Polybaric petrogenesis of Neogene alkaline magmas in an extensional tectonic environment: Viliga Volcanic Field, northeast Russia

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A B S T R A C T

Neogene alkaline intraplate volcanic rocks from the Viliga Volcanic Field (NE-Russia) were studied both to precisely characterize their geochemical composition and to unravel their petrogenetic history. The sampled volcanic rocks crop out within the voluminous calc-alkaline sequences of the Cretaceous Okhotsk-Chukotka Volcanic Belt, an Andean-type arc formed during subduction of the Paleo-Pacific Plate beneath modern far-east Asia. The mantle xenolith- and xenocryst-bearing basalts and nephelinites have intraplate ocean island basalt-type geochemical features. Sr and Nd isotopes combined with major and trace element systematics and rare-earth element modeling suggest polybaric melt generation of these alkaline magmatic rocks from a homogeneous garnet peridotite facies source with minor involvement of spinel peridotite facies partial melts. The basaltic samples indicate segregation PT conditions around 1500 °C at 33–38 kbar whilst the nephelinites reflect smaller melt fractions segregated at over 40 kbar. During ascent, olivine (up to 7%) was the main fractionating phase in the basanites; whereas in the nephelinites, both olivine and minor clinopyroxene fractionation occurred. Crustal contamination during ascent was insignificant. We argue that the melt generation of these alkaline magmas from the Viliga Volcanic Field was triggered by an extending lithosphere resulting in upwelling asthenosphere and decompression melting, analogous to geodynamic models of the coeval alkaline volcanic rocks along the adjacent North Pacific continental margins, rather than by subduction- or plume-related processes.

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1. Introduction

Primitive alkaline rocks with compositional features essentially unaffected by magmatic differentiation, crustal contamination or alteration can help unravel melt generating and petrogenetic processes in the Earth’s mantle. The analysis of small volume high-alkaline magmas in intraplate continental and continental margin settings not only contributes to our understanding of magma generation, but also provides crucial information for developing a clearer geodynamic picture of an area. Investigations of the sporadically occurring primitive lavas in northeastern Asia, including the region around Magadan, the Chukotka Peninsula and Kamchatka, will improve our understanding of the geological evolution of the northeastern Eurasian continental margin, which is composed of a complex assemblage of amalgamated and accreted terranes, overlain and intruded by volcanic arcs.

Within the spatially extensive Cretaceous continental arc-type volcanic successions of the Okhotsk-Chukotka Volcanic Belt (OCVB) at the southern continental margin of northeastern Russia, isolated and little studied volcanic necks of Neogene alkaline lavas crop out. One of these, the Viliga Volcanic Field (VVF), lies in the Magadan area close to the Viliga River, and comprises mantle xenolith- and megacryst-bearing basalts as well as nephelinites. The initial discovery of the VVF magmas was made in 1943 by D. S. Kharkievitch, with a short description given by A. L. Krist in 1949. The first major element data on samples from the VVF were obtained by Ichetovkin et al. (1970). More details, including some trace element and Sr, Nd, and Pb isotopic data, were published by Akinin and Apt (1997) and Apt et al. (1998). These preliminary data were all obtained from samples from only one outcrop, in the Aliki River area (VL5, in our study). The most recent and more detailed studies focused on the mantle xenoliths and magencrysts (Akinin et al., 2005; Ntaflas et al., 2008; Tschegg et al., 2004), following an international expedition in 2003.

In this study, new data on the mineralogical and bulk major and trace element compositions and Sr and Nd isotope ratios from four individual localities of the VVF are presented. From these data, we propose a petrogenetic model of the magmatic suite, including mantle source characteristics, pressure/temperature estimates of melt generation, degrees of partial melting, and fractional crystallization processes. Further, the data are compared with Late Cenozoic alkaline lavas emplaced along the northern Pacific continental margin between South-East Asia and Alaska.
2. Geological setting and sampling locations

The Okhotsk–Chukotka Volcanic Belt, an extensive Andean-type Early–Late Cretaceous continental volcanic arc that covers over 3000 km of Asia’s eastern continental margin (Hourigan and Akinin, 2004) is one of the most voluminous magmatic provinces in northeastern Asia. At the beginning of the Cenozoic, all collision and accretion events had finished and the subduction front of the Paleo-Pacific oceanic plate moved eastwards in the direction of the modern Kamchatka Peninsula. Subsequently, the consolidated continental margin of northeastern Asia experienced intensive destruction along major fault systems and seismically active plate boundaries.

Sparsely distributed Neogene alkaline mafic rocks intrude through, and erupt over, the complete Cretaceous calc-alkaline volcanic successions of the OCVB. On the northern shore of the Sea of Okhotsk, near Magadan, these rocks are represented by basanites and nephelinites of the Viliga Volcanic Field and farther north, on the Chukotka peninsula, by basanites, tephrites and foidites of the Enmelen River Volcanic Field (ENM, Akinin and Apt, 1994; Fig. 1). Some of these primitive magmatic rocks, whose petrogenesis and regional implications in this continental arc-type environment are poorly understood, contain mantle xenoliths and upper mantle xenocrysts, which were studied by Apt et al. (1998), Akinin et al. (2005) and Ntafos et al. (2008). Neither the Neogene volcanic rocks in the area, which post-date the Cretaceous Paleo-Pacific plate subduction, nor the underlying lithospheric mantle contains geochemical features related to the previous subduction process (Ntafos et al., 2008). Although the subduction front has moved eastwards since the Cretaceous, towards its present position at the Kamchatka Peninsula, the VVF is still seismically very active, with six recent earthquakes of magnitudes >3.5 and hypocenter depths of 30–35 km (Gunbina et al., 2007). This reflects its position adjacent to the southeastern branch of the dominant Chersky Seismic Belt, the modern boundary between the Eurasian and North-American continental plates and the Okhotsk Block (Fujita et al., 2009).

