

Diverse Lavas of the Tigilsky Dol and Mount Oxi Massif (Sredinny Range, Kamchatka): a Perspective from the New Sr–Nd Isotope Data

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Abstract—Unique compositional diversity of volcanic rocks was recently discovered in an active fault zone of the Sredinny Range (Kamchatka) located in the zone of monogenetic volcanism near the Tigil and Oxi volcanoes. The lavas in the zone represent common for SR medium-K, high-K and high-Ti, and also unique for Kamchatka high-LREE and high-Mg varieties. In this contribution, we present new Sr–Nd isotope data for a representative set of lava samples from this area. The isotopic and geochemical characteristics of the majority of selected samples can be explained by the differences in the amount of fluid, fluid sources and melting conditions, proposed earlier for the SR. The high-LREE picritic basalts, however, differ significantly from the other Kamchatka volcanic rocks—their highly unusual high-LREE, high-Li and low-LILE geochemical characteristics combine with the highest $^{87}\text{Sr}/^{86}\text{Sr}$ (0.70365) and second-highest ϵNd (9.9) values ever reported for lavas from the SR. We suggest that they represent the product of melting of the specific SR lithosphere domain that has been metasomatized by melts derived from a strongly degassed slab.

Keywords: Sr–Nd isotopes, high-Mg lavas, Sredinny Range, Kamchatka

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INTRODUCTION

The Sredinny Range (SR) is a volcanic province that was a volcanic front of Kamchatka in the Miocene before the relocation of the subduction zone to its present position ~200 km eastward (Avdeiko et al., 2006). The modern Pacific slab has not been traced under most of the SR (Gorbatov et al., 1997), however, the volcanic activity in the area did not cease even in the Holocene (Pevzner, 2015 and references therein). The origin of this post-Miocene volcanic activity has been a matter of debate in the scientific literature for the last several decades (Volynets, 1994; Churikova et al., 2001; Nekrylov et al., 2018a; Nekrylov et al., 2021; Volynets et al., 2010; Volynets et al., 2024). Recently it has been proposed that at least in the case of some Late-Quaternary volcanoes of the SR

the source of fluids inducing mantle melting likely resides in the lithosphere (Nekrylov et al., 2021). At the same time, the general trace element and isotopic enrichment could also be linked to the melting of previously metasomatized lithospheric lithologies (Volynets et al., 2024). However, until recently, there was no data on primitive (high-Mg) end-members for the SR volcanic rocks, which would allow researchers to make more robust conclusions about the magma origin. The discovery of the high-Mg basalts and picrobasalts from the Tigilsky Dol and Mount Oxi massif in the active fault zone filled this knowledge gap (Volynets et al., 2023).

The lavas from Tigilsky Dol and Mount Oxi massif are extremely diverse and were earlier divided into 5 groups based on their major and trace element compositions: (1) medium-K; (2) high-K; (3) high-Ti; (4) high-Mg and (5) high-Mg and high-LREE (Volynets et al., 2023). In the present paper, we report new

[†] Deceased.

