

# Mantle temperature control on composition of arc magmas along the Central Kamchatka Depression

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## ABSTRACT

Abundant volcanism in the Central Kamchatka Depression (CKD) adjacent to the Kamchatka–Aleutian Arc junction occurs where the Pacific slab edge is subducting beneath Kamchatka. Here we summarize published data on CKD rocks and demonstrate a systematic south-to-north change of their compositions from moderately fractionated basalt-andesite tholeiitic series to highly fractionated basalt-rhyolite calc-alkaline series including high-magnesian andesites near the slab edge. Localized slab melting at the slab edge cannot explain these regional geochemical variations. Instead, we propose that the thermal state of the mantle wedge can be the key factor governing the composition of CKD magmas. We integrate the results from petrology and numeric modeling to demonstrate the northward decrease of the mantle wedge temperatures beneath CKD volcanoes, which correlates with decreasing slab dip, length of mantle columns, and magma flux. We envision two petrogenetic models, which relate the composition of erupted magmas to the subduction parameters beneath the CKD. The first model suggests that mantle temperature governs melt-peridotite equilibria and favors generation of andesitic primary melts in cold mantle regions above the shallowly subducting Pacific slab edge. Alternatively, mantle temperature may control magmatic productivity along the CKD, which decreases sharply toward the slab edge and thus allows more extensive magma fractionation deeper in the crust and mixing of highly evolved and mantle-derived magmas to generate Si-rich “primitive” magmas. These results point to a possible casual link between deep mantle and shallow crustal magmatic processes. Similar effects of mantle temperature on the composition and productivity of arc magmatism are expected elsewhere, particularly in volcanic regions associated with significant slab dip variation along the arc.

**Keywords:** Kamchatka, island arc, subduction, calc-alkaline, tholeiite, high-magnesian andesite, mantle wedge, mixing, numeric modeling.

## INTRODUCTION

Mantle composition, thermal state, and dynamics have significant effects on the composition, localization, and productivity of arc magmatism (Plank and Langmuir, 1988; Tamura et al., 2002; Kelemen et al., 2003; Cagnioncle et al., 2007; Portnyagin et al., 2007b). Recent numeric models suggest that the dynamics of a mantle wedge might be complexly influenced by a number of subduction parameters (Cagnioncle et al., 2007). Whether the model predictions fit geophysical and geochemical data is unclear, and the understanding of the casual link between subduction and mantle wedge processes and composition of primitive and evolved arc magmas remains one of the most fundamental problems of arc magma genesis.

In this study we compare the results from an extensive data set on composition of volcanic rocks of the Central Kamchatka Depression (CKD) with the results from numeric modeling and demonstrate that systematic decrease

of mantle temperature and magmatic productivity with decreasing subduction dip might be responsible for the transition from tholeiitic to calc-alkaline volcanism along the arc strike in northern Kamchatka.

## GEODYNAMIC FRAMEWORK

The Kamchatka Peninsula, as part of the circum-Pacific “Ring of Fire,” forms the northern part of the Kuril–Kamchatka volcanic arc in the NW Pacific Ocean and represents one of the most volcanically active regions on Earth. The largest and most productive volcanoes in Kamchatka occur in the northern part of the CKD, in proximity to the Kamchatka–Aleutian Arc junction (Fig. 1A).

In order to reconcile the transition from subduction beneath Kamchatka to strike-slip plate movements along the western Aleutian Arc, several authors proposed that the Pacific plate is likely torn along the Aleutian fracture zone and its edge is currently subducting beneath Kamchatka at the arc junction (Levin et al., 2002a; Yagodinski et al., 2001) (Figs. 1A and 1B). Under this premise, the largest active CKD vol-

canoes (Shiveluch, Klyuchevskoy, and Tolbachik) are located above the subducting Pacific plate, 60–200 km southwest from the slab edge. The Shisheisky Complex of Late Pleistocene–Holocene monogenetic volcanic centers occupies the position nearly above the proposed slab edge. Farther to the north, the Late Pleistocene sporadic volcanism near Nachikinsky volcano is unrelated to the ongoing subduction and originated due to short-lived mantle upwelling after slab detachment beneath northern Kamchatka (Portnyagin et al., 2005; Levin et al., 2002a).

