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Permo-Triassic plume magmatism of the Kuznetsk Basin, Central Asia: geology, geochronology, geochemistry, and geodynamic consequences

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Abstract

The Kuznetsk Basin is located in the northern part of the Altay–Sayan Folded Area (ASFA), southwestern Siberia. Its Late Permian–Middle Triassic section includes basaltic stratum-like bodies, sills, formed at 250–248 Ma. The basalts are medium-high-Ti tholeiites enriched in La. Compositionally they are close to the Early Triassic basalts of the Syverma Formation in the Siberian Flood basalt large igneous province, basalts of the Urengoi Rift in the West Siberian Basin and to the Triassic basalts of the North-Mongolian rift system. The basalts probably formed in relation to mantle plume activity: they are enriched in light rare-earth elements (LREE; La_n = 90–115, La/Sm_n = 2.4–2.6) but relatively depleted in Nb (Nb/La_{bse} = 0.34–0.48). Low to medium differentiation of heavy rare-earth elements (HREE; Gd/Yb_n = 1.4–1.7) suggests a spinel facies mantle source for basaltic melts. Our obtained data on the composition and age of the Kuznetsk basalts supports the previous idea about their genetic and structural links with the Permian–Triassic continental flood basalts of the Siberian Platform (Siberian Traps) possibly related to the activity of the Siberian Superplume which peaked at 252–248 Ma. The abruptly changing thickness of the Kuznetsk Late Permian–Middle Triassic units suggests their formation within an extensional regime similar to the exposed rifts of southern Ural and northern Mongolia and buried rifts of the West Siberian Basin.

Keywords: basaltic magmatism; Siberian Superplume; Permian–Triassic boundary; Ar-Ar dating; trace-element composition of basalts

Introduction

The Kuznetsk Basin (often abbreviated as Kuzbass) is situated in the northwestern ASFA and separated from the world's largest Mesozoic West Siberian oil-and-gas basin by the Paleozoic Salair and Kolyvan'–Tomsk uplifts (Fig. 1). In the south and the east, the basin is bounded by the Gorny Altai and Kuznetsk Alatau mountainous systems, respectively (Fig. 2). The Kuznetsk Basin is dominated by a Late Paleozoic coal-bearing molasse (Serpukhovian to Late Permian). In the central part of the basin, the molasse covers Visean terrigeneous-carbonate units and at the periphery it is underlain, with a sedimentation break, by Upper Devonian–Serpukhovian carbonates.

The Paleozoic units of the Kuznetsk Basin are covered by a series of separate Triassic and Jurassic subbasins. The Jurassic sediments, a coal-bearing molasse, are separated from the overlying and underlying rocks by sedimentation breaks and structural unconformities and constitute the Doronin, Central-Kuzbass and Podobassko–Tutuyasskaya large depressions and several smaller troughs (Fig. 2).

The Triassic section is dominated by trap basalts of the Saltymakov paleovolcanic structure (Kurtigeshev et al., 2008; Lavrenov et al., 2008a,b). In the central and eastern parts of the Kuznetsk Basin the Triassic units overlap the Late Paleozoic coal-bearing units with a sedimentation break and, together with the Jurassic molasse, they constitute the Bongorap trough.

The territory of Kuznetsk basalts, which are often referred to as Kuzbass trap formation (Kutolin, 1963; Usov, 1937), is located between the Permo-Triassic Siberian Traps of the Siberian Platform, which erupted during a short time period at 252–248 Ma (e.g., Al'mukhamedov et al., 1999a,b; Buslov

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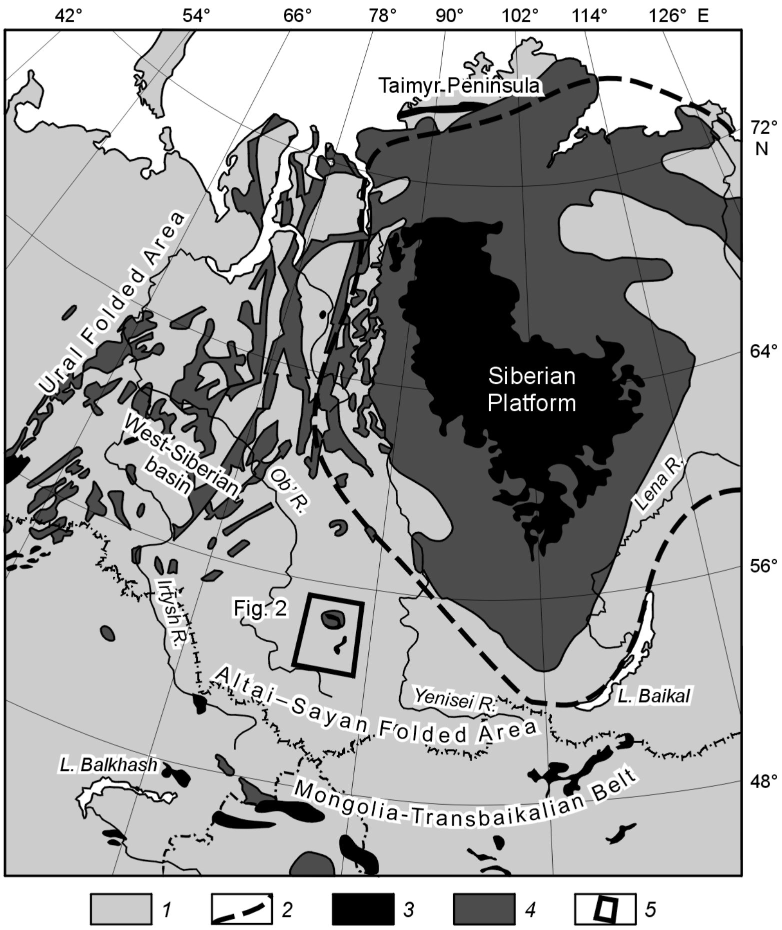

