Andean-type scenario (Gallhofer et al., 2015; Kolb et al., 2012). If this scenario were applicable, the magmatism along the Sava zone would be situated within the forearc region of the European upper plate, which is traditionally considered to be cold and generally amagmatic. Exceptional volcanism would be confined to zones of local extension within arc-front, forearc and accretionary prism settings, and would be controlled by ridge subduction and subsequent slab window formation (Cole & Stewart, 2009; Wilson, McCrory, & Stanley, 2005), similar to the volcanic fields of western California and southern Alaska where occasional adakites occur beside basalts. If applied to the Sava Zone, such a scenario could explain the broad contemporaneity of arc magmatism in the Late Cretaceous Apuseni-Banat–Timok–Srednjegorje magmatic and metallogenic belt with magmatism in the Klepa block located near the trench.

II. The Sava Zone delimits a diffuse tectonic boundary between Adria and Europe, which had already collided in the late Jurassic (Csontos & Vörös, 2004). Regional subsidence resulted in peneplanisation during the late Jurassic and formation of lateritic crust and bauxites, suggesting that the whole region was potentially a continental environment at that time. Both sides of the Sava Zone, that is, the Lower Pelagonian unit (Kilias et al., 2010) and the Dacia unit (Reiser, Schuster, Spikings, Tropper, & Fügenschuh, 2016), have been overprinted by Early Cretaceous regional metamorphism, which is not easy to understand if the two areas were separated by an open ocean at that time. Furthermore, the absence of Early/Late Cretaceous ophiolites in the Balkans together with Late Jurassic ages of metamorphic soles all over the Balkan Peninsula (Borojević Šoštarić et al., 2014 and references therein) seem to indicate that convergence and ocean closure took place during the Late Jurassic. The overall evidence is far from clear-cut, however, because Early Cretaceous metamorphism at the Adriatic margin could be related to an obduction event rather than to continental collision (Tremblay, Meshi, Deschamps, Goulet, & Goulet, 2015) and the absence of the remnants of the Sava Ocean could be due to complete subduction of the oceanic lithosphere at the end of the Cretaceous. Nevertheless, if scenario II is applicable, the mafic rocks of the Klepa area may represent intracontinental volcanism related to transtensional tectonics. Discrete magmatic centres along the Sava zone include Moslovačka Gora (Starijaš, Gerdes, Balen, Tibljas, & Finger, et al. 2010), Požeška Gora (Pamić & Šparica, 1983) and Prosara (Ustaszewski et al., 2010) in Croatia, Kozara (Ustaszewski et al., 2009) in Bosnia and Tešića Majdan (Prelević, Wehrheim, Božović, Romer, & Boev, 2014) in Serbia (Figure 1). The origin and geodynamic significance of these centres have been considered either enigmatic (Ustaszewski et al., 2009) or clearly not ophiolitic (Cvetković et al., 2014). These centres, however, may have developed in a similar setting to the Klepa basalts, with which they are coeval. Analogous geodynamic situations worldwide occur along the north and east Anatolian faults (Hubert-Ferrari et al., 2009; Tatar et al., 2007) and in the pull-apart basins in the western United States (Tibaldi, Pasquarè, & Tormey, 2010) where magmatic products demonstrate similar geochemical affinity.

6 | CONCLUSIONS

The Klepa volcanic rocks demonstrate the geochemical signature of basalts derived from continental lithosphere rather than of basalts from typical oceanic crust. This geochemical signature agrees well with other geological observations including the absence of other ophiolite members, especially those more typical of “normal” oceanic crust such as MORB/BAB rocks. In the context of Cretaceous large-scale regional development, magmatism in the Sava Zone may have been generated either within a fore-arc of an active Andean-type subduction due to ridge subduction, or along a diffuse transtensional tectonic boundary between Europe and Africa, which had collided earlier.

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