Seismic data suggest progressively shallower subduction dip of the Pacific plate toward its northern edge, from  $\sim 45^\circ$  beneath Tolbachik volcano to  $\sim 30^\circ$  beneath Shiveluch volcano (Gorbatov et al., 1997) (Fig. 1). The upward bending of the subducting Pacific plate toward its northern edge results in large variations in depths to the subducting slab beneath CKD volcanoes (from  $\sim 190$  to  $\leq 90$  km). Since the crustal thickness beneath the CKD is relatively constant ( $\sim 35$  km) (Levin et al., 2002b), the mantle wedge narrows from  $\sim 155$  km beneath Tolbachik volcano to  $\sim 55$  km beneath Shiveluch volcano (length of mantle column beneath a volcano) and may be even thinner above the slab edge.

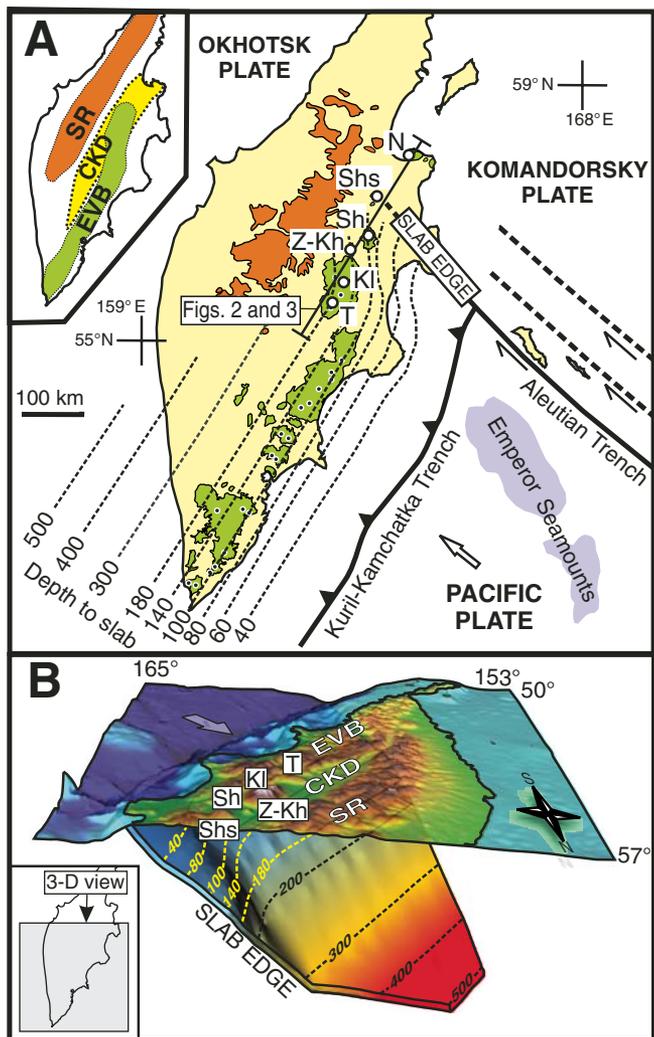
## SYSTEMATIC GEOCHEMICAL VARIATIONS ALONG THE CKD

In this study we use a compilation of  $\sim 1000$  published and original analyses of the late Quaternary volcanic rocks from the CKD previously described by Portnyagin et al. (2007a) and further updated for the present work. The latest version of the database is available at <ftp://ftp.ifm-geomar.de/users/mpportnyagin/Kamchatka>. A distinctive feature of the CKD volcanoes compared to other volcanoes in Kamchatka is the presence of primitive rocks with  $Mg\# > 0.65$  ( $Mg\# = MgO/(MgO + FeO^*)$ ) calculated on a molar basis, where  $FeO^*$  is total Fe expressed as FeO, approaching compositions of parental mantle-derived melts. This allowed direct comparison between primitive and evolved rocks for the CKD volcanoes and examination of their compositional trends along the arc strike (Fig. 2).

