GEOLOGICAL NOTE

New $^{40}Ar/^{39}Ar$ Ages of Cretaceous Continental Volcanics from Central Chukotka: Implications for Initiation and Duration of Volcanism within the Northern Part of the Okhotsk Chukotka Volcanic Belt (Northeastern Eurasia)

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ABSTRACT

We used the single-crystal sanidine laser fusion $^{40}Ar/^{39}Ar$ method to date five samples of volcanic rocks from the northern (Chukotka) part of the Cretaceous Okhotsk-Chukotka volcanic belt (northeastern Eurasia). Ages of four samples from lowermost stratigraphic units range from 87.94 to 87.08 Ma, and one sample from the top of the section shows the age of 87.55 Ma. New results combined with previously published $^{40}Ar/^{39}Ar$ data indicate that volcanism within the northern part of the belt started in Coniacian time, at ca. 88 Ma, and was very short-lived (ca. 1–6 m.yr.).

Online enhancement: table.

Introduction

The Okhotsk-Chukotka volcanic belt (OCVB) is located in northeastern Eurasia (fig. 1). Extending for ca. 3200 km and comprising roughly 1.2 million km^3 volcanic and associated plutonic rocks (Belyi 1994), the OCVB is among the largest subduction-related volcanic provinces of the planet. At present, geochronology of the OCVB is uncertain; this obstructs development of efficient stratigraphic models and severely impairs understanding of Mesozoic evolution of northeastern Eurasia and the entire Circum-Pacific system. Our study provides new data on timing of initiation and duration of large-volume eruptions within the northern (Chukotka) segment of the OCVB (central Chukotka area). Primary focus is placed on the oldest volcanic units that were not previously characterized by the $^{40}Ar/^{39}Ar$ method. We recognize that five new $^{40}Ar/^{39}Ar$ dates reported in this short article are insufficient to unequivocally constrain the age of this continental-scale volcanic province. Thus, we refrain from drawing fundamental conclusions or extrapolating our results over the entire volcanic belt. Rather than that, we intend to highlight the problem of the OCVB geochronology and stimulate new discussions and studies in this area.

Regional Tectonic Background

The Cretaceous OCVB stretches along the southeastern margin of Mesozoic Verkhoyansk-Chukotka tectonic province and is sharply discordant to its structural trends (fig. 1). Volcanic rocks are undeformed and overlie Verkhoyansk-Chukotka Mesozoic structures with angular unconformity (Zonenshain et al. 1990; Sengör and Natal'in 1996). Compositionally, volcanics vary from basalts to rhyolites; intermediate and felsic rocks predomi-

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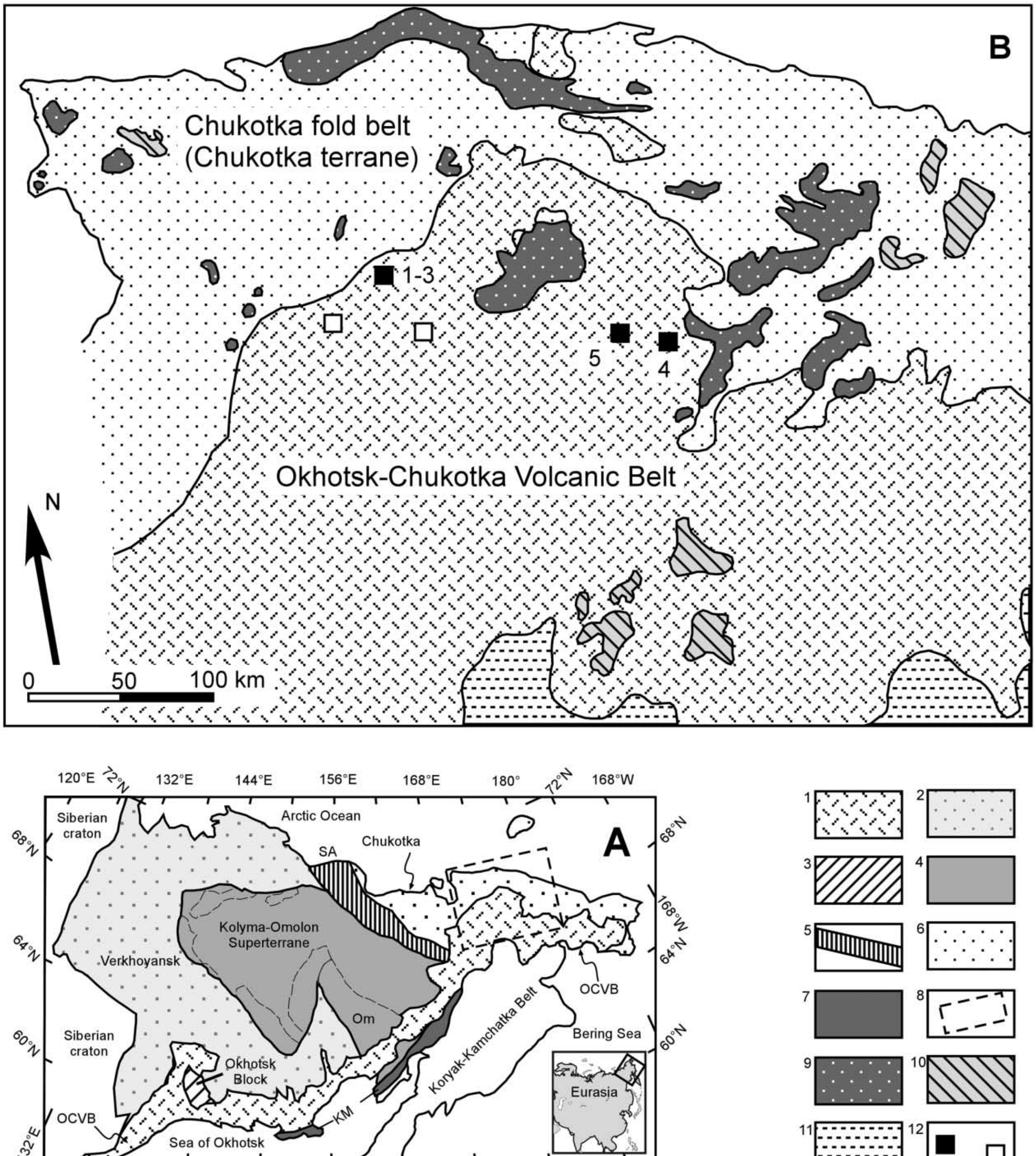

