Mid-Cretaceous Hawaiian tholeiites preserved in Kamchatka

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ABSTRACT

We report geochemical data on a peculiar group of Albian–Cenomanian (120–93 Ma) basalts preserved in ophiolites on the Kamchatsky Mys peninsula (Kamchatka, Russia) that share trace element and isotopic compositions with enriched tholeiites from the Detroit and Meiji Seamounts in the Hawaiian-Emperor Seamount chain. Melt inclusions in chromium spinel from these rocks, representative of melt composition unaffected by post-magmatic alteration, exhibit Hawaiian-type $[Th/Ba]_n$ (0.25–0.77; i.e., distinctively low compared to the majority of oceanic island basalts and mid-oceanic ridge basalts). Low $^{208}Pb^{*}/^{206}Pb^{*}$ of ~0.93 in rocks and high $[Nb/La]_n$ = 1.1–4.6 in melt inclusions suggest the presence of a distinctive "Kea"–type component in their source. We propose that the ophiolitic basalts represent older (Early to middle Cretaceous) products of the Hawaiian hotspot (older than preserved on the northwest Pacific seafloor) that were accreted to the forearc of Kamchatka. The presence of similar compositional components in modern and Cretaceous Hawaiian hotspot lavas suggests a persistent yet heterogeneous composition of the mantle plume, which may have sampled ≥15% of the core-mantle boundary layer over the past ~100 m.y.

INTRODUCTION

The Hawaiian-Emperor Seamount Chain, produced during the passage of the Pacific plate over the Hawaiian hotspot, extends for 5800 km from the currently active island of Hawaii and Loihi Seamount northwest to the Detroit (71–76 Ma) and Meiji (older than 81 Ma) Seamounts (Duncan and Keller, 2004), seaward of the Kamchatka–Aleutian arc junction (Fig. 1). Despite the extensive data set on the composition and evolution of the Cenozoic Hawaiian magmatism, there is little known about the earlier (before 80 Ma) history of the hotspot. Several studies have proposed that an igneous plateau formed by the plume head at the initiation of the Hawaiian hotspot and that older seamounts formed above the plume tail may have been preserved rather than subducted (Avdeiko, 1980; Niu et al., 2003; Saveliev, 2003; Portnyagin et al., 2005; Steinberger and Gaina, 2007). There are, however, currently no convincing geochemical data that support preservation of older Hawaiian fragments on land or on the seafloor. In this work we present evidence that older products of the Hawaiian hotspot have been accreted to the forearc of the Kamchatka subduction zone. This study has important implications for the persistence of chemical characteristics of hotspots over ~100 m.y. and the spatial scale of the compositional heterogeneity in the Earth's mantle.

GEOLOGIC SETTING AND STUDIED SAMPLES

The studied rocks were collected in the Africa Mys block in the southwestern part of the Kamchatsky Mys peninsula (eastern Kamchatka) (Fig. 1), which consists of an intensively deformed ophiolite association of ultramafic rocks, gabbros, dolerites, basalts, and sediments (Fedorchuk, 1992; Khotin and Shapiro, 2006). The ophiolites are interpreted to be a part of an accretionary wedge of the paleo-Kronotsky arc formed during the Late Cretaceous–Eocene at lat 36–45°N (Khotin and Shapiro, 2006; Lander and Shapiro, 2007); the arc is now a constituent of the Kamchatka forearc. The ophiolite rocks are heterogeneous in origin and were formed in different tectonic settings that changed through time (Khotin and Shapiro, 2006). Volcanic rocks in the ophiolites occur in the ~1.5-km-thick Smagino association together with hyaloclastites and intercalated red jasper and pink pelitomorphic limestone, consistently dated paleontologically as Albian–Cenomanian (120–93 Ma; Khotin and Shapiro, 2006, and references therein). Volcanic rocks of the Smagino association range from trace element–depleted to slightly enriched mid-oceanic ridge–like basalts (MORB) to alkali basalts (Fig. 2), occurring in tectonically separated blocks (Fedorchuk, 1992; Portnyagin et al., 2005; Saveliev, 2003; Khotin and Shapiro, 2006). This magmatic assemblage is characteristic of P (plume) type ophiolites originating from plume-related oceanic ridges and plateaus (Pearce, 2008). The present work focuses on geochemical characteristics of a distinctive group of rocks, trace element–enriched tholeiites from the Kamchatsky Mys ophiolites (KM enriched tholeiites), which crop out near the source of the Mutnaya River in the northern part of the ophiolite massif (GSA Data Repository Table DR1[1]).