Fig. 1. Location of Late Permian (?)–Triassic basalts related to the Siberian Superplume and Mesozoic volcanogenic-sedimentary units of Northern Mongolia–Transbaikalia. *1*, continental units; *2*, outline of the Siberian Platform; *3–4*, Late Permian–Triassic mafics (basalt, dolerite, gabbro): *3*, outcrops, *4*, subcrops; *5*, Kuzbass trap basalts.

et al., 2007; Reichow et al., 2009), and the Mesozoic Mongolia-Transbaikalian volcanic province (Vorontsov et al., 2007; Yarmolyuk and Kovalenko, 2003; Yarmolyuk et al., 1999, 2002) (Fig. 1). The Kuznetsk basalts and subvolcanic basaltoids are commonly compared with the Early Triassic traps of the West (buried) and East (exposed) Siberia (Al'mukhamedov et al., 1998, 1999a; Medvedev et al., 2003; Reichow et al., 2005). The occurrences of Permo-Triassic basalts form the East Siberian Trap Province or Siberian Flood Basalts (e.g., Fedorenko, 1994; Fedorenko et al., 1984; Hawkesworth et al., 1995; Venkatesan et al., 1997; Zolotukhin and Al'mukhamedov, 1988), are often attributed to the eruption of the Siberian superplume (Dobretsov, 1995, 1997).

These plume-related basalts have been studied over a huge territory extending from the Urals to East and West Siberia and to Kuzbass. More evidence for a short interval of eruption of these intracontinental plume-related basalts (250 ± 2 Ma) came from the recently reported high-quality $^{40}Ar/^{39}Ar$ ages (Reichow et al., 2009). Nevertheless, there are abundant localities of Early–Middle Triassic basaltic lavas, sills, tuffs and tuffites according to the geological and geochronological data on plume-related magmatic rocks in the Southern Urals, which form a series of grabens (Ivanov, 1974; Tuzhikova and Kurbezhekova, 1973).

A very disputable question in the magmatic geology of the Kuznetsk Basin is the nature of basaltic bodies—are they subvolcanic (sills) or volcanic (lava flows). Therefore, of particular importance is precise determination of their age and, as a result, the duration of the whole magmatic event. Finally, it is important to evaluate the type of mantle source of basaltic melts and to understand if there is a link between the mantle sources and the types of basic magmas, which eventually formed the Permo-Triassic traps of the Urals, East and West Siberia on one hand and the Mesozoic, mostly Triassic, volcanogenic–sedimentary units of the Mongolia–Transbaikalia region on the other.

The main purpose of this paper is to discuss new geochronological and geochemical data on the Kuznetsk traps. The paper characterizes litho-stratigraphic relationships between magmatic and sedimentary units, presents detailed descriptions of several better exposed magmatic bodies and describes their associations with their hosting rocks. Special attention will be paid to the age ($^{40}Ar/^{39}Ar$ isotopy) and geochemistry of dolerites and basalts of the Saltymakov complex, including

