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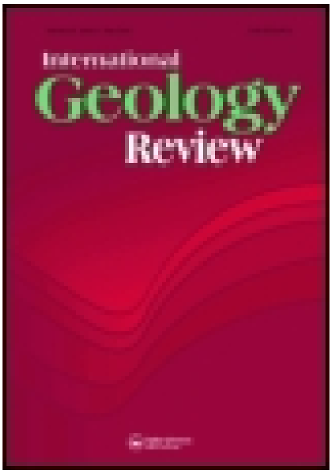

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Volcanic Pipes as Clues to Upper Mantle Petrogenesis: Mesozoic Ar-Ar Dating of the Minusinsk Basalts, South Siberia

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Volcanic Pipes as Clues to Upper Mantle Petrogenesis: Mesozoic Ar-Ar Dating of the Minusinsk Basalts, South Siberia

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Abstract

^{40}Ar/^{39}Ar dating of alkali basalt pipes and dikes of the North Minusinsk basin has provided an important chronologic framework for Altay-Sayan fold belt and Central Asia region. These Mesozoic basalt pipes have become the subject of special interest due to the abundant occurrence of garnet-spinel and spinel lherzolite xenoliths. These rocks reveal information about the composition, structure, and thermal state of the Mesozoic upper mantle beneath the southwestern margin of the Siberian craton. Our detailed ^{40}Ar/^{39}Ar dating has shown that the pipes and their related NW-trending dikes formed coevally, during a Late Cretaceous, short-time, magmatic impulse. Twelve plateau ages on feldspar megacryst and whole rocks between 72 ±2.7 and 79 ±2 Ma have been determined. Abundant E-W–trending dikes, previously though to be related to the Meso-Cenozoic subvolcanic complex, have a less alkaline composition, compared to the basanite pipes, with Early Permian ^{40}Ar/^{39}Ar ages. The trachyte NW-trending dikes yielded an Early Permian, whole-rock plateau age of 262 ±2.5 Ma. The trachybasalts of the North Minusinsk basin have a ^{40}Ar/^{39}Ar age of 392 ±11 Ma, i.e., Devonian.

Introduction

IT HAS BECOME apparent over the last several years that continental regions of various ages are underlain by lithospheric mantle (extending down to 200–300 km in some cases) of different composition, structure, and thermal state (Chesley et al., 1999; O'Reilly et al., 2001 and references therein; Gao et al., 2002). This observation has important consequences for the tectonic behavior of continents, for the interpretation of geophysical data on the continents, and ultimately for theories concerning the formation of the continents and their cratons. In particular, the differences between Archean and younger lithosphere provide invaluable clues as to how the first continental masses formed almost 4 billion years ago, and how major tectonic processes affecting the Earth have changed through time.

Evaluation of a large body of empirical data derived from xenoliths and xenocrysts in volcanic rocks shows that the composition of the subcontinental lithospheric mantle (SCLM) varies systematically with the tectono-thermal age (the age of the last major magmatic event) of the overlying crust (Griffin et al., 1998, 1999a). The SCLM beneath Archean areas is highly depleted, whereas that

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beneath younger areas is progressively less depleted. This first-order observation implies that the SCLM and the overlying crust have formed quasi-simultaneously, and have remained linked together for billions of years. However, the mechanisms that produce this evolution remain to be defined. It is not clear from existing data whether it reflects sporadic generation of new SCLM in areas where new crust is formed, or simply progressive modification of ancient SCLM.

The strongly buoyant nature of ancient SCLM (Poudjom Djomani et al., 2001) suggests that it may be very persistent, because it would be difficult to recycle into the denser underlying asthenosphere. If it remains beneath the continents, it could be progressively modified by metasomatic processes through time, to produce the observed evolutionary changes in composition. This idea is supported by reports of Archean Re-Os ages for xenoliths erupted through Proterozoic terrains (e.g., Botswana; Carlson et al., 1999) and Proterozoic Re-Os ages on xenoliths and peridotite massifs from Phanerozoic central Europe (Roy-Barman et al., 1996). On the other hand, the SCLM beneath many Phanerozoic terrains is relatively dense, and hence easily recycled (O'Reilly et al., 2001; Poudjom Djomani et al., 2001), and the oceanic or island-arc SCLM that would be expected beneath these areas apparently is absent (Griffin et al., 1999a). Both of these observations suggest that new SCLM is still being produced in these areas. To understand these processes, a key piece of information is missing: the age structure of the SCLM in different tectonic settings.

