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The Okhotsk–Chukotka Volcanic Belt: Age of Its Northern Part According to New Ar–Ar and U–Pb Geochronological Data

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Abstract—Current geochronological data on the Okhotsk–Chukotka volcanic belt (OCVB) and relevant problems are discussed. The belt evolution is suggested to be modeled based on $^{40}Ar/^{39}Ar$ and U–Pb dates more useful in several aspects than common K–Ar or Rb–Sr dates and methods of paleobotanical correlation. Based on new $^{40}Ar/^{39}Ar$ and U–Pb dates obtained for volcanic rocks in the OCVB northern part, the younger (Coniacian) age is established for lower stratigraphic units in the Central Chukotka segment of the belt, and the eastward migration of volcanic activity is shown for terminal stages of this structure evolution.

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Key words: Okhotsk–Chukotka belt, active continental margins, volcanism, stratigraphy, geochronology.

INTRODUCTION

Geochronology of the Okhotsk–Chukotka volcanic belt (OCVB), the largest one in the Earth geological history, was under debates over forty years.[1] According to initial ideas, evolution of this structure was tens million years long and lasted from the Late Jurassic (Ustiev, 1959) or the Aptian (Belyi, 1969) to the Paleocene. Later on, Jurassic and Neocomian sequences of subaerial volcanics were excluded from the OCVB structure based on relevant geological and paleontological information, and two alternative hypotheses of the belt development, which were suggested in the 1970s, competed until the mid-1990s. One of them (Belyi, 1977) constrained the OCVB formation by the Albian–Cenomanian, while the other one (Filatova, 1988; Lebedev, 1987) argued for presence of Senonian rocks in the belt. After long-lasted debates (see in Belyi, 1982, 1992; Filatova and Lebedev, 1982; Dvoryankin et al., 1990), the last hypothesis was accepted as more reasonable in general, presence of Senonian volcanics in the OCVB has been proved, and the Albian–Campanian period of the OCVB development is out of doubt since the recent time (Belyi, 1994; Belyi and Belaya, 1998; Kotlyar et al., 2001). Nevertheless, there are still diverse viewpoints on age of the Late Cretaceous floras (Table 1), because it is difficult to avoid disagreements when studying stratigraphy in areas of continental volcanism, where sections are laterally variable, representative remains of fossil terrestrial flora are scarce and problematically correlative with sections containing marine fossils (Lebedev and Filatova, 1998; Herman, 1999). In the period of debates, results of isotopic geochronology were of secondary significance because of several reasons: by the state geological survey of 1960s to 1980s, isotopic ages were determined mostly by the K–Ar dating of whole-rock samples, and discordance of dating results and structural relations of geological bodies led to understandable skepticism with respect to isotopic geochronology in general.

Almost all the isotopic dates available for volcanic rocks of the OCVB have been reviewed in monograph by Kotlyar and Rusakova (2004) who suggested geochronological model well consistent with the last stratigraphic scheme by Belyi and Belaya (1998) mostly based on paleobotanical data. Despite doubtless value of their research, authors of the monograph used a disputable approach to evaluate age of igneous rocks (see section K–Ar and Rb–Sr geochronology), as we think.

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[1] Evolution of viewpoints on the OCVB geochronology is considered in detail by Kotlyar and Rusakova (2004).

There is a certain discordance between the results of dating the OCVB volcanics by $^{40}Ar/^{39}Ar$ in the last decade (Lane et al., 1998; Kelley et al., 1999; Hourigan and Akinin, 2004; Ispolatov et al., 2004) and the accepted stratigraphic scheme. This discordance stimulated this work aimed at geochronological dating of rocks with prime attention to the $^{40}Ar/^{39}Ar$ and U–Pb methods. The results obtained during the first stage of the work are discussed below.

GENERAL GEOLOGY OF THE OCVB NORTHERN PART

Characteristic of the OCVB is distinct longitudinal and transverse zoning in terms of structure and composition of rock complexes. Belyi (1977) discriminated the external (rear) and internal (frontal) zones of the OCVB besides four segments and two flank zones separated by transverse boundaries (Fig. 1). The later scheme of the OCVB zoning (e.g., Filatova, 1988) is the same in principle, although the number of segments is different.

As one can see in Fig. 1, structure of the OCVB northern part includes the Central Chukotka and Anadyr segments along with the East Chukotka flank zone. In the *Anadyr segment*, the OCVB rock succession begins with volcanics of intermediate to basic composition, predominantly with lavas and tuffs of basaltic andesite and andesite (the Salamikha Formation). They overlie a thick (up to 3 km) sequence of "pre-volcanogenic molasse" (Belyi, 1977) that discordantly rests, like the OCVB volcanics, on folded marine sediments and volcanogenic-sedimentary strata of the Triassic and Jurassic. The facies composition of molasse characterizes transition from coastal-marine (the Ainakhkurgen Formation) to continental (the Chimchememel Formation) sedimentation settings. Remains of the Buor-Kemyus paleoflora have been collected from sediments of the last formation and from overlying Salamikha Formation (Belyi, 1994). The main volume of volcanics is represented by rocks of differentiated basalt-andesite-dacite-rhyolite series. Above the Salamikha Formation, there are distinguished the Vilka and Tuvyiveem sequences and Koekvun Formation of basalt–andesitic composition, and dacite–rhyolitic volcanics of the Dirguveem and Pykarvaam formations and of the Aunei sequence. The Mesozoic rock succession is crowned by basaltic and trachybasaltic lava flows of the Enmyvaam Formation and Chuvanskoe sequence. Many geologists (Filatova, 1988; Kotlyar and Rusakova, 2004) believe that these lavas originated during the superimposed rifting and exclude them from composition of the OCVB.

In distinction from the Anadyr and all other segments of the OCVB external zone, volcanic succession of the *Central Chukotka segment* (*CCS*) is of the silicic-to-basic character, beginning at the base with rhyolites and dacites (the Amgen sequence, Elgynkakvyn and Kytapkai formations) but not basalts or andesites. In some local areas, basal volcanics overlie pre-volcanogenic molasse (the Aptian Kukeveem and Albian Ol'khovyi formations) and volcanic rocks of andesite–latite composition (Tytyl'vaam and Etchikun formations of the Albian).[2] The last volcanic rocks have been regarded as product of rift magmatism that antedated the OCVB origin (Kotlyar and Rusakova, 2004). Above high-silicic complexes, there are several stratigraphic units of the CCS succession (Kalenmyvaam, Notarelyan, Ekityki, Pykarvaam, Voron'ya, Koekvun, Emuneret formations etc.), which are composed in variable combinations of rocks of trachyandesite and rhyolite–dacite composition. Late plateau basalts of the Enmyvaam Formation are confined to southern part of the CCS, close to its boundary with the Anadyr segment. In addition, extended belts of basalt–dolerite dikes, which crosscut all stratified formations of the Mesozoic, occur throughout the CCS. Dikes and plateau basalts are probably comagmatic.