The VVF, which is the only known Late Neogene intraplate alkali basaltic volcanic field on the northern shore of the Sea of Okhotsk, lies on the east side of the Viliga River, at the junction of the Kananyga and the Aliki Rivers. The VVF is located at the intersection of two major fault systems; a series of NE-trending normal faults that stretch from Magadan along onshore Okhotsk, controlling the development of several neotectonic basins, and the sinistral Ulakhan strike–slip fault, which is perpendicular to the normal faults and thus parallel to the extension-direction (Fig. 1).

Isolated basaltic necks, remnants of cinder cones, dikes and lava flows crop out in the VVF. The largest outcrop is represented by a 70–80 m thick lava flow covering an area of around 1.5 km². Other dikes and cones cover 0.1 to 0.4 km² each. The VVF cuts through and partly overlies Cretaceous andesites, rhyolites, and dacites of the subduction-related calc-alkaline Okhotsk–Chukotka Volcanic Belt. More specifically, the VVF is located in the northeast trending Balygychan–Sugoi graben that is mostly filled with Cretaceous rhyolites and dacite ignimbrites. The graben developed during the early Cretaceous, within gently folded and weakly metamorphosed marine Triassic to Jurassic slates, shales, sandstones (Matveenko, 1957).

The age of VVF rocks is estimated as being Late Miocene; Ar–Ar and K–Ar ages range from 8 to 10 Ma (Akinin et al., 2005; 2008). On the Chukotka Peninsula, lavas of the same age and similar composition crop out in the Enmelen (ENM) volcanic fields (see Fig. 1; Apt et al., 1998).

The four outcrops of the VVF investigated include the previously unstudied locations VL1, VL2 and VL4 in the Kanagya River area (VL1—N 61°12′46.80″, E 155°10′10.80″; VL2—N 61°10′58.80″, E 155°24′00″; VL4—N 61°10′51.60″, E 155°22′48.00″) and the locality in the Aliki River area (VL5—N 61°23′34.80″, E 155°33′36.00″). The lavas from VL1 and VL5 contain mantle xenoliths (10–25 cm sized spinel–lherzolites) and megacrysts (augites of up to 5 cm diameter; Ntafos et al., 2008; Akinin et al., 2005), whilst only small xenoliths and xenocrysts occur in VL2 and VL4.

3. Analytical techniques

Polished thin-sections were carbon-coated and analyzed with a Cameca SX 100 electron-probe microanalyzer, equipped with one energy-dispersive and four wavelength-dispersive spectrometers (Department of Lithospheric Research, University of Vienna). Working conditions, measurement procedures and analytical errors are described in more detail in Tscheff et al. (2010); plagioclase, feldspatoid and glass measurements were analyzed using a defocused 6 μm beam technique. For bulk geochemical analysis, included xenocrysts were sequentially separated during crushing. Major and trace element abundances were analyzed on a PW 2400 X-ray fluorescence spectrometer (Department of Lithospheric Research, University of Vienna) and a Perkin Elmer ELAN 6100 DRC Inductively Coupled Plasma Mass-spectrometer (Division of Analytical Chemistry, University of Natural Resources and Applied Life Sciences, Vienna). Sample preparation and analytical methodology are described in Tscheff et al. (2008). An assessment of analytical precision and accuracy for XRD and ICP-MS measurements are given in the supplementary Table 5. Sr and Nd isotope analyses were performed on a Thermo-Finnigan Triton TI Tims (Department of Lithospheric Research, University of Vienna) following the procedures described in...
Thöni et al. (2008). Analytical errors of ± 0.000003 for $^{87}$Sr/$^{86}$Sr and $^{143}$Nd/$^{144}$Nd were assessed based on NBS987 and La Jolla international standard measurements.

4. Petrography and mineral chemistry

Representative analyses of each major mineral group forming the respective host lavas are given in the online supplement Table 1 (olivine), Table 2 (clinopyroxene), Table 3 (plagioclase, feldspathoids and glass) and Table 4 (ilmenite and Ti-magnetite). All rock samples show porphyritic textures with unaltered olivine phenocrysts up to 100 µm in size. Small clinopyroxene phenocrysts ($< 50$ µm) occur very rarely in lavas from VL4 and VL5.

Rocks from VL1 and VL2 contain well equilibrated, unzoned, rather homogeneously composed and mostly euhedral olivine phenocrysts ($F_{o77}$) with a composition similar to the groundmass olivine $(F_{o76})$. These phenocrysts show minor evidence of solution at their outermost rim but without any compositional alteration of the rim. The olivine phenocrysts in VL4 and VL5 are slightly more ferrous and show minor zoning, from $F_{o76}$ in the core to $F_{o69}$ at the rim and from $F_{o73}$ to $F_{o70}$, respectively. Groundmass olivines have $F_{o67}$ in VL4 and $F_{o68}$ in VL5. The fairly small and very rare clinopyroxene phenocrysts in VL4 and VL5 are titaniferous augites with compositions of $En_{39}Wo_{26}Fs_{11}$ and Mg# $(100 \times \text{molar MgO}/[\text{MgO} + \text{FeO}])$ ranging from 78 to 79. Titanomagnetite inclusions in augite phenocrysts are heterogeneously distributed in their host grain and have the same composition as the groundmass titanomagnetites.