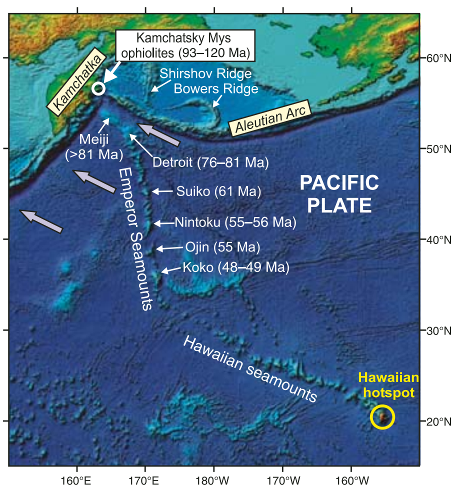

Figure 1. Hawaiian-Emperor Seamount Chain in northwestern Pacific, produced by passage of Pacific plate of variable age and thickness over the Hawaiian hotspot, and position of Kamchatsky Mys ophiolite complex. Age data for Emperor seamounts are from Duncan and Keller (2004). Bowers and Shirshov Ridges in Bering Sea were proposed to be formed by paleo-Hawaiian hotspot magmatism (Steinberger and Gaina, 2007). Bold arrows indicate direction of Pacific plate movement.

WHOLE-ROCK GEOCHEMISTRY

The rocks studied are extensively altered olivine-phyric basalts with abundant secondary calcite (8–22 wt%) replacing olivine, and chloritized groundmass (Table DR1). Because of the post-magmatic alteration, which disturbed the primary major element concentrations, we focused the study of whole rocks on immobile or weekly mobile during low-temperature alteration trace elements such as the rare earth elements (REE), high-field-strength elements (HFSE), Th, and Pb, which can be informative about the tectonic provenance and the source characteristics of the rocks (e.g., Pearce, 2008).

[1]GSA Data Repository item 2008229, Appendix DR1 (analytical and experimental techniques, references to data sources, and supplementary figures), Table DR1 (major and trace element rock compositions), Table DR2 (whole-rock isotope compositions), and Table DR3 (composition of melt inclusions), is available online at www.geosociety.org/pubs/ft2008.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

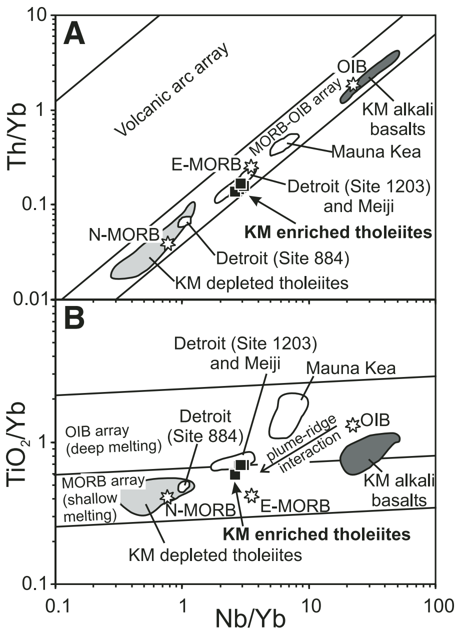

Figure 2. Discrimination diagrams show that volcanic rocks from Kamchatsky Mys ophiolites belong to P (plume) type ophiolites after classification of Pearce (2008) and that their immobile incompatible element ratios are similar to shield-stage tholeiites from Detroit (Site 1203) and Meiji Seamounts. Nb, Yb, and Th concentrations are in ppm, TiO_2 in wt%. Compositions of enriched tholeiites from the Kamchatsky Mys (KM enriched tholeiites) are from this study; KM depleted tholeiites and alkali basalts are after Saveliev (2003) and Khotin and Shapiro (2006), and references therein. Compositions of average normal mid-oceanic ridge basalt (N-MORB), enriched (E) MORB, oceanic island basalt (OIB) (Sun and McDonough, 1989), Mauna Kea rocks, and Detroit and Meiji shield-stage tholeiites are shown for comparison (data sources listed in Appendix DR1 [see footnote 1]).