A striking observation from our analysis is a systematically increasing compositional variability of both primitive and evolved rocks from

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**Figure 1.** Kamchatka subduction zone. **A:** Major geologic structures at the Kamchatka–Aleutian Arc junction. Thin dashed lines show isodepths to subducting Pacific plate (Gorbatov et al., 1997). Inset illustrates major volcanic zones in Kamchatka: EVB—Eastern Volcanic Belt; CKD—Central Kamchatka Depression (rift-like tectonic structure, which accommodates the northern end of EVB); SR—Sredinny Range. Distribution of Quaternary volcanic rocks in EVB and SR is shown in orange and green, respectively. Small dots are active volcanoes. Large circles denote CKD volcanoes: T—Tolbachik; KI—Klyuchevskoy; Z—Zarechny; Kh—Khar-chinsky; Sh—Shiveluch; Shs—Shisheisky Complex; N—Nachikinsky. Location of profiles shown in Figures 2 and 3 is indicated. **B:** Three-dimensional visualization of the Kamchatka subduction zone from the north. Surface relief is shown as semi-transparent layer. Labeled dashed lines and color (blue to red) gradation of subducting plate denote depths to the plate from the earth surface (in km). Bold arrow shows direction of Pacific Plate movement.



south to north along the CKD. Although primitive basalts occur in all localities, the range of primitive rock compositions increases toward the slab edge so that their mean and maximum  $\text{SiO}_2$  and  $\text{Na}_2\text{O}$  contents increase and  $\text{MgO}$ ,  $\text{FeO}$ ,  $\text{TiO}_2$ , and  $\text{CaO}$  decrease. Many primitive rocks from Shiveluch volcano and Shisheisky Complex are high-magnesian andesites (HMAs) with  $\text{SiO}_2$  up to 63 wt%. The presence of HMAs among eruptive ejecta of the northern CKD volcanoes coupled with elevated Sr/Y ratio was particularly emphasized and referred to as an “adakitic signature” in the recent literature (e.g., Yogodzinski et al., 2001).

Evolved rocks also become more Si-rich and Ca-, Fe-, and Ti-poor toward the slab edge (Fig. 2). High-Al basalts and basaltic andesites are the predominant type of evolved rocks of the southern Klyuchevskoy Group of volcanoes. The most evolved rocks of these volcanoes (e.g., Bezymianny) are andesites with  $\text{SiO}_2$  rarely exceeding 60 wt%. Farther to the north, evolved magmas approach dacitic (Shiveluch volcano)

and even rhyolitic (Shisheisky Complex) compositions. Overall, we observe the transition of predominating rock types along the CKD, from high- and middle-Fe (tholeiitic) series in the south to low-Fe (calc-alkaline) series in the north (Fig. DR1 in the GSA Data Repository<sup>1</sup>), which correlates with the appearance of HMAs among the most primitive rocks of the northern volcanoes.

To the north from the active subduction zone, rocks of Nachikinsky volcano span a wide range of compositions from basalts to rhyolites (Fig. 2). Primitive to moderately evolved magmas of this volcano do not follow the general geochemical trend of the CKD, indicating a drastic change in conditions of magma gen-

<sup>1</sup>GSA Data Repository item 2008128, Appendix DR1 (numeric modeling procedure, supplementary figures, and mean compositions of CKD rocks), is available online at [www.geosociety.org/pubs/ft2008.htm](http://www.geosociety.org/pubs/ft2008.htm), or on request from [editing@geosociety.org](mailto:editing@geosociety.org) or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

eration. The origin of this volcanism through decompression mantle melting followed by assimilation in the lithospheric mantle and crust is justified by Portnyagin et al. (2005). This volcanism is beyond the scope of the present work, which focuses on the origin of subduction-related magmas in the CKD.

To explain the south-north regional variations of subduction-related CKD rocks, three end-member models can be envisaged. These models invoke that variability of erupted magmas is related to (1) variable contribution from slab melts, (2) different conditions of mantle melting, or (3) crustal fractionation. Below we explore these hypotheses.