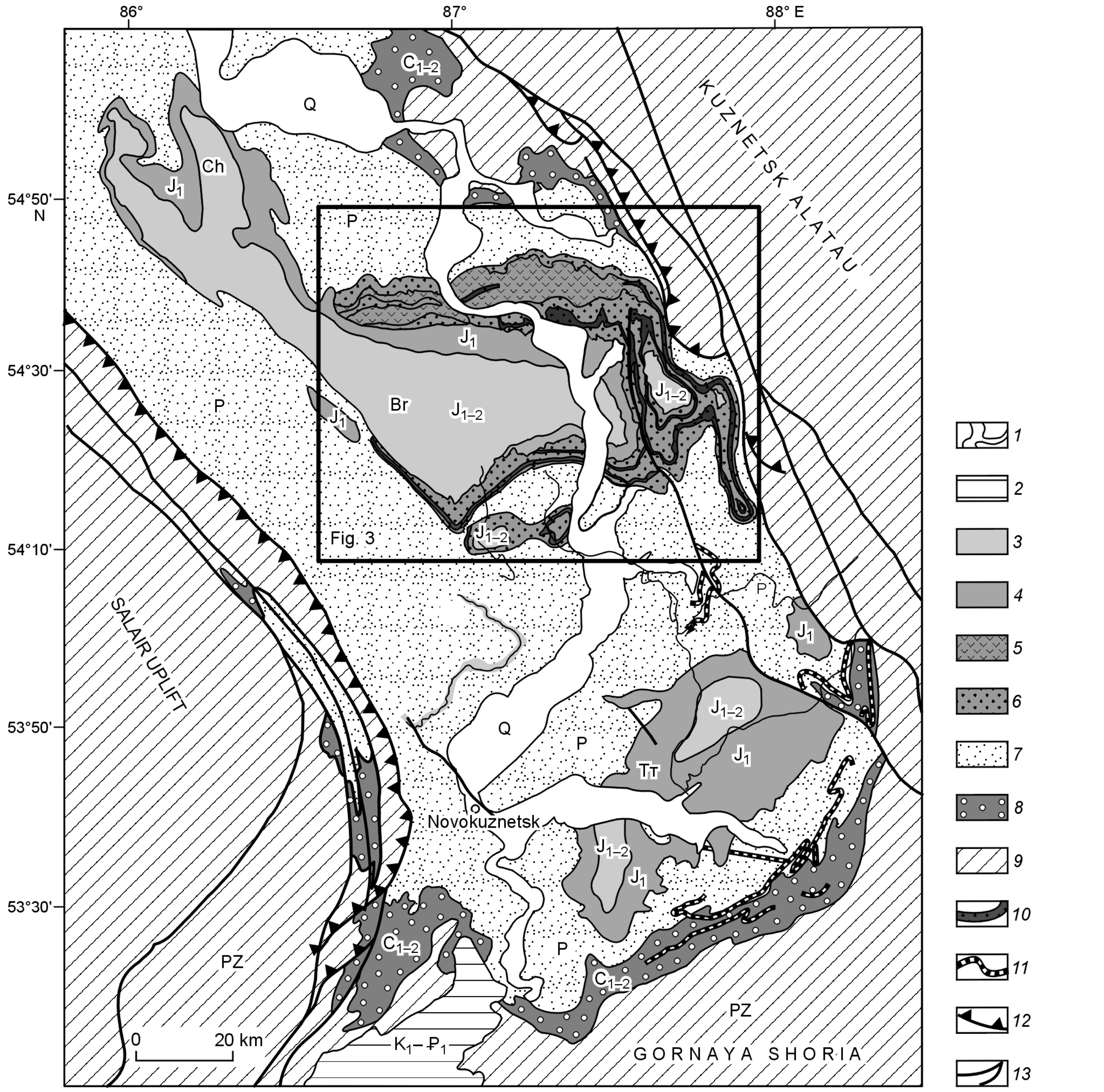

Fig. 2. Geological scheme of the Kuzbass trap basalt province. *1*, Quaternary alluvium; *2*, Lower Cretaceous–Paleogene sediments; *3–4*, Jurassic coal-bearing molasse: *3*, Lower–Middle Jurassic, *4*, Lower Jurassic; *5–6*, Late Permian (?)–Middle Triassic: *5*, undivided tuff-sedimentary and magmatic rocks, *6*, tuff-sedimentary rocks; *7*, Permian coal-bearing molasse; *8*, Lower–Upper Carboniferous coal-bearing sediments; *9*, Cambrian to Early Carboniferous sedimentary-metamorphic and magmatic units; *10*, sills of the Saltymakov complex, *11*, sills and dykes of the Syrkashev complex; *12*, thrust; *13*, strike-slip fault. Troughs: Ch, Chusovitin; Br, Bungorap; Tm, Tutuyass.

the Karakan and Kyrgai open-pits, the Osinovka drilled core and their comagmatic gabbros of the Syrkashev sill, which is hosted by Upper Paleozoic sediments at the base of Kuznetsk Basin section. In conclusion, the paper discusses the position of the Permo-Triassic boundary in the Kuzbass stratigraphic section, volcanic and/or subvolcanic nature of basaltic bodies, age of trap magmatism and its possible relation to the Siberian Superplume, fractional crystallization, crustal contamination, degrees of partial melting and types of mantle sources of basaltic melts. Mutual relationships between the localities of Permo-Triassic plume-related magmatic rocks of Kuzbass, South Ural, northern Mongolia and West Siberian will also be discussed.

Geological position of basaltic bodies

The geological structure and stratigraphy of the Kuznetsk Basin have been carefully studied during many years of geological survey, exploration, prospecting and scientific

Table 1. Stratigraphic scheme of the Kuznetsk Basin (Kyzbass) (Decree..., 1982; Lavrenov et al., 2008a,b; Kurtigeshev et al., 2008)

Period	Series	Subseries, formation	Thickness, m	Position of basaltic bodies
Cretaceous		Neninskaya Formation (K_2–Pnn)	150	
		Ilek Formation (K_1il)	500	
Jurassic	Tarbagatan, J_{1-2}	Tersyuk Formation (J_{1-2}tr)	200–450	
		Osinovka Formation (J_1os)	0–450	
		Abashevskaya Formation (J_1ab)	75–270	
		Raspadskaya Formation (J_1rs)	180–460	
Triassic	Abinskaya, T_{1-2}	Yaminskaya Formation (T_2iam)	100–700*	
		Sosnovka Formation (T_{1-2}ss)	200–625	
		Mal'tsevo Formation (T_1ml)	170–1000*	
Permian	Kolchugin, P_2	Erunakovo subseries (P2er)	930–2130	
		Il'inskaya subseries (P_2il)	1250–2530 up to 370–650	
		Kuznetskaya subseries (P_2kz)	180–1100	
	Balakhonskaya, C_2–P_1	Verkhne-Balakhonskaya subseries (P_1bl_2)	580–1160 up to 170	
Carboniferous		Nizhne-Balakhonskaya subseries (C_2–P_1bl_1)	300–1000	
		Ostrog subseries (C_1^3os)	200–600	

Note. The gray rectangle—a newly proposed Permian–Triassic boundary taking into account the new data of basaltic sills; black rectangles—position of basaltic sills: 1, Syrkashev; 2, Karakan.

research (Bogomazov et al., 1996; Buslov et al., 2007; Geology of the USSR, 1967; Kurtigeshev et al., 2008, 2001; Lavrenov et al., 2008a,b; Senderzon et al., 1971; Sidorenko and Fomichev, 1969; Verbitskaya, 1996). Below we present a summary of previously obtained results. The base of the Kuzbass stratigraphic section consists of Middle Devonian-Lower Carboniferous carbonate-terrigenous shelf sediments, which, by the periphery of the basin, are overlapped by the Upper Carboniferous coal-bearing molasse up to 7000–8000 m thick (Fig. 2, Table 1). In the central part of the basin, i.e., within the Bongorap trough, the coal-bearing deposits are conformably, but with a sedimentation break, overlapped by the Lower–Middle Triassic volcanogenic-sedimentary units of the Abinskaya Series, which hosts Kuzbass traps (Fig. 3). The Abinskaya Series and the coal-bearing molasse are, in turn, overlapped, with a structural and stratigraphic unconformity, by a Jurassic coal-bearing molasse (Fig. 2).

The Abinskaya stratotype locality is situated near the Babii Kamen' Cliff on the Tom' River and consists of alternated sedimentary and tuff-sedimentary packages (Fig. 3). According to drilling data, the Abinskaya Series attains its maximal thickness of 2000 m in the north-eastern part of the basin. From that point, several tens of kilometers to the south and west the thickness decreases to 700–800 m. The Series is dominated by tuffaceous-sandstone and tuffaceous-mudstone with subordinate ash tuffite, tuff, sandstone, siltstone and conglomerate. The content of pyroclastics decreases up the section and from NE to SW over the Bungorap trough. The Abinskaya Series is divided into Mal'tsevo, Sosnovka and Yaminskaya Formations (Table 1).

