

Late Pleistocene-Holocene Volcanism on the Kamchatka Peninsula, Northwest Pacific Region

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Late Pleistocene-Holocene volcanism in Kamchatka results from the subduction of the Pacific Plate under the peninsula and forms three volcanic belts arranged in an echelon manner from southeast to northwest. The cross-arc extent of recent volcanism exceeds 250 km and is one of the widest worldwide. All the belts are dominated by mafic rocks. Eruptives with $\text{SiO}_2 > 57\%$ constitute ~25% of the most productive Central Kamchatka Depression belt and ~30% of the Eastern volcanic front, but <10% of the least productive Sredinny Range belt.

All the Kamchatka volcanic rocks exhibit typical arc-type signatures and are represented by basalt-rhyolite series differing in alkalis. Typical Kamchatka arc basalts display a strong increase in LILE, LREE and HFSE from the front to the back-arc. La/Yb and Nb/Zr increase from the arc front to the back arc while B/Li and As, Sb, B, Cl and S concentrations decrease. The initial mantle source below Kamchatka ranges from N-MORB-like in the volcanic front and Central Kamchatka Depression to more enriched in the back arc. Rocks from the Central Kamchatka Depression range in $^{87}\text{Sr}/^{86}\text{Sr}$ ratios from 0.70334 to 0.70366, but have almost constant Nd isotopic ratios ($^{143}\text{Nd}/^{144}\text{Nd}$ 0.51307–0.51312). This correlates with the highest U/Th ratios in these rocks and suggest the highest fluid-flux in the source region.

Holocene large eruptions and eruptive histories of individual Holocene volcanoes have been studied with the help of tephrochronology and ^{14}C dating that permits analysis of time-space patterns of volcanic activity, evolution of the erupted products, and volcanic hazards.

INTRODUCTION

Models of active volcanism along subduction zones presume that lithospheric plates have been moving uniformly

over thousands of years and that magma in subduction zones is generated continuously and at a constant rate. However, eruptions of magma at the surface are episodic or clustered, rather than constant or periodic in time [e.g. *Cambay and Cadet, 1996; Sigurdsson, 2000; Gusev et al., 2003*]. Furthermore, the volcanic belt may consist of vents, scattered out over a much wider zone and erupting more variable magmas than anticipated by a simple model of subduction-generated magma flow. In Kamchatka, subduction is responsible for most of recent volcanism [e.g. *Volynets,*

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Volcanism and Subduction: The Kamchatka Region
Geophysical Monograph Series 172
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10.1029/172GM15

1994; *Churikova et al.*, 2001, 2007; *Avdeiko et al.*, 2006; *Portnyagin et al.*, 2007a, b]. However, its spatial distribution and time patterns are rather complicated. In this paper, we present data on the latest period of volcanic activity in Kamchatka, which started 50–60 ka BP [*Erlich et al.*, 1979]. It was during this period when dominantly pyroclastic classical conic stratovolcanoes started to form, which now comprise a typical volcanic landscape of Kamchatka (Fig. 1).

The Kamchatka Peninsula overlies the northwestern margin of the Pacific plate subducting under Kamchatka at ~8 cm/yr [*DeMets*, 1992]. In the north, the Kamchatka subduction zone terminates at the transform fault zone of the Western Aleutians (Figs. 2A, B). Close to the northern terminus of the subduction zone, slab dip is believed to shallow from 55° to 35°, with probable loss of a slab fragment [*Levin et al.*, 2002; *Park et al.*, 2002]. Plate geometry in this northwest “corner” is currently under debate [e.g. *Riegel et al.*, 1993; *Mackey et al.*, 1997; *McElfresh et al.*, 2002; *Bourgeois et al.*, 2006]. Some authors treat Kamchatka as a part of the North American plate [e.g. *Park et al.*, 2002], while others locate it on a smaller Okhotsk block (or microplate) [e.g. *Zonenshain and Savostin*, 1979; *Riegel et al.*, 1993] and add a Bering block east of it [e.g. *Lander et al.*, 1994; *Mackey et al.*, 1997]. Whatever the plates’ evolution may have been, it is likely recorded in the time-space patterns of Kamchatka volcanism and in geo-

chemical affinities of the volcanic rocks. The best example of this connection are findings of adakite-like rocks in northern Kamchatka, probably reflecting the edge of the subducting Pacific plate being warmed or ablated by mantle flow [*Volynets et al.*, 1997b, 1999b, 2000; *Peyton*, 2001; *Yogodzinski et al.*, 2001a]. Research aimed at understanding of the nature of various volcanic zones in Kamchatka and their relation to the changing tectonic environment is currently going on in many areas of Kamchatka [e.g., *Avdeiko et al.*, 2006; *Churikova et al.*, 2001, 2007; *Duggen et al.*, 2007; *Perepelov*, 2004; *Perepelov et al.*, 2005; *Portnyagin et al.*, 2005, 2007a, b; *Volynets et al.*, 2005] and hopefully will result in the understanding of this dynamic region.

SPATIAL DISTRIBUTION

Traditionally, recent Kamchatka volcanoes are assigned to two volcanic belts: Eastern volcanic belt and Sredinny Range (SR). The Eastern belt may be further subdivided into the Eastern volcanic front (EVF) and the Central Kamchatka Depression (CKD) volcanic zone (Fig. 2A). In fact, all the belts are not exactly linear and have a complicated structure (Fig. 2B). This might reflect subduction of sea mounts [e.g. *Churikova et al.*, 2001] and peculiarities of the tectonic situation near a triple junction of lithospheric plates [e.g. *Yogodzinski et al.*, 2001a; *Park et al.*, 2002; *Portnyagin et al.*,



Figure 1. Eastern volcanic front, view to the south. Active Komarov volcano at the foreground, two late Pleistocene cones of Gamchen massif farther south, and Kronotsky volcano at the background. Classic cones of dominantly pyroclastic stratovolcanoes started to form only in late Pleistocene [*Braitseva et al.*, 1974]. Photo courtesy Philippe Bourseiller.

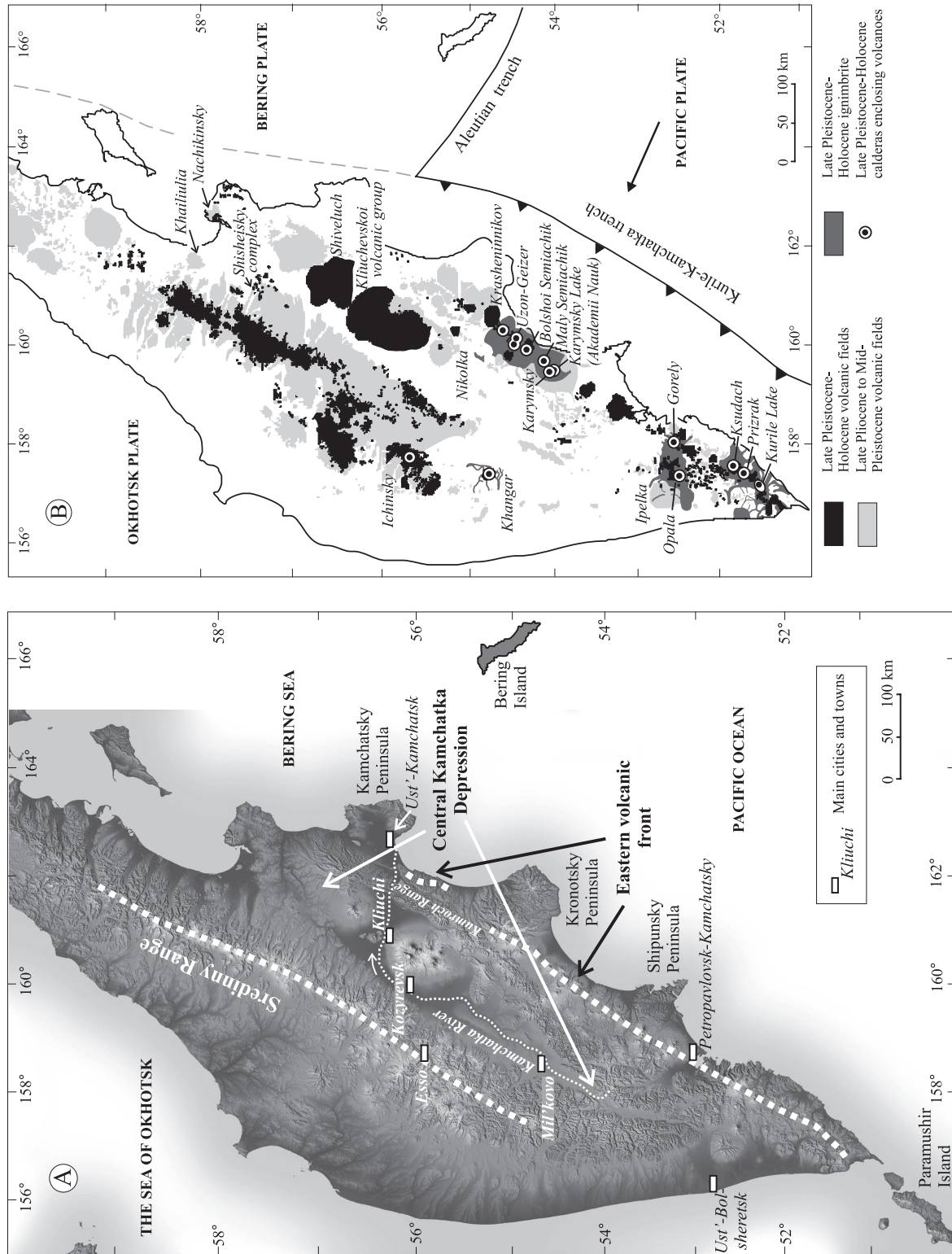


Figure 2. A. Shaded SRTM elevation model of Kamchatka showing main topographic features. Image released by NASA/JPL/NIMA. Dashed white lines schematically show EVF and SR volcanic belts. For SR volcanic belt, a line along its axial part is shown: from the southernmost Khangar volcano to the northern terminus of the late Pleistocene volcanism. **B.** Sketch map of late Pliocene-Holocene Kamchatka volcanic fields based on the 1:100 000 and 1:300 000 unpublished geological maps by Ivan Melekestsev, and *Map of Mineral Resources of Kamchatka region* (1:500 000) [1999]. Volcanic fields include debris avalanche and lahar deposits at the volcanoes foot. Gray dashed line shows a presumed boundary of the Bering plate [Lander et al., 1994]. Late Pleistocene-Holocene calderas and selected volcanoes are labeled.

2005; 2007b]. Distribution of the late Pleistocene-Holocene volcanic vents follows in general that of the preceding late Pliocene - mid-Pleistocene volcanic fields (Fig. 2B). The latter, however, cover far larger areas and comprise extensive mafic lava plateaus and huge shield volcanoes, still preserved in the topography [Braitseva et al., 1974].

There is no evident spatial correlation between late Pleistocene-Holocene volcanic centers and major active fault systems that bound main neotectonic structures of the peninsula (Fig. 3A). The only regional fault system that may be spatially linked to volcanism is found along the axis of the EVF and is different, both geometrically and kinematically, from other, “amagmatic”, fault systems. The faults comprising this system exhibit dominantly normal displacement, probably with a small left-lateral component, and form a graben-in-graben structure ~130 km long and 10–18 km-wide [Florensky and Trifonov, 1985; Kozhurin, 2004].

Historically active volcanoes are located only in the Eastern volcanic belt (both in the EVF and CKD) (Table 1). This is likely the reason for a widely accepted opinion that Sredinny Range volcanism either is dying [e.g. Avdeiko et al., 2002, 2006] or is already dead [e.g. Park et al., 2002]. “Historical” time in Kamchatka, however, is very short—200–300 years—and tephrochronological studies and ¹⁴C dating show that some Sredinny Range volcanoes have been active as recently as few hundreds of years ago [Pevzner, 2004, 2006]. Late Pleistocene-Holocene volcanic fields cover large areas in the Sredinny Range not lesser than in the eastern Kamchatka (Fig. 3A), [Ogorodov et al., 1972].

Three late Pleistocene-Holocene volcanic belts (those of EVF, CKD and SR) in plan view are arranged in an echelon manner from southeast to northwest (Fig. 2B). Within the belts, most of the eruptive centers are concentrated in 15–10 km wide axial areas. Best expressed is the EVF, which lies 200–250 km west of the Kurile-Kamchatka trench. It trends for ~550 km from SW to NE, from Kambalny volcano at the south to a relatively small group of late Pleistocene cinder cones dotting the eastern slope of the Kumroch Range almost as far north as the mouth of the Kamchatka River (Fig. 2A). These cones (including Kovrizhka and Krasny (Fig. 4B)) are commonly disregarded, in which case the EVF is considered to stretch only up to the Gamchen volcanic group and then step westward to the CKD via Kizimen volcano (Fig. 3A) [e.g. Churikova et al., 2001; Park et al., 2002]. EVF *per se* has a more or less linear plan view with westward offshoots to Opala volcano in the south and to Bakening volcano (against Shipunsky Peninsula) (Fig. 3A). The volcanic front consists of rather tightly spaced stratovolcanoes only 15–30 to 60 km apart from each other. Maly Semiachik and Krashennikov volcanoes consist

of 2–3 overlapping cones stretching along the axial fault zone (Figs. 3A and 5), while Zhupanovsky, Kozelsky-Avachinsky-Koriaksky, Gorely and Koshelev volcanoes form prominent across-front ranges [*Holocene volcanoes in Kamchatka*, <http://www.kscnet.ru/ivs/volcanoes/holocene>]. Most of 5–18 km wide collapse calderas and associated ignimbrite fields are located in the EVF, forming chains between Kronotsky and Karymsky lakes and then from Ksudach to Kurile Lake (Fig. 2B) and (Table 2).

The next volcanic belt to the northwest is the CKD one, hosting the most vigorous volcanoes of Kamchatka (Figs. 2, 3 and 4). Most of the volcanic centers, including large volcanoes and clusters of monogenetic vents, are concentrated in a 150-km-long belt from Tolbachik lava field in the south to Shiveluch volcano in the north. A few smaller monogenetic vents are scattered over old Nikolka volcano ~30 km south of this zone, and near old Nachikinsky volcano ~150 km NE of Shiveluch. Some authors trace this zone farther south via monogenetic vents at old Ipelka volcano (west of Opala) and then to a back-arc western volcanic zone of the Kurile arc (Fig. 3A) [Melekestsev et al., 1974; Laverov, 2005]. A number of monogenetic vents scattered on the eastern slope of the Sredinny Range in the Elovka River basin (sometimes called “Shisheisky Complex”) 60–80 km NNW of Shiveluch (Fig. 2B) likely also should be attributed to the CKD rather than to SR volcanic zone based on their geochemical features [Portnyagin et al., 2007b]. Geographically, however, many of those belong to Sredinny Range, so in (Table 1) we enlist the Holocene vents from this group (Bliznetsy, Kinenin and Shisheika, (Fig. 4B) under “Sredinny Range”. No ignimbrite-related calderas are known to date in CKD; 3–5 km wide summit calderas on Plosky Dalny (Ushkovsky) and Plosky Tolbachik volcanoes resulted from the collapse due to lava drainage [Melekestsev et al., 1974].