Like in many other OCVB segments, rock succession of the *East Chukotka flank zone* begins with intermediate to basic volcanics (Nyrvakinot sequence) grading upward into rocks of mostly silicic composition (Amgen sequence). In places, volcanic rocks are underlain by the Valanginian–Albian molasse (Irvyneiveem sequence, Ol'khovyi and other formations). Rocks of the Amgen Formation are successively overlain by the Ekityki and Leurvaam formations of andesitic and dacite–rhyolitic composition, respectively. As it is typical of the OCVB, the youngest volcanics here are basaltoids with insignificant proportion of silicic rocks (Nunligran Formation).

It is remarkable that volcanogenic sequences are persistent in lateral direction to a variable extent. For instance in the Pegtymel Depression (the northwestern CCS, middle reaches of the El'khkakvun, Palyavaam and Pegtymel rivers), stratigraphic subdivisions can be discriminated with confidence based on lithologic criteria, because lava flows of relatively constant composition are traceable here as far as tens kilometers (Belyi, 1969). A more complex situation is in the southeastern part of the same segment near its boundary with the East Chukotka flank zone, where sections of adjacent, almost isometric volcanic structures 7 to 15 km in diameter are frequently very dissimilar (Tikhomirov, 1996). Stratigraphy of such volcanics is unclear, if marker horizons cannot be discriminated and fossil plant remains have not been found.

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[2] Age of all local subdivisions is quoted from the legend to geological map, scale 1 : 500000 (*Informational Report…*, 2004). Stratigraphic position of studied samples is coordinated with the same map.

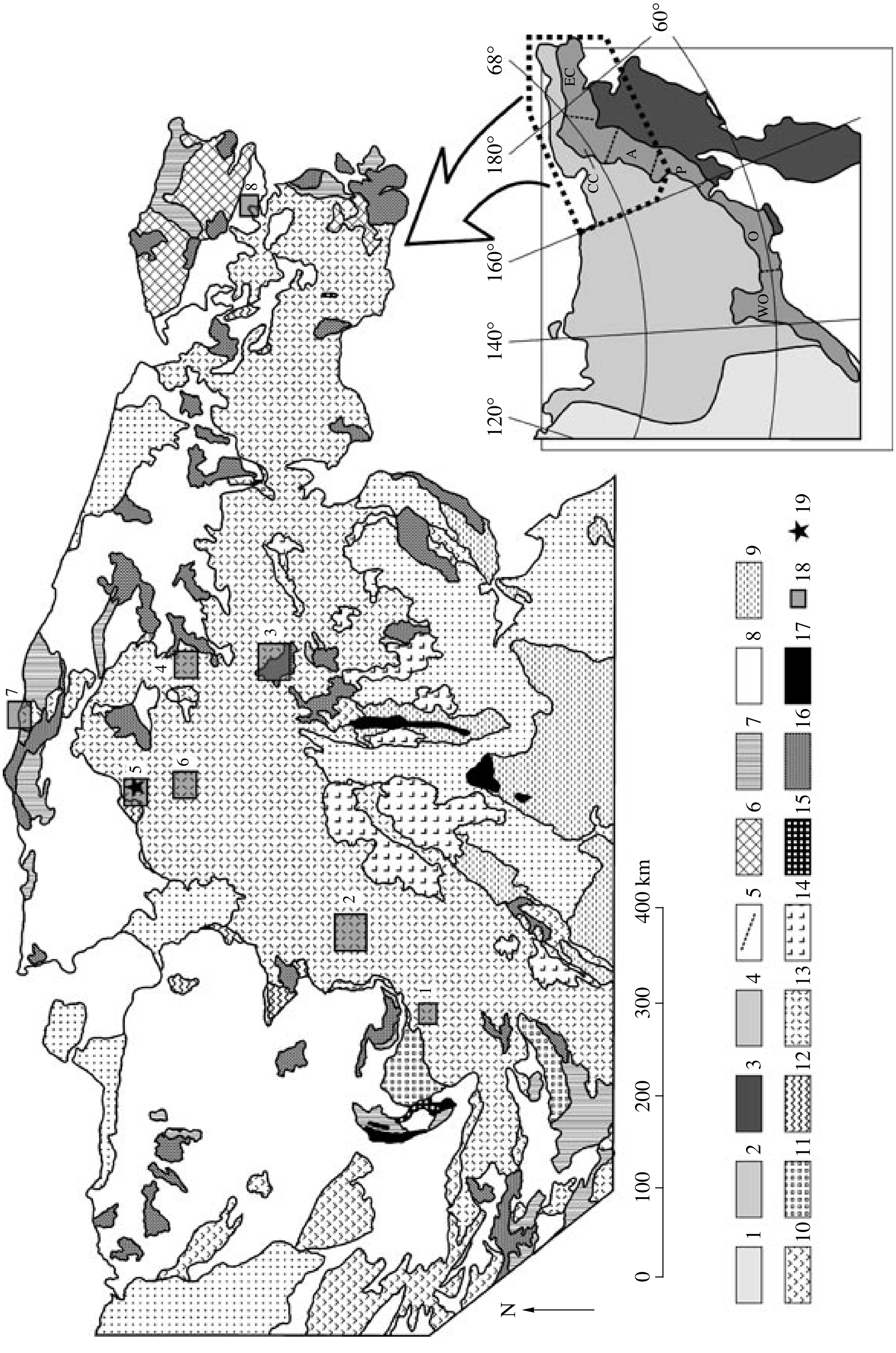
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Fig. 1. Geological structure of the Okhotsk–Chukotka volcanic belt (after Geological Map of the USSR, 1983, scale 1: 2 500 000, with minor modifications) and its position in generalized structure of Northeast Asia (inset map): (1) Siberian platform; (2) Verkhoyansk–Chukotka foldbelt; (3) Koryak–Kamchatka fold area; (4) Okhotsk–Chukotka volcanic belt; (5) boundaries between the West Okhotsk flank zone (WO), Okhotsk (O), Penzhina (P), Anadyr (A), Central Chukotka (CC) segments and East Chukotka flank zone (EC) of the OCVB; (6) outcrops of Precambrian and (7) Paleozoic basement rocks; (8) folded rocks of the Triassic, Jurassic and Neocomian (Verkhoyansk–Chukotka foldbelt); (9) Cretaceous–Cenozoic complexes of the Koryak–Kamchatka foldbelt; (10) rocks of Late Jurassic–Neocomian volcanic arcs; (11) Lower Cretaceous deposits of "pre-volcanogenic molasse" (Belyi, 1977); (12) rifting-related volcanogenic rocks of the Tytyl'vaam, Etchikun and other formations antedating the OCVB origin (Kotlyar and Rusakova, 2004); (13) volcanic rocks of the OCVB; (14) late plateau basalts; (15) Pleistocene basaltoids; (16) large granitoid and gabbro-granitoid plutons; (17) mafic-ultramafic massifs; (18) sampling sites in (1) the Pravyi Chimchememel River basin, (2) upper reaches of the Malyi and Bol'shoi Anyui rivers and (3) Tanyurer River, which are dated first in this work, and sites of formerly known ^{40}Ar/^{39}Ar dates in (4) the Palyavaam and Chaantal'vegyrgyn river heads (Ispolatov et al., 2004), (5) Etchikun River basin (Ispolatov et al., 2004), (6) middle reaches of the Palyavaam River (Kelley et al., 1999), (7) Cape Yakan (Lane et al., 1998) and (8) Koolen Lake southern coast (Akinin and Calvert, 2002); (19) sampling site for U–Pb dating.