The groundmass minerals are in general fine grained (10–30 µm) and comprise olivine, clinopyroxene, nepheline, leucite, plagioclase, Ti–Fe oxides and glass. The commonly observed groundmass clinopyroxenes have a very small range of compositions ($En_{39}Wo_{26}Fs_{12–13}$) with Mg# $77–79$ and TiO$_2$ concentrations between 2.6 and 2.8 wt.%, nearly identical to the cpx-phenocrysts in VL4 and VL5. Feldspathoids, nepheline, and leucite are compositionally similar in all samples of the suite. Leucites are all compositionally very similar, with $Ne_{24}K_{s4}Q_{72}$ compared to those from VL4 and VL5 ($Ne_{26–25}K_{s4}Q_{20–67}$). Groundmass plagioclases are rare, occurring only in VL1 and VL2, and have bytownite compositions ($Ab_{21}An_{78}Or_{1}$). Titanomagnetites have TiO$_2$ varying from 22 to 25 wt.% and FeO from 65 to 67 wt.% in VL1 and VL2, whereas in VL4 and VL5 their composition ranges from 23 to 27 wt.% TiO$_2$ and 66–69 wt.% FeO, respectively. Al$_2$O$_3$ in the titanomagnetites of VL1 and VL2 is systematically higher (~1.7 wt.%) compared to VL4 and VL5 (~0.2 wt.%). Ilmenites were only found in VL1 and VL2 and have 39–41 wt.% FeO and 51–51 wt. % TiO$_2$. Interstitial glasses vary in composition between the analyzed samples with the most significant difference shown between VL1–VL2 (basanites) and VL4–VL5 (nephelinites). Whereas glasses from VL1 and VL2 have an orthoclase-like chemistry (SiO$_2$: 57–59 wt.%, Al$_2$O$_3$: 23–26 wt.%, and K$_2$O: 7 wt.%), the glasses in VL4 and VL5 have a more silica-undersaturated composition (SiO$_2$: 45–48 wt.%, Al$_2$O$_3$: 23–26 wt.%, K$_2$O: 5–6 wt. %, and CaO: 5 wt. %, with BaO concentrations between 2 and 3 wt.%). Accessory apatite was also observed in all studied samples.

Apart from the phenocrysts present, petrographic evidence indicates a crystallization sequence in the groundmass passing from olivine through clinopyroxene, Ti–Fe oxides, leucite, nepheline, plagioclase and finally to glass.

5. Major and trace element and Sr–Nd isotope chemistry

5.1. Classification

In the TAS (total alkalis vs. silica; Le Maitre et al., 1989) diagram (Fig. 2a.), the samples from VL1 and VL2 (SiO$_2$: 43–45 wt.%) all plot in the tephrite/basaltic field. Due to their high olivine contents (normative olivine: 14–19%), they can all be classified as basanites (Le Maitre, 2002). The VL4 and VL5 samples (SiO$_2$: 42–43 wt.%) are transitional between basanites and foidites. Since they are rich in nepheline (normative ne: > 20%), we used the term nephelinites (after Le Maitre, 2002) for these rocks in the following text. In Fig. 2a., for comparison, rock compositions from the VVF and ENM, as well as from Neogene and Paleogene volcanic rocks of northeastern Russia and Alaska are plotted.

5.2. Major elements

Major and trace element concentrations of all analyzed samples are given in Table 1; major element abundances are illustrated in Fig. 2, trace elements in Fig. 3. Within the basanites from VL1 and VL2, MgO varies from 10.3 (VL2-T2) to 12.8 wt.% (VL1-40) whilst the studied nephelinites (VL4 and VL5) have lower MgO concentrations (8.8–9.7 wt.%). Total alkali contents vary only marginally within both the basanites ($K_2O = 2.5–2.9$ wt.% and $Na_2O = 4.1–4.3$ wt.%) and the nephelinites ($K_2O = 2.9–3.1$ wt.% and $Na_2O = 4.7–5.5$ wt.%), with the latter having slightly higher amounts of alkalis. Both alkalis increase in concentration with decreasing concentrations of MgO (Fig. 2b). SiO$_2$ is systematically higher in the basanite samples (43.5–44.6 wt.%) compared to the nephelinites (42.4–42.9 wt.%). Al$_2$O$_3$ shows a linear increase in concentration, from 13 to 14 wt.%, in the basanites with decreasing MgO but remain constant, around 10 wt.%, in the nephelinites (Fig. 2e). FeO and TiO$_2$ are enriched (12.2–12.7 wt.% and ~3 wt.% respectively) in the nephelinites compared to the basanites (10.9–11.2 wt.% and 2.5–2.8 wt.%). The basanites again show linear trends for these elements, when plotted against MgO (Fig. 2f). The CaO/Al$_2$O$_3$ ratios (Fig. 2g) remain fairly constant for the basanites (0.67–0.71) and show a narrow range and higher values for the nephelinites (0.73). The calculated Saturation Index SI (Fitton and James, 1991; Fig. 2h) underlines the slight silica undersaturation of the basanites (SI: ~4.6 to ~7.7) and the significantly more undersaturated nature of the nephelinites (SI: ~10.5 to ~14.7).

5.3. Trace elements

The compatible trace elements Ni (Fig. 3a) as well as Co and Cr (not shown) correlate positively with MgO. In the basanites (VL1 and VL2), Ni contents range from 201 to 320 ppm and in the nephelinites (VL4 and VL5) from 145 to 160 ppm. Co and Cr vary from 36 to 46 ppm and 252 to 414 ppm, respectively, in the basanites and from 38 to 40 ppm and 160 to 197 ppm in the nephelinites.

The LILE (Large Ion Lithophile Elements) Ba and Rb are present in lower amounts in the basanites (Ba: 493–583 ppm, Rb: 37–46 ppm) compared to the nephelinites (Ba: 628–655 ppm, Rb: 63–79 ppm); neither shows a linear correlation with MgO. Concentrations of Sr and the HFSE (high field strength elements) Zr, Nb, Hf, Th, Ta and the REE (rare-earth elements) are quite homogeneous in the basanites of VL1 and VL2-T3, whereas VL2-T2 and VL2-T4 are more enriched in these elements. All the basanites (VL1 and VL2) show a negative correlation with MgO. The nephelinites (VL4 and VL5) systematically show the highest abundances in HFSE except for Th. Zr/Y ratios remain almost constant, varying only between 8.26 and 9.25 in the basanites but are higher in the nephelinites (10.0–10.5; Fig. 3b). La/Nb ratios range from 0.58 to 0.63 in the basanites (VL1 and VL2), whereas in the nephelinites (VL4 and VL5) the values are lower, varying from 0.52 to 0.57.