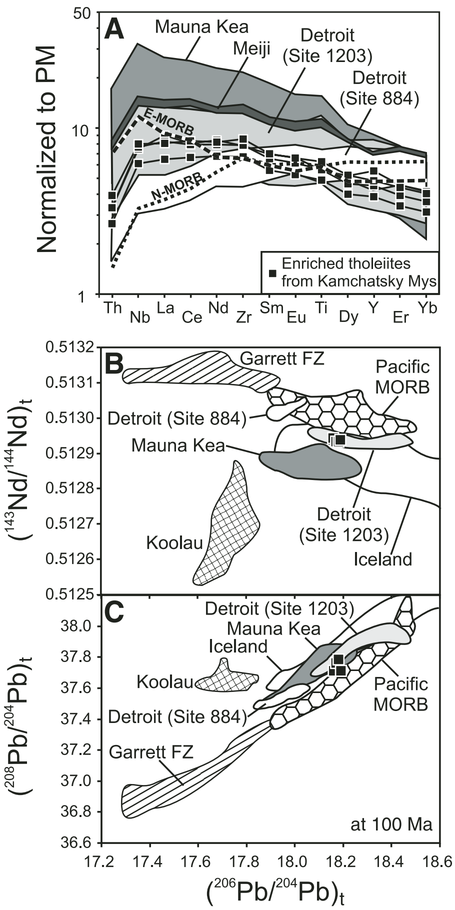

Figure 3. Trace element and isotope compositions of enriched tholeiites from Kamchatsky Mys ophiolites. Compositions of typical Pacific mid-oceanic ridge basalt (MORB), depleted MORB from Garrett Fracture Zone (FZ), shield-stage tholeiites from Hawaiian-Emperor Seamount Chain (Mauna Kea, Koolau, Meiji, and Detroit) and Icelandic rocks are shown for comparison (data sources listed in Appendix DR1 [see footnote 1]). Average normal (N) MORB, enriched (E) MORB, and primitive mantle (PM) compositions are after Sun and McDonough (1989). All isotopic compositions are age corrected to 100 m.y. (Table DR2).

The rocks have smooth, slightly enriched patterns of incompatible trace elements normalized to primitive mantle (PM) composition, plotting completely within the Detroit Site 1203 field (Fig. 3). REE patterns are nearly flat from the light (L) to middle (M) REEs (PM normalized $[La/Sm]_n$ = 1.2–1.3) and more strongly fractionated from the MREEs to heavy (H) REEs ($[Sm/Yb]_n$ = 2.0–2.3). Fractionated patterns of the MREEs to HREEs and also high TiO_2/Yb, marginally above the MORB array (Fig. 2B), distinguish the rocks from enriched MORB (e.g., Niu and Batiza, 1997) and imply higher pressures of mantle melting (Pearce, 2008) and/or an oceanic island basalt (OIB) type Ti-rich source (Sun and McDonough, 1989). Thorium concentrations are remarkably low relative to LREEs and Nb ($[Th/La]_n$ = 0.36–0.49, $[Th/Nb]_n$ = 0.44–0.49) (Figs. 2 and 3A).

Initial isotope ratios of neodymium and lead, which can be well reconstructed for low-temperature altered rocks (e.g., Regelous et al., 2003; Hauff et al., 2003; Appendix DR1), form very narrow ranges [$(^{206}Pb/^{204}Pb)_t$ = 18.160–18.189, $(^{207}Pb/^{204}Pb)_t$ = 15.455–15.473, $(^{208}Pb/^{204}Pb)_t$ = 37.710–37.787, $(^{143}Nd/^{144}Nd)_t$ = 0.51293–0.51294, where subscript t denotes initial isotope ratio 100 m.y. ago] (Table DR2, Figs. 3B and 3C). Similar to the incompatible element contents, the isotope ratios of the KM enriched tholeiites are also distinct from Pacific MORB. At a given $(^{206}Pb/^{204}Pb)_t$, the Kamchatka rocks have slightly higher $(^{208}Pb/^{204}Pb)_t$ and lower $(^{143}Nd/^{144}Nd)_t$ than Pacific MORB, including Mesozoic MORB samples from Ocean Drilling Program and Deep Sea Drilling Project cores (Figs. 3B and 3C) (e.g., Janney and Castillo, 1997; Hauff et al., 2003). Incompatible element and isotopic compositions of the KM enriched tholeiites, however, overlap in composition with samples from the Detroit Seamount (Site 1203) belonging to the Hawaiian hotspot track (Regelous et al., 2003; Huang et al., 2005).