AGE OF THE OCVB

Paleobotanical Data

Available stratigraphic schemes of the OCVB (*Resolutions of the Second...*, 1978; Belyi, 1994; Lebedev, 1987; Filatova, 1988; Herman, 1999) are based on dating results of plant remains collected from the belt sections. Opinions of specialists about age of paleofloras changed with time (Table 1). During the last decade, the main tendency consisted in replacing the invariant schemes of successive changes in stratoflora evolution over the entire territory of Northeast Asia (Samylina, 1986; Belyi, 1982; Lebedev, 1987; Filippova and Abramova, 1993) by a more complex interpretation admitting coexistence of different floras originated in diverse paleogeographic settings (Shchepetov, 1995; Herman, 1999).

Commencement of the OCVB development is determined by age of the Buor-Kemyus paleoflora whose remains have been collected over a considerable area from "pre-volcanogenic molasse" and the Salamikha, Tylkhoi, Berezovaya, and other volcanogenic-sedimentary formations considered as basal stratigraphic divisions of the OCVB rock succession (Belyi, 1994). Almost all researchers attribute this paleoflora to the Albian (Table 1). Nevertheless, molassic deposits are frequently overlain by volcanogenic sequences barren of representative assemblages of fossil plants. When precise isotopic dates are unavailable, these sequences are attributed a priori to the Albian based on the age authorized for the OCVB in general. As for the upper parts of volcano-sedimentary sequences, even if they yield representative plant remains, their age is commonly established based on correlation with marine sequences containing fossil fauna, although this is admissible only for host deposits containing plant remains of coastal lowlands. With such an approach, however, it is difficult to date paleofloras of volcanic uplands. The idea that flora assemblages of similar taxonomic composition but from different paleogeographic settings are synchronous is also doubtful (Lebedev and Filatova, 1998; Herman, 1999).

K–Ar and Rb–Sr Geochronology

K–Ar and Rb–Sr dates known at present for the OCVB volcanics range within a broad interval from 110 to 50 Ma (Kotlyar and Rusakova, 2004). Statistic maximums of dates are within the interval of 84–70 Ma. Taking into consideration the observable concordance of some oldest K–Ar and Rb–Sr dates, Kotlyar and Rusakova suggested absence of excess argon in igneous rocks of Northeast Asia and suggested a model, in which volcanogenic sequences are dated based on oldest Rb–Sr or K–Ar dates (Kotlyar and Rusakova, 2004). According to their model, the OCVB proper is of the Albian–Cenomanian age (110–93 Ma), while the Khakarin–Enmyvaam epicontinental volcanic belt superimposed on the OCVB originated in the Santonian–early Campanian time (85–78 Ma). ^{40}Ar/^{39}Ar dates have not been regarded as more confident and all Ar–Ar dates were considered as resulting from later isotopic system reset.

Some of the above statements seem deserving criticism. First, the reversed isochrons established by Hourigan and Akinin (2004) represent the direct evidence of radiogenic argon excess in monomineral fractions separated from the OCVB volcanics. Facts of this kind are not rare (Esser et al., 1997; Winick et al., 2001; Kelley et al., 2002), and it would be strange, in contrast, to think that a vast region incorporating ancient continental blocks could be lacking the ^{40}Ar excess. Second, rocks collected for the Ar–Ar dating are free of signs of meaningful epigenetic alterations and even retain fresh volcanic glass sometimes (Ispolatov et al., 2004). Provided that argon diffusion rate in sanidine is relatively low (Dodson, 1973), one can hardly expect resetting of Ar isotopic system in this mineral, when coexisting glass, the metastable phase, is preserved. Third, data of incremental heating imply an insignificant ^{40}Ar loss for most analyzed samples (Kelley et al., 1999; Hourigan and Akinin, 2004). A complete loss of radiogenic components from sanidine and amphibole is usually a consequence of regional metamorphism (under greenschist grade not lower) or of contact influence of plutons (Faure, 1989). In this case, composition and optical properties of the minerals should be changed, but none of the samples subjected to Ar–Ar dating reveals

Table 1. Correlation scheme of paleofloras from Northeast Asia (abridged after Kotlyar and Rusakova, 2004, and coordinated with geochronological scale by Gradstein et al., 1994)

Epoch	Age	Time	Age, Ma	*Resolutions...*, 1978	*stratoflora*, Samylina (1986, 1987, 1988)		*flora*, *assemblage*, Belyi (1988)		*flora*, Belyi (1994, 1997)		*flora*, Belyi (2001, 2003)		*flora*, *assemblage*, Lebedev (1987)			*assemblage*, Filippova and Abramova (1993)	*assemblage* Filippova (1997)		*taphoflora*, *stratoflora*, Shchepetov (1991, 1992)				*horizon*, Shchepetov (1995)		*stage*, *flora*, *horizon*, Herman (1999)		
Late Cretaceous	Maastrichtian		67									Rarytkin				Rarytkin		Koryak, Gornaya Rechka						Gornaya Rechka	Koryak	Koryak, Rarytkin	
			68																								
			69								Koryak														Gornaya Rechka		
			70									Gornaya Rechka					Mygdykit	Barykov					Khurenda Arkagala, Grebenka, Penzhina, Barykov, Chauna)				
			71																								
	Campanian		72													Barykov											
			73																								
			74																								
			75																								
			76										Murgal	Ust-Emuneret	Delokachan												
			77																								
			78																						Barykov	Barykov	Ust-Emuneret, Ol, Arkagala
			79																								
			80								Barykov		Ayanka														
			81																								
			82																								
			83								? Arkagala (Yst-Emuneret, Ayanka, Murgal, Delokachan, Dukchanda, etc.)																
	Santonian		84	Tyl’pegyrginai						Arkagala						Anadyr	Arkagala, Ola	Anadyr								Valizhgen	
			85																								
	Coniacian		86		Valizhgen								Kuiviken	Ketanda		Tyl’pegyrgynai	Leurerveem	Tyl’pegyrgynai	Chingandzha				Elan (Arman, Chauna, Grebenka, Penzhina, Kaivayam)		Kaivayam (Tyl’pegyrgynai)	Chauna	
			87																								
			88																								Chingandzha
			89																								
	Turonian		90	Grebenka												Arkagala	Chauna, Amgen	Penzhina, Ekityki							Penzhina (Chineiveem)		
			91																								
			92		Grebenka		Grebenka (Delokachan)		? Grebenka, Valizhgen, Chingandzha				Kholokhovchan	Dukchanda (Grebenka)		Chauna				Palyavaam (Chauna, Arkagala)	Grebenka				Grebenka (Grebenka, Eliseevo, Middle Ginter)	Arman, Amka	
			93																								
	Cenomanian	late	94	Arkagala												Grebenka and Arman	Arman	Grebenka									
		middle	95		Arkagala						Amka (Okonaito, Eropol, Alik, etc.)		Eropol	2	Amka												
			96																Alik, Teukich								
		early	97	Arman									Okontai	3								Eliseevo					
			98										Oklan	4			Nyrvakinot, Barandzha								Early Ginter		
Early Cretaceous	Albian	late	99		Arman	Chauna	1			Chauna	Arman, Chauna (Arind, Chingandzha, etc.)			5		Toptan											
			100						? Arman																		
			101				Arman (Kholokhovchan)	Chauna											Zora							Buor-Kemyus, Toptan	
			102	Toptan													Toptan										
			103													Buor-Kemyus	Omsukchan		Toptan								
		middle	104	Buor-Kemyus	Toptan				Buor-Kemyus		Buor-Kemyus (Emanra, Toptan, Omsukchan, Barandzha)		Vilyuikin	Emanrin									Omsukchan (Silyap, Buor-Kemyus, Toptan)				
			105				Toptan																				
			106																								
		early	107		Buor-Kemyus		Buor-Kemyus						Buor-Kemyus	Yadra					Buor-Kemyus								
			108																								
			109																								
			110																								
			111																								
	Aptian		112	Silyap	Silyap														Силяпская								
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			114																								
			115																								
			116				? Silyap																				
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Note: (1) Arkagala (Ust-Emuneret, Ayanka), (2) Gyrbykan (Arkagala), (3) Ust-Amka, (4) Uenmin and (5) Arinda (Arman, Barandzha) floral assemblages.