All samples show sub-parallel REE patterns (Fig. 3c) and with general LREE (light rare-earth element) as well as HREE (heavy rare-earth element) enrichment when normalized to chondrite composition. The basanites from VL1 are generally slightly less REE enriched (La: 175–201 × C1, Lu: 7.9–8.6 × C1) compared to the nephelinites (La:
Fig. 2. Bulk major element compositions of the lavas from the VVF. Black arrows show calculated olivine fractionation trends starting at the most primitive sample VL1-40 (MgO: 12.8 wt.%). Black dots on the arrow indicate 3.2% olivine fractionation at MgO: 11.7 wt.% and 6.9% olivine fractionation at MgO: 10.3 wt.%.

(a) TAS (total alkaline vs. silica) diagram after Le Maitre (1989); for comparison, data from the VVF, ENM (Apt et al., 1998) and both Neogene and Palaeogene volcanic rocks from northeastern Russia (Akinin et al., 2008) are plotted. Late Cenozoic alkaline basalts from the Bering Sea Volcanic Province (Wirth et al., 2002) are shown (dashed field) as well as two rocks from the Alaskan Prindle Volcano (PV, crosses; Andronikov and Mukasa, 2010); (b) MgO vs. total alkalies; (c) MgO vs. SiO₂; (d) MgO vs. Al₂O₃; (e) MgO vs. CaO; (f) MgO vs. FeOtotal; (g) MgO vs. CaO/Al₂O₃; (h) MgO vs. Saturation Index (SI; Fitton and James, 1991).
samples show very similar HREE patterns, with (Tb/Yb)_N ranging from 2.8 to 3.3. Eu anomalies are generally absent.

Table 1

| Basanites     | VL1-31 | VL1-36 | VL1-37 | VL1-38 | VL1-39 | VL1-40 | VL2-T2 | VL2-T3 | VL2-T4 |
|---------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| SiO2          | 43.5   | 43.3   | 44.4   | 44.0   | 44.6   | 44.0   | 44.0   | 43.8   | 43.8   |
| TiO2          | 2.78   | 2.73   | 2.61   | 2.72   | 2.49   | 2.68   | 2.67   | 2.84   | 2.65   |
| ALO3          | 13.1   | 13.5   | 13.4   | 13.4   | 13.5   | 13.0   | 14.0   | 13.2   | 14.0   |
| FeO          | 11.0   | 11.0   | 11.1   | 11.0   | 10.9   | 11.0   | 11.1   | 11.2   | 11.0   |
| MnO          | 0.18   | 0.19   | 0.19   | 0.19   | 0.19   | 0.19   | 0.21   | 0.20   | 0.22   |
| MgO          | 12.7   | 12.1   | 12.6   | 12.0   | 11.7   | 12.8   | 10.3   | 12.4   | 10.6   |
| CaO          | 8.91   | 9.05   | 9.05   | 9.20   | 9.44   | 8.92   | 9.96   | 9.18   | 9.79   |
| Na2O         | 4.19   | 4.17   | 4.15   | 4.23   | 4.21   | 4.11   | 4.34   | 4.17   | 4.25   |
| K2O          | 2.84   | 2.86   | 2.48   | 2.75   | 2.56   | 2.83   | 2.68   | 2.71   | 2.68   |
| P2O5         | 1.06   | 1.01   | 0.98   | 1.03   | 0.99   | 0.96   | 1.46   | 1.12   | 1.45   |
| TOTAL        | 100.4  | 100.9  | 100.8  | 100.5  | 100.6  | 100.7  | 100.7  | 100.8  | 100.5  |
| LOI          | 0.72   | 0.65   | 0.37   | 0.61   | 0.05   | 0.16   | 0.86   | 1.02   | 1.23   |
| FeOt         | 2.8    | 2.6    | 2.6    | 2.5    | 2.5    | 2.6    | 2.5    | 2.6    | 2.6    |
| MgO          | 12.7   | 12.1   | 12.6   | 12.0   | 11.7   | 12.8   | 10.3   | 12.4   | 10.6   |
| CaO          | 8.91   | 9.05   | 9.05   | 9.20   | 9.44   | 8.92   | 9.96   | 9.18   | 9.79   |
| Na2O         | 4.19   | 4.17   | 4.15   | 4.23   | 4.21   | 4.11   | 4.34   | 4.17   | 4.25   |
| K2O          | 2.84   | 2.86   | 2.48   | 2.75   | 2.56   | 2.83   | 2.68   | 2.71   | 2.68   |
| P2O5         | 1.06   | 1.01   | 0.98   | 1.03   | 0.99   | 0.96   | 1.46   | 1.12   | 1.45   |
| TOTAL        | 100.4  | 100.9  | 100.8  | 100.5  | 100.6  | 100.7  | 100.7  | 100.8  | 100.5  |
| LOI          | 0.72   | 0.65   | 0.37   | 0.61   | 0.05   | 0.16   | 0.86   | 1.02   | 1.23   |
| FeOt         | 2.8    | 2.6    | 2.6    | 2.5    | 2.5    | 2.6    | 2.5    | 2.6    | 2.6    |

FeOt = Total amount of iron; LOI = Loss on ignition.

229–243 × C1, Lu: 9.1–9.7 × C1), with the exception of basanite samples VL2-T2 and VL2-T4 (La: 241–244 × C1, Lu: 9.8 × C1) which have similar REE abundances as VL4 and VL5 lavas. Beyond this, VL1 basanites have a minor spread of LREE concentrations, shown by varying (La/Yb)N ratios (18.2–22) whilst in the nephelinites the concentrations do not vary significantly (La/Yb)N: 22.2–22.4. All samples show very similar HREE patterns, with (Th/Yb)N ranging from 2.8 to 3.3. Eu anomalies are generally absent.