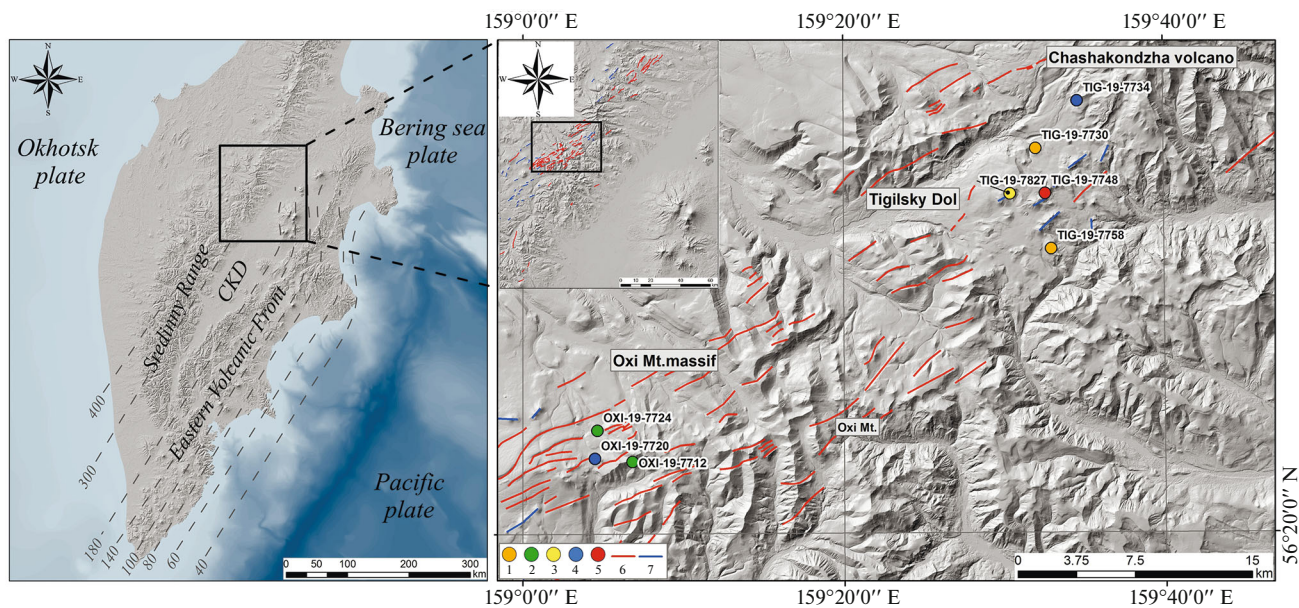


Fig. 1. A schematic map of Kamchatka, showing the location of studied samples. (1) medium-K rocks; (2) high-K rocks; (3) high-Ti basalts; (4) high-Mg basalts; (5) high-REE picobasalts; (6) active faults; (7) magma feeding fissures. The grey dashed lines represent the depth of the Wadati-Benioff zone under Kamchatka after Gorbatov et al. (1997).

Sr–Nd data for representative samples from those 5 groups and discuss their origin in light of the new data.

MATERIALS AND METHODS

Eight samples representing all five major groups of the Tigilsky Dol and Mount Oxi lavas were selected for the study. Those include 2 medium-K basaltic andesites, 1 high-Ti basalt, 1 high-Mg basalt and 1 high-LREE picobasalt from Tigilsky Dol, and 2 high-K basalts and 1 high-Mg basalt from Mount Oxi massif (Fig. 1). The contents of major and trace elements for the selected samples were previously published by Volynets et al. (2023).

The Sr and Nd isotope compositions were determined in IGEM RAS with a multicollector Thermal Ionization Mass Spectrometer “Sector 54” (Micro-mass, UK). The reliability of the analyses of the isotopic ratios $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ was controlled by

systematic analyses of the international standard of Sr “SRM-987” with mean external reproducibility (2sd) of ± 0.000025 (0.004%) and an in-house Nd isotopic standard “Nd-IGEM” with mean external reproducibility (2sd) of ± 0.000014 (0.003%), which is calibrated to the La Jolla international standard. The uncertainty of the measured $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ values did not exceed 0.003%. In the case of the $^{87}\text{Rb}/^{86}\text{Sr}$ and $^{147}\text{Sm}/^{144}\text{Nd}$ ratios, the errors were 1 and 0.2%, respectively (2σ). Details of the analytical method are reported by Chernyshev et al. (2012). The obtained data is presented in Table 1.