The Mal'tsevo Formation (T_1*ml*) consists of lower sedimentary and upper tuff-sedimentary packages. The greenish-grey terrigenous rocks of the lower package, which are interbedded with conglomerates, form up to 20 m thick lens-like bodies of fluvial sediments. In the Tom' right river bank, the Mal'tsevo Formation overlaps the Upper Permian coal-bearing sediments without a visual unconformity, and the boundary between these two stratigraphic units is arbitrary put 4–5 meters above the uppermost coal seam. The drilling of the north-eastern Bungorap trough intersected the upper package of the Mal'tsevo Formation as there are no outcrop exposures. In the NE of the Bungorap trough its thickness reaches 300–500 meters and decreases to zero southwestwards. The upper package is dominated by tuff-sandstone beds hosting seven basaltic bodies, which are several meters to several tens of meters thick. In total, the thickness of the Mal'tsevo Formation ranges from 400–1000 to 320–400 meters in the northern and southern parts of the Bungorap trough, respectively. The site of the maximal thickness of the formation is located 4 km upstream from the mouth of the Bungorap River, from its mouth, and is characterized by high gravity field values (Lavrenov et al., 2008a,b). Evidence for the Early Triassic age of the Mal'tsevo Formation comes from remnants of insects, flora, ostracods and spores.

The Sosnovka Formation ($T_{1\text{-}2}$*ss*) starts and finishes with tuffaceous-sedimentary packages and is characterized by cyclical nature. There are found 10 to 16 cycles, each consisting of interbedded motley terrigenous and sedimentary rocks interbedded with zeolitized tuffs. The bed thickness ranges from 1 to 10 m, rarely 20–50 m. Mineralogically and petrographycally the Sosnovka tuffs are analogous to the Mal'tsevo tuffs. The tuffs locally are shell-sphere cleavaged and contain abundant zeolite mineralization replacing volcanic glass and basic matrix. The thickness of the Sosnovka