Central and northern Asia, including the Siberian craton and the part of the Siberian platform adjoining it to the south, are fertile regions for such a SCLM study. The Siberian craton has an Archean core, bordered on its northern margin by Proterozoic terrains, and on the south by a broad belt of Phanerozoic island arcs and accreted terrains. The craton is intruded by a large number of kimberlites that provide SCLM samples. The deep structure of the craton along a SW-NE traverse has been defined by Griffin et al. (1999b) using xenocryst minerals from a large number of these kimberlites.

The southern margin of the Siberian platform is part of the East Central Asia Orogenic Belt, a complex of island arcs, former ocean basins, and micro-continents swept against the cratonic core of the platform during Paleozoic time. Significant new crust was generated during this accretion (Han et al., 1997). In this region, there are many late alkali-basalt fields carrying mantle-derived xenoliths, which make it possible to study the development of the SCLM in a complex mobile belt.

Eruptive breccias and basanites from the Late Cretaceous pipes of the North Minusinsk basin incorporate a wide variety of mantle xenoliths (Malkovets, 2001). A large body of information about mantle nodules in Quaternary basalts of the southern Siberian platform has been reported (Ionov et al., 1993, 1997, and references therein; Litasov et al., 2000a, 2000b, 2000c). Nevertheless, the composition and structure of the Mesozoic upper mantle of this region under consideration remains incompletely studied.

Geologic Background

The North Minusinsk basin is located in the Salair segment of the Altay-Sayan fold belt, extending along the southwestern margin of the Siberian platform. Trachybasalt-trachyte-trachydacite, and basanite-phonotephrite volcanic series erupted there in Early to Middle Devonian time. From Middle Devonian to Early Permian, the basin was filled with carbonate-terrigenous sediments. Re-activated faulting in the Salair basement of the basin was accompanied by flexure folding of its sedimentary cover and intrusion of basaltic dikes.

There are two points of view about the genesis of Lower Devonian volcanogenic-sedimentary rocks. The first, by Zubkov (1986), related the formation of a thick (about 1.5 km) Lower Devonian volcanogenic-sedimentary unit to the formation of a NW-trending Devonian paleorift. This inference is supported by the position of the Moho boundary, the depth of which is 39–42 km beneath the Minusinsk and Kuznetsk depressions, increasing to 45–48 km toward the southeast and Southwest (Surkov et al., 1988). The second view, by Zonenshain et al. (1990) held that the Devonian basaltic rocks were formed during the movement of the Siberian continent, together with the accreted Altay-Sayan margin, over a hot spot.

The post-Carboniferous magmatic units are alkali basalt dikes, necks and pipes, and scarce trachyte dikes. The young basalts are regularly distributed within the Minusinsk intermountain trough. All known outcrops occur within the North Minusinsk basin; necks and dikes of young basalts cut the periphery of the Kop'yevo anticlinal uplift, located in the central part of the basin (Fig. 1).