RESULTS

Sr-Nd Isotope Compositions

The measured $^{87}\text{Sr}/^{86}\text{Sr}$ values for 7 out of 8 samples are typical for the SR lavas and vary from 0.703270 for medium-K basaltic andesites (sample TIG-19-7730)

Table 1. $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ isotopic compositions of the selected samples from Tigilsky Dol and Mount Oxi massif

Group	Main feature	Sample number	Latitude (°N)	Longitude (°E)	$^{87}\text{Sr}/^{86}\text{Sr}$	2σ	$^{143}\text{Nd}/^{144}\text{Nd}$	2σ	ϵNd
1	Medium-K	TIG-19-7758	56.497	159.55	0.703386	0.000011	0.513000	0.000050	7.1
		TIG-19-7730	56.555	159.534	0.703270	0.000009	0.513054	0.000006	8.1
2	High-K	OXI-19-7712	56.375	159.114	0.703360	0.000010	0.513107	0.000006	9.1
		OXI-19-7724	56.393	159.077	0.703474	0.000009	0.513136	0.000006	9.7
3	High-Ti	TIG-19-7827	56.529	159.507	0.703311	0.000009	0.513089	0.000006	8.8
4	High-Mg	TIG-19-7734	56.582	159.577	0.703461	0.000009	0.513054	0.000006	8.1
		OXI-19-7720	56.377	159.075	0.703389	0.000009	0.513084	0.000006	8.7
5	High-LREE	TIG-19-7748	56.529	159.544	0.703650	0.000008	0.513147	0.000006	9.9