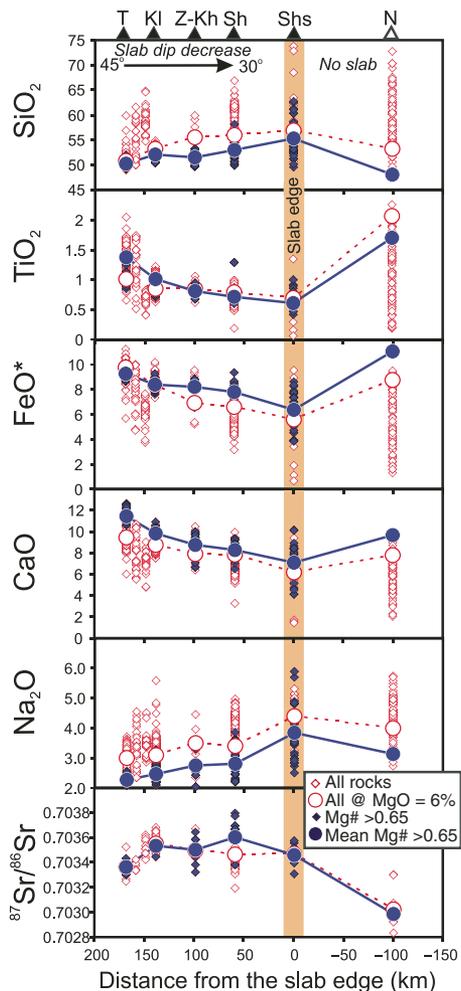
### MIXING OF SLAB- AND MANTLE-DERIVED MAGMAS

Yogodzinski et al. (2001) suggested that the edge of the Pacific slab beneath Kamchatka ablated by hot mantle from three sides can be hot enough to melt. They argued that contribution from the slab melting is responsible for the specific geochemical features of the northern CKD volcanoes. Following this model, the entire systematics of primitive CKD magmas could be explained by mixing of mantle-derived basaltic magmas and Si-rich slab melts, whose contribution increased near the slab edge.

Quantitative thermal modeling (Fig. 3) predicts temperatures at the Pacific slab edge  $>800^\circ\text{C}$  at 70–80 km depth and thus confirms the possibility of water-saturated eclogite melting. It is, however, evident from experimental studies (e.g., Yaxley and Green, 1998) that easy transport of eclogite melts through the mantle wedge and mixing with basaltic mantle-derived melts is a very improbable scenario. Because eclogite melts are highly reactive with peridotite, these melts should quickly approach equilibrium with the mantle wedge (e.g., Kelemen et al., 2003) or be frozen in the mantle due to reaction with mantle olivine (e.g., Yaxley and Green, 1998; Sobolev et al., 2005). We therefore doubt a direct involvement of slab melts in the origin of variably Si-rich primitive magmas in the CKD.

### TEMPERATURE CONTROL ON PRIMITIVE MAGMA COMPOSITIONS

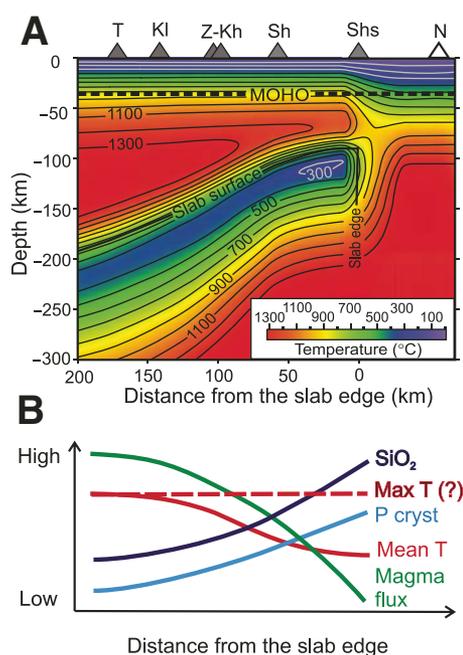
The composition of mantle melts complexly depends on the source composition and physical conditions of melting (temperature, pressure, and water content) (e.g., Gaetani and Grove, 1998; Parman and Grove, 2004), which are difficult to reconcile for arc magmas. Nonetheless, among other parameters, temperature has been suggested to have the largest effect on composition of mantle melts and to favor generation of Si-rich hydrous melts in low-temperature mantle regions (Parman and Grove, 2004; Hirose, 1997; Grove et al., 2003). Therefore, assuming that