The next late Pleistocene-Holocene volcanic belt to the northwest, that of SR, starts from the isolated Khangar intra-caldera volcano in the south, then widens for 100 km farther north and finally merges into a single narrow belt following the axis of the Sredinny Range (Figs. 2A and B). Unlike EVF and CKD with their conic stratovolcanoes, SR hosts mostly lava fields and a few shield-like volcanoes (with the exception of Khangar and Ichinsky intra-caldera edifices).

The widest possible cross-arc extent of recent volcanism (and one of the widest worldwide) forms a ~250x250 km² zone stretching from the Pacific coast inland along the projection of the Aleutian trend (Fig. 3B). This unusually wide range of recent volcanism coincides with slab shallowing [Gorbatov et al., 1997] and likely results from the subduction of the Emperor Seamount chain [Churikova et al., 2001].

Table 1. Kamchatka volcanoes active in Holocene

Name	Location of an active crater, Lat. N Long.E	Description	Last dated eruption, AD or ¹⁴ C yr BP	Dominating Holocene rocks
Eastern volcanic front				
Central Kamchatka Depression				
Shiveluch	56° 38' 161° 19' (Young Shiveluch)	Late Pleistocene stratovolcano with a collapse crater hosting Holocene Young Shiveluch eruptive center	AD 2007	Medium-K, high-Mg and Cr basaltic andesite-andesite series
Plosky Dalny (Ushkovsky)	56° 04' 160° 28'	Late Pleistocene stratovolcano with two summit calderas and Holocene flank vents (e.g., Lavovy Shish)	≤8600	Medium- and high-K basalt - basaltic andesite
Kliuchevskoi	56° 03' 160° 39'	Holocene stratovolcano with numerous flank vents	AD 2007	Medium-K basalt-basaltic andesite
Bezymianny	55° 58' 160° 36'	Holocene stratovolcano with growing lava dome	AD 2007	Medium-K basaltic andesite-andesite series
Plosky Tolbachik	55° 49' 160° 23'	Late Pleistocene stratovolcano with two summit calderas, active in Holocene	AD 1975–76	High-K basalt
Tolbachik lava field (south and northeast of Plosky Tolbachik)		Numerous Holocene cinder cones and associated lava field	AD 1975–76	High-K, high-Al basalt and medium-K, high Mg basalt
Kizimen	55° 08' 160° 20'	Holocene volcano made of lava domes and flows	AD 1927–28	Medium-K basaltic andesite - dacite series
Eastern volcanic front				
Vysoky	55° 04' 160° 46'	Holocene stratovolcano	~2500	Transitional from low- to medium-K basaltic andesite-andesite series
Komarov	55° 02' 160° 44'	Holocene stratovolcano, likely successor to Vysoky	<1000	Transitional from low- to medium-K calc-alkaline andesite
Gamchen (Baranii Cone)	54° 58' 160° 43'	Holocene dominantly pyroclastic volcano with flank lava domes	~2500	Low-K basaltic andesite-andesite
Kronotsky	54° 45' 160° 32'	Late Pleistocene stratovolcano with Holocene flank cinder cones	AD 1923	Low-K basalt-basaltic andesite; andesite?
Cinder cones between Kronotsky Lake and Krasheninnikov caldera		Numerous cinder cones with lava flows, maar	~3400 (Zametny Cone)	Medium-K tholeiitic basaltic andesite
Krasheninnikov	54° 38' 161° 19' (Northern Cone)	Two coalesced Holocene stratovolcanoes with flank vents inside a late Pleistocene caldera	400–500	Medium-K tholeiitic basalt-dacite series
Cinder cones south of Krasheninnikov caldera		A number of cinder cones	3200–3300 (Duga Cone)	Medium-K tholeiitic basaltic andesite-andesite

Table 1. *Cont.*

Name	Location of an active crater, Lat. N Long.E	Description	Last dated eruption, AD or ¹⁴ C yr BP	Dominating Holocene rocks
Kikhpinych	54° 29' 160° 16' (Savich Cone)	Two coalesced Holocene stratovolcanoes and a lava dome	~500	Low-K basalt-basaltic andesite
Taunshits	54° 32' 159° 48' (young dome)	Late Pleistocene stratovolcano with Holocene collapse crater and lava dome	~2400	Medium-K calc-alkaline basaltic andesite-andesite
Monogenetic craters inside Uzon caldera		Dalnee Lake tuff ring and a number of maars	Small phreatic eruption in AD 1989; Dalnee Lake 7600-7700	Dalnee Lake -medium-K tholeiitic basaltic andesite
Monogenetic lava domes in Bolshoi Semiachik caldera		Lava domes, some with lava flows	Ezh and Korona domes ~ 5600	Low-K andesite
Maly Semiachik	54° 07' 159° 39' (Troitsky Crater)	Three coalesced stratovolcanoes inside a late Pleistocene caldera	AD 1952	Medium-K tholeiitic basalt-andesite series and low-K basalt (?)
Karymsky	54° 03' 159° 27'	Holocene caldera enclosing a stratovolcano	AD 2007	Medium-K calc-alkaline basaltic-andesite-rhyolite series
Tuff rings near the northern shore of the Karymsky Lake		At least two Holocene tuff rings	AD 1996	Medium-K calc-alkaline basaltic andesite
Cinder cones in Levaia Avacha River valley (east of Bakening): Zavaritsky, Veer, etc.		Scattered cinder cones with lava flows, maar	1600-1700 (Veer Cone)	Medium-K basalt-basaltic andesite
Novo-Bakening	53° 57' 158° 06'	Large monogenetic center with lava flows	Early Holocene	Medium-K andesite - dacite
Bakening	53° 55' 158° 05'	Late Pleistocene stratovolcano	Early Holocene	Medium-K andesite
Cinder cones south of Bakening		Scattered cinder cones with lava flows, maars	~600 (Kostakan)	Medium-K basalt-basaltic andesite
Zhupanovsky	53° 35' 159° 08'	Late Pleistocene-Holocene volcanic range made of stratovolcanoes and lava domes	AD 1956-57	Transitional from low-to medium-K basalt-andesite series
Lava cones and flows west of Zhupanovsky		Lava cones with extensive and thick lava flows	~1600	Medium-K andesite
Koriaksky	53° 19' 158° 43'	Late Pleistocene-Holocene stratovolcano	AD 1956-57	Medium-K basalt-andesite series
Avachinsky	53° 15' 158° 50'	Late Pleistocene stratovolcano with a collapse crater hosting Young Cone Holocene stratovolcano	AD 2001	Low-K basaltic andesite-andesite series
Kozelsky	53° 14' 158° 53'	Late Pleistocene stratovolcano with a collapse crater	Early Holocene	Low-K basaltic andesite-andesite series

Table 1. *Cont.*

Name	Location of an active crater, Lat. N Long.E	Description	Last dated eruption, AD or ¹⁴ C yr BP	Dominating Holocene rocks
Cinder cones south of Nachikinsky Lake (north of Tolmachev lava field)		A number of cinder cones	?	?
Cinder cones north of Viliuchinsky		Scattered cinder cones with lava flows	Middle Holocene	Medium-K basaltic andesite
Viliuchinsky	52° 42' 158° 17'	Late Pleistocene stratovolcano	Early Holocene	Medium-K basaltic andesite
Tolmachev lava field		Late Pleistocene-Holocene cinder cones and associated lava field	1600-1700	Medium-K basaltic andesite
Chasha Crater (Tolmachev lava field)	52° 38' 157° 33'	A large monogenetic crater	~4600	Transitional from medium to high-K rhyolite
Opala	52° 33' 157° 20'	Late Pleistocene-Holocene volcano on the rim of the late Pleistocene caldera with flank vents including a large crater Baranii Amphitheater with lava domes inside	AD 1776	Transitional from medium to high-K basaltic andesite-rhyolite series
Cinder cones and maar SSW of Opala caldera		Two cinder cones and maar	Early Holocene?	?
Gorely	52° 33' 158° 02' (Active Crater)	Late Pleistocene-Holocene volcanic ridge inside the late Pleistocene caldera	AD 1986	Medium- and high-K basaltic andesite - andesite
Mutnovsky	52° 28' 158° 10' (Active Crater)	Late Pleistocene volcanic massif with a Holocene stratovolcano	AD 2000	Low- and medium-K basalt-basaltic andesite
Asacha	52° 21' 157° 50'	Large volcanic center with Holocene cinder cones at the western flank	?	?
Khodutkinsky Crater (NW of Khodutka)	52° 05' 157° 38'	Large monogenetic crater with a lava dome	~2500	Medium-K rhyolite
Khodutka	52° 04' 157° 43'	Late Pleistocene-Holocene stratovolcano	~2000?	Low-K basalt-andesite series
Cinder cones W-SW of Khodutka		Cinder cones with lava flows	Holocene	?
Ksudach	51° 49' 157° 32' (Stübel Cone)	Large caldera complex with 3 Holocene calderas and Stübel stratovolcano	AD 1907	Low-K basaltic andesite-rhyolite series
Zheltofsky	51° 35' 157° 20'	Late Pleistocene stratovolcano with Holocene lava domes	AD 1923	Low-K basalt-andesite series
Iliinsky	51° 30' 157° 12'	Holocene stratovolcano with flank vents inside a Holocene collapse crater on the pre-Iliinsky volcano	AD 1901	Transitional from low- to medium-K tholeiitic basalt to dacite series

Table 1. *Cont.*

Name	Location of an active crater, Lat. N Long.E	Description	Last dated eruption, AD or ¹⁴ C yr BP	Dominating Holocene rocks
Kurile Lake caldera		Holocene caldera enclosing lava domes	~7600	Transitional from low- to medium-K basaltic andesite to rhyolite series
Ukho and Gorely cinder cones (NW of Koshelev)		Cinder cones with lava flows	~6000	Medium-K basalt
Dikii Greben'	51° 27' 156° 59'	Holocene extrusive massif	~1600	Medium-K dacite - rhyolite
Koshelev	51° 21' 156° 45' (Eastern Cone)	Pleistocene volcanic ridge with Holocene cinder cone and lava flows	AD 1741 ?	Medium-K basaltic andesite to dacite series
Kambalny	51° 18' 156° 53'	Holocene stratovolcano	AD 1767	Low-K basalt-basaltic andesite
Sredinny Range				
Tobeltsen	58° 15' 160° 44'	Cinder cone with lava flows	~3500	Medium-K basalt
X Cone	58° 10' 160° 48'	Lava cone with a lava flow	~4000	Medium-K basalt
Spokoiny (Kutina ¹)	58° 08' 160° 49'	Late Pleistocene-Holocene stratovolcano	~5400	Transitional from medium to high-K dacite-rhyolite
Nylgimelkin (Atlasov ¹)	57° 58' 160° 39'	Small shield-like volcano topped with two cinder cones (likely one eruption)	~5500	Medium-K basalt
Ozernovsky	57° 35' 160° 38'	Cinder cone with lava field	9000–10,000	Medium-K basalt
Titila	57° 24' 160° 07'	Shield-like volcano	2500–3000	Transitional from medium to high-K basalt
Sedanka lava field		Cinder cones and associated lava flows	2500–3000	Transitional from medium to high-K basalt
Kinenin Maar	57° 21' 160° 58'	Maar with some juvenile tephra	~1100	Medium-K basaltic andesite
Bliznetsy ("Twins")	57° 21' 161° 22'	Lava domes and flows	~3000	Medium-K andesite
Gorny Institute	57° 20' 160° 11'	Late Pleistocene-Holocene stratovolcano	<700	Transitional from medium to high-K basaltic andesite-dacite
Shisheika	57° 09' 161° 05'	Lava dome and flow	4200	Medium-K andesite-dacite
Alney	56° 41' 159° 38'	Pleistocene volcanic massif with a Holocene eruptive center	<350	Medium-K andesite

Table 1. Cont.

Name	Location of an active crater, Lat. N Long.E	Description	Last dated eruption, AD or ¹⁴ C yr BP	Dominating Holocene rocks
Kireunsky (east of Alney)	56° 41' 159° 44'	Cinder cone and lava flow	~2600	Medium-K andesite
Lava flow in Levaia Belaia River (east of Alney)	56° 38' 159° 43'	Cinder cone and lava flow	~2600	Medium-K basaltic andesite-andesite
Kekuk Crater	56° 34' 158° 02'	Tuff ring?	7200–7300	Medium-K dacite
Ichinsky	55° 41' 157° 44'	Late Pleistocene-Holocene stratovolcano	AD 740	Transitional from medium to high-K andesite-dacite
North Cherpuk	55° 36' 157° 38'	Cinder cone and lava flow	~6500	Medium-K basaltic andesite-andesite
South Cherpuk	55° 33' 157° 28'	Cinder cones and lava field	~6500	Medium-K basalt-basaltic andesite
Khangar	54° 45' 157° 23'	Late Pleistocene-Holocene stratovolcano inside a late Pleistocene caldera	~400	Medium-K dacite-rhyodacite

¹ Volcano names as in *Ogorodov et al., 1972*. Other names in parentheses in column 1 are other names used for this volcano in the literature. Volcano names in parentheses in column 2 indicate a summit in the volcanic massif whose coordinates are provided. Classification of the Holocene erupted products is based on SiO₂-K₂O classification by *LeMaitre [1989]*. The rock series, which are close to the classification lines or cross it, but form individual trends, are marked as transitional. Volcano data from the following sources: Central Kamchatka Depression and Eastern volcanic front [*Bindeman and Bailey, 1994; Braitseva and Melekestsev, 1990; Braitseva et al., 1991, 1998; Churikova et al., 2001; Dirksen et al., 2002; Dorendorf et al., 2000b; Fedotov and Masurenkov, 1991; Melekestsev et al., 1992, 1995, 1996a, 2003b; Ozerov, 2000; Ponomareva, 1990; Ponomareva et al., 2004, 2006b; Selyangin and Ponomareva, 1999; Vlodayets, 1957; Volynets et al., 1989, 1999a*]; Sredinny Range [*Bazanova and Pevzner, 2001; Churikova et al., 2001; Dirksen et al., 2003; Pevzner, 2004, 2006; Pevzner et al., 2000; Volynets, 2006*]. Question mark indicates that the data are lacking.

AGE ESTIMATES

Very few radiometric age determinations exist for late Pliocene - mid-Pleistocene volcanic rocks, underlying the late Pleistocene - Holocene volcanoes. A few ⁴⁰Ar/³⁹Ar determinations on lava plateaus in different parts of Kamchatka demonstrate that they span from 6 to 1 Ma [*Volynets et al., 2006*]. K/Ar dates obtained on various volcanic rocks in the area from Bakening to Mutnovsky volcanoes cover 0.5 to 5 Ma range, with two groups of welded tuffs dated at around 1.5 and 4 Ma [*Sheimovich and Karpenko, 1997; Sheimovich and Golovin, 2003*]. Lava plateaus underlying Kliuchevskoi volcanic group were dated at ~260–270 ka [⁴⁰Ar/³⁹Ar, *Calkins, 2004*]. Mid-Pleistocene age was also attributed to the oldest preserved stratovolcanoes (e.g. Gorny Zub, the oldest stratovolcano within the Kliuchevskoi volcanic group) based on their relationship with glacial deposits [*Melekestsev et al., 1971; Braitseva et al., 1995*].