Figure 1. *A*, Tectonic setting of the Okhotsk-Chukotka volcanic belt. *B*, Location of samples in the northern (Chukotka) part of the belt. *1*, Okhotsk-Chukotka volcanic belt (*OCVB*). *2–7*, Verkhoyansk-Chukotka Mesozoides. *2*, Verkhoyansk fold belt: passive margin of the Siberian craton. *3*, Okhotsk cratonal block. *4*, Kolyma-Omolon Superterrane: tectonic collage of the Omolon cratonal block (*Om*), several passive continental margin terranes, and Late Paleozoic to Mesozoic (Early Cretaceous) magmatic arcs. *5*, South Anui suture zone (*SA*). *6*, Chukotka terrane: passive continental margin, predominantly carbonate Paleozoic and clastic Mesozoic rocks. *7*, Koni-Murgal volcanic belt: Triassic to Early Cretaceous island arcs. *8*, Area shown in *B*. *9*, *10*, Early and Late Cretaceous granitoids, respectively. *11*, Cenozoic clastic sediments. *12*, Sample locations: closed squares correspond to samples of this study (*1–3* correspond to the western sampling area, *4* and *5* represent the eastern area), open squares depict sample locations of Kelley et al. (1999). *A* compiled from Tilman and Bogdanov (1992), Layer et al. (2001), Nokleberg et al. (2001), and Zonenshain et al. (1990); *B* adapted from Nalivkin (1983).

nate (Kotlyar et al. 1981). In regional geodynamic evolution, volcanism postdated accretion of the Okhotsk block, Kolyma-Omolon Superterrane, and Chukotka terrane to the Verkhoyansk passive margin of the Siberian craton (fig. 1). This sequence of collisions terminated earlier island arc volcanism, caused deformations and emplacement of granitoids, and led to formation of composite Verkhoyansk-Chukotka orogen (Parfenov and Natal'in 1985, 1986; Parfenov 1991; Layer et al. 2001). Subaerial, chiefly explosive volcanism of the OCVB occurred afterward and was related to northward subduction of the Kula oceanic plate under the newly assembled tectonic collage (Parfenov and Natal'in 1986; Zonenshain et al. 1990; Zonenshain and Kuzmin 1992). The Verkhoyansk-Chukotka collided with the Okhotomorsk block, and the subduction zone shifted eastward (Parfenov and Natal'in 1986). As a consequence of these two events, the Andean-style volcanism ended. Temporal relationships of volcanism and major regional tectonic events make the OCVB an important geodynamic marker. Inauguration of volcanism constrains the upper time limit for Mesozoic consolidation of northeastern Eurasia. Lack of compressional deformations of volcanic rocks, their discordance to fold trends, and subaerial nature of volcanism indicate that by the time of onset of volcanic activity, collisional orogenesis within the Verkhoyansk-Chukotka province largely vanished, and the heterogeneous tectonic collage evolved into a coherent continental plate with the Andean-type margin. On a broader regional scale, the initiation of the OCVB manifests a major change in the tectonic framework of the Circum North Pacific and establishment of a nearly continuous continental-margin magmatic arc stretching from eastern Eurasia to Alaska and Canadian Cordillera. The OCVB constituted most of the Eurasian sector of this transcontinental arc system (Nokleberg et al. 2001). The termination of the OCVB volcanism is also important because it marks another significant plate rearrangement that involved major eastward shift of the subduction zone (Parfenov and Natal'in 1986).