The primitive mantle (PM) normalized multi-element diagram (Fig. 3d) again illustrates the higher abundances of the highly to moderately incompatible elements in the nephelinites and the slightly lower concentrations in the basanites, again with the exception of VL2-T2 and VL2-T4. In general, all analyzed samples have PM-normalized patterns with slight negative anomalies in Th and Zr as well as positive anomalies of Nb, Sr and P with respect to their neighboring elements. The nephelinites differ from all the basanites (including VL2-T2 and VL2-T4) in being enriched in trace elements, except for Rb, Ba, K and Ti. In all samples, a general trend of increasing normalized element concentration with increasing incompatibility is observed until K; for the most
incompatible elements (Nb–Rb), the gradient remains fairly constant (Fig. 3d).

5.4. Sr–Nd isotope chemistry

Measured $^{78}$Sr/$^{86}$Sr and $^{143}$Nd/$^{144}$Nd isotope ratios are reported in Table 1; initial ratios are plotted in Fig. 4, calculated to 9 Ma for all lavas. Both basanites and nephelinites plot within a very small field, with $^{78}$Sr/$^{86}$Sr varying from 0.703065 to 0.7030154 and $^{143}$Nd/$^{144}$Nd from 0.513028 to 0.513039. Epsilon Nd ($\varepsilon$Nd) ranges from 7.7 to 7.9. The more isotopically depleted samples plot close to the PREMA (prevailent mantle) field, between HIMU (high μ) and DMM (depleted MORB mantle), at the intersection of MORB (mid ocean ridge basalt)- and OIB (ocean island basalt)-type melts (Hofmann, 1997; Stracke et al., 2005; and Zindler and Hart, 1986). Apt et al. (1998) reported similar Sr and Nd isotopic ratios from the Viliga and Enmelen volcanic fields. The clinopyroxene isotopic signatures from spinel–lherzolite xenoliths in the VVF are not related to the investigated melts as they are more depleted in radiogenic isotopes ($^{143}$Nd/$^{144}$Nd: 0.513234–0.513622, Ntaflos et al., 2008).

6. Petrogenesis of the rocks from the Viliga Volcanic Field

The basanites and nephelinites from the VVF indicate relatively primitive compositions, having both high compatible element contents and mantle xenoliths that appear almost unaffected by the host lavas. However, the major and trace element compositions indicate that the rocks do not represent primary magmas and that there were minor but significant differences in the melt generating processes between basanites and nephelinites. Petrographic, mineral and bulk geochemical evidence suggests that the basanites are a co-genetic suite of rocks, while the nephelinites represent melt from a slightly deeper but very similar source. In the following sections, both the petrogenetic processes, including the degree and depth of partial melting, fractional crystallization and crustal contamination and the mantle source that produced the lavas are considered.
6.1. Crustal contamination

Prior to the assessment of source characteristics and subsequent magmatic differentiation processes, the amount of crustal contamination affecting the samples must be evaluated. The primitive basanitic and nephelinitic magmas of the VVF have Zr/Nb ratios between 2.9 and 3.2, typical for alkaline rocks with OIB character (Weaver, 1991). Due to higher Zr/Nb ratios in crustal rocks, alkaline lavas contaminated by continental crust would have significantly higher values (Taylor and McLennan, 1985). La/Nb and K/P ratios in magmas affected by substantial degrees of crustal components normally reach 1.5 and 7 respectively (Hart, 1988), in contrast to the rocks of this study, which have much lower values (La/Nb: ~0.6 and K/P: ~4.6). Fig. 5 (Nb vs. Nb/U) clearly shows the similarity of the basanites and nephelinites from the VVF to OIB-type, mantle derived lavas. The range in Nb/U ratios (39–49) of the VVF lavas does not show any evidence for crustal contamination. Moreover, a positive linear correlation between SiO2 and 143Nd/144Nd, commonly regarded as key for crustal contamination (Chang et al., 2009), is completely absent in the studied rocks from the VVF.

The geochemical evidence clearly indicates that no or at least only insignificant assimilation of continental crustal rocks occurred during the rapid ascent of the lavas. This includes the ratios of the trace elements discussed previously, the mantle source characteristics (high Nb, low Zr, Th and K), the depleted 143Nd/144Nd isotopic signature, and also the lack of crustal xenoliths or xenocrysts in the rocks.

6.2. Fractional crystallization

The petrographic investigation of the studied samples suggests that olivine fractionation was the main magmatic differentiation process in the basanites, while in the nephelinites the fractionation of olivine together with minor clinopyroxene phenocrysts was important. Theoretical olivine fractionation trends were calculated for the major elements (after Pearce, 1978; plotted in Fig. 2), starting at the rocks of this study, which have much lower values (La/Nb: ~0.6 and K/P: ~4.6). Fig. 5 (Nb vs. Nb/U) clearly shows the similarity of the basanites and nephelinites from the VVF to OIB-type, mantle derived lavas. The range in Nb/U ratios (39–49) of the VVF lavas does not show any evidence for crustal contamination. Moreover, a positive linear correlation between SiO2 and 143Nd/144Nd, commonly regarded as key for crustal contamination (Chang et al., 2009), is completely absent in the studied rocks from the VVF.

The geochemical evidence clearly indicates that no or at least only insignificant assimilation of continental crustal rocks occurred during the rapid ascent of the lavas. This includes the ratios of the trace elements discussed previously, the mantle source characteristics (high Nb, low Zr, Th and K), the depleted 143Nd/144Nd isotopic signature, and also the lack of crustal xenoliths or xenocrysts in the rocks.

Fig. 5. Nb/U vs. Nb for the basanites and nephelinites from the Viliga Volcanic Field. Figure modified after Hofmann et al. (1986).
MORB source that fairly recently (<170 Ma) was metasomatized by a young HIMU component, and was not influenced by pelagic or continental sediments (Chang et al., 2009). In the Bering Sea, such a model is feasible, since subduction and the related dehydration of the slab has occurred continuously since the Paleocene.