In late Pleistocene, both volcanic and non-volcanic mountains of Kamchatka hosted extensive alpine glaciers, which deposited moraines at the surrounding lowlands. Glacial deposits identified on the air- and space images, indicate two stages of the late Pleistocene glaciation with maxima assigned to ~79–65 and 24–18 ka BP based on North America analogues (Early and Late Wisconsinian) [*Braitseva et al., 1995*]. Recently obtained ¹⁴C ages related to the last glacial maximum (LGM) deposits yield ~21 ka BP and fit well into the latter interval [*Braitseva et al., 2005*].

Since very few radiometric ages are available for the late Pleistocene volcanoes, age estimates for them are based mostly on their morphology and on the stratigraphic relationship of their products with the LGM deposits. Volcanoes, which started to form ~50–60 ka BP, between the two glacial maxima, are only moderately reshaped by erosion and surrounded by moraines. Preliminary data indicates that this period of volcanic activity was preceded by rather a long repose [*Melekestsev et al., 1974; Calkins, 2004*], however, this needs to be confirmed by further

Table 2. Late Pleistocene and Holocene calderas associated with ignimbrites

Caldera Name	Age (Method)	Caldera dimension (km)	References
Ichinsky III	Late Pleistocene (Stratigraphy)	5x3	<i>Erlich, 1986; Volynets et al., 1991</i>
Khangar II	38–40 ka (¹⁴ C)	8	<i>Braitseva et al., 1995, 2005</i>
Krashennnikov	35–38 ka (¹⁴ C)	12x10	<i>Florensky, 1984; Erlich, 1986</i>
Uzon-Geizerny twinned caldera	39 ka (¹⁴ C)	18x9	<i>Florensky, 1984; Erlich, 1986; Leonov and Grib, 2004</i>
Bolshoi Semiachik II	Late Pleistocene (Stratigraphy)	10	<i>Erlich, 1986; Leonov and Grib, 2004</i>
Maly Semiachik	~20 ka (Stratigraphy)	7	<i>Selyangin et al., 1979; Erlich, 1986; Leonov and Grib, 2004</i>
Karymsky	7.9 ka (¹⁴ C)	5	<i>Braitseva et al., 1995; Erlich, 1986</i>
Akademii Nauk (Karymsky Lake)	28–48 ka (Fission-track)	5	<i>Ananiev et al., 1980; Erlich, 1986; Leonov and Grib, 2004</i>
Gorely II	33–34 ka (¹⁴ C)	12x9	<i>Erlich, 1986; Braitseva et al., 1995</i>
Opala	39–40 ka (¹⁴ C)	15	<i>Erlich, 1986; Braitseva et al., 1995</i>
Ksudach I	Late Pleistocene (Morphology)	9	<i>Erlich, 1986; Melekestsev et al., 1996b</i>
Ksudach II	Late Pleistocene (Morphology)	8	<i>Melekestsev et al., 1996b</i>
Ksudach III	8.8 ka (¹⁴ C)	?	<i>Braitseva et al., 1995; Melekestsev et al., 1996b; Volynets et al., 1999a</i>
Ksudach IV	6 ka (¹⁴ C)	?	" "
Ksudach V	1.8 ka (¹⁴ C)	6x3	<i>Braitseva et al., 1995, 1996; Volynets et al., 1999a</i>
Prizrak I	Late Pleistocene (Morphology)	6	<i>Melekestsev et al., 1974; Erlich, 1986</i>
Prizrak II	Late Pleistocene (Morphology)	?	
Kurile Lake (-Iliinsky)	7.6 ka (¹⁴ C)	7	<i>Ponomareva et al., 2004</i>

Note: Calderas are enlisted from north to south. Roman numbers indicate a number of this caldera in a sequence of Quaternary calderas in the volcanic center.

Most of the calderas are superimposed not on individual volcanic cones but on volcanic complexes, which combine edifices of different ages.

dating efforts. Younger volcanoes preserve most of their original topography and many of them continued their activity into the Holocene [*Braitseva et al., 1995*].

Better age estimates are available within the range of the ¹⁴C method, the last 40–45 ka. *Braitseva et al. [1993]* described a special technique for estimating age of volcanic deposits by dating associated paleosol horizons. A number of ¹⁴C-dated ignimbrites related to the large calderas fall within a period of 30–40 ka BP (a warm interstadial) (Table 2) and serve as markers for dating other volcanic deposits [*Braitseva et al., 1995, 2005*]. In CKD, late Pleistocene eolian

sandy loams preserve tephra layers deposited during the last 40 ka. The stratigraphic position of these tephras also suggests that explosive volcanic activity peaked at 35–40 ka BP [*Braitseva et al., 2005*]. It may be glacial unloading, that caused an upsurge of explosive activity at this time. On the other hand, this cluster of dates may be explained by the fact that only these ignimbrites are associated with datable paleosols, which did not form during earlier or later colder climates. The best ¹⁴C-dated volcanic deposits and landforms (>3000 dates) are the Holocene ones, and we discuss them in a special section below.

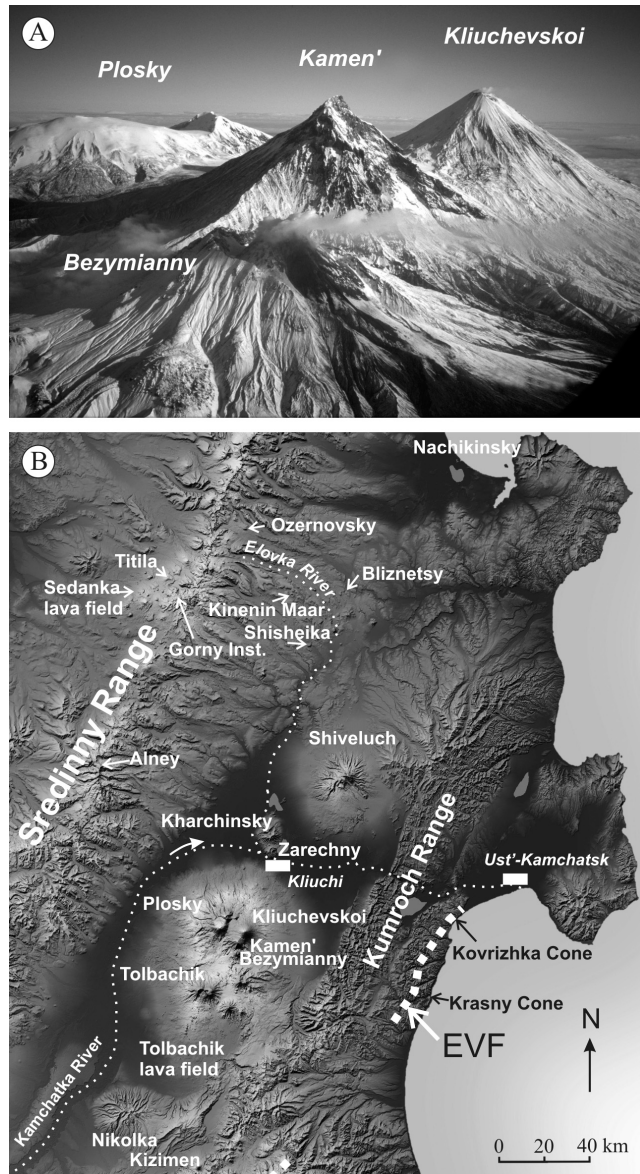


Figure 4. A. Highest volcanoes of the Kliuchevskoi group: Kliuchevskoi, 4835 m a.s.l.; Kamen', 4585 m; Plosky massif with higher Plosky Blizhny, 4057 m (on the right), and flat Plosky Dalny (or Ushkovsky), 3903 m; Bezymianny, 2869 m a.s.l. View from the south. B. Shaded SRTM elevation model showing the volcanoes of the Central Kamchatka Depression and northern parts of EVF and Sredinny Range. A part of the image released by NASA/JPL/NIMA.

HOLOCENE VOLCANISM

Post-glacial volcanic deposits, both tephra and lava, are well preserved in Kamchatka. This permits detailed reconstructions of eruptive activity over the last 10–11.5 ka. One of the main tools in the Holocene studies is a so-called soil-

pyroclastic cover, which is a continuously accumulating sequence of tephra and soil layers (Fig. 6). In Kamchatka, such cover is Holocene in age: ^{14}C dates obtained for its lowermost parts commonly are as old as ~9.5–10 ka, and in rare cases, go back almost to 12 ka [Braitseva et al., 2005; Pevzner et al., 2006]. The Holocene soil-pyroclastic cover blankets most of Kamchatka, while older sequences of this kind have been mostly removed during glaciation and occur only in isolated outcrops. We ascribe a Holocene age to an eruption based on relationship of its products with the LGM deposits and presence of its tephra in the soil-pyroclastic cover. In the literature some volcanoes are ascribed to Holocene time based on “freshness” of their lava flows [e.g. Vlodavets, 1957; Ogorodov et al., 1972]. In fact, “freshness” of the lava flows depends not only on their age but also on thickness of the overlying soil-pyroclastic cover, which is accumulating faster near active volcanoes. This means that, for example, in many parts of Sredinny Range, far from most active volcanoes, a lava flow will retain its primary topography longer than, say, in Kliuchevskoi volcanic group (Fig. 7). Thus, “freshness” of volcanic landforms alone is not a sufficient criterion for determining Holocene eruptions. In addition, several cases have been reported of fresh-looking lava flows that, in fact, had been deposited over a glacier and then were “projected” onto the underlying surface when the glacier melted [Leonov et al., 1990; Ponomareva, 1990]. World catalogues of the Holocene volcanoes [e.g., Simkin and Siebert, 1994] include a lot of “fresh” volcanoes in their Kamchatka listing, especially for SR, based on old Russian publications. Re-examination of SR volcanic centers has allowed us confirm Holocene status only for some of them (Fig. 3A), [Pevzner, 2006].

Distribution and Types of the Holocene Volcanic Edifices

In Kamchatka, 37 large volcanic centers have been active during the Holocene. In addition, a few hundred monogenetic vents (cinder cones, maars, isolated craters, lava domes, etc.) were formed. Holocene eruptions took place in most of the late Pleistocene volcanic fields, excluding only few in SR (Fig. 3A).

In Kamchatka, most of the stratovolcanoes, which were active throughout Holocene, started to form either in the end of late Pleistocene or in Holocene [Braitseva et al., 1995]. Shield-like volcanoes are not typical for Holocene and likely only Titila in SR and Gorely in South Kamchatka may be termed in this way. A few Holocene volcanic edifices are composed of andesitic-rhyodacitic lava domes. Examples include Young Shiveluch, Kizimen, and Dikii Greben' volcanoes [Melekestsev et al., 1991, 1995; Ponomareva et al., 2006].

Some stratovolcanoes (e.g., Krashennikov, Fig 4, Maly Semiachik, and Bezymianny), are built of 2–4 overlapping cones. It is presumed that when the volcano reaches some elevation limit, not allowing magma to erupt through its summit crater, the magma conduit shifts and a new cone starts to form at the flanks of the earlier one. In case this shift is impossible due to limited permeability of the upper crust, a lowering of the edifice by explosion or collapse may happen, and then the activity will continue [Braitseva et al., 1980; Ponomareva, 1990].

Of 37 recently active large Kamchatka volcanoes, at least 18 have been modified by major sector collapses, some of them repetitively [Ponomareva et al., 2006]. The largest sector collapses identified so far on Kamchatka volcanoes, with volumes of 20–30 km³ of resulting debris-avalanche deposits, occurred at Shiveluch and Avachinsky volcanoes in the late Pleistocene. During the Holocene the most voluminous sector collapses have occurred on extinct Kamen' (4–6 km³) and active Kambalny (5–10 km³) volcanoes. The largest number of repetitive debris avalanches (>10 during just the Holocene) occurred at Shiveluch volcano. Large failures occurred on both mafic and silicic volcanoes and were mostly related to volcanic activity.

In the Holocene, five collapse calderas associated with explosive eruptions were formed, all within the EVF: Karymsky, three calderas on Ksudach volcanic massif, and Kurile Lake caldera (Fig. 2B), (Table 2). Karymsky and Kurile Lake caldera-forming eruptions were separated by only a couple of centuries [Braitseva et al., 1997a]. Holocene ignimbrites commonly are not welded.

There are several lava fields in Kamchatka, the largest of them are the Sedanka, Tolbachik, and Tolmachev fields (Fig. 3A). Sedanka and Tolmachev cinder cones are scattered over a large territory. Mid- to late Holocene vents in the Tolbachik field form a 3–5 km wide belt, that stretches for 40 km in a SSW-NNE direction, then crosses late Pleistocene Plosky Tolbachik volcano (where it is responsible for Plosky Tolbachik's Holocene activity) and then goes for another 14 km to the northeast (Fig. 5B).

This alignment may suggest that the position of the vents is determined by a system of faults [Piip, 1956]. Some volcanoes host many flank cinder cones, Kliuchevskoi definitely being a leader (>50 cones) (Fig. 4B). Some cinder cones occur as isolated vents not associated with any large volcanoes or cone clusters (Fig. 3A).

Another type of monogenetic eruptive center in Kamchatka is large craters that have produced voluminous rhyolitic tephra falls. Three such Holocene craters are located in South Kamchatka: Chasha Crater, situated among the mafic cinder cones of the Tolmachev lava field [Dirksen et al., 2002]; Baranii Amphitheater on the ESE slope of Opala volcano;

and Khodutkinsky Crater northwest of Khodutka volcano (Tables 1 and 3) [Melekestsev et al., 1996a; <http://www.kscnet.ru/ivs/volcanoes/holocene>]. Chasha and Khodutkinsky craters have magmas different from those of the adjacent volcanoes, while Baranii Amphitheater rhyolite fits into the overall geochemical trend for Opala volcano [Fedotov and Masurenkov, 1991]. The closest historical example of such a volcanic vent is Novarupta near Katmai volcano, Alaska [Hildreth, 1983]. Unlike Katmai, no caldera collapse was associated with these Kamchatka craters, that allowed I.V. Melekestsev [1996a] to call them “craters of sub-caldera eruptions”.

Ages of Volcanic Cones and How They Grow

Reconstruction of the eruptive histories of the Holocene volcanoes based on geological mapping, tephrochronology and radiocarbon dating have allowed us to 1) determine the ages and growth rates of volcanic edifices; 2) identify temporal patterns of the eruptive activity; 3) document and date the largest explosive eruptions (Table 3); and 4) correlate their tephra over Kamchatka in order to obtain a tephrochronological framework for dating various deposits [Braitseva and Melekestsev, 1990; Braitseva et al., 1980, 1984, 1989, 1991, 1997a, b, 1998; Melekestsev et al., 1995, 1996b; Ponomareva, 1990; Ponomareva et al., 1998, 2004, 2007; Selyangin and Ponomareva, 1999; Volynets et al., 1989, 1999a].