Apart from geodynamic significance, the OCVB constitutes an important metallogenic province. The belt hosts several economic volcanism-related epithermal gold and silver systems such as Karamken, Dukat, and Valunistoe (Nokleberg et al. 1997). Other ore deposits, including a large Maiskoe-disseminated gold system (Nokleberg et al. 1997), are hosted in a Mesozoic folded complex along the inland margin of the OCVB and may also be related to the volcanism.

In spite of geodynamic and metallogenic importance of the OCVB, its geochronology remains a controversial subject. It has been accepted that the volcanism was broadly synchronous throughout the belt and lasted from the Albian (ca. 106–100 Ma) to the Campanian or even the Maastrichtian (ca. 83–70 Ma), that is, for ca. 20–35 m.yr. (Filatova 1988; Zonenshain et al. 1990; Belyi 1994; Kotlyar et al. 2001). Specifically in the northern (Chukotka) portion of the OCVB, the volcanism is believed to have occurred in two phases, ca. 106–97 Ma and ca. 94–82 Ma, with total duration of ca. 24 m.yr. (Belyi and Belaya 1998). However, these reconstructions are based mainly on phytostratigraphic correlations and whole-rock K-Ar and Rb-Sr dates that apparently cannot provide sufficiently robust time constraints. There is no universal agreement on the age of characteristic fossil floras; as a result, same "index" assemblages are assigned to different geologic ages by different authors (Lebedev 1987; Filatova 1988; Belyi and Belaya 1998; Kelley et al. 1999). K-Ar and Rb-Sr dates span from ca. 105 to ca. 60 Ma, generally have rather high uncertainties, and frequently disagree with directly observed stratigraphic relationships (Kotlyar et al. 2001).

The $^{40}Ar/^{39}Ar$ age determinations of OCVB volcanics are rather sparse (Belyi and Belaya 1998; Kelley et al. 1999; Akinin et al. 2000), but in contrast to K-Ar and Rb-Sr dates, they are more precise, show better internal consistency, and, in most cases, conform to field rock relationships. Reported ages fall into the 90–74 Ma interval, suggesting that volcanism could have started later and lasted less time than the traditional model implies. Perhaps partially due to a paucity of $^{40}Ar/^{39}Ar$ age determinations and the near lack of truly systematic studies, the validity of $^{40}Ar/^{39}Ar$ dates, especially their suitability for constraining initiation of volcanism, has not been universally recognized. A number of geologists disregard the $^{40}Ar/^{39}Ar$ ages as related to postdepositional isotopic resetting by some thermal events (Belyi 1994; Kotlyar et al. 2001). Also, the oldest units of the OCVB, especially in Chukotka area, were insufficiently characterized by the $^{40}Ar/^{39}Ar$ method, and thus the accepted Albian time of initiation of volcanism could not be confirmed or disapproved.

Sample Selection

We selected five samples from two areas in central Chukotka, ca. 170 km apart (i.e., comparable with the OCVB width; fig. 1). Samples 1–3 represent the western marginal portion of the OCVB where five well-stratified and laterally continuous large-volume volcanic units, Alkakvun, Kalenmuvaam, Pykarvaam, Voron'ina, and Koekvun Formations, are traditionally distinguished on a lithologic basis (fig. 2). These formations constitute the Chauna Group, which, according to the accepted geochronologic model, represents the early Albian-Cenomanian (ca. 106–97 Ma) phase of the evolution of the OCVB (Belyi and Belaya 1998). Kelley et al. (1999) challenged the accepted Albian-Cenomanian age of the upper portion of the Chauna Group by reporting $^{40}Ar/^{39}Ar$ ages ca. 88.7–87 Ma (i.e., Coniacian Age) for the Pykarvaam, Voron'ina, and Koekvun formations. The lower portion of the section was not characterized by the $^{40}Ar/^{39}Ar$ method, and although Kelley et al. (1999) suggested that lowermost formations are unlikely to be significantly older, there were no precise radiometric data to confirm this. Samples 1–3 analyzed in this study were collected from the Alkakvun Formation, the lowermost member of the Chauna Group.