### 6.4. Melt facies and degree of partial melting

For qualitative and semi-quantitative source and partial melting modeling, REE systematics were used. Diagrams plotting LREE and HREE against MREE and HREE (e.g. La/Yb – Dy/Yb, see Fig. 6a) allow a distinction to be made between melting in the garnet or spinel peridotite stability fields (Baker et al., 1997). If both sources contribute to the melting process, the melts produced should lie on tie-lines connecting the two sources.

All samples indicate a strong fractionation of HREE (Dy/Yb > 3), typical of magmas derived from garnet peridotite. The varying ratios of (La/Yb)N from 18.2 to 22.7 in the basanites are interpreted to be a result of slightly different degrees of partial melting of the same source, since all other trace element concentrations remain almost identical. Semiquantitative fractional melt modeling of a primitive mantle composition was carried out to determine whether different degrees of partial melting could have been responsible for the observed element trends (see Fig. 6). The observed linearity for La/Yb vs. Dy/Yb (Fig. 6a) cannot be explained by fractional crystallization or crustal contamination processes. The positive correlation of the analyzed samples indicates that all the basanites and nephelinites originated from a source having a very similar REE signature and, that the nephelinites with higher La/Yb and Dy/Yb represent smaller degrees of partial melting compared to most basanites. The highest CaO/Al₂O₃ values in the nephelinites also correlate with the lowest calculated melt fractions.

The melting models (after Shaw, 1970) presented in Fig. 6a and b were performed to assess the nature of partial melting that formed the VVF rocks as well as to theoretically assign the melts to distinct sources. The primitive mantle composition of McDonough and Sun (1995) was taken as a starting material that melted from 0.5 % to 20% under garnet as well as under the spinel peridotite field conditions; exact modal compositions of the source and melt proportions are given in the figure caption of Fig. 6. The La/Yb vs. Dy/Yb and La/Yb vs. Yb diagrams (Fig. 6a, b) indicate that the generation of the VVF rocks cannot be explained by variable degrees of partial melting of an exclusively garnet-bearing or a spinel-bearing lherzolite source. The suite lies on a near linear mixing line between theoretical garnet and spinel-bearing source melts, so that the simplest melt model involves an initial major partial melting in the garnet stability field followed by mixing of these melts with small melt fractions of spinel peridotite. This model, adapted from Baker et al. (1997), suggests that a 1 % melt of garnet peridotite mixed with a melt produced by 0.5 % melting of spinel peridotite. The theoretical mixing proportions lie between 90–95% melt of garnet peridotite and 5–10% of spinel peridotite. The samples from VL1 indicate slightly higher degrees of partial melting.
and moreover, somewhat larger melt fractions from the spinel stability field. Mixing of these two upper mantle melts is also documented by the negative correlation of La/Yb with Yb (Fig. 6b) in the basanites, with the same range of mixing proportions. Due to higher Yb concentrations (1.8–1.9 ppm) in the nephelinites and the two most differentiated basanite samples, these rocks do not plot exactly on the mixing line defined by most of the basanites with Yb ranging between 1.5 and 1.6 ppm. Although these melting models are only theoretical approaches and strongly dependent on the starting mantle composition as well as the partition coefficients, we conclude that the analyzed lavas are products of small volume partial melting of a garnet peridotite source and that the melts mixed with melts from spinel–lherzolite. In addition, the nephelinites, which do not plot exactly on the melting trends, indicate lower degrees of melting, probably at higher pressures, compared to the basanites (see next Section 6.5).

Based on petrographic and geochemical observations, evidence for hydrous K-rich minerals (such as amphibole or phlogopite) that could have been present in the mantle source and contributed to the primary magma melting, has not been detected. Negative K anomalies in normalized incompatible multi-element diagrams are usually indicative of either K-rich phases that fractionated from the primary magmas or K-rich phases that remained in the source during melting. As neither phenocrysts of such hydrous phases nor negative K anomalies (with respect to the neighboring elements) are observed in the primary mantle normalized diagram (Fig. 3d), the presence of amphibole or phlogopite during melting is unlikely. Rb/K2O values (with respect to the neighboring elements) are indicative of K-rich phases that fractionated from the primary magma melting, has not been detected. Negative K anomalies have been present in the mantle source and contributed to the hydrous K-rich minerals (such as amphibole or phlogopite) that could be present in the mantle source.

Section 6.5. Temperature and pressure estimates of melting

Pressure/depth and temperature estimates of mantle melting were carried out following the procedures described in Albarède (1992), Scarrow and Cox (1995), Putirka (2005—model A) and Lee et al. (2009). However, most of these barometers have not been calibrated for silica-undersaturated rocks. Due to this, only the Scarrow and Cox (1995) barometer was used to assess the nephelinite melt segregation pressures. For the basanites, which fulfill all requirements for the applied geothermobarometers, the yielded pressure estimates range from 33 to 37 kbar (Albarède, 1992), 34–38 kbar (Scarrow and Cox, 1995) and 44–50 kbar (± 2 kbar; Lee et al., 2009). All three show good positive linear correlations with each other. A particularly good overlap is obvious for the calculated pressure of Albarède (1992) and Scarrow and Cox (1995) while systematically ~10 kbar higher pressures are given for the pressure estimates using Lee et al. (2009), (see Fig. 6c). Lee et al. (2009) noted that the pressure estimates from Albarède (1992) are underestimated by up to 10 kbar, when pressures >30 kbar are obtained. However, the studied basanites are close to nephelinite composition (undersaturated in SiO2), so that the calculated high pressures from Lee et al. (2009) are likely to be overestimated. Based on the good agreement of the two individual barometers of Albarède (1992) and Scarrow and Cox (1995), we infer a pressure range of 33–38 kbar for the basanites from the VVF. For the nephelinite samples of this study, Scarrow and Cox (1995) barometry gives 42–44 kbar; even when treated with caution, this clearly indicates a deeper source compared to the basanitic samples of the suite. Furthermore, the nephelinites have the highest FeO, CaO and trace element contents within the studied rock suite, at substantially lower SiO2 concentrations compared to the basanites, which also reflect deeper melt segregation levels (Hirose and Kushiro, 1993).