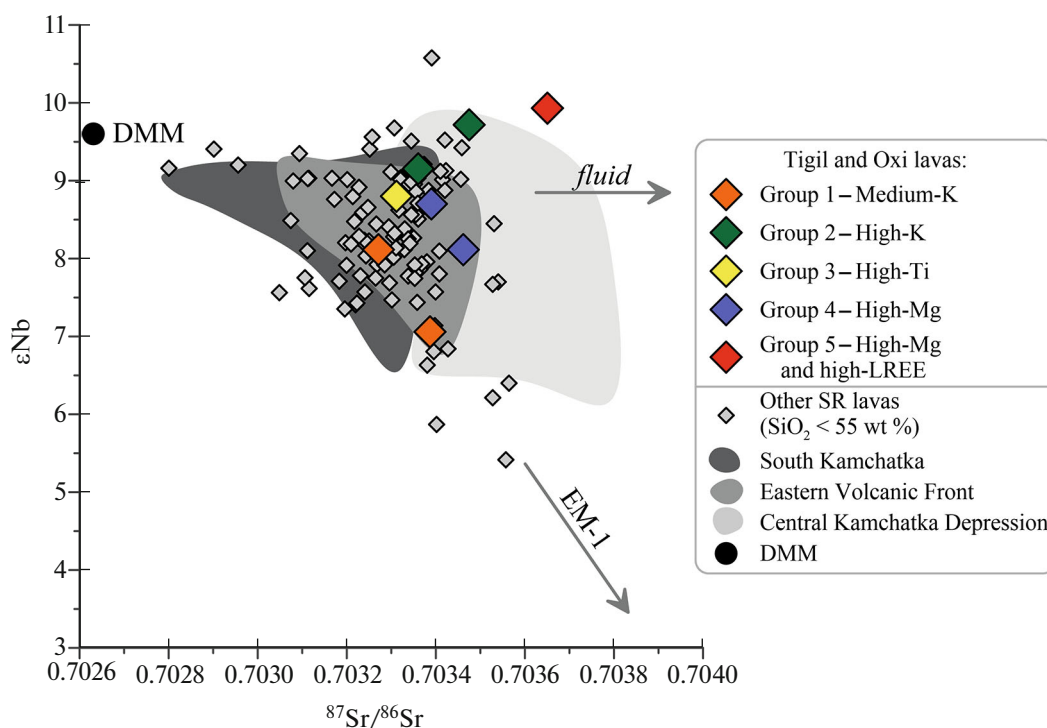


Fig. 2. Sr–Nd isotopic composition of the Tigilsky Dol and Mount Oxi massif lavas compared with the other SR lavas. The compositions of the other SR lavas are plotted after Volynets et al. (2024), the DMM value is plotted after Workman and Hart (2005). “EM-1”—trend to the Enriched Mantle-1 source, discussed by Volynets et al. (2024). “Fluid” characterizes the addition of the slab-derived fluids from pelagic sediments altered oceanic crust (see section 4.2). Data for other volcanic zones of Kamchatka are plotted according to the precompiled dataset for Kamchatka, which was downloaded from the GEOROC database (<https://georoc.eu/>) DIGIS Team, 2024, GEOROC Compilation: Convergent Margins, <https://doi.org/10.25625/PVFZCE>.

to 0.703474 for high-K basalts (OXI-19-7724). The high-LREE picobasalt sample (TIG-19-7748) is reaching an unusually high value of 0.703650, which is higher than in any other SR lava reported to date. Only some rocks from the Central Kamchatka Depression have such high $^{87}\text{Sr}/^{86}\text{Sr}$ values among the recent volcanic rocks of the peninsula (Fig. 2).

The $^{143}\text{Nd}/^{144}\text{Nd}$ values of studied rocks vary from 0.513000 ($\epsilon\text{Nd} = 7.06$, calculated relative to CHUR value of 0.512638) for medium-K basaltic andesites (TIG-19-7758) to 0.513147 ($\epsilon\text{Nd} = 9.93$) for the high-LREE picritic basalt sample (TIG-19-7748) (Fig. 2). Similarly high ϵNd in SR has only been reported for one Pliocene lava of the Uksichan volcano (sample ES-1826, Davydova et al., 2019).

Relationships between Sr–Nd Isotopes and Major and Trace Elements Contents

Sr–Nd isotopes do not show any co-variations with MgO content in the studied samples and the majority of them fall into the field of basalts and basaltic andesites of the SR (Figs. 3a, 3b). The high-Mg sample (TIG-19-7734) does not fall into this field due to very high MgO content, while the high-LREE

picritic basalt sample (TIG-19-7748) has both unusually high MgO and anomalous isotope composition.

The samples follow the weak positive K_2O – $^{87}\text{Sr}/^{86}\text{Sr}$ correlation (Fig. 3c) peaking with the high-K basalt (OXI-19-7724). The high-LREE picobasalt (TIG-19-7748) is again an exception from this trend having anomalously low K_2O content at high $^{87}\text{Sr}/^{86}\text{Sr}$. In terms of Nd isotopes, it should be noted that the highest K_2O content is accompanied by one of the highest ϵNd values, precluding the influence of continental crust on the enrichment in K_2O (Fig. 3d).

The majority of Large-Ion Lithophile Elements (LILE) have nearly the same co-variation patterns with Sr–Nd isotopes as K_2O (e.g., Figs. 3e, 3f). The Li content is exceptionally high in the high-LREE picobasalt sample (TIG-19-7748) (Figs. 3g, 3h). The High Field Strength Elements (HFSE) do not show any particular correlation with Sr–Nd isotopes, while a negative correlation of Nb/Zr with ϵNd is present for the majority of SR lavas (Fig. 3j). The high-LREE picobasalt (TIG-19-7748) has an unusually high Nb/Zr value for its isotope composition in comparison with the rest of the studied samples (Figs. 3i, 3j).

The REEs contents, distribution patterns (LREE/HREE) and their relations to the Sr–Nd iso-