The eastern sampling area, where we collected samples 4 and 5, is structurally more complex. It comprises several tightly clustered volcanic centers in proximity to which lithostratigraphic units tend to be laterally discontinuous and are strongly disrupted by caldera tectonics. A local stratigraphic model of the eastern area is constrained by results of geologic mapping; however, correlation to other stratigraphic complexes, including the Chauna Group, remains problematic. Several unpublished mutually conflicting correlation models exist, but due to the absence of robust regional stratigraphic markers and the lack of precise geochronologic data, reliability of these models appears questionable and is impossible to evaluate. For this reason, we show the setting of samples 4 and 5 with regard to local stratigraphic divisions that were used for geologic mapping (fig. 2). (V. O. Ispolatov and P. L. Tikhomirov participated in the mapping and attest to the reliability of the stratigraphic details.) These samples represent the lowermost and the uppermost stratigraphic units of the eastern area and thus, irrespective of correlation models, are appropriate for constraining timing of initiation and duration of volcanism for the corresponding part of the OCVB.

Samples selected for isotopic analysis contain microscopically pristine clear sanidine. As shown

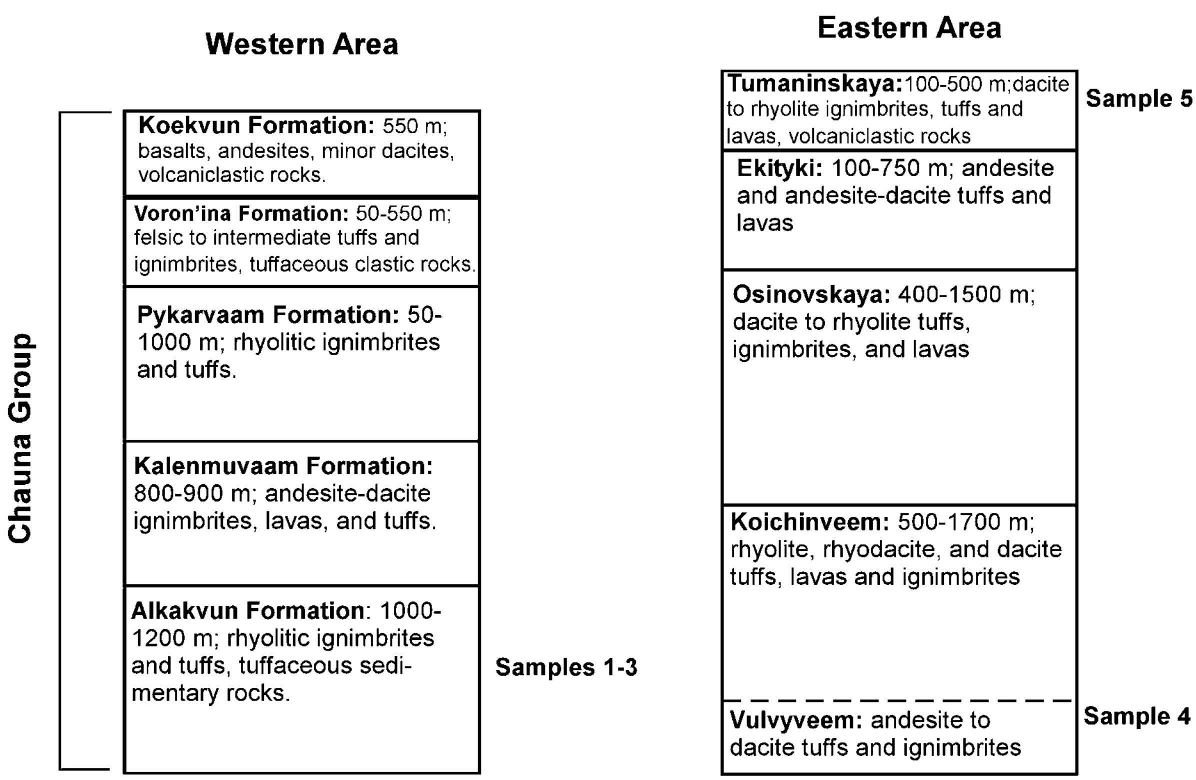

Figure 2. Stratigraphic setting of analyzed samples. Stratigraphic column of the western area is after Kelley et al. (1999). Names and descriptions of stratigraphic units of the eastern area are based on unpublished results of geologic mapping.

by several articles (Deino and Potts 1990; McIntosh et al. 1990; Walter 1994), sanidine is particularly suitable for high-resolution $^{40}Ar/^{39}Ar$ chronostratigraphic studies of volcanics because of high K content and reasonably good Ar retentivity (Zeitler 1987; McIntosh et al. 1990).