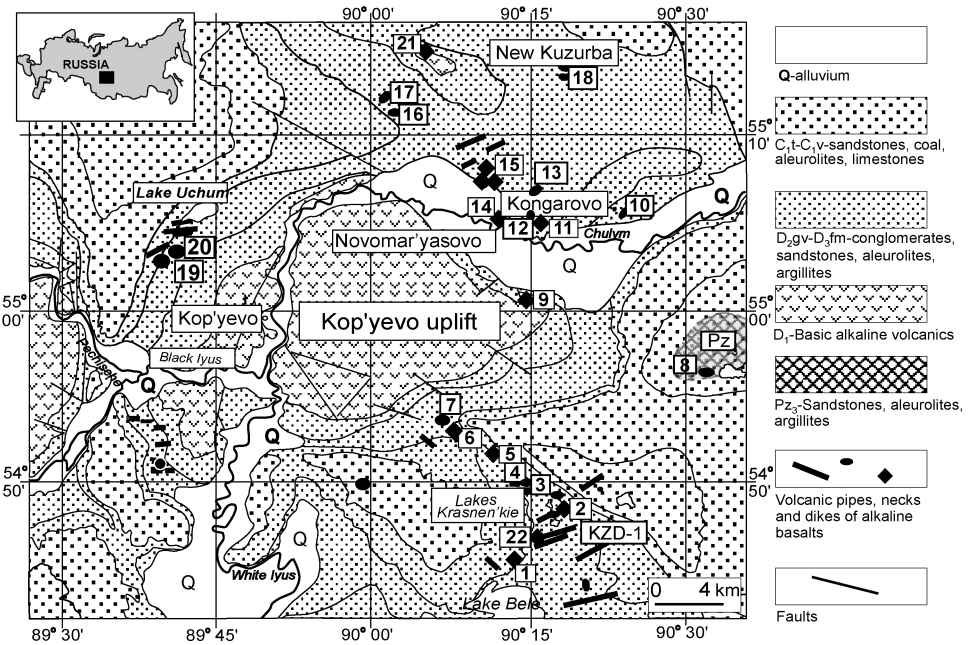

FIG. 1. Location map and geologic setting of the North Minusinsk depression. Symbols for volcanics in this study: filled diamonds = samples dated by ^{40}Ar/^{39}Ar method. Pipes: 1 = Bele; 2 = Krasnoozersk; 5 = Tergesh; 6 = Tochilnaya; 9 = Baradzhul; 11 = Sister; 14 = Kongarovsk; 15 = Three Brothers; 21 = Devonian lava flow; 22 = Trachyte dike.

Within the North Minusinsk basin, the alkali basalt pipes, necks, and dikes occur over an area of nearly 200 km^2 and surround the Kop'yevo uplift. Six of the 21 pipes in the North Minusinsk basin represent double intrusives. These pipes consist of two separate, closely associated necks (called main pipes and satellites). Such pairs of volcanic necks are usually separated by undisturbed sedimentary rocks. The largest pipes and necks can be up to 600 m in diameter.

The formation of the pipes began with intensive gas releases and crushing of host rocks. Then basanitic melts percolated into the axial zone of eruptive breccia and fractures (Luchitskiy, 1960; Kryukov, 1964a, 1964b). There are two dike systems. NW-trending (5 dikes) and NE- to E-W–trending (25 dikes). Formation of the NW-trending basanitic dikes is spatially related to the pipes. The dikes are up to several hundred meters long along strike and have a medium thickness, which locally can reach 10–15 meters. These NW-trending dikes, particularly in the vicinity of the Bele, Tergesh, and Dzhirim pipes, are deformed by a number of NE-trending dextral strike-slip faults. Such patterns are considered evidence that during the period of alkali-basalt-melt penetration, the upper crust was undergoing a tangential NE extension and NW compression. Even more complicated dike deformations were observed near the Chebaldak pipe, where NW-trending dikes have been terminated by yet another set of strike-slip faults, in a different direction. Because of the lack of radiogenic dates, the age of the dikes, until now, has been accepted only as post-Carboniferous, and related to a single magmatic episode.

Besides traditional occurrences of alkaline basalts in continental rifts, oceanic and continental hot spots, there are certain localities where the tectonic setting has not been well characterized. Alkali-basalt feeding dikes and lava flows have been reported from active orogenic belts, including Tien Shan, Pamir, and Tibet (Dobretsov and Zagruzina,1977; Baratov et al. 1988; Lutkov, 1988). Inner Asia, as well, provides numerous localities, which may not be directly identified as the result of rifting or hot-spot activity (Barry et al., 2003). An alternative mechanism for basaltic melt generation is decompressional melting of the upper mantle due to deeply stretched, tectonic deformations within an extensional environment in the lithosphere (Hole et al., 1993). Collision of two continental plates caused dramatic folding in the overlying plate, which is manifested as mosaic conjunction of blocks, having undergone both compression and extension. The presence of basic magma products is evidence for deep penetration of deformation into the lithosphere. However, the depths to which these deformational tectonics can extend remains unknown. We suggest a decompressional-melting model as the major mechanism responsible for formation of the Minusinsk basanites (Litasov et al., 2002). The driving force for the decompression may have been the geodynamic rearrangement of the Central Asian lithosphere, at the initiation of the India-Eurasia collision. It is well known that the clockwise rotation of the Siberian platform caused local extensional-compressional environments, thereby providing stretching and probable decompressional melting to great depths (Khramov, 1997). Previously, it was generally accepted that major rotation of the platform abruptly slowed down at the end of the Early Mesozoic. Our new data from the present study suggests that the extensional regime along the southwestern boundary of the Siberian platform continued until at least the Late Cretaceous, possibly younger. Hereby, we present evidence for a short-term event in Inner Asia, albeit with no obvious driving force.