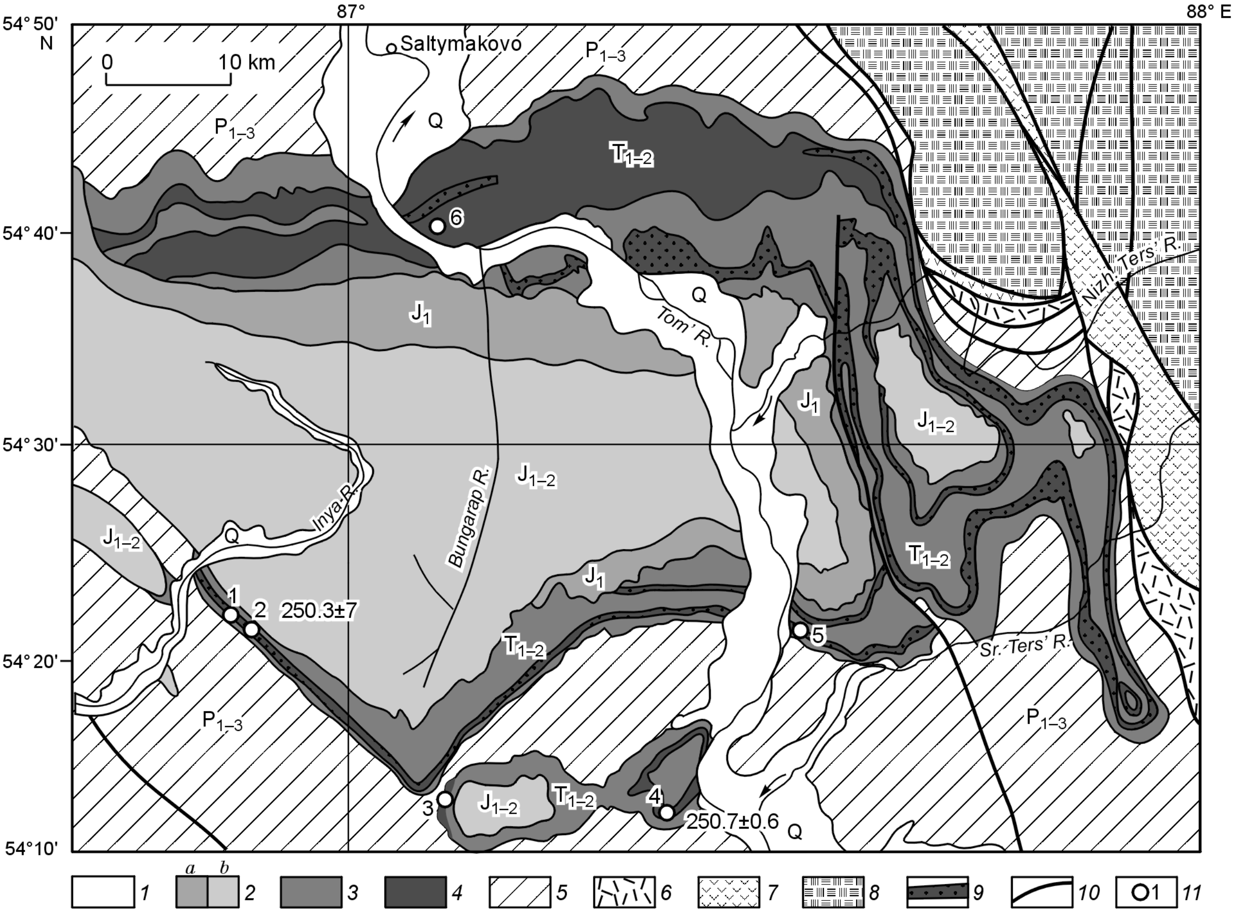

Fig. 3. Geology of the Bungarap Trough in the Kuznetsk Basin. *1*, Quaternary alluvial sediments; *2*, Jurassic coal-bearing molasses: *a*, Lower, *b*, Upper; *3*, Upper Permian (?)–Middle Triassic volcanic-sedimentary rocks of the Abinskaya Series; *4*, undivided Early-Middle Triassic tuff-sedimentary and magmatic rocks; *5*, Permian coal-bearing molasse; *6*, Early Devonian volcanic-sedimentary rocks; *7*, Early Ordovician volcanic-sedimentary rocks; 8, Early Paleozoic accretionary complex: ophiolites, paleoceanic islands, olistosromes; *9*, Late Permian–Early Triassic sills; *10*, strike-slip faults; *11*, sample location points and absolute ages: 1, 22 (Karakan open pit); 2, S4.1 (Planernyi open pit); 3, K-04-5-5, S15.2 (Kyrgai open pit); 4, Kp-13, FGS-8 (Osinovka); 5, K-04-3-4/2 , S10.1 (Babii Kamen'); 6, 28 (Bychii).

Formation in the stratotype section north of the Babii Kamen' Cliff is 675 m and abruptly decreases to the west and north. Formation sediments contain Lower and Lower–Middle Triassic flora and fauna remnants and spores.

The Yaminskaya Formation (T_{2jam}) is 100–700 m thick reaching its maximum near the Babii Kamen' Cliff and in the north-eastern Bungorap trough. The formation is divided into the lower tuffaceous (up to 200 m thick) and upper terrigeneous packages, which finish the Triassic section of Kuzbass. The formation includes mottled terrigeneous sediments, coarse-grained clastics, with less pyroclastics and zeolites. Likewise the Sosnovka Formation, the Yaminskaya Formation abruptly decreases in thickness southwestwards. In the southern Bungorap trough, on the bank of the Tom' River, the lower package hosts two big lava flows (covers) of basalts up to 20 m thick, which are separated by a 1.5 m thick bed of tuffaceous-mudstone. The package is normally 4.5 to 60 m thick but reaches 200 m at the right bank of the Nizhnyaya Ters' River due to the increased thickness of basaltic bodies. According to its position in the stratigraphic column the age of the formation is referred to Middle Triassic (Table 1) (Lavrenov et al., 2008a,b).

The Abinskaya Series is overlain by the *Tarbagatan Series* ($J_{1\text{-}2}$) separated by a break in sedimentation and a regional unconformity. The Tarbagatan Series is up to 1500 m thick and consists of alternating fluvial facies, such as conglomerate, sandstone and mudstone, organic-rich siltstones and seams of coal and lignite. The sediments are facially variable and contain abundant remnants of Lower and Middle Jurassic flora, fauna and palynological complexes.

The Kuznetsk Jurassic deposits formed in a single paleogeographic environment coeval with the Jurassic sediments of the Kansk–Achinsk Basin (Le Heron et al., 2008). In Jurassic time, a foremontane depression was filled by sedimentary material supplied by rivers from the south-east, i.e., from the Mongol–Okhotsk orogenic belt. Within the Kuznetsk Basin, basaltic bodies are hosted by sediments of two stratigraphic levels: 1) Upper Carboniferous and Lower Permian of the Nizhne-Balakhonskaya and Verkhne-Balakhonskaya subseries (dolerite-gabbro sills; Table 1); 2) Early–Middle Triassic tuffaceous-sedimentary units of the Mal'tsevo and Yamoinskaya Formations (basaltic bodies of unclear nature).

The Upper Carboniferous–Lower Permian sediments (Fig. 2) host sills and dykes of gabbro, dolerite and mon-

Table 2 . 40Ar/39Ar dates and availability of geochemical data for mafic rocks of the Kuznetsk Basin

No.	Sample	Coordinates		Location	Rock type	Wall rock	Name of magmatic body	Geochronological age, Ma, mineral	Geochemistry	
		N	E						ME	TE
1	27	54°21′	087°07′	Bychii Brook mouth	dolerite	Mal'tsevo Formation, T_1ml	Saltymakov stratum-like body (central part)	n.d.	+	n.d.
2	28	54°40′	087°10′	2 km down the Bychii Brook mouth	dolerite			n.d.	+	n.d.
3	22	54°15′	087°06′	Karakan open pit	basalt	Mal'tsevo Formation, T_1ml	Karakan Sill (western part)	n.d.	+	n.d.
4	Kp-25	54°24′	086°52′	Planernyi open pit	basalt	Mal'tsevo Formation, T_1ml	Karakan Sill (eastern part)	250.3 ± 0.7 (plagioclase)*	n.d.	+
5	S4.1								+	+
6	K-04-34/1	54°22′	087°32′	Babii Kamen', Tom' River, 11 km downstreams from Ust'-Naryk	basalt	Mal'tsevo Formation, T_1ml	Karakan Sill (eastern part)	n.d.	+	+
7	K-04-34/2				basalt			n.d.	+	n.d.
8	S10.1				basalt			n.d.	+	+
9	K-04-55	54°15′	087°06′	Kyrgai open pit	basalt	Mal'tsevo Formation, T_1ml	Kyrgai stratum-like body	n.d.	+	n.d.
10	S15.2				basalt			n.d.	+	+
11	FGS-8	54°19′	087°25′	2 km south of Osinovka Vil., 441 m a.s.l. hill (core sample)	basalt	Mal'tsevo Formation, T_1ml	Osinovka stratum-like body	250.7 ± 0.6 (plagioclase)*	n.d.	n.d.
12	Kp-13				basalt			n.d.	n.d.	+
13	FGS-1 (2K-2)	53°34′	087°47′	Mrassu left bank, Tatarka Vil.	gabbro	Balakhonskaya series, C_{2-3}bl–P_1^2bl$_2$	Syrkashev Sill	252.2 ± 0.5 (biotite)*	n.d.	n.d.
14	FGS-5 (Kzbs-7)	53°39′	088°01′	Krasnogorskii open pit	gabbro			252.3 ± 0.6 (biotite)*	n.d.	n.d.