Analytical Technique

We used single-crystal laser fusion $^{40}Ar/^{39}Ar$ analysis capable of detecting multiple populations of crystals (Deino and Potts 1990, 1992). Sanidine grains were separated using standard magnetic, heavy liquid, and handpicking techniques. Concentrates were irradiated for 14 h in D-3 position at Nuclear Science Center, College Station, Texas. Fish Canyon Tuff sanidine (FC-1) with assigned age 27.84 Ma (Deino and Potts 1990), relative to hornblende Mmhb-1 at 520.4 Ma (Samson and Alexander 1987), was used as a neutron flux monitor. Irradiated samples were analyzed at New Mexico Geochronological Research Laboratory, New Mexico Institute of Mining and Technology, Socorro, New Mexico. Sanidine crystals were fused by a 50-W Synrad CO_2 laser in automated high-vacuum all-metal extraction system. Reactive gases were removed during a 2-min reaction with 2 SAES GP-50 getters operated at 450°C and 20°C. In addition, gas was exposed to a tungsten filament and cold finger operated at ca. 2000°C and −140°C, respectively. Ar isotope ratios were measured in Mass Analyzer Products 215–50 mass spectrometer, with electron multiplier sensitivity averaged 1.44×10^{-16} mol/pA. Typical all-system analytical blank and background values constituted 800, 5, 2, 3, and 8×10^{-18} mol for masses 40, 39, 38, 37, and 36, respectively. J-factors were determined to a precision of ±0.1% by CO_2 laser fusion of four single crystals from each of four radial positions around the irradiation tray. Correction factors for interfering nuclear reactions were determined using K-glass and CaF_2 and are listed in table 1 in the online edition of the *Journal of Geology* and are also available from the *Journal*'s Data Depository in the *Journal of Geology* office upon request.

Weighted mean ages were calculated using the inverse of variance as weighting factor. Errors of weighted mean ages were determined according to the method of Taylor (1982). In addition, the mean square of weighted deviates (MSWD) was calculated for $n - 1$ degrees of freedom (n represents number of single-crystal ages used for weighted mean age calculation). In cases when the MSWD fell outside the 95% confidence window for $n - 1$ degrees of freedom (cf. Mahon 1996), the errors were additionally multiplied by the square root of the MSWD. Decay constants and isotopic abundances used for age calculations are from Steiger and Jäger (1977). All final errors are reported at $\pm 2\sigma$. In addition to apparent ages, K : Ca ratios were estimated from measured $^{37}Ar/^{39}Ar$ ratios. These ratios were used to confirm K-feldspar composition of analyzed grains and to exclude results produced by accidentally present plagioclase crystals.

Results

Analytical results are summarized in figure 3, which depicts age probability diagrams plotted according to Deino and Potts (1992). Full analytical data are listed in table 1. Samples 1–3, from the western sampling area (Alkakvun Formation), yielded weighted mean ages (87.08 ± 0.21, 87.59 ± 0.53, and 87.25 ± 0.21 Ma) that are indistinguishable at 2σ. All three samples show rather uniform Gaussian distribution of ages (fig. 3). Outliers are sparse (1–3 per sample) and are distinct by K : Ca ratios below unity and high analytical errors. Assuming that these abnormal results probably represent plagioclase crystals, we excluded them from mean age calculations. Sample 4, from the lowermost volcanic unit of the eastern area, returned weighted mean age of 87.94 ± 0.32 Ma. Of 30 analyzed crystals, two returned low K : Ca ratios diagnostic of plagioclase composition, and one crystal with relatively high K : Ca ratio yielded an anomalously old age of ca. 90 Ma. Most probably this result was affected by excess ^{40}Ar or was produced by a xenocryst, perhaps of clastic or granitic K-feldspar. We excluded it from mean age calculations along with plagioclase results. Sample 5, from the youngest volcanic unit of the eastern sampling area, returned uniform age distribution with mean age 87.55 ± 0.21 Ma. One single-crystal age was disregarded due to low K : Ca ratio indicating plagioclase composition.