CHROMIUM SPINEL AND MELT INCLUSIONS

In order to collect additional information on the composition of parental magmas of the Kamchatka basalts, we extended this study to include a detailed examination of chromium spinel and primary melt inclusions in this mineral, because spinel is particularly resistant to post-magmatic alteration (Kamenetsky et al., 2001). Accessory chromium spinel occurs in the studied basalts as inclusions in olivine, currently replaced by calcite, and as separate subphenocrysts to 0.5 mm in size. The spinels have moderately high Mg# = 0.64–0.73 [Mg# = $Mg/(Mg+Fe^{2+})$ calculated on molar basis], Cr/(Cr + Al) = 0.37–0.55, low Fe^{2+}/Fe^{3+} = 2.4–3.7, and relatively high TiO_2 (primarily between 0.5 and 1.0 wt%) content, only partly overlapping with spinel compositions in MORB (Kamenetsky et al., 2001).

Many spinel crystals contained partly crystallized (glass + high-Ca pyroxene + fluid bubble + sulfide) melt inclusions isolated from the altered whole-rock matrix by the host mineral. They were experimentally homogenized at 1250 °C and quenched to glass prior to analytical studies (Appendix DR1). The homogenized melt inclusions have tholeiitic (SiO_2 = 49.4–53.6 wt%, $Na_2O + K_2O$ = 2.4–3.9 wt%) compositions (Table DR3). Despite a narrow range of the host rocks, melt inclusions exhibit a substantial range of the MREEs to HREEs ($[Sm/Yb]_n$ = 1.3–3.0), TiO_2 (1–3 wt%), and particularly variable concentrations of highly incompatible trace elements and their ratios (e.g., K_2O = 0.06–0.62 wt%; K_2O/TiO_2 = 0.03–0.58; $[La/Sm]_n$ = 0.35–1.70) (Table DR3; Fig. DR1). LREE-depleted inclusions have distinctive convex PM-normalized trace element patterns ($[Sm/Yb]_n > 1$, $[La/Sm]_n < 1$).

At first approximation, the highly variable compositions of inclusions suggest preservation of unmixed mantle-derived melts, which originated from a heterogeneous mantle source (variable ratios of highly incompatible elements) in the garnet stability field (high MREE/HREE ratios). Detailed examination of the melt inclusion compositions will be presented elsewhere. Here we note that a general compositional peculiarity of all studied melt inclusions is a strong negative Th (and U) anomaly in PM-normalized spectra relative to Ba and La ($[Th/La]_n$ = 0.37–0.62, $[Th/Ba]_n$ = 0.25–0.77) (Fig. 4A). The Th deficit does not correlate with