The age of the pipes has been estimated by several investigators. Luchitskiy (1960) regarded the pipes as Permian–Triassic, based on the fact that the basanites intrude Devonian–Carboniferous lavas and sediments. Jurassic deposits are of limited occurrence, and no geological contacts with the pipes have been found. Zircons from a heavy-mineral separate from the Bele pipes have an U/Pb age of 77.9 Ma—i.e., Late Mesozoic (Sobolev et al., 1988).[2] K-Ar whole rock ages range from 71 to 28 Ma—i.e., Late Mesozoic to the early part of the Middle Cenozoic (i.e., Oligocene; Table 1; Zubkov et al., 1991).

The Tergesh, Kongarovsk, and Krasnoozersk satellite pipes contain well-studied garnet-spinel peridotite and pyroxenite xenoliths (Malkovets, 1998, 2000, 2002). The major- and trace-element data indicate that the upper mantle beneath the Minusinsk region has a layered structure: (1) the deeper garnet-spinel and spinel lherzolites from the Tergesh pipe have fertile modal compositions and slightly depleted trace-element patterns; (2) the shallower spinel lherzolites from the Krasnoozersk and Kongarovsk pipes have a wider range of modal abundances and are commonly less fertile than the Tergesh lherzolites. Their clinopyroxenes are typically enriched in highly incompatible trace elements and have negative high-field-strength-element (HFSE) anomalies, indicating a complicated history, which may have involved repeated depletions and metasomatic events (Malkovets et al., 1998, 2002).

Clinopyroxene in metasomatized spinel peridotites from the Kongarovsk and Krasnoozersk pipes have ^{143}Nd/^{144}Nd (0.51283–0.51327) and ^{87}Sr/^{86}Sr (0.70292–0.70378) values similar to those for the basanites. It is likely, therefore, that the fluids responsible for the metasomatism were derived from the same source as the magmas hosting the xenoliths. The LREE-depleted clinopyroxene from spinel lherzolites of the Tergesh pipe have Sr-Nd isotope compositions (^{143}Nd/^{144}Nd = 0.51323–0.51358; ^{87}Sr/^{86}Sr = 0.70250–0.70295) similar to the model DMM source (Malkovets et al., 2000).

There are two possible explanations for the observed differences in trace-element and isotopic compositions of mantle xenoliths from different pipes. The upper mantle beneath the North Minusinsk basin might consist of two geochemically and isotopically different layers. Alternatively, according to the K/Ar dating of the basanites hosting the mantle xenoliths, mantle metasomatism might have occurred significantly later. The present study was undertaken in an attempt to settle this situation by the application of ^{40}Ar/^{39}Ar methods, which have been proven to be highly successful in dating flood volcanism (e.g., Duncan and Pyle, 1988; Renne et al., 1992, 1996).

Methodology

Several of the basaltic pipes of the North Minusinsk basin were sampled, as well as the E-W–trending trachyte dike and a Devonian trachybasalt, the last two for comparison (Table 1). Age determinations with ^{40}Ar/^{39}Ar systematics were performed in the Laboratory of Radiogenic and Stable Isotopes (Siberian Division, Russian Academy of Sciences, Novosibirsk).

Pure mineral concentration for sample Bg-671 and whole-rock samples for others (250–125 μm size) were prepared by magnetic separation and

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[2] The date was obtained at the Geophysical Laboratory of the Carnegie Institution of Washington.