The calculated temperatures for the basanites VL1 and VL2 give a narrow field of 1495–1509 °C according to Putirka (2005) and 1537–1563 °C according to Lee et al. (2009). Fig. 6d compares the PT conditions of the analyzed basanites, based on two different PT calculations. The pressure conditions based on Albarède (1992), which were converted to depth using the method of Scarrow and Cox (1995), yielded 104–116 km for the basanites (and 150–164 km for the nephelinites; see Fig. 6d). Such segregation temperatures and pressures in a continental intraplate setting indicate partial melting in the garnet peridotite field either caused by a deep-seated thermal anomaly (e.g. plume) or, as in this case, by extension of a thick continental lithosphere that either buffers heat beneath continents due to lithospheric insulation or mantle return flow due to the preceding subduction (Lee et al., 2009 and ref. therein). Even if a slight mixing with spinel peridotite facies melts can be modeled for the studied rocks, the lavas retain the major and primary melt conditions of the garnet peridotite facies, so that the calculated PT estimates may be underestimates.

6.6. Polybaric melt evolution

Plotting (La/Yb)n against the estimated P conditions (Fig. 6c) gives a positive linear trend, illustrating the correlation between the pressure of melting (based on major element mass–balance solutions) and the degree of fractional melting (based on REE systematics). The basanite petrogenesis, therefore, suggests that the samples segregated at deeper levels reflect lower degrees of partial melting, compared to the samples from shallower depths that indicate slightly larger melt fractions. This mirrors a polybaric melt evolution – with increasing degrees of partial melting at decreasing depth – of a common garnet peridotite source and apparently minor mixing with spinel peridotite partial melts during ascent, most likely en-route or during very short-lived “pooling” periods. The nephelinites ([(La/Yb)n] between 21 and 22) also indicate low fraction melting, at higher depths though, but still following the trend of higher melt fractions triggered through progressive pressure decrease. Since the isotopic Sr and Nd signal of the melts shows no significant differences, the melt fractions of the spinel peridotite field that contributed to the garnet–facies melts were either too marginal to influence the isotopic signature of the lavas or the melt contributing garnet– and spinel–facies mantle sources were isotopically fairly homogeneous.

7. Magmatism and regional tectonics

The Late Neogene mantle xenolith-bearing basanites and nephelinites from the VVF are similar to the melaneephelinites, tephrites and basanites analyzed by Apt et al. (1998) from the Viliga and the Enmelen (Chukotka Peninsula) volcanic fields in their major and trace element and Sr–Nd isotopic composition (Figs. 2a and 4). Additionally, the combined field of Late Neogene alkaline basalts from northeast Russia is similar in major element composition to the VVF lavas (Fig. 2a). The Neogene volcanic rocks, at least from the Viliga and Enmelen volcanic fields, formed within the same period and in a very similar tectonic setting. They also have an almost identical major element composition and Sr and Nd isotope signature, so that they are quite likely to be derived from the same or a very similar garnet peridotite source and erupted at contemporary associated volcanic events.

The trace element and isotope geochemistry of the young alkaline lavas from the VVF do not indicate any significant influence of Paleo-Pacific slab components, which previous studies and regional geological constraints suggest should be preserved below the surrounding Cretaceous arc (Hourigan and Akinin, 2004). In contrast,
late Cretaceous (~81–83 Ma) extrusive rocks (mainly basalts, basaltic andesites and rhyolites) from the Ola volcanic field (close to Viliga, approx. 130 km N from Magadan) directly post-dating the Paleo-Pacific subduction activity, clearly contain subduction-related components (Hourigan and Akinin, 2004; Letin et al., 2010). The slightly younger Mygdykit basalts (74–78 Ma), also cropping out within the OCVB, were formerly also attributed to late stage subduction-related volcanism. However, their distinctly younger age compared to the underlying calc-alkaline series and the fact that these capping basalts already have intraplate geochemical features indicate that they are more likely related to post-subduction extension than being directly subduction-related (Hourigan and Akinin, 2004 and ref. therein).

Based on our geochemical and radiogenic isotope observations as well as calculations of PT conditions of melting, we infer that the petrogenesis of the studied rock suite is related to post-subduction passive mantle upwelling in an extensional regime, rather than to melt generation through local heat anomalies. The cessation of the subduction (87 Ma, Hourigan and Akinin, 2004) and the following “piecemeal breakup” (Nafllos et al., 2008) of the slab, combined with extension due to subsidence and back-rotation of the oceanic crust, provided space between the slab pieces and thus facilitated diabatic upwelling of the asthenosphere, combined with decompression melting and ascent of the studied lavas. The breakup of the northeastern Asian continental margin along seismically highly active belts and major faults, situated at plate boundaries and along the Sea of Okhotsk margin, occurred simultaneously with rare intraplate alkaline volcanism in the area. Seismic studies from the area indicate a thin crust (30–35 km) at the Okhotsk margin as well as beneath the OCVB and transparency on seismic profiles (lack of reflectivity) under the Omsukchan trough (Goryachev et al., 2007; Nikolaevsky, 1967). The N–S trending rift-type structural lineament of the Omsukchan trough is closely related to the evolution of the OCVB (Sidoren et al., 2009), as seen on seismic profiles from almost 200 km further north of the VVF (C–C profile from Goryachev et al. (2007) is shown in Fig. 1). The lack of seismic reflection is interpreted as thinning of the lithosphere combined with the upwelling of asthenospheric material.