Ages of some stratovolcanoes were determined based on the assumption that initial construction of such edifices was by continuous explosive activity. At the foot of all the Holocene stratovolcanoes we have identified tephra packages that meet the following criteria: 1) they underlie the oldest lava flows from the volcano; 2) are widely dispersed and easily identified around the volcano; 3) consist of a number of individual layers sometimes separated by thin sandy loam horizons; and 4) overlie thick paleosol layers suggesting that no activity from the volcano took place earlier. Radiocarbon dates on such paleosols or other associated organic matter have allowed us to date these tephra packages and thus constrain when cone-building eruptions started on various eruptive centers (Table 4). Ages of Kizimen and Dikii Greben extrusive volcanoes have been estimated based on the stratigraphic position of their initial tephra relative to the LGM deposits and the 7.6 ka Kurile Lake caldera ignimbrite, respectively.

Growth rates have been estimated for some stratovolcanoes [Braitseva et al., 1995]. The largest Holocene volcano, Kliuchevskoi (~4800 m a.s.l.) started to form at 1700 m on the slope of Kamen' volcano at ~5.9 ka (¹⁴C) (or ~6.8 calibrated ka) and likely reached its modern height within about 3000 years, after which its first flank vents

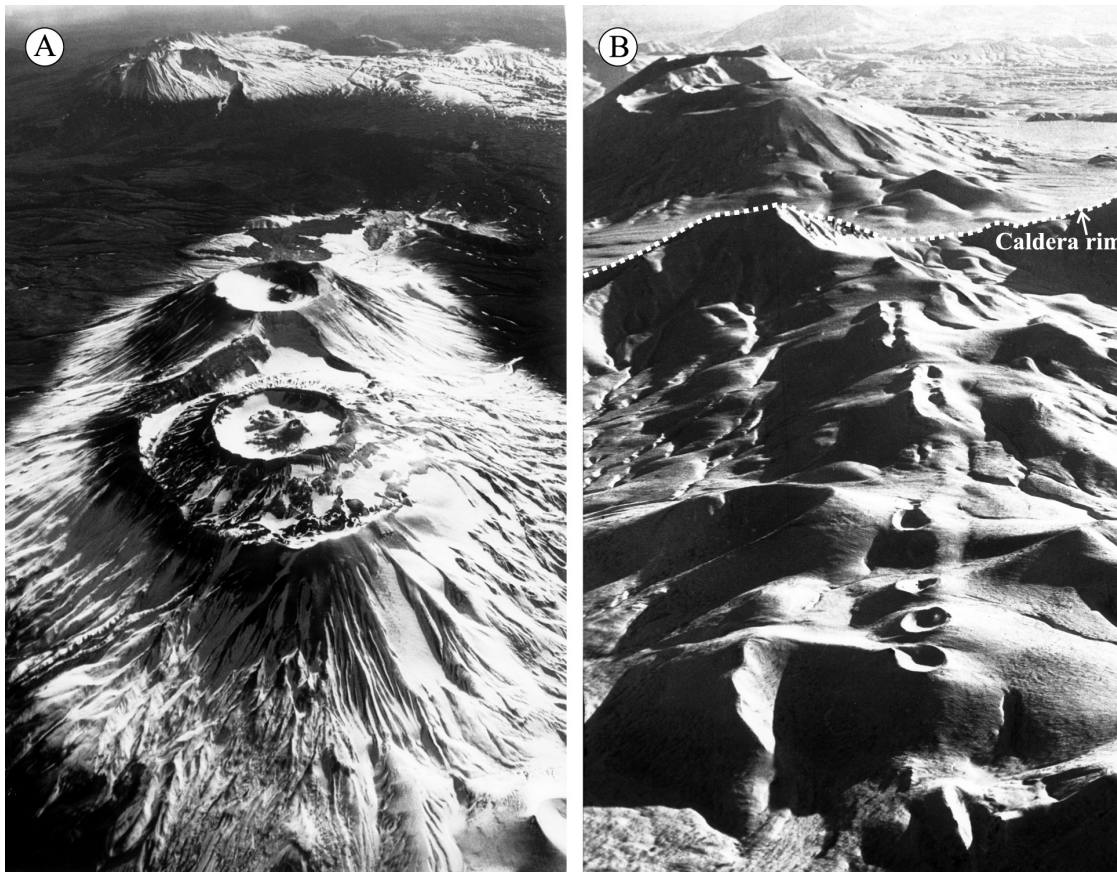


Figure 5. A. Krasheninnikov volcano, view to the south. This Holocene volcano is nested in a ~35–38 ka old caldera and consists of two large coalesced cones. The northern cone is crowned with a caldera enclosing a smaller cone with a lava cone inside. Large cones as well as numerous monogenetic vents north and south of the late Pleistocene caldera are aligned along the regional fault zone parallel to the general strike of the volcanic belt [Florensky and Trifonov, 1985]. B. Cinder cones north of Krasheninnikov caldera. The cones are aligned along the regional fault zone. Krasheninnikov volcano is in the background. Photos courtesy Vasilii Podtabachny.

started to form. This is about the duration of the main cone-building phase for other large volcanoes (Young Cone of Avachinsky, North Cone of Krasheninnikov, Karymsky, etc.). Small edifices with volumes of ~2 km³, e.g. each of the two cones composing Kikhpinych volcano or Stübel Cone in Ksudach massif, formed in the main during a few hundred years.

Eruptive activity of all the studied volcanoes was organized in spurts, with alternating active and repose periods. Repose periods as long as 1000–3000 years were rather common. Longer repose periods with the durations of >3000 years occurred at Bezymianny, Kikhpinych, Zheltovsky, Dikii Greben', and Kambalny volcanoes [Melekestsev et al., 2001]. The longest known period of quiescence (~3500 years), after which the volcano was able to resume its activity, was at Dikii Greben' volcano [Ponomareva et al., 2006]. Even volcanoes notable for

their frequent historic eruptions and intense magma supply like Shiveluch or Avachinsky appeared to have had ~900 years-long repose periods (or at least periods of low activity) [Braitseva et al., 1998; Ponomareva et al., 2007]. Zones of cinder cones behaved much as the large volcanoes: their eruptions tended to cluster into active periods separated by quiescence not exceeding 3000–4000 years [Braitseva et al., 1984; Dirksen and Melekestsev, 1999]. In certain cases, we can identify long periods of volcanic rest shared by several neighboring volcanoes. For example, three such periods recorded by thick paleosols have been documented for the southernmost part of Kamchatka, which hosts five active volcanoes (Zheltovsky, Iliinsky, Dikii Greben', Koshelev and Kambalny). The earlier two periods of quiescence lasted for a minimum of 1400 to 1500 years, and the latest one—for 750 years [Ponomareva et al., 2001]. Long (up to 3500 years) repose periods do not seem

Table 3. The largest explosive eruptions in Kamchatka during the last 10,000 years

Source volcano	Tephra code	Average ¹⁴ C age, yr BP (or calendar age for historical eruptions)	Volume of tephra, km ³	Composition of tephra
Shiveluch	SH ₁₉₆₄	AD 1964	0.6-0.8	Andesite
	SH ₁₈₅₄	AD 1854	~1	" "
	SH ₁	250	≥2	" "
	SH ₂	950	≥2	" "
	SH ₃	1400	≥2	" "
	SH ₁₄₅₀	1450	≥2	" "
	SH ₅	2550	~1	" "
	SH ₂₈₀₀	2800	≥1	" "
	SHsp	3600	~1	Basalt
	SH	3750	≥1	Andesite
	SHdv	4100	≥2	" "
	SH ₄₇₀₀	4700	≥2	" "
	SH ₄₈₀₀	4800	≥2	" "
	SH ₅₆₀₀	5600	≥1	" "
	SH ₆₈₅₀	6850	1.2	" "
	SH	7900	≥1	" "
	SH	8100	≥2	" "
	SH	8200	≥1	" "
	SH	8300	≥2	" "
Bezymianny	B ₁₉₅₆	AD 1956	1.8-2	" "
Kizimen	KZ	7550	4-5	Dacite
Khangar	KHG	6850	14-16	Dacite-rhyodacite
Karymsky caldera	KRM	7900	13-16	Rhyodacite
Avachinsky	II AV ₃	3300	>1.2	Basaltic andesite
	II AV ₁ (AV ₁)	3500	≥3.6	" "
	IAv24 (AV ₂)	4000	≥0.6	Andesite-basaltic andesite
	IAv20 (AV ₃)	4500	≥1.1	Andesite
	IAv12 (AV ₄)	5500	≥1.3	" "
	IAv2	7150	≥8-10	" "
Chasha Crater	OPtr	4600	0.9-1	Rhyolite
Opala, Baranii				
Amphitheater Crater	OP	1500	9-10	" "
Khodutkinsky Crater	KHD	2500	1-1.5	Rhyodacite
Ksudach, Stübel cone	KSht ₃	AD 1907	1.5-2	Basaltic andesite-dacite
	KSht ₁	950	0.8-1	" "
Ksudach calderas	KS ₁	1800	18-19	Rhyolite
	KS ₂	6000	7-8	Andesite
	KS ₃	6350	0.5-1	Rhyodacite-andesite
	KS ₄	8850	1.5-2	Andesite
Iliinsky	ZLT	4850	1.2-1.4	" "
Kurile Lake caldera	KO	7600	140-170	Rhyolite-basaltic andesite

Note: Volcanoes are enlisted from north to south. Radiocarbon ages are averaged to nearest 50 yrs. Original ages are from *Bazanova* and *Pevzner*, 2001; *Bazanova* et al., 2004; *Braitseva* et al., 1997a,b, 1998; *Dirksen* et al., 2002; *Pevzner* et al., 1998; *Ponomareva* et al., 2004, 2007, and *Zaretskaya* et al., 2007. For Avachinsky eruptions new tephra codes are from *Bazanova* et al., 2004, and old codes (in parentheses) are from *Braitseva* et al., 1997a,b; 1998.

to exhibit any specific chemical or spatial association. Data on the Holocene eruptive histories of Kamchatka volcanoes show that long repose periods can occur both at dominantly basaltic (e.g. Kikhpinych) and rhyodacitic (Dikii Greben')

volcanoes, dominantly explosive (e.g. Ksudach) and effusive (Dikii Greben') volcanoes, and those located closer to the Kamchatka trench (Kikhpinych) and farther west (Kizimen) [*Melekestsev* et al., 2001].

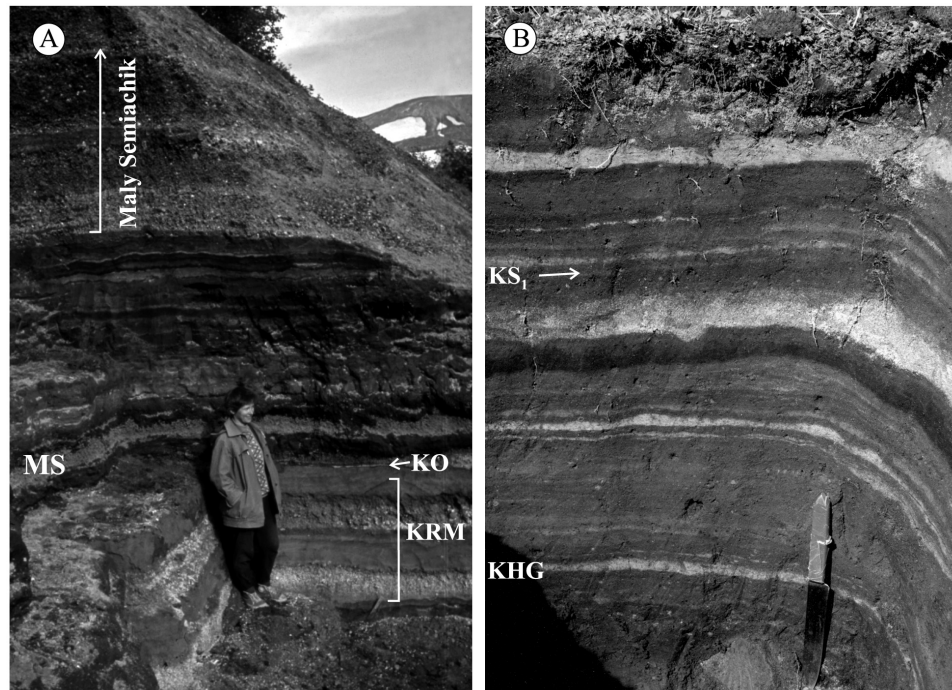


Figure 6. Holocene soil-pyroclastic cover in Kamchatka. **A.** EVF, Maly Semiachik volcano region. Local tephra: MS - cinder of the initial cone-building eruptions from Kaino-Semiachik, the youngest cone of Maly Semiachik volcano (7300–7400 ^{14}C yr BP); Maly Semiachik - stratified cinders from Kaino-Semiachik (~4000 ^{14}C yr BP). Regional marker tephra: KRM - a package of the Karymsky caldera deposits (7900 ^{14}C yr BP); KO - a thin ash layer from the Kurile Lake caldera (7600 ^{14}C yr BP). A person is ~155 cm tall. Photo courtesy Oleg Seliangin. **B.** Northern part of Sredinny Range, Sedanka lava field. Regional marker tephra: KHG - Khangar volcano (6850 ^{14}C yr BP). KS_1 - Ksudach (1800 ^{14}C yr BP). A knife is ~25 cm long.

Largest Explosive Eruptions

Table 3 lists major Holocene explosive eruptions in Kamchatka. Large eruptions took place in various parts of Kamchatka (Table 3), (Fig. 3A). The largest eruption was associated with formation of Kurile Lake caldera and yielded a tephra volume of 140–170 km^3 , making it the largest Holocene eruption in the Kurile–Kamchatka volcanic arc and ranking it among Earth’s largest Holocene explosive eruptions. Tephra from the Kurile Lake caldera-forming eruption was dispersed mostly to the northwest at a distance of ~1700 km [Ponomareva et al., 2004]. The second largest explosive Holocene eruption was associated with a caldera at Ksudach (KS_1) (Table 3). Its tephra was dispersed to NNE and covered most of Kamchatka providing a wonderful marker for Holocene studies [Braitseva et al., 1996, 1997b]. Tephra associated with other caldera-forming and larger sub-caldera eruptions reached volumes of 9–19 km^3 . Most large tephra ranged from andesite to rhyolite in composition. The only large mafic (basaltic andesite) tephra erupted from Avachinsky volcano and yielded a volume of $\geq 3.6 \text{ km}^3$.

Dated tephra layers are widely used for dating and correlating various volcanic and non-volcanic deposits [Braitseva et al., 1997b] as well as archaeological sites [Braitseva et al., 1987] and serve as a main tool in reconstructing eruptive histories of the Holocene volcanoes [Braitseva and Melekestsev, 1990; Braitseva et al., 1980, 1984, 1989, 1991, 1998; Melekestsev et al., 1995; Ponomareva, 1990; Ponomareva et al., 1998, 2004, 2007; Selyangin and Ponomareva, 1999; Volynets et al., 1989, 1999a], paleoseismic events (tsunami and faulting) [Pinegina et al., 2003; Bourgeois et al., 2006; Kozhurin et al., 2006], and environmental change [e.g. Dirksen, 2004]. As of now, no Kamchatka tephra has been positively identified in the Greenland ice cap, but some peaks in the GISP-2 core have been tentatively correlated with the largest Kamchatka eruptions based on age estimates [Braitseva et al., 1997a]. Finding the Aniakchak tephra from Alaska in Greenland ice [Pearce et al., 2004] suggests the possibility of finding Kamchatka tephra there as well.