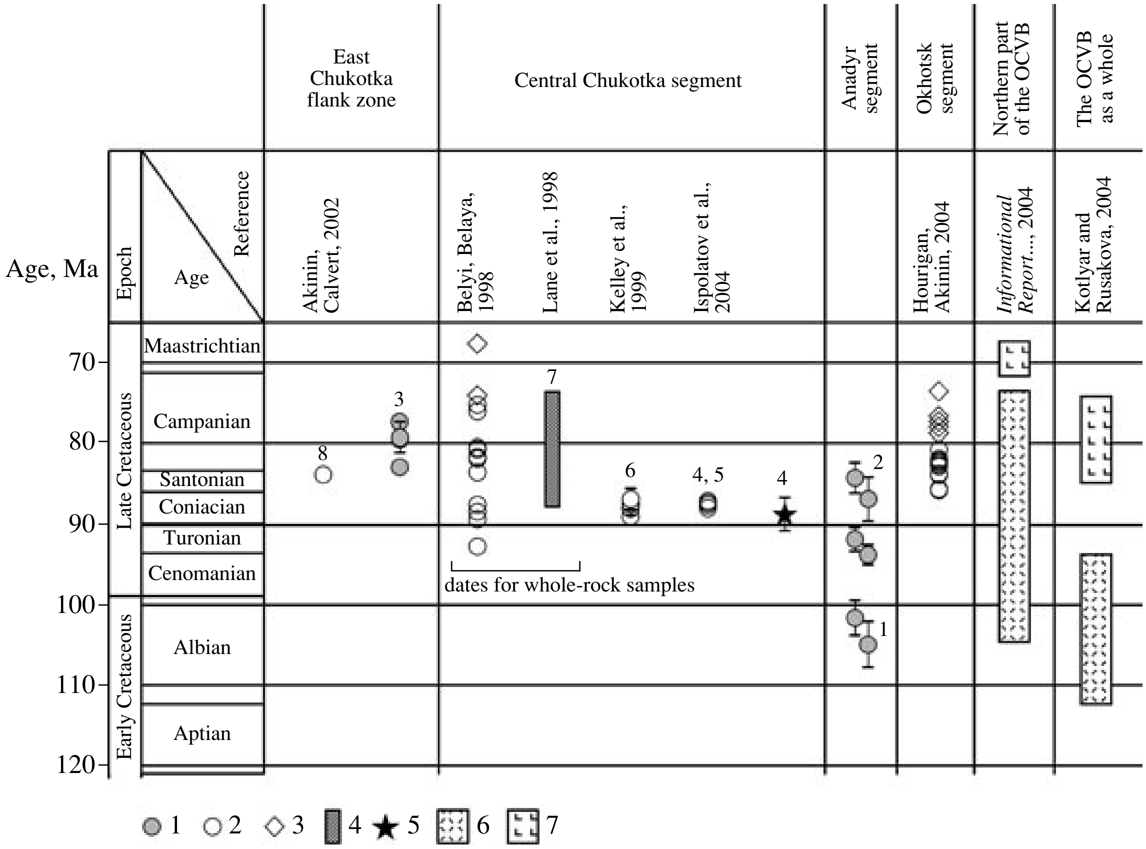

Fig. 2. Ar–Ar and U–Pb dates for igneous rocks of the OCVB and late plateau basalts: (1) Ar–Ar dates first presented in this work; (2, 3) Ar–Ar dates known formerly for OCVB volcanics (2) and late plateau basalts (3); (4) interval of Ar–Ar ages for OCVB volcanics without indicated concrete dates and analytical uncertainty (after Lane et al., 1998); (5) U–Pb date; (6, 7) formation periods of the OCVB (6) and late plateau basalts (7) according to viewpoints of different researchers (data points are numbered as sampling sites in Fig. 1, and 2σ uncertainty bars are shown, when they are greater than 1 m.y.).

expectable changes. Fourth, correctness of Ar–Ar dating is proved by data of U–Pb geochronology (Moll-Stalcup et al., 1995; Luchitskaya et al., 2003; this work). The closure temperature of zircon isotopic system is about 900°C (Dahl, 1997), and one can hardly expect the isotopic system resetting, when rocks retain fresh appearance. The above arguments are more convincing, as we think, than statements of Kotlyar and Rusakova. Consequently, an alternative geochronological model of the OCVB should be based primarily on ^{40}Ar/^{39}Ar and U–Pb dates.

^{40}Ar/^{39}Ar and U–Pb Geochronology Review of Published Results

At present, there are known 54 ^{40}Ar/^{39}Ar dates published for the OCVB volcanics (15 samples from the Okhotsk segment; 38 from the CCS, and one from the East Chukotka flank zone). Seven age determinations characterize the late plateau basalts of the Mygdykit and Enmyvaam formations (Okhotsk segment and CCS, respectively), but these rocks do not belong to the OCVB (Fig. 2), and 12 determinations are performed for igneous rocks of the Taigonos Peninsula (Bondarenko et al., 1999), the OCVB affinity of which is uncertain (Nekrasov, 1976).[3] Two ^{40}Ar/^{39}Ar dates are also known for granitoids of the Magadan batholith in inner zone of the Okhotsk segment (Farrar, 1992). In total, 36 of 75 mentioned dates are obtained for whole-rock samples. As compared to results obtained for monomineral fractions, they reveal a wider distribution range (Fig. 2) thus being of a lower precision and confidence. Ar–Ar ages characterizing sanidine, amphibole, biotite and plagioclase fractions from volcanic rocks of the OCVB range from 82 to 89 Ma (Coniacian–Campanian). Basalts of the Mygdykit Formation dated at 77–74 Ma (late Campanian) originated 4 to 6 m.y. later, and this implies that they have no genetic relations with the OCVB. Granitoids of the Magadan, East Taigonos and Coastal Taigonos massifs are older, corresponding in age to the late Albian (100–103 Ma). As bearing of these plutons on the OCVB geological history is unclear, the relevant dates cannot be used at present in the belt geochronological model. According

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[3] Dates for hydrothermal and metasomatic rocks are omitted from consideration.