The ^{40}Ar/^{39}Ar ages were obtained in the Massachusetts Institute of Technologies [Reichow et al., 2009]. ME - major elements; TE, trace elements including rare earths; n.d., no data.

zodiorite of the Syrkashev Complex, which subvolcanic/intrusive origin is out of doubt (Kutolin, 1963). The Syrkashev, Maizass and Makarive Sills are located southeast of the Bungorap trough and extended to several tens of kilometers along strike (Fig. 2). The sills are 100–130 m thick and surrounded by conjugated NW-striking steep dykes. The contact zones between the sills and hosting sediments show compact texture, sericitization, biotitization and epidotization. As can be seen from the geological maps (Fig. 2), these sills have a complicated shape and are conformable with the strike of their hosting Upper Carboniferous–Permian sediments.

The upper level is characterized by stratum-like bodies of basalts and hyalodolerites of the Saltymakov Complex (Fedoseev, 2004). These bodies are hosted by the Mal'tsevo and Yaminskaya Formations; they are exposed along the periphery of the Bungorap trough (Figs. 2, 3) and form topographically well expressed ridges. The basaltic bodies reveal little deformation and have visible thicknesses of tens to hundreds of meters. A lower basaltic body, Karakan Sill, occurs at the base of the Lower Triassic Mal'tsevo Formation and has been studied in details in the Karakan, Planernyi and Kyrgai open-pits (Fig. 3; Table 2). A further conformable basaltic body of unclear origin and stratigraphic position has also been studied in a core drilled near the Osinovka Village.

The Karakan open-pit is located 5 km north of Karakan Village, on the top of the Karakan Range, 1.5 km to the NW from the Planernyi open-pit (Fig. 3). In the open-pit, the basaltic body is exposed in its central and lower parts with a visible thickness of at least 50 m. The central party of the body is massive dolerite while its base consists of anamezite and typical basalt. In places, the basalts possess spheroidal amygdaloidal structure, and as well as columnar cleavage. All this is typical of volcanic rocks. Up to several meters thick zones with abundant opal, chalcedony and quart amygdales are typical. Nevertheless, no upper or lower contacts of the basaltic body can bee seen in the open-pit, and therefore we can not confidently define its volcanic or subvolcanic origin.

The Planernyi open-pit is located 800 m north-east of the Karakan open-pit, along the strike of the main ridge axis. It allows insight of the lower contact of the basaltic body: the relatively smooth surface of the contact is seen in an exposed face 15 m long and 3–4 m high (Fig. 4, *a*). There are no amygdales in basalts near the contact. The hosting sediments show no signatures of hot contact with basalts, which is typical of subvolcanic bodies. On the other hand, no signatures of heating of host rocks can be seen, which would be typical of extrusive volcanic lavas.

The Kyrgai open-pit is located 15 km south-east of the Planernyi open-pit (Fig. 3) and shows a 15–20 m thick stratum-like basaltic body, which is probably a part of the Karakan body. There, the subvolcanic nature of the basaltic body is evident thus allowing us to regard it as a sill. The

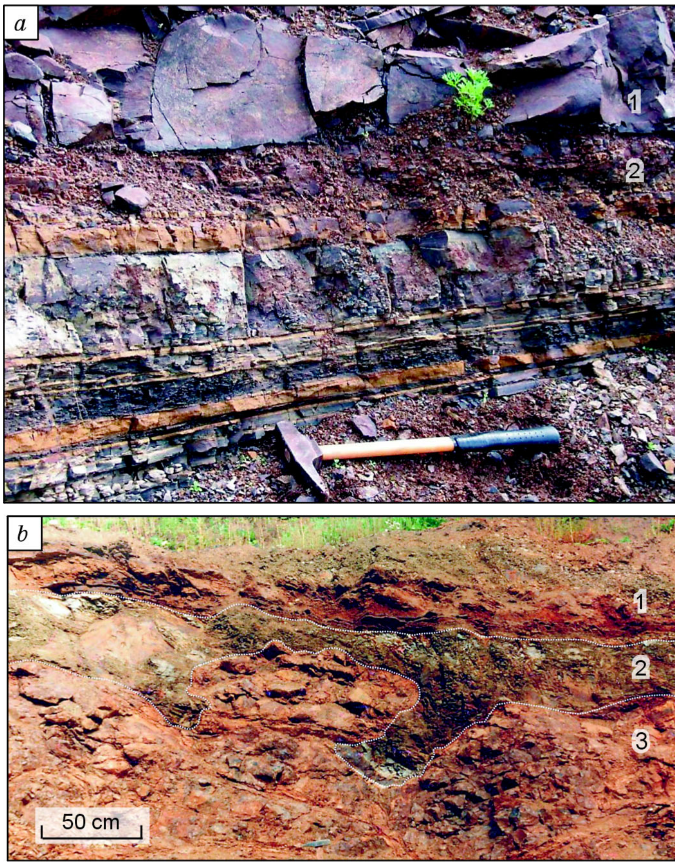

Fig. 4. Photos of contacts of stratum-like basaltic bodies. (*a*) The lower contact of the Karakan Sill (Planernyi open pit): 1, basalt; 2, alternated sandstone and mudstone. (*b*) The upper contact of the Kyrgai body (Kyrgai open pit: 1, medium-grained red sandstone; 2, lime-clayish grey mud-sandstone; 3, basalt.

hosting sediments are motley sandstones, mudstones and lenses of conglomerates. The upper contact of the basaltic body is seen in the western wall of the open-pit: a thin bed of gray sand-mudstone with carbonate-clay matrix envelopes numerous pods of basalts forming specific "wavy" pockets in the host sediments (Fig. 4, *b*). The upper contact of this bed is relatively smooth allowing us to suggest a kind of gravitational "flowing" of the carbonate-mudstone-sandstone material. The overlying bed of red-grey sandstones has a persistent thickness and shows no signs of deformation. Locally, it is cut by small strike-slip faults and folds. The overlying beds have monocline bedding. There are no signs of hot interaction between basalts and sandstones neither in the upper, not in the lower contacts. Amygdaloidal structures and secondary dykes are absent as well.