Discussion

Before geologic interpretation, the new data need to be evaluated for consistency with stratigraphic relationships, compatibility with earlier $^{40}Ar/^{39}Ar$ results, and the possibility of postdepositional isotopic disturbance. All five $^{40}Ar/^{39}Ar$ ages fall into a narrow interval between 87 and 88 Ma that corresponds to the Coniacian Age of the Cretaceous (we use the Mesozoic timescale of Gradstein et al. 1994 following Belyi and Belaya 1998 and Kelley et al. 1999). Within each sampling area, ages are indistinguishable at 2σ (fig. 4). Similarity of ages pro-

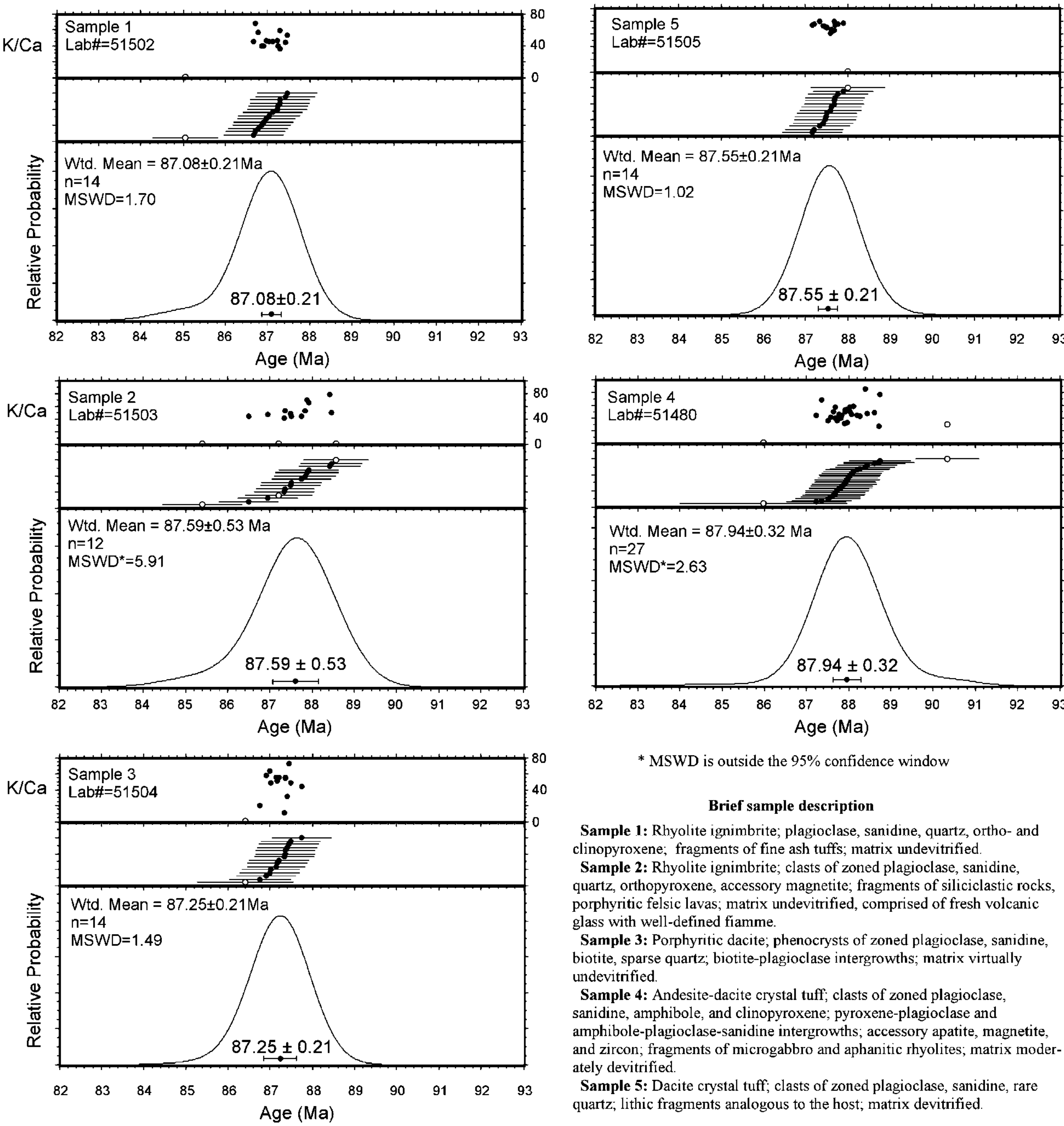

Figure 3. Age probability diagrams for five analyzed samples. Each plot comprises (from bottom to top) age probability distribution spectrum (ideogram; Deino and Potts 1992), distribution of individual single-crystal ages with 2σ errors, and K : Ca ratios estimated from measured $^{37}Ar/^{39}Ar$ ratios. Open circles depict analyses excluded from mean age calculation. Age probability distribution graphs incorporate all analyses. Weighted mean ages are reported with 2σ errors; *n* is the number of single-crystal analyses used for mean age calculation.

duced by samples 1, 2, and 3 is consistent with their origin from the same Alkakvun Formation. Samples 4 and 5, which represent, respectively, the base and the top of the volcanic section, also returned overlapping ages. Although somewhat unexpected, this relationship does not conflict with stratigraphic setting of the samples but more probably reflects very fast accumulation of the volcanic pile. New results agree with most of ages reported by Kelley et al. (1999), although strict comparison is