Post-subduction extension related intraplate alkali magmatism has been described in a number of plate margin settings (Fiji, Mexican Volcanic Belt, New Zealand, Western U.S.; Wirth et al., 2002 and references therein). They are distinct from continental rift settings as they do not include felsic magmatism. Comparing the lavas from this study to alkaline rocks (basanites and alkali–olivine basalts) from Late Cenozoic volcanic fields of the Bering Sea (Bering Sea Volcanic Province), a strong similarity is evident in both the major and trace elements as well as the Sr and Nd isotopes (see Figs. 2a, 3d and 4). These younger, isolated but widely dispersed intraplate volcanic centers in the Bering Sea region have been proposed to be the products of small fraction melts of a fertile mantle. Furthermore, they reflect a very similar composition and emplacement history as the Late Cenozoic volcanics of Southeast Asia (collectively termed “diffuse igneous province”), which are also related to tectonic extrusion and extension along regional faults (Hoang et al., 1996; Wirth et al., 2002).

In the North Cordilleran Volcanic Province, Alaska, Cenozoic intraplate volcanic rocks can be found that are compositionally analogous to the rocks from the VVF. Basanites from the Prindle Volcano (PV), for example, are slightly less alkaline in nature, but have almost identical trace element patterns and isotopic compositions (Figs. 2a, 3d, and 4). Based on their composition and their mantle xenolith-bearing nature, the lavas from Prindle Volcano are thought to be near-primary magmas (Andronikov and Mukasa, 2010). Late Cenozoic volcanism in this region is attributed to extension, triggered by the change of relative plate motion between the North-American and the Pacific Plates and related faulting. Extension of the lithosphere resulted in upwelling asthenosphere, and episodic decompression melting from the Late Tertiary to Quaternary. This melting was localized at plate boundary regions but also in interior Alaska (Andronikov and Mukasa, 2010). Even though produced in an extensional tectonic environment due to decompression melting of a garnet-bearing asthenospheric source, a minor influence of subduction-related fluids of the North Pacific lithosphere beneath Alaska has not been entirely excluded during the genesis of the Prindle Volcano basalts (Andronikov and Mukasa, 2010).

The formation of the very young (Pliocene to Holocene) alkaline volcanism on the Pribilof Islands (Alaska) is reported as being both related to lithospheric extension inducing passive upwelling and decompression melting of a metasomatized upper mantle (Chang et al., 2009). Even though the extensional peak in the Bering Sea region occurred around Middle- to Late-Cretaceous times (Dumitru et al., 1995), the regionally active tectonic movements (normal faults, Basin and Range type tectonics) were related to extension until recent times. As postulated for the magmatic activity in the VVF, mantle plume activity was unlikely to have been involved in the basalt formation on the Pribilof Islands (including also the rest of the Bering Sea Basaltic Province) but passive mantle upwelling controlled by the present ex- or transtensional geodynamic features (Chang et al., 2009). Apart from their petrogenetic and geodynamic similarities, the basalts, trachybasalts and basanites from the Pribilof Islands are compositionally similar to the rocks from this study, mainly confirmed by their overlapping Sr and Nd isotopic signatures (see Fig. 4).

The Cenozoic intraplate extensional tectonics and its related magmatism further south, along the whole East Asian continental margin (from northeast Russia to eastern China), are also proposed to be linked to the subduction of the Pacific Plate under Eurasia (Pirajno et al., 2009). However, the magmatism is not restricted to the East Asian continental margin but extends inland from the Eurasian Plate boundary. Here alkaline volcanic series are generally situated in subduction-linked, fault-dominated settings, suggesting intraplate mantle processes as a cause of their emplacement (Pirajno et al., 2009). Crustal extension and fault-related extrusion, lithospheric thinning and asthenospheric mantle upwelling undoubtedly are the key driving forces for plutonic and volcanic activity in the North Pacific adjacent to continental margin settings during the Cenozoic period. The magmatic activity in the Viliga Volcanic Field can be attributed to similar geodynamic features.

8. Concluding remarks

- According to their major and trace element geochemical composition, the lavas from the Viliga Volcanic Field represent a co-genetic suite of intraplate OIB-type basalts and nephelinites.
- Though intruding the calc-alkaline Cretaceous continental arc rocks of the Okhotsk–Chukotka Volcanic Belt, the Neogene alkaline lavas of the VVF do not contain subduction-related geochemical or isotopic features.
- Sr and Nd isotope ratios, as well as trace element systematics suggest melting of the studied lavas from a homogeneous garnet-bearing mantle source (at the depletions end of the OIB array), without a contribution from K-rich phases.
- Mantle melt modeling and PT estimates reveal that the basalts from the VVF were produced by partial melting under garnet peridotite facies conditions (33–38 kbar and ~1500 °C) and mixed with minor melt proportions from the spinel peridotite field. The nephelinites clearly reflect melting at deeper levels (~40 kbar).
- The VVF lavas were produced by passive mantle upwelling that triggered decompression melting. Evidence of polybaric melt formation can be observed in the studied rocks. Lavas with higher melt segregation pressures systematically reflect lower degrees of partial melting and co-genetic lavas with lower segregation pressures reflect larger melt fractions.
- En-route, the basalts experienced up to 7% olivine fractionation. Olivine together with some minor clinopyroxene fractionation is
observable only in the nepheline fields. Contamination of the lavas during ascent by continental crust components cannot be verified. – Similar to many of the other volcanic fields around the northern Pacific that are adjacent to continental margins, the genesis of the VVF was most probably triggered by post-subduction extension, crustal-scale plate reorganization, adiabatic asthenospheric mantle upwelling and decompression melting, resulting in the episodic and sporadic construction of intraplate volcanic provinces during Cenozoic. Large-scale trans- and extensional tectonics in the area around the Viliga Volcanic Field are still documented by a number of highly active faults and strong seismicity.

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