In the right bank of the Tom's the magmatic rocks are exposed at the "Babii Kamen'" Cliff and characterized by circular cleavage. The EW-striking hosting sediments dip at an angle of 20–25º. Neither upper, not lower clear contacts can be seen. A package of coal-bearing sandstones of the Middle Permian Yerunakovskaya Formation is exposed several meters below the suggested lower contact (Table 1).

For geochronological and geochemical studies the Karakan Sill was sampled in the Planernyi (samples S4.1; p. 1) and Kyrgai (samples K-04-5-5, S15.2; p. 2) open-pits. The "Babii Kamen'" Cliff was sampled as well: samples K-04-34/1, K-04-34/2, S10.1—p. 4). In addition, we studied the Osinovka drilled core: samples Kd-13, Kd-13a, 22, FGS-8 (p. 3). In the northern part of the Bungorap trough we sampled an outcrop at the Bychii Brook mouth, sample 28, p. 5 (Fig. 3). Samples FGS-1 and FGS-5 were taken outside the Bungorap trough, from the Syrkashev Sill, which is hosted by Upper Paleozoic sediments of the lower level (Fig. 2).

Petrography

The stratum-like bodies of the Saltymakov Complex are fine- to medium-grained dolerites and basalts consisting of plagioclase, clinopyroxene and volcanic glass. Relatively large phenocrysts of clinopyroxene with plagioclase laths and transitional to poikilophioltic textures are found in the central parts. Vice versa, the peripheral parts contain more glass and have pielotaxitic and hyaline textures similar to those of hyaldolerites and basalts. Very small spherical and intersertal amygdales are zonal or filled with radially arranged crystals. Linearly aligned agglomerates of 1–2 cm amygdales filled by chalcedony, quart and zeolite are present at the contact zones. The largest amygdales up to 15–20 cm in diameter have been found in outcrops of the Tom' left bank, upstream of Azhendarovo Village. The accessory minerals are fine-grained magnetite, ilmenite and rutile and the secondary minerals are albite, carbonate, epidote-zoisite, leucoxene and zeolite. In fine-grained and cryptocrystalline rock varieties, microlites and small phenocrysts of basic plagioclase and clinopyroxene compose up to 30 vol.% and are immersed into volcanic glass, which is partly or completely replaced by palagonite. Generally, the dolerites are special for a low degree of crystallization and have a monotonous appearance.

The Karakan Sill consists of black plagioclase-porphyric or, to a lesser degree, aphyric basalts. The contact zones are composed of vitreous rocks with abundant (up to 50 vol.%) amygdules up to 5–20 mm in diameter filled by chlorite, zeolite, calcite, opal, chalcedony and quartz. The inner parts of the sill are more crystallized and have microdoleritic and poikiloophitic textures. The phenocrysts are basic plagioclase, diopside and augite (up to 25–30%), and less often—strongly altered olivine. The weakly altered transparent glass (10–15 vol.%) is brown-grayish and contains laths of plagioclase and microlites of pyroxene, ilmenite and Ti-magnetite.

The tuffs and tuffites consist of fine fragments of plagioclase, K-feldspar, quartz, pyroxene and hydromicas (Lavrenov et al., 2008a,b) with a chlorite-zeolite-calcite matrix.

Analytical methodology

For geochemical studies samples were chosen from the least deformed and altered flows and dykes with the minimum amounts of veinlets and amygdales. Samples S4.1, S10.1, and S15.2 (Table 3) were analyzed in the University of Leicester, UK. The samples were ground in a Tema agate mill. Major and trace element data were obtained on fusion beads and powder pellets, respectively, by X-ray fluorescence analysis using a Philips PW1400 multi-component mass-spectrometer with an anode voltage of 3kW at the University of Leicester. The analyses were performed by standard methods as described by Harvey et al. (1996). To improve precision for elements such as Ba, Rb, Nb, Ni, V, Y and Zr, these elements were determined by XRF using long counting times; this procedure both lowered the detection limits (Ba 4 ppm, Rb 0.5 ppm, Nb 0.4 ppm, Ni 0.8 ppm, V 1 ppm, Y 0.5 ppm, Zr 0.5 ppm) compared to normal counting statistics and resulted in a precision better than 1%. Calibrations were set using internal and international rock reference material (e.g., BCR-1, BHVO-1, W-2). Rare earth elements (REE) were pre-concentrated using ion exchange columns; these solutions were then analyzed on a JY-Ultima-2 IC OES (inductively coupled optical emission spectrometer) at the University of Leicester, UK. The rest of the geochemical analyses included in data processing (samples K-04-34/1, K-04-34/2, Kd-13, Kd-13a, 22, 28) were obtained in the Institute of Geology and Mineralogy SB RAS, Novosibirsk (IGM SB RAS). Major

Table 3. Major oxides, wt %, and trace elements, ppm, in basalts of the Kuznetsk Basin and other localities of western and eastern Siberia