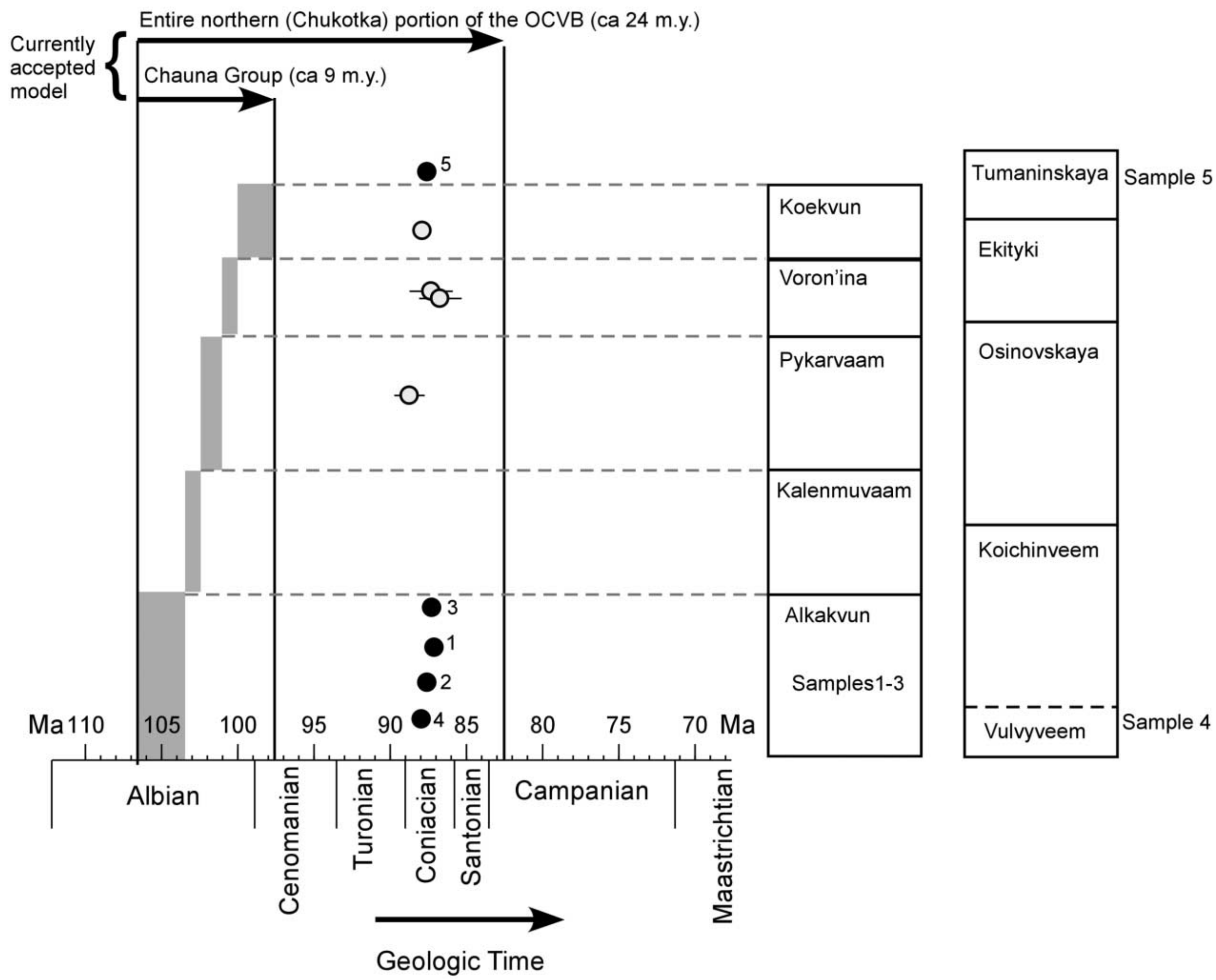

Figure 4. Comparison of new $^{40}Ar/^{39}Ar$ data (*filled circles*), results of Kelley et al. (1999; *gray circles*), and the cronostratigraphic model that is currently accepted for the northern portion of the Okhotsk-Chukotka volcanic belt (OCVB; after Belyi and Belaya 1998, fig. 29 therein). Error bars correspond to 2σ errors; where not shown, error values are smaller than the symbol size. Arrows depict duration of volcanism for the Chauna Group (early stage of the OCVB activity) and for the entire northern part of the belt as suggested by the currently accepted model (Belyi and Belaya 1998). Shaded rectangles depict traditionally accepted geologic ages of individual formations of the Chauna Group (Belyi and Belaya 1998). The timescale of the Cretaceous period is that of Gradstein et al. (1994). New data are consistent with results of Kelley et al. (1999), suggesting that the volcanism in Chukotka started later and ended sooner than is currently believed.

difficult due to larger analytical uncertainties of step-heating ages (fig. 4).