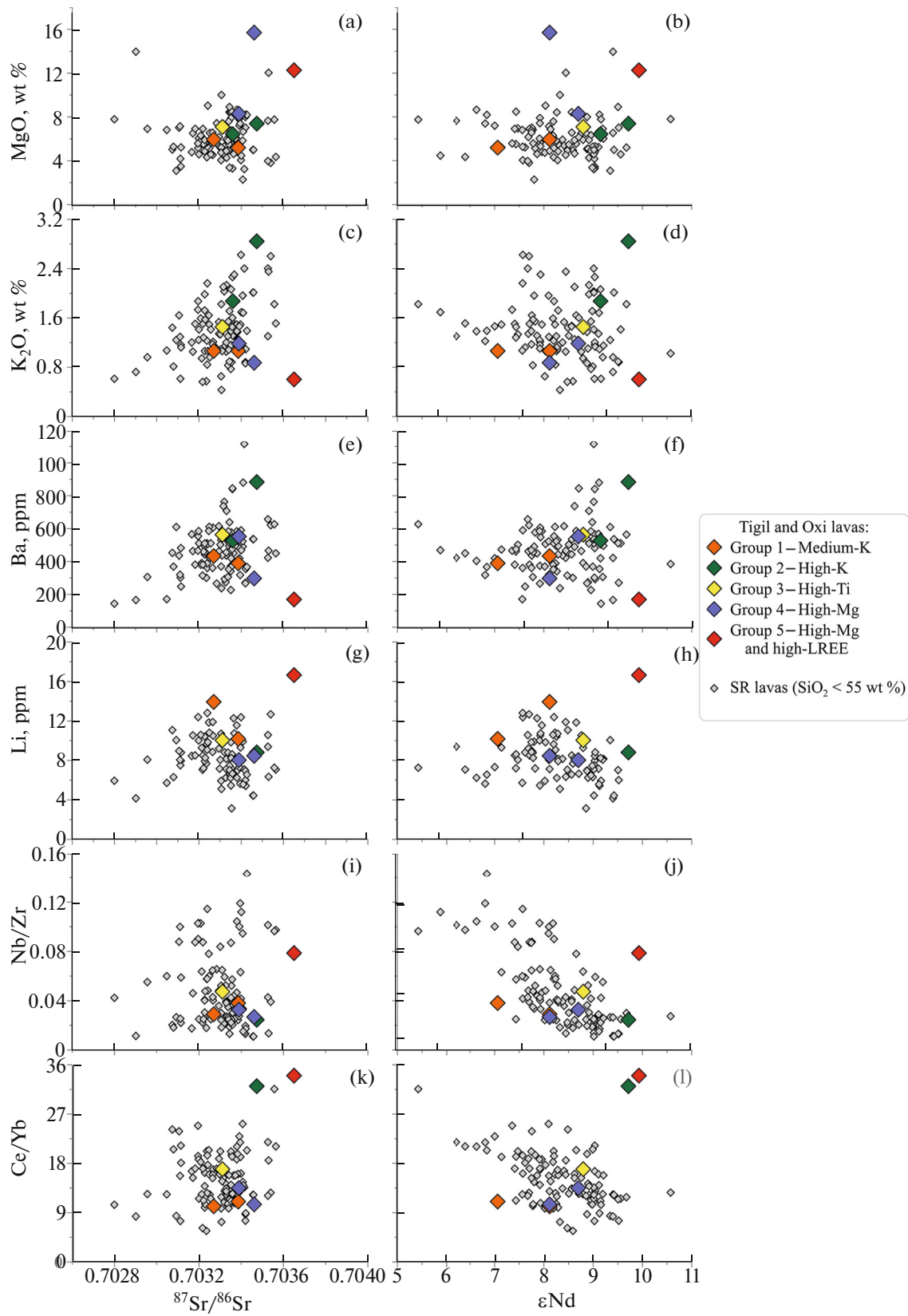


Fig. 3. Variation diagrams of Sr–Nd isotopes vs. major and trace element characteristics of studied lavas. The compositions of the other SR lavas are plotted after Volynets et al. (2024).

tope characteristics of samples from groups 1, 3 and 4 are typical for other basalts and basaltic andesites of the SR. However, samples from groups 2 and 5 have anomalously high LREE contents combined with high $^{87}\text{Sr}/^{86}\text{Sr}$ and ϵNd values (Figs. 3k, 3l).