Table 2. Brief characterization of samples and their ages

Sample no.	Rock	Geological body	Locality	Formation/complex	Isotopic age, Ma
03-137*	Amphibole andesite	Lava flow of unknown thickness	Upper reaches of the Pravyi Chimchemimyl River; lat. 66°20′44.60″ N, long. 167°30′58.40″ E	Salamikha (upper Albian)	104.9 ± 2.9 (amphibole) 101.6 ± 2.3 (plagioclase)
03-10*	Amphibole dacite	Lava flow 20–25 m thick	Mechkereva–Malyi Anyui watershed; lat. 66°48′55.57″ N, long. 169°35′26.06″ E	Pykarvaam (Turonian)	84.2 ± 1.9 (amphibole)
03-11*	Rhyolite tuff, crystal-vitric	Bed 5–7 m thick	The same locality; lat. 66°50′03.62″ N, long. 169°44′39.89″ E	Pykarvaam (Turonian)	93.7 ± 1.2 (amphibole) 91.8 ± 1.6 (plagioclase)
03-12*	Olivine basalt	Lava flow 8–10 m thick	The same locality; lat. 66°50′22.99″ N, long. 169°45′56.30″ E	Emuneret (Coniacian–Campanian)	86.8 ± 2.7 (plagioclase)
2403a*	Granodiorite	Tanyurer pluton, main intrusive phase	Upper reaches of the Tanyurer River, right bank; lat. 66°56′30.38″ N, long. 176°48′21.31″ E	Leurvaam (Turonian–Coniacian	79.2 ± 1.9 (amphibole) 82.9 ± 0.7 (biotite)
2465a*	Quartz diorite	Ditto	The same locality; lat. 66°51′47.29″ N, long. 176°55′14.77″ E	Leurvaam (Turonian–Coniacian	79.7 ± 0.4 (biotite) 77.3 ± 0.4 (plagioclase)
2584/460**	Rhyolite	Lava flow of unknown thickness	Upper reaches of the Etchikun River; lat. 68°40′15″ N, long. 174°28′30″ E	Kytapkai (Albian)	88.6 ± 2.1 (zircon)

Notes: (*) ^{40}Ar/^{39}Ar dating; (**) SHRIMP U-PB dating; ages of subdivisions are quoted from the legend to geological map, scale 1 : 5000000 (*Informational Report…*, 2004).

to other Ar–Ar dates under consideration, the period of active eruptions was not longer than 7 m.y. all over the OCVB and than 4 m.y. in separate segments. Both time spans are considerably shorter than those accepted in existing stratigraphic schemes (Table 1, Fig. 2). In some sections, which are as thick as 3–4 km, time span between early and late eruptions is about 1 m.y. only (Ispolatov et al., 2004). The oldest age values obtained for monomineral fractions correspond to the Coniacian Age, although most samples have been collected near the base of volcanogenic sequences. Accordingly, the greatest age discordance up to 17–18 m.y. is obvious for the lower stratigraphic subdivisions of the OCVB.

Ar–Ar ages of whole-rock samples are comparable in general with dates obtained for monomineral fractions, being of a wider range, however (92 to 67 Ma), that is natural, since capability of particular minerals to retain radiogenic argon is different. It is especially difficult to estimate the retentivity extent of isotopic systems in groundmass of volcanic rocks (Koppers et al., 2000). The Barremian age value of 123 Ma (Lane et al., 1998) has been obtained for sole basalt sample from the Cape Yakan at the Arctic coast (Fig. 1). Four samples of andesites and basaltic andesites collected at the same site (from Kytapkai and Notarelyan formations, presumably) yielded Ar–Ar age values of 76 to 87 Ma that is comparable with values characterizing other volcanic rocks of the OCVB.

Published U–Pb dates characterize silicic igneous rocks from two areas: (1) rhyolite (87 ± 2 Ma) of the Kytapkai Formation (?) from the Cape Yakan, the Arctic coast (Moll-Stalcup et al., 1995), and (2) granitoids of the East Taigonos (104.6 ± 1.1 to 97.0 ± 1.1 Ma) and Coastal Taigonos massifs (106.5 ± 0.9 to 105.5 ± 0.9 Ma). Discordance with results of Ar–Ar geochronology of volcanic rocks is below analytical uncertainty (1–2 m.y), being slightly greater (2–3 m.y.) for plutonic rocks. This can be explained by a relatively longer cooling of granitoid plutons and by difference between closure temperatures of U–Pb and K–Ar isotopic systems (Faure, 1989).

New Results

Six ^{40}Ar/^{39}Ar and one U–Pb dates were obtained in 2004 for igneous rocks from the OCVB northern part.

Selected samples. Samples for ^{40}Ar/^{39}Ar dating have been collected in three areas, two in the external zone of the Anadyr segment and one situated between the CCS and East Chukotka flank zone (Fig. 1). The sites sampled during fieldworks of 2002 and 2003 extend the former area of geochronological study and reduce deficiency of Ar–Ar dates. We selected six sam-

Table 3. Results of U-Pb zircon dating, rhyolite sample 2584/460, Kytapkai Formation, Etchikun River basin

Spot no.	^{206}Pb, %	U (ppm)	Th (ppm)	Th/U	^{238}U/^{206}Pb	^{207}Pb/^{206}Pb	Age, Ma
2584-1	–0.16	132	70	0.55	74.75 ± 1.34	0.0464 ± 0.0035	85.8 ± 1.4
2584-2	–0.23	254	106	0.43	71.17 ± 0.90	0.0460 ± 0.0026	90.2 ± 1.1
2584-3	0.20	419	225	0.55	73.28 ± 0.87	0.0493 ± 0.0020	87.2 ± 0.9
2584-5	0.39	392	182	0.48	72.09 ± 0.76	0.0508 ± 0.0020	88.5 ± 0.8
2584-6	0.04	283	158	0.58	70.70 ± 0.88	0.0482 ± 0.0024	90.5 ± 1.0
Average age = 88.6 ± 2.1 (2.4%) 95%. MSWD = 3.0, probability = 0.016.							

Note: Determinations are performed on high-resolution ion microprobe of reverse geometry SHRIMP RG at the Open Laboratory of Stanford University and US Geological Survey, analyst V.V. Akinin. Isotopic ratios have not been corrected for common lead. The ^{206}Pb/^{238}U ages are corrected for ^{207}Pb in accord with model by Stacey and Kramer (1975) and for measured ^{207}Pb/^{206}Pb, the monitor of common lead. Uncertainties are quoted at 1σ level.

ples of collected rocks appropriate for dating, containing magmatic amphibole, biotite and plagioclase with minimal signs of epigenetic alterations.