TABLE 1. ^{40}Ar/^{39}Ar Results for the North Minusinsk Pipes Compared with K/Ar and ^{206}Pb/^{238}U Ages[1]

Sample	Pipe name	^{40}Ar/^{39}Ar age, Ma	K-Ar age Ma[1]	^{206}Pb/^{238}U age Ma[2]	Geographic coordinates[3] E. Long.,°	Geographic coordinates[3] N. Lat, °
Bele	Bele	79 ± 2	62 ± 3	77.94	90°14'55"	54°45'87"
KG-2	Kongarovsk	74 ± 5.5	45 ± 2		90°13'83"	55°06'95"
TSCH-2	Tergesh	77 ± 1.9	65 ± 3		90°13'62"	54°51'52"
BG-1	Baradzhul	77 ± 2.1	49 ± 3		90°14'82"	55°00'75"
BG-671[5]		77 ± 5				
KZ-2	Krasnoozersk-major	77 ± 3.9	62 ± 3		90°16'55"	54 °48'87"
KZ-M	Krasnoozersk-satellite Satellite	74 ± 2 74 ±2	28 ± 2 28 ±2		90°16'69" 90î16'69"	54°48'76" 54 î48’76"
TB-1	Three Brothers (NW neck)	75 ± 2.4	58 ± 3		90°11'88"	55°07'88"
TB-2	Three Brothers (SE neck)	72 ± 2.7				
Tch-1	Tochilnaya (NW neck)	76 ± 1			90°07'43"	54 °53'06"
Tch-2	Tochilnaya (SE neck)	73 ± 2.5				
Ses-1	Sister	75 ± 6.2	71 ± 4		90°15'79"	55 °05'25"
KZD-1	Trachyte dike	262 ± 2.5			90°16'35"	54°47'57"
HK-1	Devonian lava flow	392 ± 11			90î03'85"	55 î15'46"

[1] From Zubkov et al., 1991.

[2] From Sobolev et al., 1998

[3] Coordinates were measured by a "Magellan" device. Minutes of latitude/longitude are reported in the traditional way; second values are percentages (i.e., 100 seconds = 1 minute).

[4] Zircon from heavy concentrate.

[5] Sanidine megacryst.

hand picking. These were wrapped in Al foil, vacuum-sealed in quartz vials, and irradiated under Cd-shielding, in the VEK-11 carrier of the VVR-K research reactor of the Politechnical Institute at Tomsk, Russia. A K-Ar standard biotite (MCA-11), calibrated with LP-6 biotite and MMhb-1 hornblende, was put between every two samples for neutron-gradient monitoring. The neutron gradient did not exceed 0.5% of the sample size.

Step-heating for ^{40}Ar/^{39}Ar determinations were accomplished in a quartz reactor heated by an external furnace. Temperature was monitored with a Pt/Pt10Rh thermocouple. Released gases were purified by exposure to a Ti-getter and two SAES getters. The Ar isotope composition was measured with a Micromass 5400 static-mass spectrometer. The 1200°C blank of ^{40}Ar did not exceed $n*10^{-9}$ STP. For plateau age calculations, the gaseous fractions were sampled according to the criteria described by Fleck et al. (1977).

The wide interval of K/Ar ages of the North Minusinsk pipes, ranging from 71 to 28 Ma (Table 1), suggests significant variations of potassium and radiogenic argon. The measurements of whole-rock K and ^{40}Ar in various basanites from the Bele and Krasnoozersk main pipes and the data reported in Zubkov et al. (1991) showed wide variations of both elements. Potassium and ^{40}Ar contents in the basanites of the Bele pipe range from 1.35 to 1.47 wt% and from 2.22 to 3.22 ($\times10^{-3}$) nmm^3/g, respectively (from 46 to 62 Ma). The contents of K and ^{40}Ar in the basanites of the Krasnoozersk main pipe range from 1.16 to 1.41 wt% and from 2.6 to 3.4 (×10^{-3}) nmm^3/g, respectively (from 62 to 68 Ma). We suggest that the subvolcanic rocks experienced tectonic deformation, resulting in the loss of radiogenic argon. The deformation further induced fracturing, which resulted in secondary alteration of the rocks, a possible decrease in K content, and further liberation of radiogenic argon.

The above comments can explain the numerous erroneous K/Ar ages that have been obtained for the whole-rock samples of Mesozoic and early part of the Middle Cenozoic volcanic rocks in this region. For example, the K/Ar age spread for the duration of the eruption of the Deccan traps exceeds 50 Ma, whereas their ^{40}Ar/^{39}Ar dating and paleomagnetic data show that they only erupted within 69–65 Ma—i.e., in a much narrower age interval (Courtillot et al., 1988). The K/Ar age determinations of plateau basalts in Ethiopia show an interval of 12 to 50 Ma, whereas the ^{40}Ar/^{39}Ar results and paleomagnetic data show that they erupted at nearly 30 Ma, during a short time interval of less than 1 Ma (Hofman et al., 1997).