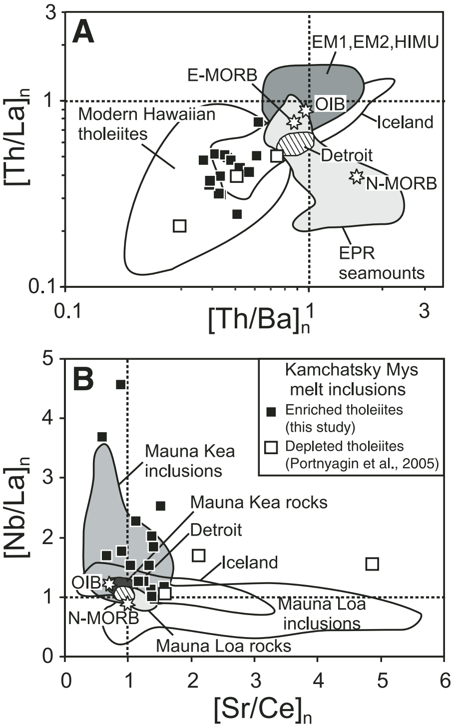

Figure 4. Trace element compositions of melt inclusions in spinel from Kamchatsky Mys ophiolites. A: Inclusions have Hawaiian-type Th/Ba and Th/La ratios, which are systematically lower compared to majority of oceanic island basalt (OIB) and mid-oceanic ridge basalt (MORB). (B) High Nb/La ratios in melt inclusions from enriched tholeiites (this study) suggest contribution of Kea–type component; inclusions from depleted tholeiites have high Sr/Ce ratios indicating contribution from Loa–type component (Portnyagin et al., 2005). Compositional field of modern Hawaiian tholeiites and OIB field, including representatives of HIMU [high μ ($^{238}U/^{204}Pb$), St. Helena], EM1 (enriched mantle, Pitcairn) and EM2 (Society Island), are shown after Hofmann and Jochum (1996). Compositions of glasses from Deep Sea Drilling Project Site 884 on Detroit Seamount (Huang et al., 2005), glasses from East Pacific Rise (EPR) seamounts (Niu and Batiza, 1997), Icelandic rocks, and Mauna Loa and Mauna Kea melt inclusions (Sobolev et al., 2002) are shown for comparison. Average normal (N) MORB, enriched (E) MORB, and primitive mantle (PM) compositions are after Sun and McDonough (1989).

Sr enrichment in melt inclusions (Fig. DR1); therefore, low Th/Ba cannot result from interaction of mantle melts with crustal gabbro and instead reflects mantle source characteristics of the studied rocks (e.g., Saal et al., 2007). The low-Th mantle source composition is similar to that of the Hawaiian hotspot and Icelandic lavas, but was not documented for MORB and OIB from other localities (e.g., Hofmann and Jochum, 1996; Yang et al., 2003). Many inclusions exhibit moderate to strong Nb enrichment relative to other highly incompatible elements ($[Nb/La]_n$ = 2.0–4.6, Nb/U = 42–155) (Fig. 4B). It is also noticeable that melt compositions with $[Nb/La]_n$ up to 4.6 were not described in oceanic settings other than Mauna Kea volcano, whose lavas host Nb-rich melt inclusions in olivine (Sobolev et al., 2002).

HAWAIIAN ROCKS IN KAMCHATKA OPHIOLITES

It has been proposed previously that the Kamchatsky Mys ophiolites may represent atypical oceanic crust formed under the influence of a hotspot (Saveliev, 2003; Portnyagin et al., 2005; Khotin and Shapiro, 2006). The present detailed geochemical study demonstrates that enriched tholeiites preserved in the Kamchatsky Mys ophiolites share specific geochemical features with the Hawaiian hotspot lavas. These features include trace element and isotopic compositions of whole rocks, which are different from Pacific MORB but very similar to the northernmost seamounts in the Emperor Seamount chain (Detroit and Meiji Seamounts) (Figs. 2 and 3). Melt inclusions in spinel have low Th/Ba, which is a distinct feature of Hawaiian hotspot lavas, not observed in other hotspot-related localities in the Pacific region (Hofmann and Jochum, 1996; Yang et al., 2003). These geochemical data suggest that the ophiolite basalts were very likely derived from a Hawaiian-type mantle source, and thus are evidence for the existence of the Hawaiian hotspot 120–93 Ma.

The studied rocks occur as lava flows in association with slow-accumulated deep-sea sediments (intercalated cherts and limestones) and hyaloclastites. It is therefore unlikely that the mid-Cretaceous volcano-sedimentary Smagino association of the Kamchatsky Mys ophiolites represents a fragment of an accreted Hawaiian guyot. More plausibly, the lavas could have originated on the deep flank of a seamount or on a mid-ocean ridge, strongly affected by interaction with the neighboring Hawaiian hotspot.

Recent paleotectonic reconstructions (Steinberger and Gaina, 2007) suggest that an older than ca. 80 Ma part of the Emperor Ridge may be located behind the Aleutian trench in the Bering Sea (Fig. 1). Some parts of the Emperor Ridge may also have been accreted to the forearc of the proto-Aleutian arc. Some of the accretionary wedge preserved in the Kamchatsky Mys ophiolites belongs to the paleo-Kronotsky arc, which is considered to be a part of the Proto-Aleutian arc (Lander and Shapiro, 2007). Therefore, the Albian–Cenomanian Smagino volcano-sedimentary association of the Kamchatsky Mys ophiolites can readily host Hawaiian hotspot-related rocks, accreted in the early Tertiary and transported later northwest to their present position in the Kamchatka forearc.