In Figure 8, there are two peaks of magma output in explosive eruptions at AD 200–700 and BC 6650–4900, with

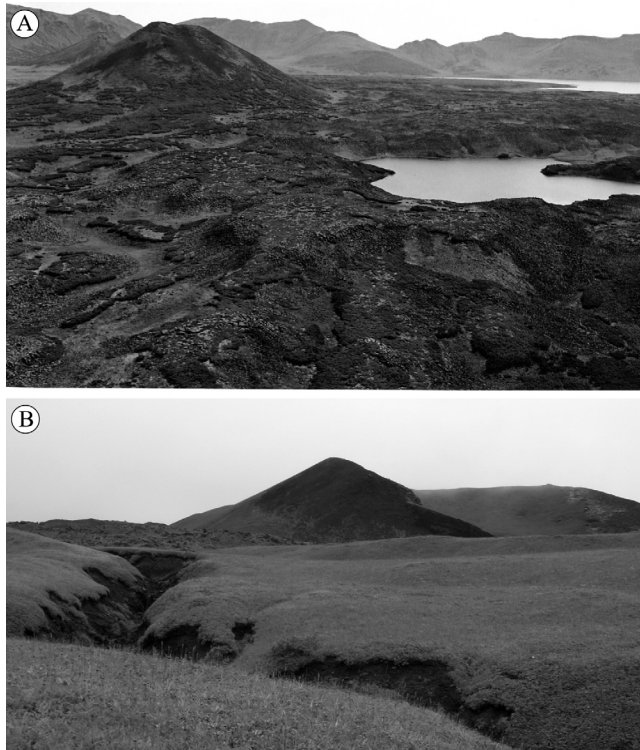


Figure 7. **A.** Late Pleistocene cinder cone and lava flow in the central part of Sredinny Range. Both cinder cone and lava flow look very fresh; however, tephra of this eruption is not present in the soil-pyroclastic cover. Lava is bare in many places, but soil-pyroclastic cover can be found in the depressions on its surface and is as old as that overlying the LGM deposits. **B.** Flat surface on the foreground is a ~2 ka old lava flow overlain by more than a 3 m thick soil-pyroclastic cover (Kliuchevskoi volcano foot). Original topography of the lava flow is smoothed and lava crops out mostly in the river valleys. A young lava flow likely formed in late 1800s is at the far left. A ~3.5 ka old cinder cone is at the right.

especially high production between BC 6600 and 6400 (“a century of catastrophes” [Melekestsev et al., 1998]). During these peaks, larger eruptions are *relatively* more frequent, whereas the frequency of all eruptions (above some certain size level, say, 1 km³) remains near average [Gusev et al., 2003]. Considering the general temporal structure of the event sequence, one can say that in the discussed time-ordered list of eruptive volumes, large-size explosive eruptions happen in tight clusters “too often” (as compared to a randomly-shuffled list of the same events). The reality of this tendency was successfully checked by statistical analysis and is called “order clustering” of the largest explosive eruptions [Gusev et al., 2003].

In addition, we analyzed magma output rate averaged over small time intervals. We found that this rate, as a function of time (at time scales 300–10,000 yrs), has a well-expressed

episodic character. This fact contradicts commonly assumed random or periodic temporal distribution of eruptions [e.g. Wickman, 1966; Ho et al., 1991; Jones et al., 1999] and supports qualitative conclusions about non-uniform or episodic character of volcanism derived from the distribution of tephra layers in deep-sea boreholes [Kennet et al. 1977; Cambray and Cadet, 1996; Cao et al., 1995; Prueher and Rea, 2001] or from the on-land tephrostratigraphy [Braitseva et al., 1995].

Mafic intrusion into a silicic magma chamber has been proved to be a common trigger for an explosive eruption [Sparks and Sigurdsson, 1977]. In Kamchatka, cases of such triggering have been demonstrated for most of the large explosive eruptions [e.g., Volynets, 1979; Melekestsev et al., 1995; Volynets et al., 1999a; Eichelberger and Izbekov, 2000; Ponomareva et al., 2004]. So the observed clusters of larger explosive eruptions over a large territory might have been caused by large-scale changes in the crustal stress field that have allowed an ascent of deeper mafic melts over most of the Kamchatka volcanic region. A typical explanation of such a phenomenon is glacial unloading [Wallman et al., 1988], but it hardly can be applied to the younger of the two Kamchatka volcanic peaks (AD 200–700). We hope that further detailed studies of spatial-temporal patterns of the well-dated Holocene Kamchatka volcanism combined with the records of the largest crustal and subduction-related earthquakes will allow us to explain its episodic character.

Volcanic Hazard Assessment

Volcanic hazard assessment has been implemented for many Holocene volcanoes based on their reconstructed eruptive histories [e.g. Melekestsev et al., 1989; Ponomareva and Braitseva, 1991; Bazanova et al., 2001]. About 80% of the ~350,000 people inhabiting Kamchatka concentrate in three cities: Petropavlovsk-Kamchatsky and Elizovo, located ~30 km south of Koriaksky and Avachinsky volcanoes, and Kliuchi, located 30 km north of Kliuchevskoi and 45 km south of Shiveluch volcanoes. For the historical period (~300 years), these sites have experienced volcanic influence only by minor ashfalls and flooding in outermost suburbs. During the Holocene, the main hazard for these territories was also associated with tephra falls and lahars. Recurrence of large tephra falls (with thickness of buried tephra ≥ 1 cm) in Petropavlovsk-Kamchatsky during the last 8000 yrs was ~1 fall per 420 yrs [Bazanova et al., 2005]. In Kliuchi (Fig. 2A), an average recurrence of large tephra falls in Holocene was ~1 fall per 700 years; however, it reached a value of 1 per 300 years during the last 1000 years [Pevzner et al., 2006]. Such remote towns as Ust'-Bolsheretsk received only

Table 4. Radiocarbon ages of some volcanic edifices

Volcano	Onset of edifice formation, yr B.P. (¹⁴ C)	Reference
Kliuchevskoi	~5900	<i>Braitseva et al., 1995</i>
pre-Bezymianny	10,000–11,000	<i>Braitseva et al., 1991; Braitseva et al., 1995</i>
Bezymianny	~4700	" "
Kizimen	12,000–11,000	<i>Braitseva et al., 1995; Melekestsev et al., 1995</i>
Komarov	1500	<i>Ponomareva, 2000, unpublished data</i>
Gamchen (Baranii Cone)	3600	<i>Ponomareva et al., 2006</i>
Krasheninnikov		<i>Ponomareva, 1990; Braitseva et al., 1995</i>
North Cone	5500	" "
Mid-North Cone	1300	" "
Kikhpinych		<i>Braitseva et al., 1989; Braitseva et al., 1995</i>
West Cone	4200	" "
Savich Cone	1400	" "
Maly Semiachik		
Paleo-Semiachik	20,000?	<i>Braitseva et al., 1980, 1995; Melekestsev et al., 1989</i>
Meso-Semiachik	11,000	
Kaino-Semiachik	7300–7400	
Karymsky	5300	<i>Braitseva and Melekestsev, 1990; Braitseva et al., 1995</i>
Avachinsky (Young Cone)	3500	<i>Braitseva et al., 1995; Bazanova et al., 2003</i>
Ksudach (Stübel Cone)	1600	<i>Braitseva et al., 1995; Volynets et al., 1999a</i>
Iliinsky	7600	<i>Ponomareva et al., 2004</i>
Dikii Greben'	7600	" "

two large tephra falls during the last 8500 years [Bazanova et al., 2005]. A long-term prediction of sector collapses on Kliuchevskoi, Avachinsky and Koriaksky volcanoes [Melekestsev and Braitseva, 1984; Melekestsev et al., 1992] highlights the importance of closer studies of their structure and stability.

AMOUNT OF ERUPTED MATERIAL

Estimates of the eruptive volumes and mass were done based on the detailed maps of the late Pleistocene-Holocene volcanoes compiled by I.V.Melekestsev. The total mass of rocks erupted during the late Pleistocene-Holocene is estimated at 18 to 19 x 10¹² tonnes [Melekestsev, 1980]. CKD volcanic belt was the most productive (~40% of all the eruptives) (Fig. 9A). The EVF production was less at 35%. SR (25%) was subordinate to both other belts. Mafic rocks dominated in all the belts. Andesite-rhyolite constituted 25–30% of the total volume erupted in CKD and EVF and only ~6% of that erupted in Sredinny Range. Within EVF, most of silicic rocks were erupted in South Kamchatka. In Holocene, CKD and EVF belts produced almost similar amount of eruptives, while SR belt productivity dropped (Fig. 9A).

The highest magma production rate both during the last 60 and 11.5 ka was in CKD (Fig. 9B). In late Pleistocene,

production rate in CKD and EVF was almost twice higher than that in Holocene. Late Pleistocene magma production rate in SR was smaller than that in CKD and EVF, but not that dramatically smaller than in Holocene. It is unclear whether this Holocene drop in SR production rate means the end of volcanic activity in SR or just reflects a relatively quiet period.

The largest late Pleistocene-Holocene stratovolcanoes yielded volumes up to 320 km³ or mass of ~0.74 x 10¹² tonnes (including tephra) [Melekestsev, 1980]. Examples include Kronotsky, Kamen', and Old Avachinsky (before the sector collapse). The largest Holocene edifice is that of Kliuchevskoi (270 km³ or 0.6 x 10¹² tonnes). The smallest Holocene stratovolcano, Stübel Cone, has a volume of ~2 km³ and mass of the rocks of ~0.005 x 10¹² tonnes. The largest Holocene explosive eruption produced 140–170 km³ (0.18 x 10¹² tonnes) of tephra and 7-km-wide Kurile Lake caldera [Ponomareva et al., 2004]; other eruptions ranked far below (Table 3). Most of the late Pleistocene calderas are significantly larger (up to 18 km, Table 2) and are surrounded by thick packages of welded tuffs. We suggest that most of the late Pleistocene caldera-forming eruptions were at least equal to the largest Holocene eruption (Kurile Lake caldera) or larger. Volume of individual Holocene lava eruptions reached 2–5 km³ [Pevzner et al., 2000; Ponomareva et al., 2006].

COMPOSITION OF ROCKS

Late Pleistocene-Holocene volcanic rocks in Kamchatka cover wide range of compositions. One of their most interesting features is a high proportion of mafic varieties (basalt-andesite) compared to that of silicic rocks (Fig. 9); [Volynets, 1994]. The amount of the sedimentary component is limited in most of the Kamchatka volcanic rocks [Kersting and Arculus, 1995; Tsvetkov et al., 1989; Turner et al., 1998] and the most mafic varieties do not show any sign of crustal contamination [e.g. Volynets et al., 1994; Dorendorf et al., 2000a], offering a chance to investigate a relatively simple system. In addition, a certain amount of more silicic rocks (dacite-rhyolite) is present in Kamchatka, mostly related to caldera systems and associated crustal magma chambers. Studies of magma evolution on the individual centers show that most of the silicic rocks have been derived from mafic melts through fractionation and mixing with related melts [e.g. Kadik et al., 1986; Ivanov, 1990; Volynets et al., 1989, 1999a; Leonov and Grib, 2004]. O and Sr isotopes studies, however, have shown that some of silicic rocks have been influenced by crustal and meteoritic/hydro-thermal water

[Bindeman et al., 2004]. In this paper, we discuss mafic products since these are most reflective of mantle processes.

Large variations of the volcanic rocks in Kamchatka and adjacent volcanic arcs clearly represent the result of several factors that control conditions of the mantle melting and future melt evolution during ascent and chamber residence before eruption. These factors may vary from arc to arc and are mainly related to crustal thickness, mantle fertility, composition and thermal state of the subducted plate [Pearce and Parkinson, 1993; Plank and Langmuir, 1988, 1993], temperature of the mantle wedge and subducted slab [England et al., 2004; Manea et al., 2005], and the amount and compositions of subducted fluids and sediments [Plank and Langmuir, 1993; Duggen et al., 2007].

Cross-arc Chemical Zonation

Cross-arc chemical zonation of the Late Pleistocene-Holocene Kamchatka volcanic rocks from east to west at different latitudes is most pronounced in their enrichment in alkalis and incompatible trace elements [Volynets, 1994; Tatsumi et al., 1995; Avdeiko et al., 2006; Davidson, 1992,

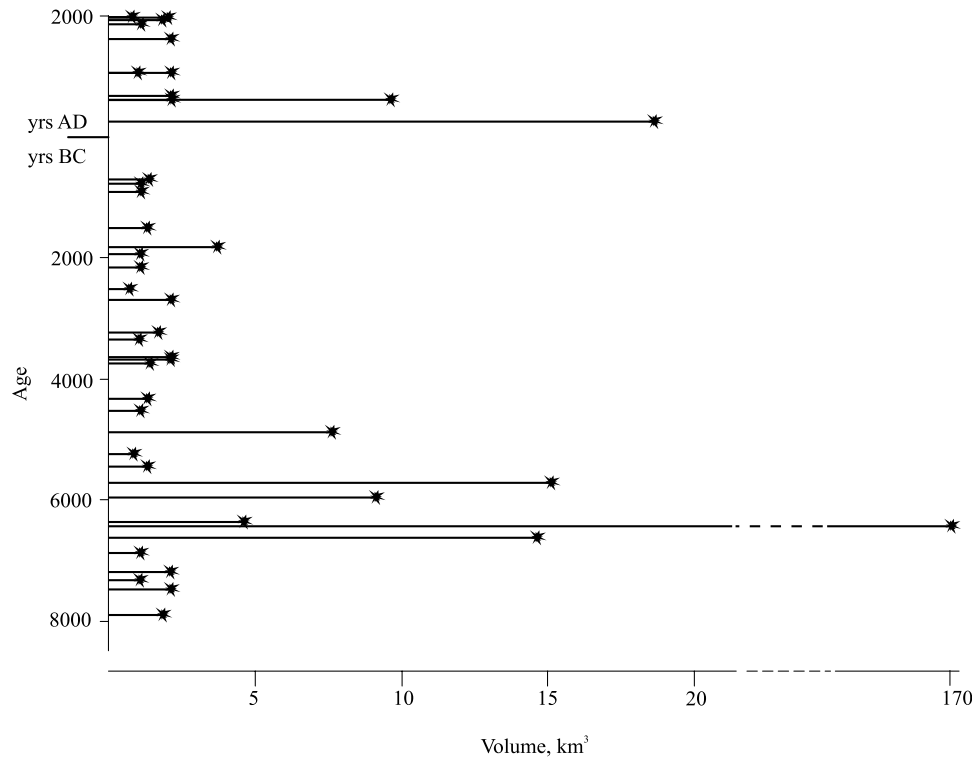


Figure 8. Volumes of the products from the largest explosive eruptions in Kamchatka in Holocene (for details see Table 3). Ages are radiocarbon ages converted to calibrated years (cal yr BP) using CALIB 5.0 [Stuiver et al., 2005]. Two peaks of magma output in explosive eruptions can be identified at AD 200–700 and BC 6650–4900, with especially high production between BC 6600 and 6400 (“a century of catastrophes” [Melekestsev et al., 1998]).