Discussion

The Ar-Ar dating technique as applied to the selected rocks of this study has produced well-defined ages. Typical spectra of Ar release of the Bele and Tergesh pipes are shown in Figure 2. They possess clearly defined plateau ages of 79 ± 2 and 77 ± 1.9 Ma, respectively. The ages of 74 ± 5.5 Ma for the Kongarovsk pipe and 75 ± 6.2 Ma for the Sister pipe are also the same age, within the precision of the analyses.

The Krasnoozersk, Three Brothers, and Tochilnaya pipes represent double intrusives. These pipes were sampled for each neck. The Krasnoozersk main pipe yielded an age of 77 ± 3.9 Ma, whereas a 74 ± 2 Ma age was determined for the Krasnoozersk satellite pipe. The NW (main) and SE (satellite) necks of the Three Brother pipe yielded ages of 75 ± 2.4 Ma and 72 ± 2.7 Ma, respectively. The Tochilnaya pipe yielded ages of 76 ± 1 Ma for NW main neck and 73 ±2.5 Ma for SE satellite neck. Within the precision of the ^{40}Ar/^{39}Ar analyses, the ages of the main bodies of the intrusives are all the same, with the satellites regularly giving slightly younger ages.

A sanidine megacryst (sample BG-671) and a whole-rock sample (BG-1) from the Baradzhul pipe yielded ages of 77 ± 5 and 77 ± 2.1 Ma, respectively. The ^{40}Ar/^{39}Ar age of 79 ± 2 Ma obtained for the Bele basanite is the same as the 77.9 Ma U/Pb age of zircon from a heavy-mineral separate from the same pipe (Sobolev et al., 1988).

The numerous E-W–trending dikes, which previously were attributed to the Meso-Cenozoic subvolcanic complex (Luchitskiy, 1960), have a less alkaline composition than the basanitic pipes. Importantly they have a ^{40}Ar/^{39}Ar age of 262 ± 2.5 Ma—i.e., Early Permian. The Devonian age of the North Minusinsk trachybasalts is supported by a ^{40}Ar/^{39}Ar date of 392 ± 11 Ma.

Although all the ^{40}Ar/^{39}Ar ages of the North Minusinsk pipes (Table 1) overlap, within the precision of the method, we feel that the Tergesh pipe may be slightly older than the Kongarovsk and Krasnoozersk satellite pipes, although the age of the Tergesh pipe is comparable with that of most other pipes (~77 Ma), as well as with the ages of the other two pipes, which correlate with the youngest dates of the age range (~74 Ma). The Tergesh pipe contains mantle xenoliths from deeper sources than those from the Kongarovsk and Krasnoozersk satellite pipes; we conclude that the shallower mantle was sampled at the final stages of basaltic magmatism. Indeed, all these pipes formed during a rather short magmatic episode in Late Cretaceous time.

Other than for the North Minusinsk basin, no ^{40}Ar/^{39}Ar dating has been performed connected with Late Mesozoic magmatic events in Central Asia; therefore, we consider the present spatial correlations of Late Mesozoic magmatic events to be tentative. The available K/Ar ages show that North Minusinsk pipes could have formed coevally with the basanitic extrusions, stocks, and laccoliths of the Nomgon and Barun-Tzohe Ranges in southern Hangai, which formed during 81–71 Ma (Yarmolyuk et al., 1995). Nephelinites occurring in the vicinity of the village of Komsomolskiy in southern Transbaykalia have a similar close interval of 70–72 Ma (Bagdasaryan et al., 1981). Our study has shown that ^{40}Ar/^{39}Ar dating is necessary for reliable reconstructions of successive Mesozoic and early Middle Cenozoic volcanic and subvolcanic units in central Asia.