CRETACEOUS PERIOD OF THE HAWAIIAN PLUME–RIDGE INTERACTION

An important result from investigations of the Meiji and Detroit Seamounts was the discovery of rocks with relatively depleted trace element and isotopic compositions (Keller et al., 2000) that were likely formed through enhanced mantle plume melting beneath thin lithosphere (Regelous et al., 2003; Huang et al., 2005; Frey et al., 2005; Ito and Mahoney, 2005). The rocks studied here share many compositional features with Meiji and Detroit tholeiites (Figs. 2 and 3). This compositional similarity can be explained if the ophiolite rocks originated in a tectonic situation similar to that of the oldest known Emperor seamounts, that is, beneath young, thin oceanic lithosphere. The Albian–Cenomanian age of the ophiolite rocks suggests that they are at least 20 m.y. older than the Meiji Seamount (Duncan and Keller, 2004). Therefore, the Hawaiian plume was likely located beneath thin oceanic lithosphere and melted extensively for at least 20 m.y. and possibly crossed the Kula-Pacific plate boundary in the mid-Cretaceous, as also suggested by recent paleo-tectonic reconstructions (Steinberger and Gaina, 2007).

PERSISTENT PLUME COMPOSITION THROUGH TIME

Low Th/Ba ratios in Hawaiian hotspot lavas and studied Kamchatkan melts deviate strongly from typical mantle values and can be explained by melting of low-Th recycled crustal material within the plume source (Hofmann and Jochum, 1996). As evident from the published data and results from this study, a contribution from the low-Th recycled material to the Hawaiian hotspot-derived magmas was persistent over the last ~100 m.y. Moreover, low $^{206}Pb^*/^{208}Pb^*$ (< 0.95; $^{206}Pb^*/^{208}Pb^*$ represents the time-integrated $^{232}Th/^{238}U$ ratio since the formation of the Earth; e.g., Abouchami et al., 2005) in the least altered Emperor Ridge rocks (Keller et al., 2000; Regelous et al., 2003; Huang et al., 2005) and lavas from the Kamchatka forearc studied here (Fig. DR2), and also unusually high Nb/La in the melt inclusions (Fig. 4B), similar to inclusions from Mauna Kea lavas, suggest that it was probably a Kea–type component (Tatsumoto, 1978; Abouchami et al., 2005; Sobolev et al., 2002), which contributed, together with a depleted plume component (Regelous et al., 2003; Huang et al., 2005; Frey et al., 2005), to prevailing compositions of Cretaceous Hawaiian hotspot lavas.

In another basaltic sample from the Kamchatsky Mys ophiolites, Portnyagin et al. (2005) reported trace element–depleted melt inclusions in spinel with elevated Sr/Ce and Ba/Th, which contain a component similar to Sr-rich Mauna Loa melts and possibly originate by mixing of peridotite-derived melts and melts from recycled oceanic gabbro (Sobolev et al., 2000). Therefore it is possible that both Kea– and Loa–type (in subtle amounts) components were sampled during the formation of rocks (melt inclusions) preserved in the Kamchatka Mys ophiolites.

A persistent yet heterogeneous composition of Hawaiian hotspot lavas suggests that their source region represents a long-lived prominent geochemical anomaly in the Earth's mantle. Assuming that the volume flux of the Hawaiian plume was similar from the mid-Cretaceous to the present (300 m^3/s; Sleep, 1990) and that the plume originates at the core-mantle boundary, we estimated that the source region of the Hawaiian plume over the past ~100 m.y. could cover an area of ≥15% of the core-mantle boundary in the form of a layer ≤40 km thick (Farnetani et al., 2002). Long-lived (≥20 m.y.), complex spatial zonation has also been shown for the Galapagos hotspot (Hoernle et al., 2000; Werner et al., 2003), and thus also requires a volumetric large-scale geochemical anomaly in the Earth's mantle, which may be an important feature of plume-related hotspot volcanism.

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