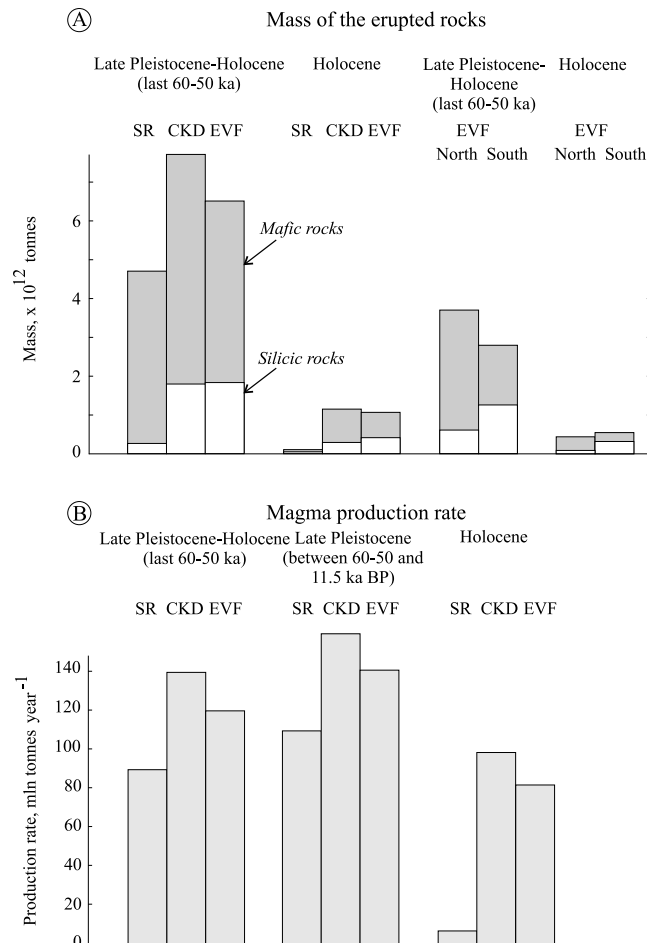


Figure 9. Mass of the late Pleistocene- Holocene erupted rocks (A) and magma production rate (B) by volcanic belts: SR - Sredinny Range, CKD - Central Kamchatka Depression, EVF - Eastern volcanic front. In A, gray and white fillings show mafic and silicic rocks, respectively. CKD was the most and SR - the least productive volcanic belts in Kamchatka during late Pleistocene-Holocene.

pers.comm.]. Some authors argue that the currently active subduction zone may be responsible for all the magma-generating processes during this period [Tatsumi et al., 1995; Churikova et al., 2001]. Others suggest the simultaneous existence of two subduction zones: one beneath the Eastern Volcanic Front and the Central Kamchatka Depression and the second one beneath the Sredinny Range [Avdeiko et al., 2006].

To evaluate both hypotheses, mafic volcanic rocks densely sampled along an E-W transect have been studied for major and trace element compositions as well as isotopes of Sr, Nd, Pb, U, Th, O and Hf [Churikova et al., 2001; Dorendorf et al., 2000a, b; Münker et al., 2004; Wörner et al., 2001]. This 220-km-long transect is comprised by 13 Upper Pleistocene and Holocene stratovolcanoes and two large lava fields. It

stretches from EVF through CKD into the back arc of SR (Fig. 3B). Since the compositions of CKD rocks north and south of the Kamchatka River are significantly different, we consider them separately as NCKD and SCKD, respectively. The transect was fitted to follow the widest possible cross-arc extent of recent volcanism, which is one of the widest worldwide.

In terms of major element composition the rocks of the EVF belong to the low- to medium-K tholeiitic and calc-alkaline series (Fig. 10). Low-K rocks stretch along the EVF and are present on the other volcanoes closest to the trench (Kronotsky, Kikhpinych, some volcanoes of Bolshoi Semiachik massif, Zhupanovsky, Avachinsky, Mutnovsky, Khodutka, Ksudach, Zheltoovsky, Kambalny) (Fig. 3B), (Table 1); [e.g. Fedotov and Masurenkov, 1991; Duggen et al., 2007]. The rocks of the back arc (SR) are medium to high-K calc-alkaline. SCKD and NCKD rocks have intermediate position between EVF and SR. Near Ichinsky volcano, we found HFSE (high field strength elements)-enriched basalts with intra-plate affinities (here: basalts of within-plate type - WPT). Recent studies have discovered rocks of this type in northern parts of Sredinny Range [Volynets et al., 2005]. Some more alkaline rocks (shoshonitic and K-alkaline basaltoids, alkaline basalts and basanites) were described in SR [Perepelov et al., 2005]. Those will not be considered in the following discussion, however, because they belong to Paleogene and Miocene.

Trace elements patterns for EVF, CKD and SR rocks are shown in (Fig. 11). All rocks have typical arc-signatures with strong but variable LILE and LREE enrichment and low HFSE. LILE and HFSE concentrations increase from the front to the back-arc. All rocks are depleted in Nb and Ta, REE, and HREE compared to NMORB. However, Nb-Ta-depletions in back arc rocks compared to neighboring LILE's are much smaller than in the EVF and CKD rocks. All the SR rocks contain a variable amount of the enriched OIB-like mantle component. The amount of this component changes from low addition on Ichinsky volcano (so called SR (IAB)) to highly enriched (up to 30–35%) in intra-plate basalts (so called SR (WPT)) [Churikova et al., 2001, 2007; Münker et al., 2004; Volynets et al., 2006].

Along the transect under study the depth to the slab changes from 100 km for EVF to 400 km for SR [Gorbatov et al., 1997]. Some CKD samples are close to a primary mantle-derived melt composition. However, EVF and SR rocks and most of CKD rocks were obviously affected by some mineral fractionation, therefore, direct comparison of trace element concentrations is impossible. For comparison, the data from each volcano were normalized to 6% MgO following the approach used by [Plank and Langmuir, 1988]. The normalized data for selected trace elements and element ratios versus

depth to the slab surface are shown in Figures 12 and 13. Most of incompatible trace elements, i.e. HFSE (Zr, Nb, Hf, Ta), LILE (Sr, Ba, Rb, Be, Pb, U, Th), LREE, some major elements (K, Na) and certain element ratios (K/Na, La/Yb, Sr/Y, Nb/Yb) are positively correlated with slab depth. Similar cross-arc changes in element concentrations and their ratios have been recently found south of the described transect [Duggen et al., 2007; Portnyagin et al., 2007a]. At the same time Y and the HREE are almost constant from front to back arc (Fig. 12H”.

The WPT at Ichinsky have higher concentrations of Na_2O , TiO_2 , P_2O_5 , Sr and all HFSE and REE, and are depleted in SiO_2 and Rb compared to the Ichinsky IAB-SR.

Isotope data for the northern transect are summarized in Figure 14. The data plot close to the MORB field; variations in all isotope systems are small and inside the previously reported ranges for Kamchatka [Kepezhinskas et al., 1997; Kersting and Arculus, 1995; Tatsumi et al., 1995; Turner et al., 1998]. There is a general increase in $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ from

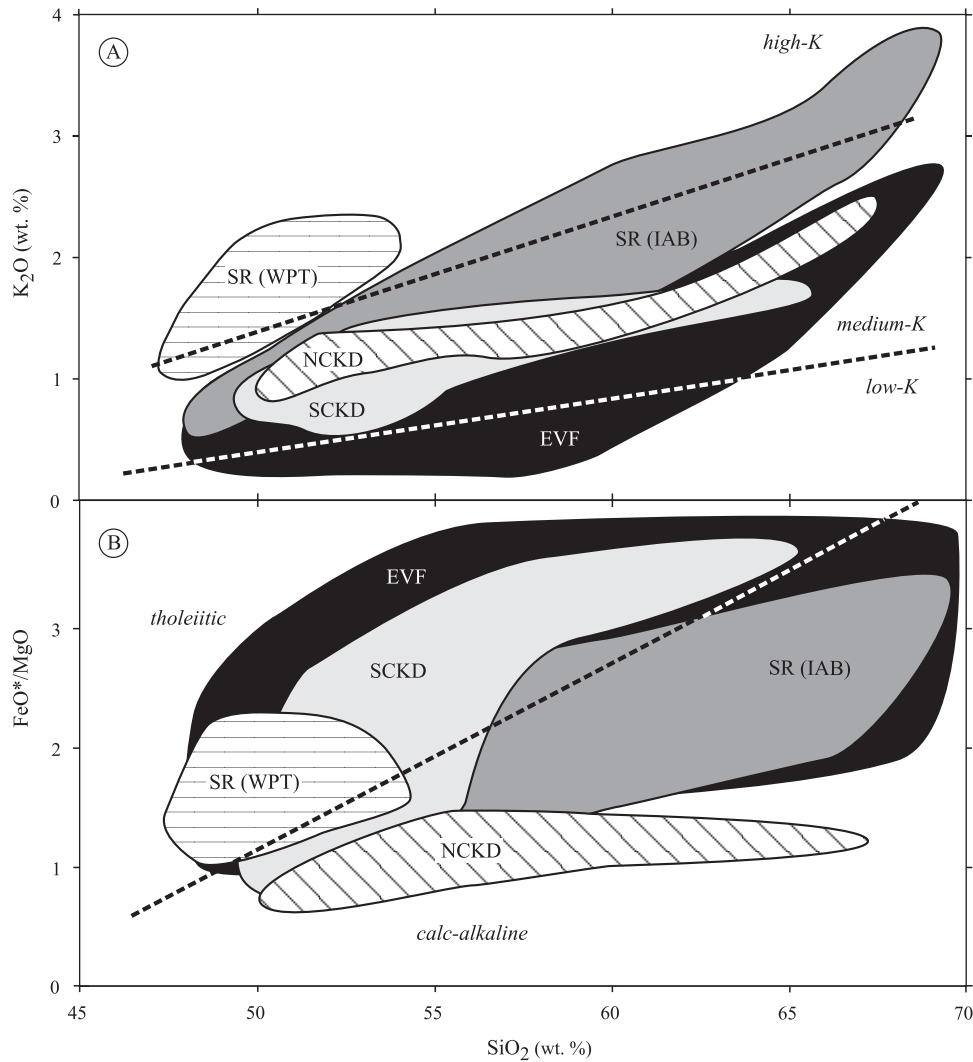


Figure 10. K_2O (A) and FeO^*/MgO (B) vs. SiO_2 for late-Pleistocene-Holocene volcanic rocks of the Kamchatka Peninsula. The rocks of different volcanic regions or of specific composition are combined in the fields marked by different colors. Only medium-K calc-alkaline rocks are shown for SCKD region. Data from Fedotov and Masurenkov [1991]; Dorendorf et al. [2000a, 2000b]; Churikova et al. [2001]; Leonov and Grib [2004]; Ivanov et al. [2004]; Volynets et al. [2005]. EVF – Eastern Volcanic Front; SCKD – volcanoes of the Central Kamchatka Depression south of the Kamchatka River; NCKD - those north of the Kamchatka River; SR (IAB) – island-arc basalt type rocks of Sredinny Range; SR (WPT) – within-plate type rocks of Sredinny Range. Element concentrations are given in wt.%. Classification lines for (A) after Le Maitre et al. [1989] and for (B) after Miashiro [1974]. FeO^* - all iron expressed as FeO .

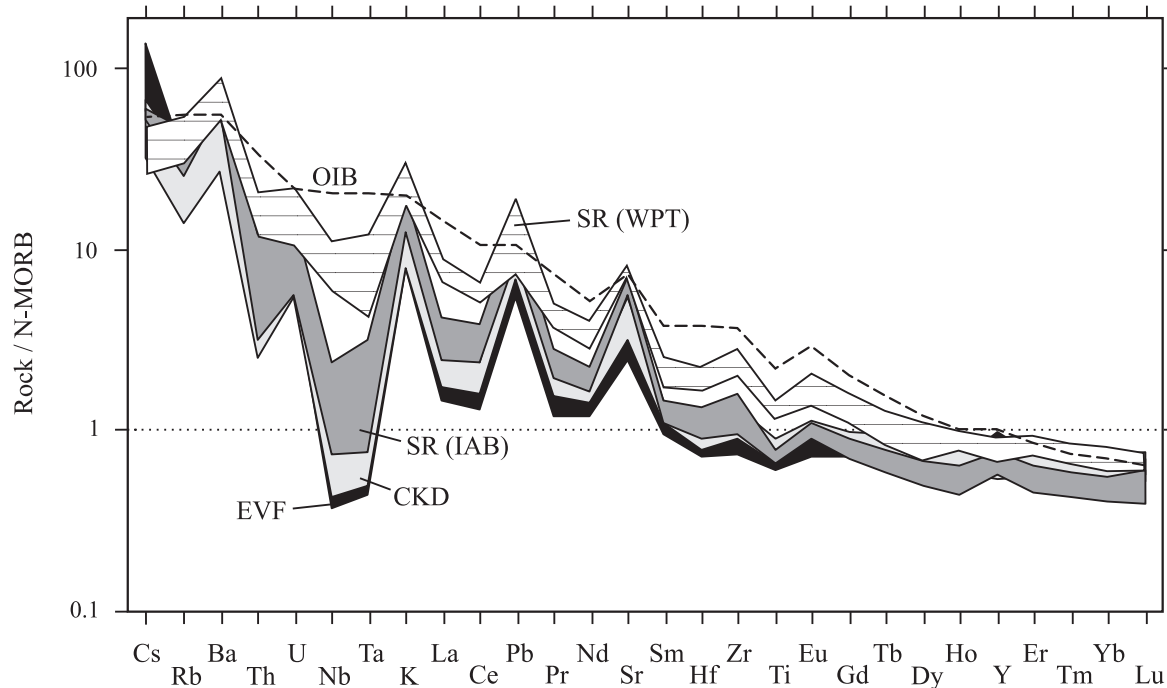


Figure 11. NMORB-normalized trace element patterns for mafic rocks of the different regions of Kamchatka. The order of incompatible elements is derived from Hofmann [1988] with Cs and all REE added. For clarity, each zone is expressed by a compositional field. SR (WPT) are significantly more enriched in all trace elements compared to all other lavas. Data from Churikova et al. [2001] and Volynets et al. [2005]. NMORB and OIB values after Sun and McDonough [1989].

the EVF to the CKD and a decrease from the CKD to the SR with strongest ^{87}Sr -enrichment in CKD samples. Three trends could be distinguished on Figure 14, suggesting involvement of three different components. A component low in $^{87}\text{Sr}/^{86}\text{Sr}$ (<0.7031) and high in $^{143}\text{Nd}/^{144}\text{Nd}$ (~ 0.5131) is a MORB source within the mantle wedge. From the MORB field one array trends to higher Sr-isotope ratios with unchanged Nd-ratios. Slab fluids (or slab melts) are expected to have such composition. The second array tends to lower Nd-isotope ratios with a correlated increase in Sr-isotopes. Such a trend probably results from mixing with an enriched mantle component and formed mainly by the SR back-arc rocks.