**Figure 2.** Variations of major elements and strontium isotope ratios in CKD rocks. Small open diamonds—compositions of all rocks; large open circles—rock compositions at MgO = 6 wt%; small solid diamonds—primitive rocks with Mg# > 0.65; large solid circles—mean compositions of primitive rocks for CKD volcanoes. Volcano abbreviations are given in Figure 1.

primitive CKD rocks correspond to the composition of parental CKD magmas, one may suggest significant temperature variations in the mantle wedge along the CKD, which actually governs the composition of parental melts. Basaltic parental melts can originate from hot mantle sources, whereas HMA parental magmas probably originate from cold mantle wedge regions, which play an increasingly more important role in the magma genesis toward the slab edge. Differentiated magmas could in this case inherit the compositional peculiarities of their parental melts and evolve to more Si-rich compositions from Si-rich parents (Fig. 2).

In order to test these predictions, we have modeled the thermal structure of the CKD subduction zone. The modeling was performed for four across-arc profiles with average resolu-



**Figure 3.** Trench-parallel along-arc thermal model (A) and summary of physical and compositional parameters of CKD magmatism (B). Volcano abbreviations are explained in Figure 1. Trench-normal thermal cross sections used to constrain along-arc profile are shown in Figure DR2. Due to likely transient regime of subduction near the slab edge, the maximum model temperature near the slab edge is underestimated (see text for explanation); it can be similar beneath all volcanoes (shown as dashed line in Fig. 3B, max T). The volume of hot mantle (>1300 °C) and therefore mean temperatures (mean T) decrease toward the slab edge, which correlates with decreasing subduction dip and magma flux and increasing SiO<sub>2</sub> in evolved and primitive magmas (SiO<sub>2</sub>) and pressure of crystallization (P cryst).

tion of 5 km following the modeling scheme of Manea et al. (2005) (Fig. DR2), which were used to construct thermal profile along the arc (Fig. 3A). These results demonstrate significant lateral changes of temperature distribution in the mantle wedge beneath volcanoes. Peak mantle temperatures gradually decline from ~1350 °C beneath Tolbachik volcano to ≤1200 °C beneath Shisheisky Complex. The initial mantle potential temperature (1350 °C) and subduction rate (7.5 cm/yr) adopted in our model were kept constant for all profiles. The established thermal heterogeneity of the mantle wedge along the CKD is therefore a pure effect of subduction dip on the mantle corner flow (Cagnioncle et al., 2007).

Due to scarcity of data on water concentrations in primitive CKD magmas, it is difficult to test whether our numeric model agrees with real liquidus temperatures of parental CKD melts. The temperatures for Klyuchevskoy parental melts (1280–1320 °C at 1.5–2 GPa)

estimated from data on melt inclusions in high-Mg olivine (Portnyagin et al., 2007a) match the numeric model well. Unfortunately, such quantitative comparison is presently not possible for the northern CKD volcanoes. Qualitative relationships between FeO and Na<sub>2</sub>O concentrations in primitive CKD rocks show, however, that the mean temperature of magma generation indeed can decrease substantially toward the slab edge (Fig. DR3).

Our numeric model appears to preclude generation of hot basaltic parental magmas for localities near the slab edge, although basalts were actually documented in Shiveluch volcano and Shisheisky Complex. A possible explanation for this discrepancy is that our model was calculated for a steady-state subduction regime. The upward bending of the subducting slab edge beneath the CKD can be, however, a relatively recent event in response to detachment of a slab fragment in the Miocene (Levin et al., 2002a). It is possible that hot mantle domains can still exist beneath the northern CKD volcanoes and be able to generate basaltic parental magmas, which erupt contemporaneously with HMAs.