The basanitic composition of upwelling melts, occurrence of xenoliths from deep sources, and magnitude of the large area of magmatism make the North Minusinsk pipes comparable with Quaternary

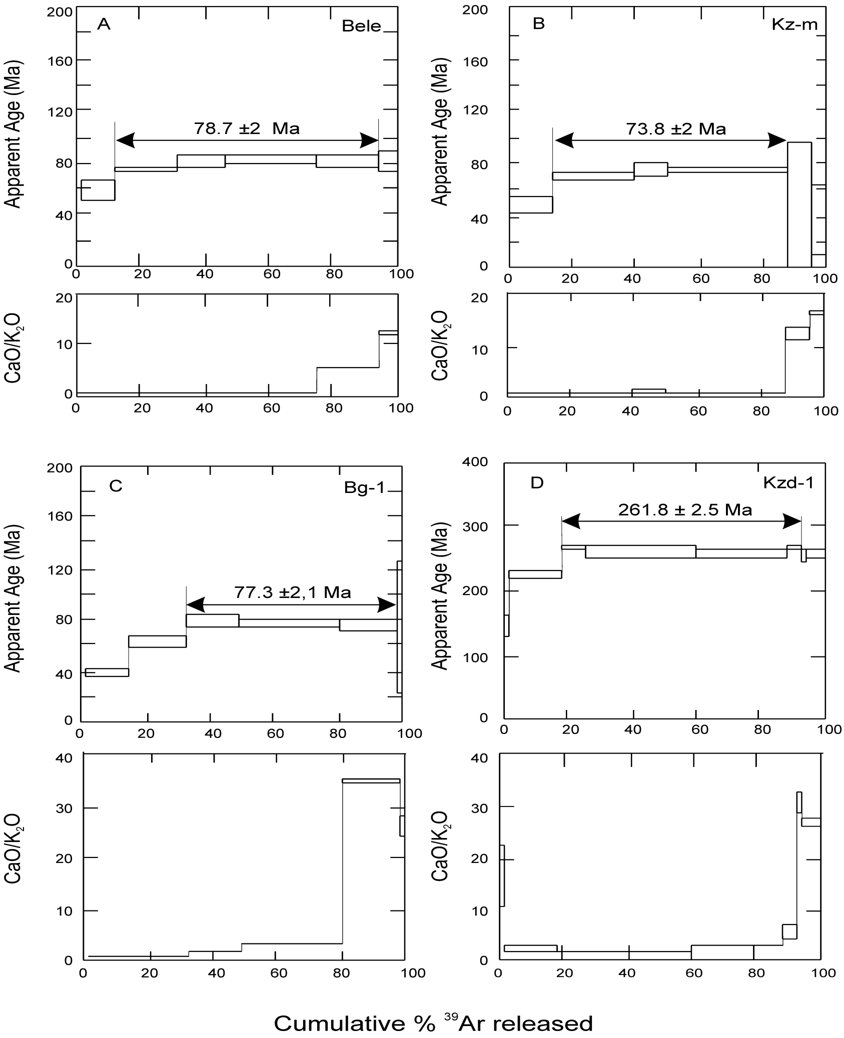

FIG. 2. Results of $^{40}Ar/^{39}Ar$ analyses of North Minusinsk basalts. Sizes of boxes encompass ±1α uncertainties.

volcanoes of the Tokinsky Stanovik. The $^{40}Ar/^{39}Ar$ dating of the Tokinsky volcanoes showed that they erupted from 0.59 to 0.28 Ma. This age interval corresponds to one of many Quaternary magmatic impulses in Central Asia (Solovyeva et al., 1983). The Tokinsky volcanoes are the result of an extensional event at the easternmost part of the Baikal rifting region, reportedly due to the counterclockwise rotation of the Amur plate relative to the Siberian platform. Such a tectonic mechanism would appear to be likely for formation of the much older Minusinsk pipes.

Conclusion

1. The major result of the present study is that all the pipes formed virtually simultaneously, during a short Late Cretaceous magmatic episode.

2. The newly recognized Permian stage of magmatic activity probably represents a shallower crustal magmatism, whose role should be evaluated through detailed study of the dikes in the North Minusinsk basin.

3. It is probable that the formation of these volcanic pipes can be attributed to decompressional melt-

ing in the NE-trending extensional environment. This was caused either by the tectonic rearrangement of the Central Asian lithosphere at the initiation of the India-Eurasia collision, or by continuing clockwise rotation of the Siberian platform during the Late Cretaceous.

4. However, our geologic observations have shown that tectonic activity continued after the initial dike formation.

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