Four samples of volcanic rocks are from the Salamikha, Pykarvaam[4] and Emuneret formations of the Anadyr segment (Table 2). New ^{40}Ar/^{39}Ar dates are obtained for basal and uppermost stratigraphic units of the OCVB studied in the Mechkereva, Bol'shoi and Malyi Anyui river basins, the total area of which is over 7000 km^2.

The Tanyurer massif situated in the boundary zone between the *CCS* and *East Chukotka flank zone* is the other object of geochronological study. According to recent viewpoints, this is a large multiphase body consisting of the Murgal (Barremian–Aptian), Ekityki (Turonian), and Leurvaam (Turonian–Coniacian) plutonic complexes. Samples have been collected in northeastern area of the massif from the last complex that may enclose, however, the relic bodies of the Ekityki complex. Rocks of the massif range in composition from amphibole gabbro to leucogranite. Host rocks are represented by volcanics of the Amgen and Ekityki formations. We dated two samples of granodiorite and quartz diorite belonging to main intrusive phase of the Tanyurer pluton.

The U–Pb dating is carried out for zircons separated from cenotypal rhyolite of the Kytapkai Formation (Etchikun River basin, Central Chukotka, Fig. 1). As is established earlier, ^{40}Ar/^{39}Ar age of sanidine from the same sample is 87.25 ± 0.21 Ma (Ispolatov et al., 2004), while the Rb–Sr isochron age of volcanic rocks from the Kytapkai Formation is much older, corresponding to 104 ± 3 Ma (Kotlyar and Rusakova, 2004). Accordingly, U–Pb dating was aimed at precise assessment of the rock age and validity of results obtained by different methods.

Analytical Methods

^{40}Ar/^{39}Ar dating. After screening from crushed sample, rock fraction 90–200 μm in size was cleaned in ultrasonic bath and washed repeatedly in alcohol and deionized water. Mineral grains (20 to 30 per each phase) have been picked up by hand under binocular microscope. From four samples, we managed to separate different K-minerals, two per each, and obtained 10 phases in total for Ar–Ar age determination (Fig. 3). Wrapped into aluminum foil and placed into aluminum container, monomineral fractions and monitor (interlaboratory standard MAC-83 biotite, age 24.36 ± 0.17 Ma, Sandeman et al., 1999) were irradiated by fast neutrons during 40 hours in nuclear reactor at the McMaster University, Ontario, Canada. Interval between standard samples in container was 1 cm. Parameters J, which are calculated per each sample by the second-order polynomial interpolation of values measured for standards, are within the interval of 0.0034–0.0038. The ion argon laser Lexel 3500 was used to melt the monitor grain and to heat incrementally the analyzed phases. During heating periods 3 min long, radiant flux increased from 1 to 8 W. After 5 min of cleaning in gas collector SAES C50, extracted argon was analyzed on mass spectrometer MAP 216. Blank before each measurement was not greater than 10^{-12} cm^3 for ^{40}Ar and 0.5×10^{-13} for ^{39}Ar, ^{37}Ar and ^{36}Ar, and these values were subtracted from experimental results. The measured isotopic ratios were extrapolated for time of gas residence in mass spectrometer. Calculations are corrected for presence of atmospheric argon (measured ^{40}Ar/^{36}Ar) and for ^{40}Ar, ^{39}Ar and ^{36}Ar originated by nuclear transformations of potassium, calcium and chlorine (Onstott and Peacock, 1987; Roddick, 1983). Age values are calculated using decay constant recommended by Steiger and Jager (1977). Plateau ages are determined on results of three successive heating stages at least, when age values with 1σ difference characterized not less than a half of extracted ^{39}Ar. For the only case of age calculation based on two heating stages (sample 03-10, Fig. 3), we use term "pseudoplateau" in this work.

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[4] We are not sure in affinity of sampled volcanic horizon with the Pykarvaam Formation, because its stratotype is situated in neighboring segment of the OCVB approximately 200 km away to the northeast from sampling site.

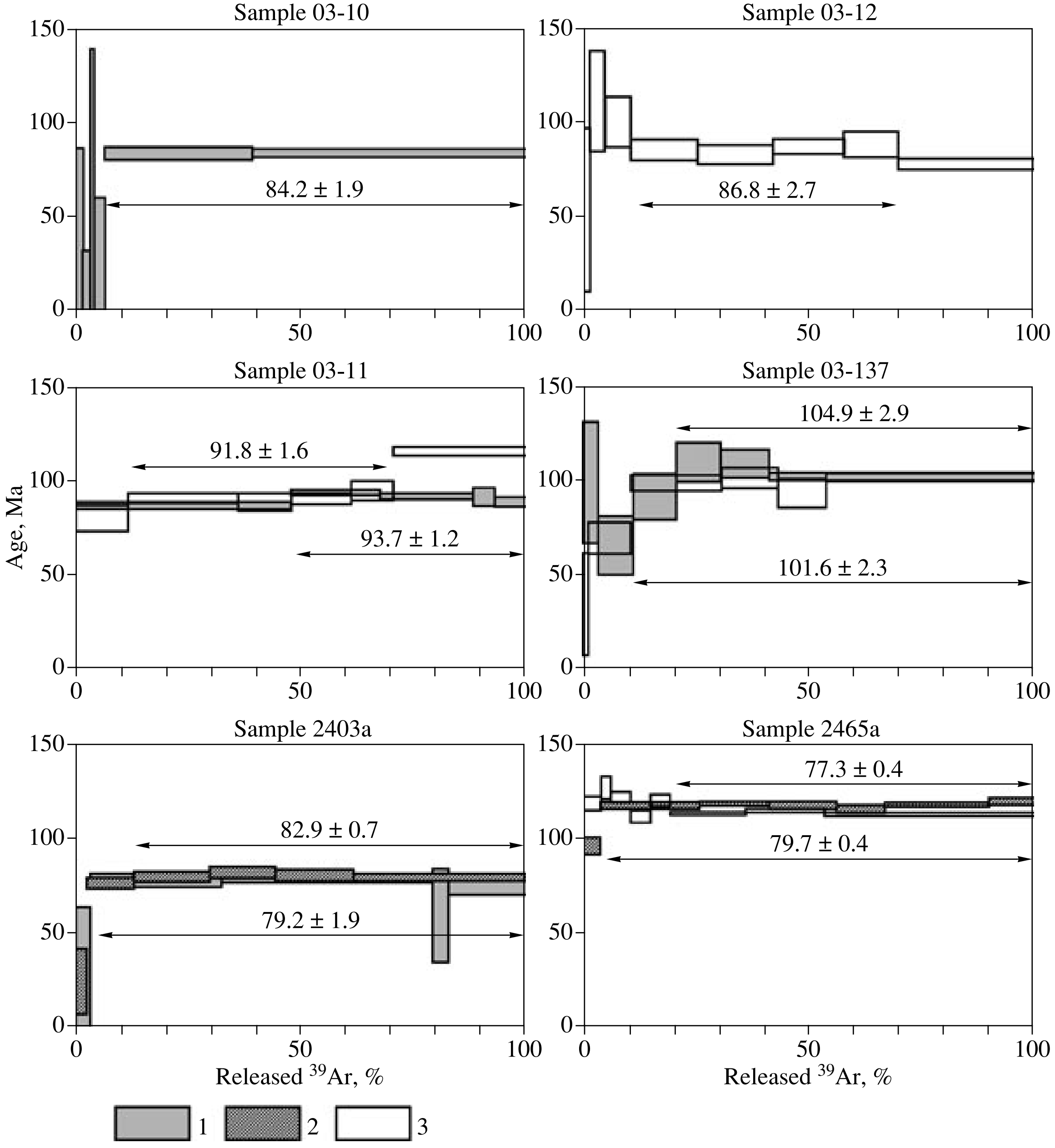

Fig. 3. Diagrams of plateau ages estimated by incremental heating of monomineral fractions of amphibole (1), biotite (2) and plagioclase (3); determinations are performed on mass spectrometer MAP 216 in Laboratory of Ar–Ar Geochronology, Queen's University, Kingston, Canada (analyst P. Alexander).