The results of thermal modeling thus support interpretation of the compositional trends of the CKD rocks as reflecting a decrease of the magma generation temperature and the length of mantle columns toward the slab edge. In this respect our results coincide with the proposed mantle temperature control on the composition of tholeiitic and calc-alkaline volcanoes in the Aleutian Arc (Kelemen et al., 2003). A major problem of this model is that mantle-derived origin cannot be undoubtedly justified for all primitive CKD rocks, whose compositions can be affected by crystal fractionation, magma mixing, and assimilation.

#### MAGMA FLUX CONTROL ON CRYSTAL FRACTIONATION AND MIXING

Processes of magmatic fractionation in the crust, such as magma mixing and/or assimilation, were shown to be particularly important in the origin of calc-alkaline rock series compared to tholeiitic series (e.g., Kay and Kay, 1985) and are relevant to the origin of HMAs (e.g., Streck et al., 2007).

One possibility is that primitive CKD rocks are variably contaminated by Si-rich crustal material. Available isotopic and trace element data on the CKD rocks, however, do not support this hypothesis (Portnyagin et al., 2005, 2007a). For example, strontium isotope ratios, which are expected to increase with increasing assimilation, do not change systematically along the CKD (Fig. 2).

Alternatively, the compositions of primitive CKD rocks can be affected by mixing with evolved magmas (Fig. DR1). A small addition of Si-rich evolved melt can significantly

increase SiO<sub>2</sub> in primitive magmas without a large change of Mg#. In this case, a particularly large effect is expected for volcanoes, where magmas evolve to very Si-rich compositions. Indeed, HMAs were found in Shiveluch volcano and Shisheisky Complex, where magmas evolve to dacites and rhyolites, but no HMAs were described in the Klyuchevskoy Group of volcanoes, where basaltic andesites and andesites predominate among evolved rocks. The composition of evolved rocks can thus explain the increasingly large variability of primitive rocks toward the slab edge. The key question is, however, why does the magnitude of the Si enrichment in evolved CKD rocks correlate with subduction parameters, for example, slab dip?

A possible answer is that the extent of magma fractionation beneath the CKD volcanoes can be controlled by the mantle magmatic productivity, which depends on subduction parameters (Cagnioncle et al., 2007). The mean extent of differentiation can be relatively small in regions of high magma flux, where magma chambers are continuously fed by primitive magmas from the mantle. In contrast, magmas can evolve to higher degrees in regions of diminished magma supply. The magma flux can also control the depth of magma fractionation (Rubin and Sinton, 2007). High magma flux can “push” buoyant magma chambers toward shallower depths, which favor crystallization of plagioclase and olivine on liquidus and a tholeiitic trend of fractionation. In turn, fractionation at deeper depths in regions of lower magma supply should favor stabilization of amphibole and pyroxenes in the crystallizing assemblage, promoting a calc-alkaline differentiation trend and Si enrichment (Kay and Kay, 1985).

In fact, the magma output decreases substantially from south to north along the CKD, which likely reflects the decrease of the absolute magma flux from the mantle to the crust (Fedotov, 1991). The magmatic output during the Holocene was the highest for the Klyuchevskoy Group of volcanoes, about two times less for Shiveluch volcano, farther to the north, and very low for Shisheisky Complex. If the effects of magma flux on the extent and the depth of fractionation are indeed as significant as suggested above, then the dramatic change in magmatic productivity along the CKD can be an alternative and a very plausible scenario to explain major element variability in CKD rocks.

Although this model is in principle different from the model of the mantle wedge temperature control on the composition of primitive magmas, the decrease of magmatic productivity along the CKD also can be related to the northward decrease of mantle temperatures beneath CKD

volcanoes (Cagnioncle et al., 2007). Therefore, the thermal state of the mantle wedge appears to be the most fundamental parameter governing composition, localization, and productivity of island-arc magmatism.

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