Using Pb isotopes data for the Kamchatka rocks and pelagic sediments from ocean drilling near Kamchatka, Kersting and Arculus [1995] argued that subducted sediments play a minor role in Kamchatka magma generation. These data were also confirmed by Be isotopes [Tsvetkov et al., 1989]. Recently, however, new data imply that subducted sediments/melts play a more important role in the genesis of the Kamchatka rocks [Duggen et al., 2007; Portnyagin et al., 2007a].

The degree of partial melting required for generation of the volcanic rocks of Kamchatka decreases from arc front to back arc. The rocks of the EVF display the highest source degree of melting of 14–20%, the CKD and SR “normal”

arc rocks show lower degrees of melting, down to 9–12%, and samples with intraplate signatures in back arc show the lowest degree of melting at 7% [Churikova et al., 2001; Portnyagin et al., 2007a].

On Th/Yb versus Ta/Yb diagram [Pearce, 1983] (Fig. 15), all samples from the EVF and NCKD and most samples from SCKD fall into the field of depleted mantle sources. However, the SR rocks form an array reaching from the oceanic arc towards an enriched mantle component. The existence of the enriched source was evidenced by the high-precision measurements of Nb/Ta, Zr/Hf, Lu/Hf ratios together with Hf isotopes [Münker et al., 2004].

Despite that, based on LREE and LILE concentrations, fluid contribution does not change across Kamchatka (Ce/Pb, Ba/Zr ratios do not show systematic change) (Figs. 13B, F), elements more sensitive to arc fluid transport show strong cross-arc variations. Using volatile and fluid-mobile elements in melt inclusions from Kamchatka’s olivines, different fluid compositions were found across Kamchatka. While fluid released in EVF and CKD carries high amounts of B, Cl and S [Portnyagin et al., 2007a], the fluid below SR is enriched in Li and F (Fig. 16), [Churikova et al., 2004, 2007]. We argue that the dehydration of different water-rich minerals at different depths explains the difference in fluid

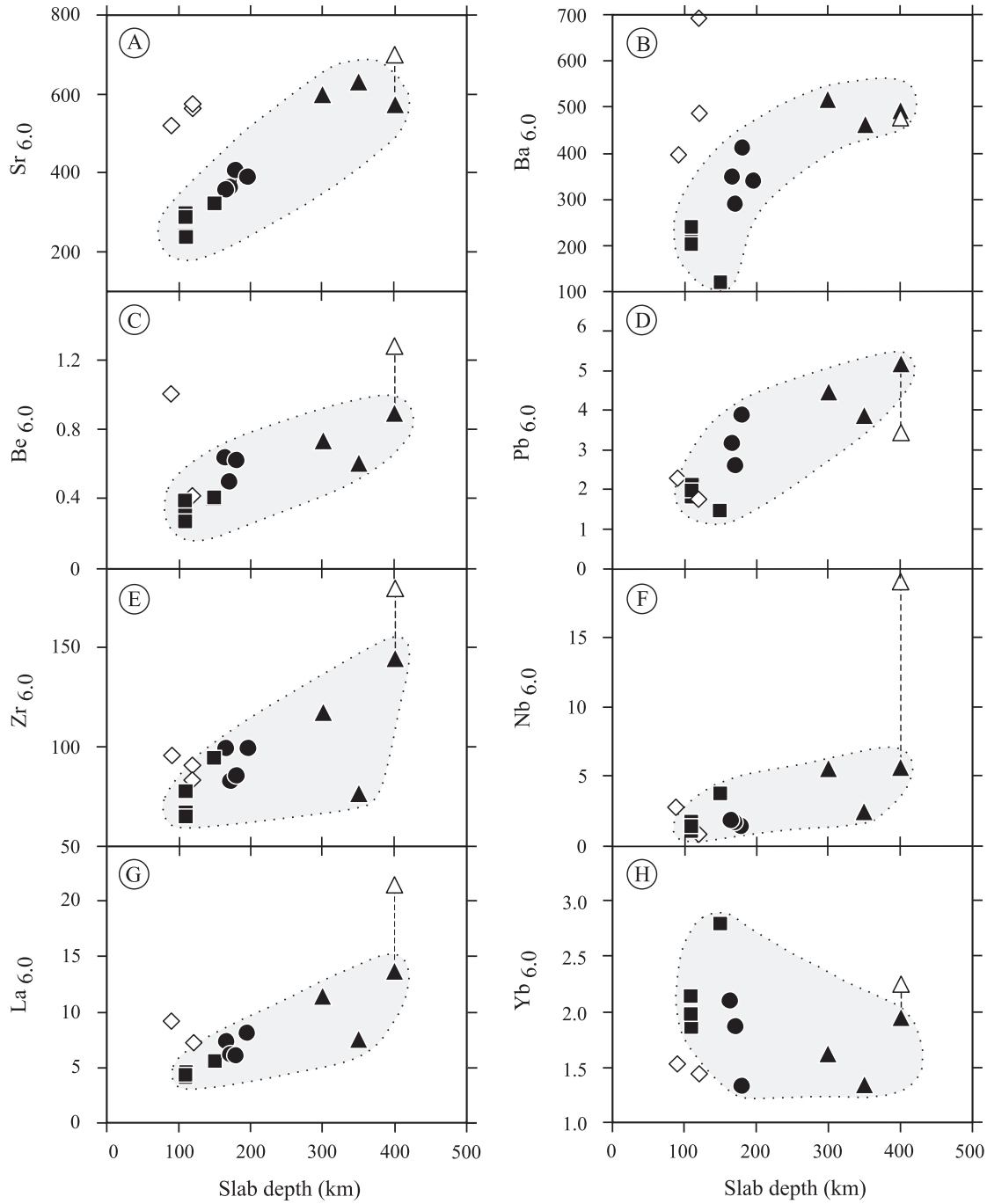


Figure 12. Fluid mobile trace element concentrations (A–D) and HFSE and REE concentrations (E–H) of single volcanoes in relation to the depth of the slab surface below the volcanoes for the northern Kamchatka transect. For correct comparison of differently fractionated volcanic series the data from each volcano were normalized to 6% MgO following the approach used by [Plank and Langmuir, 1988]. The shaded fields were drawn to underline the trends of the typical arc magmas. The typical arc series of Ichinsky are connected by a dotted line with the WPT, occurring at the same volcano. Positive linear trends are well-defined for $Sr_{6.0}$, $Ba_{6.0}$, $Be_{6.0}$, $Pb_{6.0}$, $Zr_{6.0}$, $Nb_{6.0}$, $La_{6.0}$ and a weak negative trend for $Yb_{6.0}$ which are marked by shaded fields. However, the trends for HFSE and REE are less well defined than for the fluid mobile elements. Squares – EVF; circles – SCKD; diamonds – NCKD; triangles – SR. Element concentrations are given in ppm. Modified after Churikova et al. [2001].

composition across the Kamchatka arc and may significantly influence the chemical composition of the rocks.

Systematic geochemical variations from front-arc to back-arc argue for a single subduction zone. Trace element patterns seem to be mostly governed by slab fluid and variable source compositions in the mantle wedge. Rate of magma production by individual volcanoes depends on fluid flux, mantle wedge heterogeneity and the location of their magmatic sources with respect to the dehydrating slab.

Chemical Variations Along the Kamchatka arc

No significant changes in chemical composition of the late Pleistocene-Holocene rocks have been found along EVF [Volynets, 1994] or northern part of SR (from Ichinsky to ~50 km north of Titila) (Fig. 17A) [Volynets et al., 2005; Volynets, 2006]. In CKD, however, systematic changes in trace element ratios were observed from Kliuchevskoi group northwards to Nachikinsky and Khailulia volcanoes, that suggests a transition from fluid-induced melts through

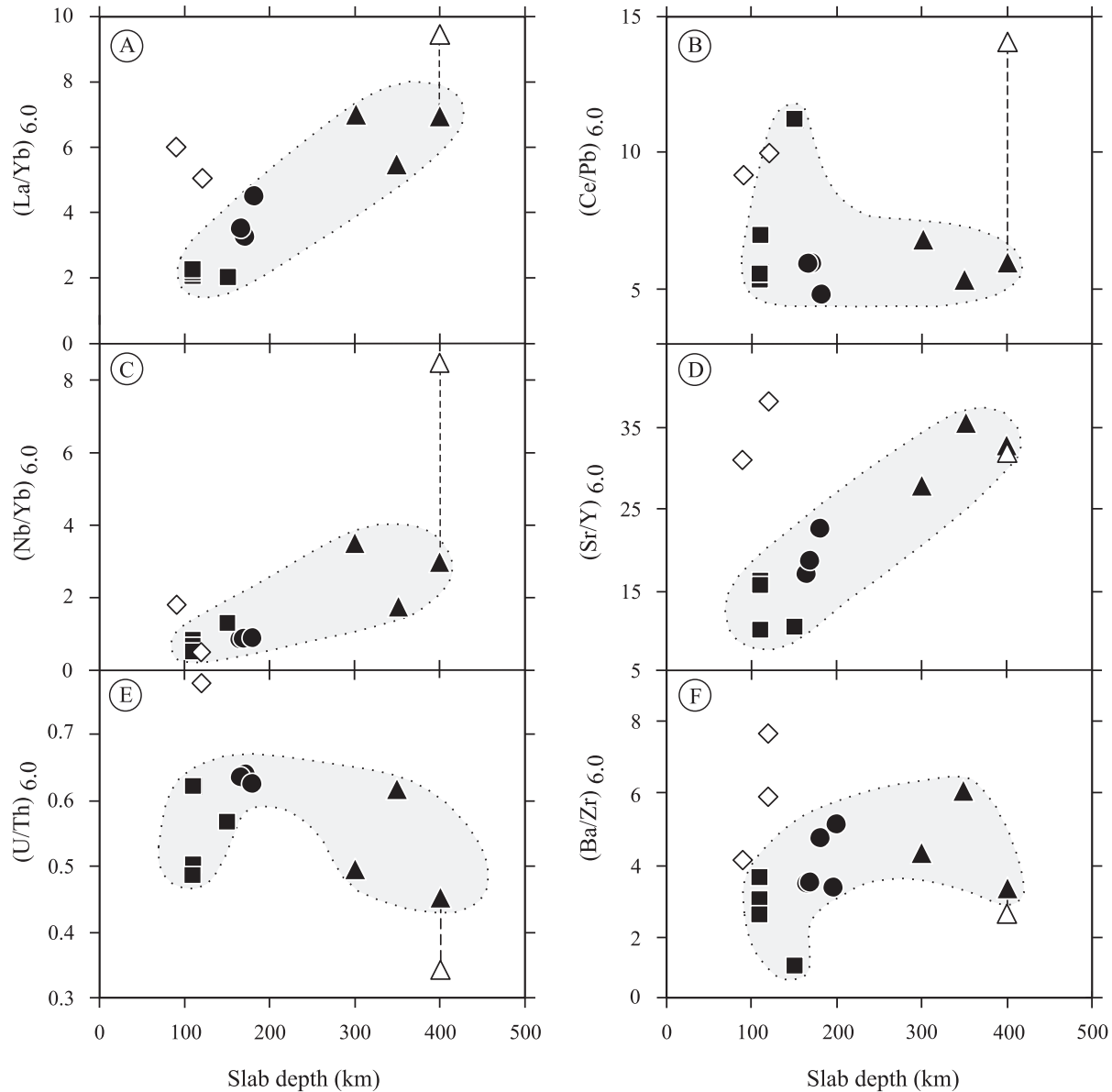


Figure 13. 6% MgO-normalized incompatible trace element ratios of single volcanoes in relation to the depth of the slab surface below the volcano. Positive linear trends exist for $(La/Yb)_{6.0}$, $(Nb/Yb)_{6.0}$ and $(Sr/Y)_{6.0}$. The $(Ce/Pb)_{6.0}$, $(Ba/Zr)_{6.0}$ and $(U/Th)_{6.0}$ ratios do not show regular trends. Symbols as in Fig. 12. Modified after Churikova et al. [2001].

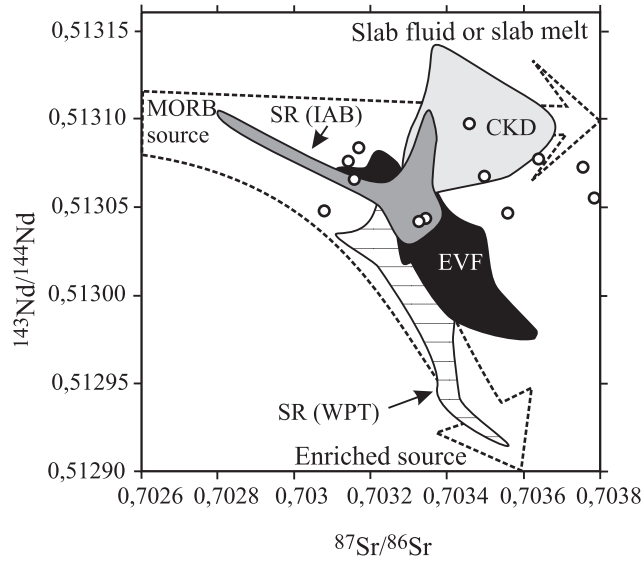


Figure 14. $^{143}\text{Nd}/^{144}\text{Nd}$ vs $^{87}\text{Sr}/^{86}\text{Sr}$ for Kamchatka rocks. Data from Churikova et al [2001]; Dorendorf et al. [2000a, b] and Volynets [2006]. The points of leached clinopyroxene from mantle xenoliths for Kamchatka [Dorendorf, 1998; Koloskov, 1999] are marked by white circles and shows for Nd-isotopes a comparable and for Sr-isotopes an even larger range than observed in the volcanic rocks. Arrows are drawn schematically to show three-component mixing between slab fluid, MORB and enriched mantle source. SR rocks show mixing line between MORB and OIB sources.

the late Pleistocene-Holocene Tolbachik, Kliuchevskoi and Shiveluch. These changes might reflect variations of melts both in space and time.