U–Pb dating. Zircon crystals were extracted from hand-crushed samples by the standard method of mineral separation in heavy liquid. Separated zircon grains and standards jointly mounted in superpure epoxy resin were polished and coated by evaporated gold. Microscopic examination of zircons was aimed at determination of crystal areas without inclusions and fissures, which are most appropriate for the ion microprobe dating. Then polished section of crystals was examined under scanning electron microscope JEOL JSM 5600 in cathodoluminescence regime in order to reveal inner structure and zoning of individual grains (Fig. 4A).

Dating of zircons was carried out on ion microprobe of reverse geometry SHRIMP RG at the Open Laboratory of Stanford University and US Geological Survey. Procedure of ion microprobe analysis was similar to that practicing at the National University of Australia for SHRIMP II (Compston et al., 1984; Williams, 1998), but SHRIMP RG microprobe is of a higher mass resolution at the given sensitivity. Resultant emission of ions was induced by beam of oxygen ions focused on spots 25 to 30 μm in diameter of analyzed crystals. Each analytical cycle consisted of five measurements. According to protocol, measurements on standards were carried out after each third or fourth measurement on zircon crystal under analysis in order to maintain well the U/Pb calibration during working shift. Standard CZ3 was used to determine U and Th concentrations. Other details of analytical procedure have been described earlier (Akinin et al., 2004) and can be found out at the Open Laboratory web site. Measurement results are processed using programs SQUID 1.02 and ISOPLOT 2.49 (Ludwig, 2001).

Dating results are presented in Tables 2, 3, and in Figs. 2 and 3B. As one can see in Fig. 3, plateau ages of samples dated by $^{40}Ar/^{39}Ar$ method are determined by averaging 52 to 95% (80% in most cases) of total argon released by incremental heating. The only exception is Sample 03-10 that released argon with constant $^{40}Ar/^{39}Ar$ ratio during two but not three heating stages as is required. Nevertheless, gas release of these two stages represents 90% of total argon, and there is no risk to regard the relevant pseudoplateau as corresponding to the time of isotopic system closure. For most samples, the relative analytical uncertainty corresponds to 0.5–1%, being somewhat greater (2–3%) for basalt and andesite samples (nos. 03-12 and 03-137) that is related to lower concentrations of potassium and, respectively, of radiogenic Ar in these rocks. The results obtained for different minerals from the same sample are close within the 2σ uncertainty. Minor deviations within the plateau intervals, which are probably caused by insignificant secondary alterations of rocks, do not influence significantly the validity of dating results. In subsequent discussion, we consider first of all the results of dating amphibole, as they are almost as confident as sanidine dates according to common opinion.

Zircon crystals from Sample 2584/460, which have been dated by U–Pb method, are of uniform morphology and internal zoning. These pale pink crystals of prismatic and pyramidal habit with even faces range in size from 50 to 200 μm; aspect ratio from 1 : 2 to 1 : 5. Under cathodoluminescence, there is visible fine oscillatory zoning of crystal rims and sectorial structure penetrating into crystal core and reflecting presumably the heterogeneous distribution of U and Th (Fig. 4A). Isotopic age is measured in cores of five individual crystals, U concentration in which ranges from 132 to 419 ppm; U/Th ratio from 0.43 to 0.58. According to composition and structural features, zircon crystals are of magmatic origin; population of xenogenous grains is absent. Being plotted on Tera–Wasserburg diagram, all data points characterizing the analyzed crystals yield concordant age values.

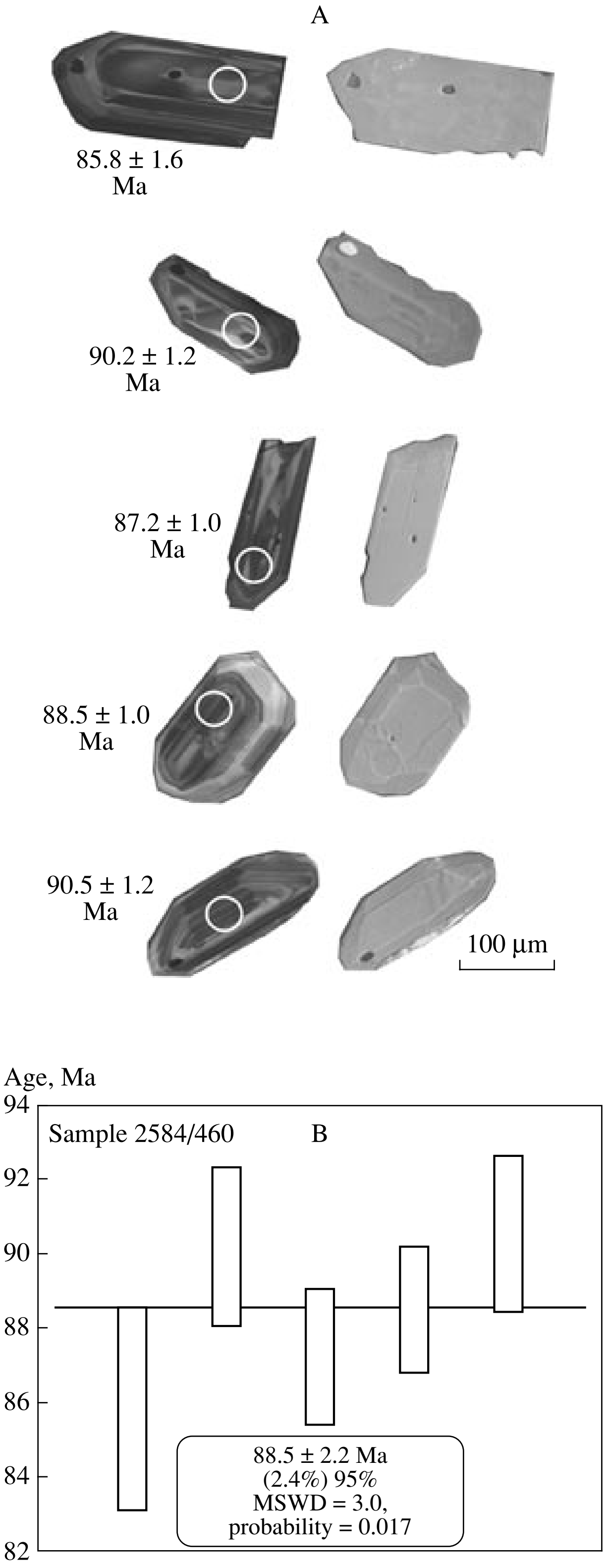

Fig. 4. Cathodoluminescence images of zircon crystals (A) from Sample 2584/460 shot under scanning electron microscope JEOL JSM 5600 (white circles denote spots numbered as in Table 3, which are analyzed by U–Pb SHRIMP method) and weighted average of estimated ages (B); height of rectangles corresponds to 2σ value.