DISCUSSION

Groups 1-4 Geochemical Variations

In general, the Sr–Nd characteristics of lavas from groups 1–4 are typical in comparison with the field of other studied SR lavas but cover a large portion of it (Fig. 2). Such significant Sr–Nd isotopic variations are likely linked to the different fluid sources and amounts of fluid for the rocks of different ages (Volynets et al., 2023) and isotope heterogeneity of the mantle source (Volynets et al., 2024). The differences between medium-K, high-K and high-Ti groups and their main geochemical characteristics can also be explained by the different amounts of fluid and fluid sources and different melting conditions. Some of the studied samples (e.g. OXI-19-7720) have a substantial estimated contribution of pyroxenite-derived melts (Volynets et al., 2023) that could also contribute to variations of trace elements contents and Sr–Nd isotope compositions.

Nature of LREE Enrichment

The high values of LREE/HREE in group 5 rocks are caused by the elevation of the LREE contents and not by the retention of HREE in the source, which could have been explained by the presence of garnet in the residue of melting (Volynets et al., 2023). Also, their mineral chemistry shows that these rocks originate from the melting of highly oxidized peridotites (Volynets et al., 2023). During the initial description of the lavas from the Tigilsky Dol and Mount Oxi massif, we suggested that such unusual LREE enrichment is likely caused by a disequilibrium melting of accessory allanite (Volynets et al., 2023). However, even though this mechanism can account for the REE patterns, it cannot be responsible for the anomalous isotopic composition of these rocks.

The geochemical features of the group 5 picrobasalts include not only the anomalously high values of LREE/HREE but also an unusual decoupling of $^{87}\text{Sr}/^{86}\text{Sr}$ and LILE contents (Fig. 3). Main mechanism of $^{87}\text{Sr}/^{86}\text{Sr}$ increase at the nearly constant ϵNd (Fig. 2) in subduction-related rocks are (1) mantle metasomatism by slab-derived fluids from high- $^{87}\text{Sr}/^{86}\text{Sr}$ –low- ϵNd source, e.g. pelagic sediments and (2) fluids from high- $^{87}\text{Sr}/^{86}\text{Sr}$ –high- ϵNd source, e.g. altered oceanic crust, which both should also enrich resulting rocks in LILE.

Recently Schettino et al. (2024) described lherzolute xenoliths from the Andean back-arc zone (Coyhaique, western Patagonia) that have quite similar

enrichment in LREE and Li, elevated Nb/Zr and high levels of oxidation recorded in mineral phases. Such features were interpreted as a consequence of a metasomatic interaction of lithospheric peridotites with a slab-derived melt. Indeed, nearly similar Sr–Nd isotope characteristics among the Quaternary volcanoes of Kamchatka are met only for the Central Kamchatka Depression (Fig. 2) where the slab-melt contribution is estimated to be substantial (Bryant et al., 2007; Nekrylov et al., 2018b; Yogodzinski et al., 2001; Zelenski et al., 2024). However, typical slab melts are also efficient LILE carriers so we suggest that group 5 might be a product of interaction of the SR lithosphere with melts derived from strongly degassed LILE-depleted slab. At the same time, the LREE enrichment of high-K rocks of group 3 might be a consequence of lithosphere metasomatism caused by more common LILE-rich slab-derived melts.

CONCLUDING REMARKS

Our study shows that the mantle sources beneath the Tigilsky Dol and Mount Oxi massif is heterogeneous in terms of Sr–Nd isotopes along the other geochemical characteristics and consists of several geochemically distinct domains. However, we suppose that there is no specific reason for the lithosphere in this part of the SR to be substantially more diverse than in the others. The main reason for the observed geochemical diversity of the volcanic rocks is likely the unusual stress field causing elevated volcanic/plutonic ratio due to abundant faults serving as magma conduits. We are confident that further study of the volcanic rocks from this unique region of the SR will provide a lot of new insights into the supra-subduction lithosphere formation and evolution.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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