CKD Volcanoes

The best studied volcanoes in Kamchatka are in CKD, with the Kliuchevskoi group south of the Kamchatka River (SCKD) and the NCKD group with Shiveluch, Zarechny and Kharchinsky volcanoes north of the river (Fig. 4) [e.g. Ozerov, 2000; Khubunaya et al., 1995, Volynets et al., 1999b; Dorendorf et al., 2000a, Kersting and Arculus, 1994; Mironov et al., 2001; Portnyagin et al., 2005, 2007a, b]. The reason for CKD's high volcanic activity could be related to intra-arc

slab-influenced source to intra-plate melt compositions (Fig. 17B), [Portnyagin et al., 2005]. Khailulia and most of Nachikinsky, however, likely started to form in early-mid-Pleistocene times, so they are significantly older than

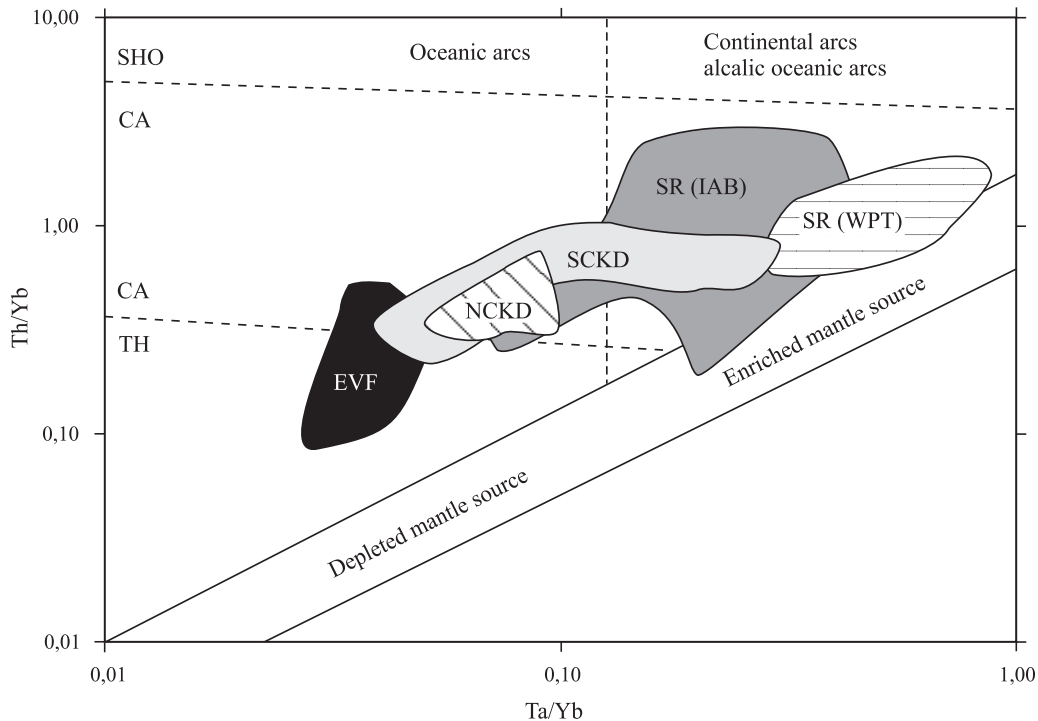


Figure 15. Th/Yb vs. Ta/Yb after Pearce [1983]. Nearly all samples from EVF and SCKD as well as most NCKD samples fall into the field of oceanic arcs formed from depleted mantle sources. In a contrast, the SR samples trend towards an enriched mantle composition (shaded field). SHO - shoshonitic series; CA - calc-alkaline series; TH - tholeiitic series. Data from Churikova et al [2001]; Dorendorf et al. [2000b], Ivanov et al. [2004], and Volynets et al. [2005].

rifting and upwelling in this area. Yogodzinski et al. [2001a] suggested that mantle wedge below CKD is extraordinary hot because of a hot mantle flow around the edge of the subducting Pacific plate. Even if the degree of melting is not very high (around 12%), a large volume of mantle could be involved in this melting due to massive decompression below the rift. CKD rocks are enriched in ^{87}Sr , and elevated U/Th and Ba/Zr ratios (Figs. 14 and 16), [e.g. Churikova and Sokolov, 1993, Dorendorf et al., 2000a, Wörner et al., 2001]. We conclude that the high magma production rate in CKD may be caused by: (1) intra-arc rifting, following upwelling and enhanced decompression melting and (2) enhanced fluid-flux from the Emperor Seamounts Chain.

Most of SCKD rocks are medium-K calc-alkaline basalt-andesite series (Fig. 10). At the same time, on Plosky Tolbachik volcano and Plosky massif high-K tholeiitic rocks occur along with “normal” medium-K calc-alkaline volcanic rocks. High-K rocks are enriched in all incompatible elements, but exhibit low HFSE, and therefore fall off the across-arc trend for most geochemical parameters. Despite the fact that such rocks were found only on a few volcanoes, they have significant volumes and so merit further detailed examination. For example, in the Tolbachik lava field, individual eruptions produced up to 1–2 km³ of high-K basalt and the total for the Holocene rocks of this composition approaches to 70 km³ [Braitseva et al., 1984; Flerov et al., 1984].

NCKD volcanoes (Shiveluch, Zarechny, Kharchinsky) display trace element patterns distinct from the SCKD

[Yogodzinski et al., 2001a; Portnyagin et al., 2005]. They have high Sr/Y ratios of ~35 and La/Yb of ~5 (Figs. 10, 12, 13), which by far exceed compositions on the across-arc trend (Figs. 10B, 12, 13, 17). Such a pattern is typical for adakites, for which an origin from slab melting is assumed [Defant and Drummond, 1990]. The adakite-type signatures were explained by tearing of the slab and warming of the slab edge by hot asthenospheric mantle [Volynets et al., 1997b; Yogodzinski et al., 2001a].

Other Rock Types

Rare rock types occur locally and include shoshonite-latitude series [Volynets, 1994], avachite (high-Mg basalt found near Avachinsky volcano), allivalites (Ol-Pi highly crystallized rocks which occur mostly as inclusions in low-K mafic and silicic tephtras), high-K high-Mg phlogopite-bearing and hornblende-bearing basalt—basaltic andesite found only in one tephra from Shiveluch volcano [Volynets et al., 1997a], etc.

Unlike most other arcs, Kamchatka rocks are rich in mantle-derived xenoliths (mostly dunites, harzburgites, and clinopyroxenites, with fewer wehrlites) [Koloskov, 1999; Bryant et al., 2005; Dektor et al., 2005] that provide an opportunity to directly observe mantle material altered by subduction processes. Trace elements indicate that Kamchatka xenoliths are depleted in Nb and Ta relative to Ba and light REEs [Turner et al., 1998; Yogodzinski et al., 2001b].

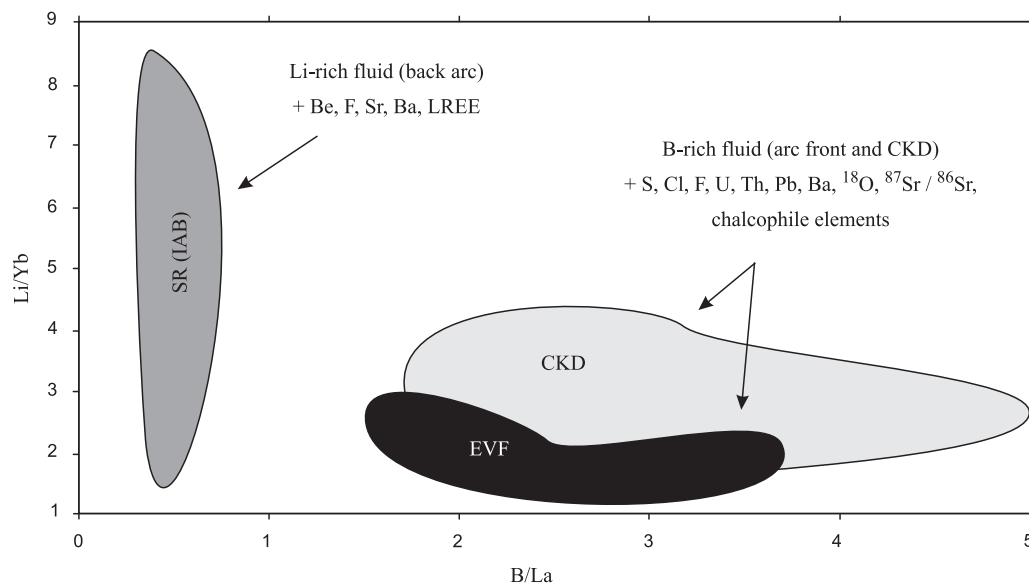


Figure 16. B-Li systematics in melt inclusions from olivines from rocks across the Kamchatka arc, showing the decoupling of B and Li. This results in high B/La in arc front magmas and a strong increase in Li/Yb towards the back arc. Field as in Figure 10.

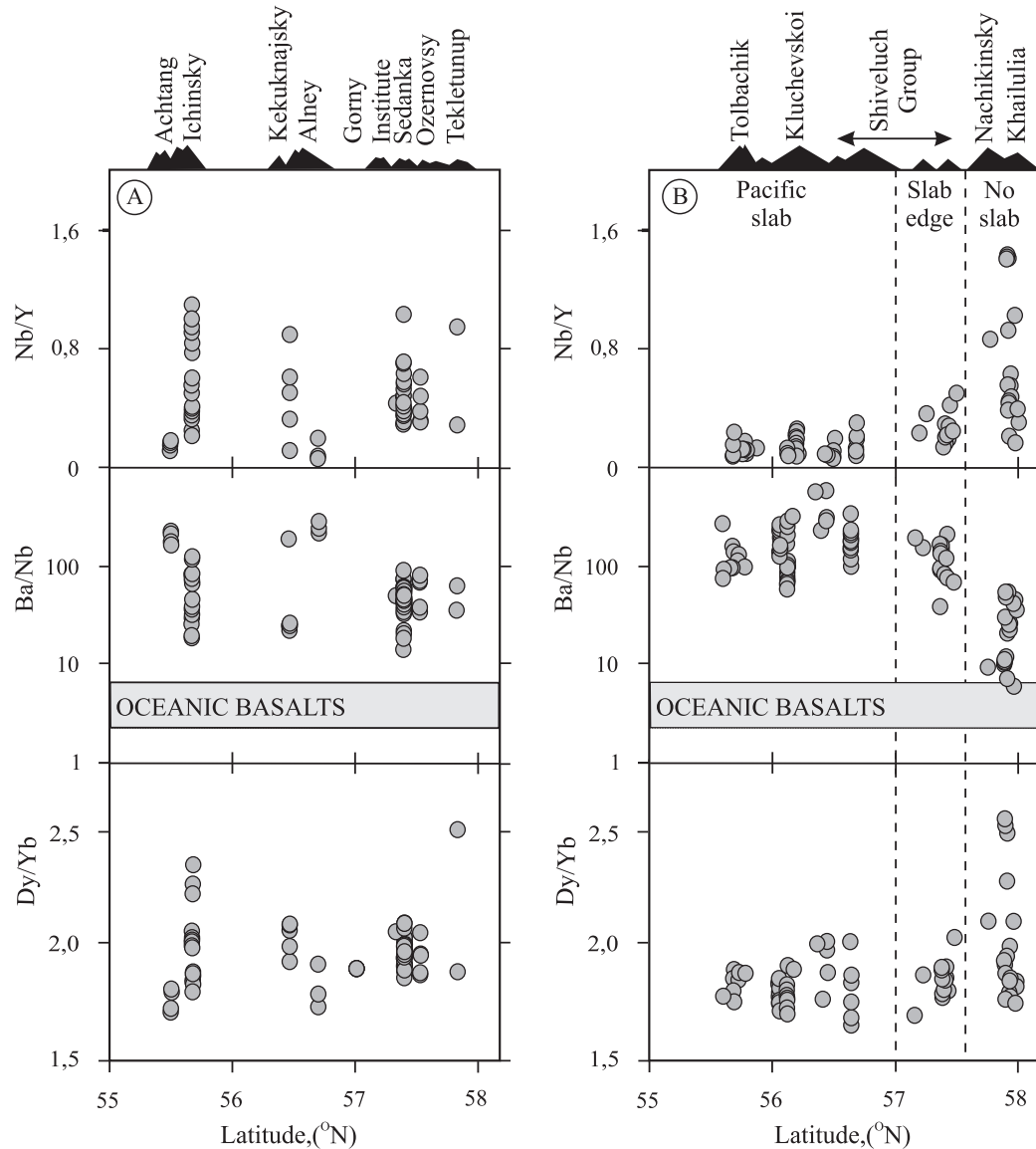


Figure 17. Along-arc variations of trace element ratios in SR (A) and CKD (B) lavas. No systematic changes have been found along the Sredinny Range (A) while the CKD lavas show a transition from fluid-induced melts over Pacific slab through slab-influenced magmas above the slab edge to intra-plate compositions farther north (B). The range of Ba/Nb for oceanic basalts (MORB and OIB) is shown after Sun and McDonough [1989]; the range of Nb/Y and Dy/Yb for oceanic basalts covers the entire range shown in diagrams. Data sources: (A) - Volynets [2006]; (B) - modified after Portnyagin et al. [2005].

CONCLUSION: FUTURE TASKS

Changes in the spatial-temporal patterns of volcanism and composition of volcanic rocks reflect large-scale tectonic processes. Further steps in understanding Quaternary volcanism in Kamchatka should, in our opinion, combine radiometric dating of the volcanic rocks with studies of their geochemical affinities. In addition to across-arc variations in rock composition, more

along-arc traverses should be studied. Special attention must be paid to northern Kamchatka, where volcanism seemingly extends beyond an active subduction zone (Fig. 2B).

Even in the best studied Kliuchevskoi group, some volcanoes like Udina or Zimina (southeastern part of the group, Fig. 4) were last visited in 1970-ies and their rocks have never been analyzed in detail. The Kliuchevskoi volcanic group has been recording tectonic processes in the Kamchatka-Aleutian

“corner” or triple junction (Fig. 2B) starting from at least mid-Pleistocene, so changes in production rates and compositions of its rocks, once reconstructed, can shed light on the evolution of this structure.

Similar efforts should be made in the studies of the pre-late Pleistocene volcanism including voluminous late Pliocene-Early Pleistocene lava plateaus in Sredinny Range and spectacular shield volcanoes. Of special interest are volcanic fields that existed during only one period and did not resume their activity later (Fig. 2B) (e.g. lava field NE of Shiveluch and fields in the northernmost part of the peninsula). These volcanic deposits likely record major events in the plate history of the region.

At the Holocene scale, attempts of correlating paleovolcanic and paleoseismic records [Bourgeois et al., 2006; Kozhurin et al., 2006; Pinegina et al., 2003] and identifying periods of overall high tectonic activity and natural catastrophes [Melekestsev et al., 1998, 2003a,b] are most intriguing. Near their sources, both volcanic and seismic events can produce marked changes in the landscape, building volcanoes, triggering large debris flows and floods, producing conspicuous ground deformation, and reorienting river drainages. At a distance, large earthquakes and volcanic eruptions also leave their mark, causing tsunamis, heavy ash falls, and atmospheric pollution. Major subduction-zone events may include many of these proximal and distal components, which combine their effects and cause more serious and variable consequences than anticipated for individual volcanic or seismic events alone. Studies of such recent geological catastrophes in Kamchatka, based on distal correlations of various deposits with the help of marker tephra layers, hopefully will help to understand the space-time patterns of catastrophic events, make long-term forecasts of future episodes, and to model potential natural catastrophes around the Pacific Rim.

Acknowledgements. The research was supported by grants ## 05-05-64776, 06-05-64960 and 06-05-65037 from the Russian Foundation for Basic Research; by the Russian Academy of Sciences Program “Environmental and Climate Change”; by the Russian Ministry of Industry and Science projects #43.700.11.0005, 43.043.11.1606 and State Contract with Federal Agency of Science and Innovations’ Department of Survey and New Technologies Development #01.700.12.0028 to Tatiana Churikova and NSF grant #EAR-0125787 to Joanne Bourgeois. Geochemical studies would not be possible without continuous support and attention from Gerhard Wörner to whom the authors are most grateful. The field work in 1996–2000, 2002, and 2004 was supported by the grants from the National Geographic Society to Vera Ponomareva. We thank John Eichelberger for editing the first version of this manuscript. We appreciate the help from Gene Yogodzinski and an anonymous reviewer, whose comments and suggestions have allowed us to improve the manuscript.

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