DISCUSSION

Amphibole from andesite of the Salamikha Formation, Pravyi Chimchemimyl River basin, is dated at 104.9 ± 2.9 Ma. This date is well consistent with the late Albian age suggested for the formation, being simultaneously beyond the age interval of 89–92 Ma characterizing all the ^{40}Ar/^{39}Ar dates obtained earlier for monomineral fractions. In addition to universally accepted early–middle Albian age of the Buor-Kemyus flora collected from rocks of the Salamikha Formation, the date obtain discredits the opinion that the OCVB as a whole is of considerably younger Coniacian–Campanian age (Ispolatov et al., 2004; Hourigan and Akinin, 2004). On the other hand, the Albian volcanics could be related in origin not with the OCVB but with older structures of the Late Jurassic–early Cretaceous time, which developed in active margins of the Paleopacific and South Anyui oceanic basins (Parfenov et al., 1999). When discussing this issue, it is necessary to keep in mind several facts. First, rocks of differentiated volcanogenic series are present in the Aptian–Albian molasse (*Informational Report*…, 2004). Second, Early Cretaceous volcanics of the Kremyanka sequence, Tytyl'vaam and Etchikun formations, the units not belonging to the OCVB, are predominantly of andesitic composition that is characteristic of suprasubduction setting to a greater extent than of the rift structures. Third, deposits of the Albian Salamikha Formation fill in troughs of sublatitudinal and northwestern orientation, i.e., arranged so as to conform to strike of late Jurassic–Early Cretaceous structures and discordant relative to the OCVB strike (Fig. 1; *Informational Report*…, 2004). A comprehensive geochemical study of volcanics may contribute to solution of this problem.

Along with the Buor-Kemyus flora age (Belyi, 1994) and Ar–Ar and U–Pb dates of granitoids in the Taigonos Peninsula (Bondarenko et al., 1999; Luchitskaya et al., 2003) and Magadan Batholith (Farrar, 1992), new results leave no doubt with respect to the Albian pulse of magmatic activity within the OCVB. Nevertheless, Ar–Ar and U–Pb dates remain unknown for geochronological interval from 102 to 94 Ma (Fig. 2). Further works should elucidate whether this is a consequence of insufficient sampling of volcanic succession, or there were two separate tectonomagmatic events. If a considerable time gap in volcanic activity is the case, it is necessary to determine connection of Albian magmatic events with either the OCVB formation, or the terminal stage in evolution of Late Jurassic–Early Cretaceous subduction systems.

Age values of 93.7 ± 1.2 (Cenomanian) and 84.2 ± 1.9 Ma (Santonian) are obtained for amphiboles from volcanics of the Pykarvaam Formation. Between the sampled levels, there is no visible evidence for the break in eruptions 10 m.y. long, because only thin (a few meters) interlayers of volcaniclastic sandstones and gravelstones are observable in the section. Moreover, the Ar–Ar age of olivine basalts, which overlap all other volcanics and correspond to the "late plateau basalts" of rifting stage, is 86.8 ± 2.7 Ma, i.e., coinciding with the last of above dates characterizing sample that has been collected from the lower horizon of section. These geochronological relations are inconsistent with post-subduction origin suggested for the upper basalts, which could be produced instead in a rear extension zone behind the active continental volcanic arc. It is possible to suggest therefore that some "late plateau basalts" distinguished in other segments of the OCVB originated in the same tectonic environments.

Amphiboles from granodiorites of the Tanyurer massif yielded the Ar–Ar age of 79.2 ± 1.9 Ma. This value is between the established "biotite" (82.9 ± 0.7 and 79.7 ± 0.4 Ma) and "plagioclase" (77.3 ± 0.4 Ma) dates. According to geochronological scale (Harland et al., 1990), all the dates correspond to the Campanian, being quite consistent with the only Ar–Ar date of 84 ± 1 Ma published for volcanic rocks of the East Chukotka flank zone (Akinin and Calvert, 2002). Thus, the results of ^{40}Ar/^{39}Ar dating the monomineral fractions show first that the upper age limit of the OCVB is younger than it was thought before, corresponding to the middle of Campanian Age at least. Second, they suggest that volcanic activity migrated eastward in the OCVB northern part, along its strike (Fig. 1), because the time gap between terminal magmatic events in two areas under consideration was 5 m.y. long, not less.

The established U–Pb age of zircons from rhyolitic ignimbrites of the Kytapkai Formation is 88.5 ± 2.1 Ma (MSWD = 3), comparable within the analytical uncertainty with results of ^{40}Ar/^{39}Ar dating carried out earlier. The U–Pb date proves once more the relatively young, Coniacian age of lower stratigraphic units in the CCS. This is consistent with silicic-to-basic succession of volcanic eruptions in the CCS: basal sequences composed here mostly of ignimbrites are age analogues of Senonian OCVB sequences, which include considerable volumes of silicic volcanic rocks, but not of the Albian, predominantly andesitic volcanics. Intensity of relevant eruptions is also remarkable: the volcanic sequence up to 3 or 4 km thick (probably thicker in places) and not less than 160 000 km^3 in volume (Kotlyar et al., 1981) was erupted in a relatively short period 1–2 m.y. long.

Thus, the results obtained are consistent in general with paleobotanical data and observable relations between geological bodies. Consequently, the ^{40}Ar/^{39}Ar dates and results of U–Pb SHRIMP dating represent a reliable database for the OCVB geochronological model.

CONCLUSIONS

1. New results of Ar–Ar dating prove the Albian age of volcanics attributed to the Salamikha Formation (external zone in the Anadyr segment of the OCVB), although it is admissible that this stratigraphic subdivi-

sion was related in origin with older structures of continental margin rather than with the OCVB proper.

2. Volcanogenic sequences observable in the Central Chukotka segment of the OCVB accumulated during a short period 1–2 m.y. long only, beginning since the Coniacian Age, i.e., 15–20 m.y. later than it was thought before.

3. Volcanic activity in external zone of the Anadyr segment ceased earlier by 5 m.y. at least than in the East Chukotka flank zone.

4. Results of U–Pb zircon dating (SHRIMP method) and ^{40}Ar/^{39}Ar age determinations for monomineral fractions, primarily for sanidine and amphibole, represent most reliable database for the OCVB geochronological model and, perhaps, for the other Mesozoic–Cenozoic belts of continental volcanism.

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