The postdepositional Ar loss appears generally improbable. Two of five analyzed samples contain fresh, undevitrified glass (fig. 3, sample descriptions) and thus are unlikely to have experienced any significant thermal events. However, samples with a devitrified matrix do not show systematically younger ages. Thus, even if the devitrification occurred at elevated temperatures, these temperatures were not sufficiently high for affecting Ar systematics, or perhaps devitrification took place during cooling immediately after emplacement of volcanics. Also, geology of sampling areas does not reveal evidence for potentially disturbing events, and resetting due to deep burial appears geologically unrealistic. The unlikelihood of regional-scale isotopic resetting is additionally supported by concordant step-heating age spectra produced by most samples in the study of Kelley et al. (1999). We believe that new $^{40}Ar/^{39}Ar$ ages are essentially undisturbed and approximate timing of emplacement of corresponding volcanic units.

The $^{40}Ar/^{39}Ar$ ages of samples 1–3 imply that Alkakvun Formation, the lowermost member of the Chauna Group, was formed at ca. 88–87 Ma. These results complement the $^{40}Ar/^{39}Ar$ data by Kelley et al. (1999), confirming that the entire Chauna Group erupted during Coniacian time at ca. 88–87 Ma. As suggested by $^{40}Ar/^{39}Ar$ ages of samples 4 and 5, previously poorly correlated volcanics in the central portion of the belt were formed at ca. 88–87 Ma and thus represent temporal equivalents of the Chauna Group.

Apart from significance for regional stratigraphy, the new data have important implications for geologic history of the volcanic belt and regional geotectonic evolution. First, new ages of the lowermost stratigraphic units of the OCVB (fig. 4, samples 1–4) comprise strong evidence that large-volume eruptions in the central Chukotka portion of the belt started in Coniacian time, at ca. 88 Ma, that is, ca. 18 m.yr. later than it has been previously believed (Belyi and Belaya 1998). The consistency of $^{40}Ar/^{39}Ar$ ages from locations ca. 170 km apart supports the regional nature of this pattern. Second, the new data combined with results of Kelley et al. (1999) provide information on the dynamics of the volcanism. In both western and central portions of the OCVB, the lower- and uppermost stratigraphic units yielded indistinguishable $^{40}Ar/^{39}Ar$ ages (fig. 4). This implies that the Chauna Group and its temporal equivalents to the east were erupted over a very short time interval (perhaps on the order of 1 m.yr.), that is, much faster than the traditional model assumes (Belyi and Belaya 1998; fig. 4). Similarly, this short span (and hence very high intensity) of volcanic activity is supported by consistent results from two geographically separated areas in central Chukotka and thus very likely reflects regional pattern. Even if the Chauna Group represents only the early phase of volcanism and the later phase ended at ca. 82 Ma (Belyi and Belaya 1998), the total duration of volcanic activity in the Chukotka portion of the OCVB would be ca. 6 m.yr. The Cretaceous subduction-related volcanism in Chukotka very likely comprised one or several short but very intense episodes rather than prolonged multistage evolution as it is presently believed.

Conclusion

New precise $^{40}Ar/^{39}Ar$ dates indicate that large-volume volcanism in the central Chukotka portion of the OCVB started in Coniacian time, at ca. 88 Ma. The activity was very short: lower- and uppermost stratigraphic units of sampled volcanic sequences yield indistinguishable $^{40}Ar/^{39}Ar$ ages. Accumulation of the voluminous volcanic pile over such a short time period indicates a very high intensity of volcanism.

This pattern significantly differs from the traditional geochronologic model that assumes the onset of volcanism in Albian time (ca. 106 Ma; Belyi and Belaya 1998) and 20–35-m.yr.-long evolution of the belt. Although we believe that new dates reliably reflect timing of volcanism in central Chukotka, we recognize that extrapolating revealed temporal patterns over other parts of the volcanic belt would be premature. The OCVB as a whole could be older and have more complex history with spatially scattered diachronous outbursts of volcanism, areas of longer duration of magmatic activity, or perhaps more systematic lateral migrations of magmatic loci. However, our results along with results of other $^{40}Ar/^{39}Ar$ studies imply that the traditional geochronologic model of the OCVB needs to be revised, and new systematic high-resolution geochronologic studies are necessary to restore geologic history of this continental-scale volcanic province.

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