Component	S10.1	S4.1	S15.2	WSB-1	WSB-2	WSB-3	Syv	Iv	Nad
SiO_2	53.22	54.29	54.30	48.32	51.66	49.44	52.58	50.63	52.03
TiO_2	1.79	1.76	1.82	1.25	1.28	1.26	1.71	2.75	0.99
Al_2O_3	14.34	14.63	14.75	15.33	15.30	15.47	15.67	15.21	15.99
Fe_2O_3	12.27	12.27	12.29	12.87	11.36	11.93	10.91	13.85	10.40
MgO	3.82	3.78	4.04	6.66	5.46	6.41	6.34	3.93	6.48
CaO	7.96	7.48	7.56	10.13	6.66	6.23	7.79	6.94	10.41
Na_2O	3.88	3.74	4.12	2.92	3.19	3.99	3.37	3.47	2.32
K_2O	0.89	1.71	0.97	0.55	2.01	1.77	1.22	2.07	1.11
P_2O_5	0.53	0.53	0.54	0.16	0.48	0.33	0.26	0.93	0.12
MnO	0.24	0.24	0.25	0.20	0.18	0.17	0.15	0.21	0.16
L.O.I.	1.32	1.13	1.19	2.74	3.29	3.80	n.d.	n.d.	n.d.
Total	100.3	101.6	101.8	101.1	100.9	100.8	n.d.	n.d.	n.d.
Mg#	39.7	39.5	41.0	52.3	50.4	53.2	56.6	38.7	58.2
Eu/Eu*	0.9	0.9	0.9	0.86	0.85	0.90	0.98	0.83	0.84
Ba	607.2	652.3	711.2	375	1236	1174	440	945	467
Nb	15.5	14.2	16.0	5.3	8.8	9.3	16.41	33.28	9.68
Rb	28.9	47.9	23.3	10.6	35.9	27.8	29.65	43.24	31.06
Sr	519.0	537.8	528.6	353	768	878	377	429	275
Y	48.3	49.2	48.8	32.1	39.9	39.3	20.6	27.2	49.18
Zr	240.9	245.5	244.9	91.8	171.1	159.1	200	351	125
La	33.3	33.0	33.0	13.0	25.8	22.3	23.1	49.0	16.5
Ce	74.4	76.4	74.2	20.0	56.2	51.6	50.2	108.6	35.6
Pr	8.5	8.6	8.3	2.7	7.2	5.9	5.8	11.7	3.9
Nd	39.8	40.4	39.1	12.0	33.5	25.2	25.5	54.0	17.3
Sm	7.9	8.1	8.0	3.4	7.4	6.3	5.7	11.1	3.9
Eu	2.1	2.2	2.2	1.1	2.0	1.8	1.8	3.0	1.1
Gd	7.1	7.0	7.1	4.5	6.4	5.8	5.4	10.3	4.0
Dy	6.5	6.7	6.7	5.0	6.2	6.2	4.9	8.8	4.0
Er	3.8	3.9	3.9	3.2	3.9	3.3	2.6	4.6	2.4
Yb	4.2	4.2	4.0	3.3	3.7	3.6	0.4	0.7	0.4
Lu	0.4	0.4	0.4	0.5	0.6	0.6	2.4	4.3	2.3
Nb/Zr	0.06	0.06	0.07	0.06	0.05	0.06	0.08	0.09	0.08
Ti/Zr	44.4	43.0	44.5	81.6	44.8	47.6	51.3	47.1	47.6

Notes. S10.1, S4.1, and 15.2, the Kuznetsk Basin; WSB-1, WSB-2, and WSB-3, western Siberia; Syv (av.), Iv (av.), and Nad (av.), eastern Siberia (average contents, after Reichow et al. (2005)); n.d., no data; Mg# = (MgO/40)/(FeO/72 + MgO/40)·100; FeO = $0.85Fe_2O_3$. Eu/Eu* is calculated after Taylor and McLennan (1985).

element contents were measured by XRF using a Nauchpribor spectrometer following State Standard (GOST) 41-08-212-82 of the Ministry of Geology of the USSR. Standard deviations were within 5% with totals $100 \pm 1\%$. The contents of trace elements, including rare earth elements (REE), were determined by INAA using Ge detectors for gamma-rays with energies from 30 to 2000 keV. The samples were radiated in the nuclear reactor of the Tomsk Polytechnic University by an integral flux of 10^{17} neutrons/cm^2. The measurements were made using a gamma-spectrometer in two stages with cooling periods of 1 week and 3 months.

Geochronology specimens were chosen on the basis of lack of visible alteration in thin section. The geochronological data were obtained in the Massachusetts Institute of Technology, USA (Table 2, Fig. 9). For analytical details and data see (Reichow et al., 2009).

Petrochemistry and geochemistry of basalts

Analyses of 12 representative samples of Kuznetsk basalts and gabbro-dolerites (for sample locations see Table 2 and Fig. 3) are listed in Table 3 and illustrated in Figs. 5–8. Table 3 shows full sets of major and trace elements for three selected samples of the Karakan Sill: S4.1, S10.1, S15.2. The samples have relatively stable chemical composition and are subalkaline potassium-sodium basalts and high-Na vs low-Al tholeiites (see also Kruk et al., 1999; Kutolin, 1964). In general, the Kuznetsk basalts are characterized by medium TiO_2 and high P_2O_5 and alkalies content (Table 3).

Figures 5–8 illustrate the geochemistry of basalts from the Kuznetsk Basin and other localities of Permian–Triassic magmatism: 1) the West Siberian Basin, samples WSB-1, WSB-2, WSB-3 contain averaged concentrations of elements, from core samples from of the Yarainer, Tagrinsk and Saemtagskaya Formations of the Urengoi rift, respectively (Reichow et al., 2005); 2) the Noril'sk area of the Siberian Traps, samples from the Ivakino (Iv), Nadezhdinsk (Nad) and Syverma (Syv) Formations (Reichow et al., 2005); 3) the Kuznetsk Basin, high-Ti basalts K-53m and K-53t (Kruk et al., 1999); 4) eastern Mongolia and Transbaikalia—sample VM-Zab from (Yarmolyuk and Kovalenko, 2003); 5) North-Mongolian rift system—medium-Ti (SM-1) and high-Ti (SM-2) basalts from (Yarmolyuk et al., 1999).

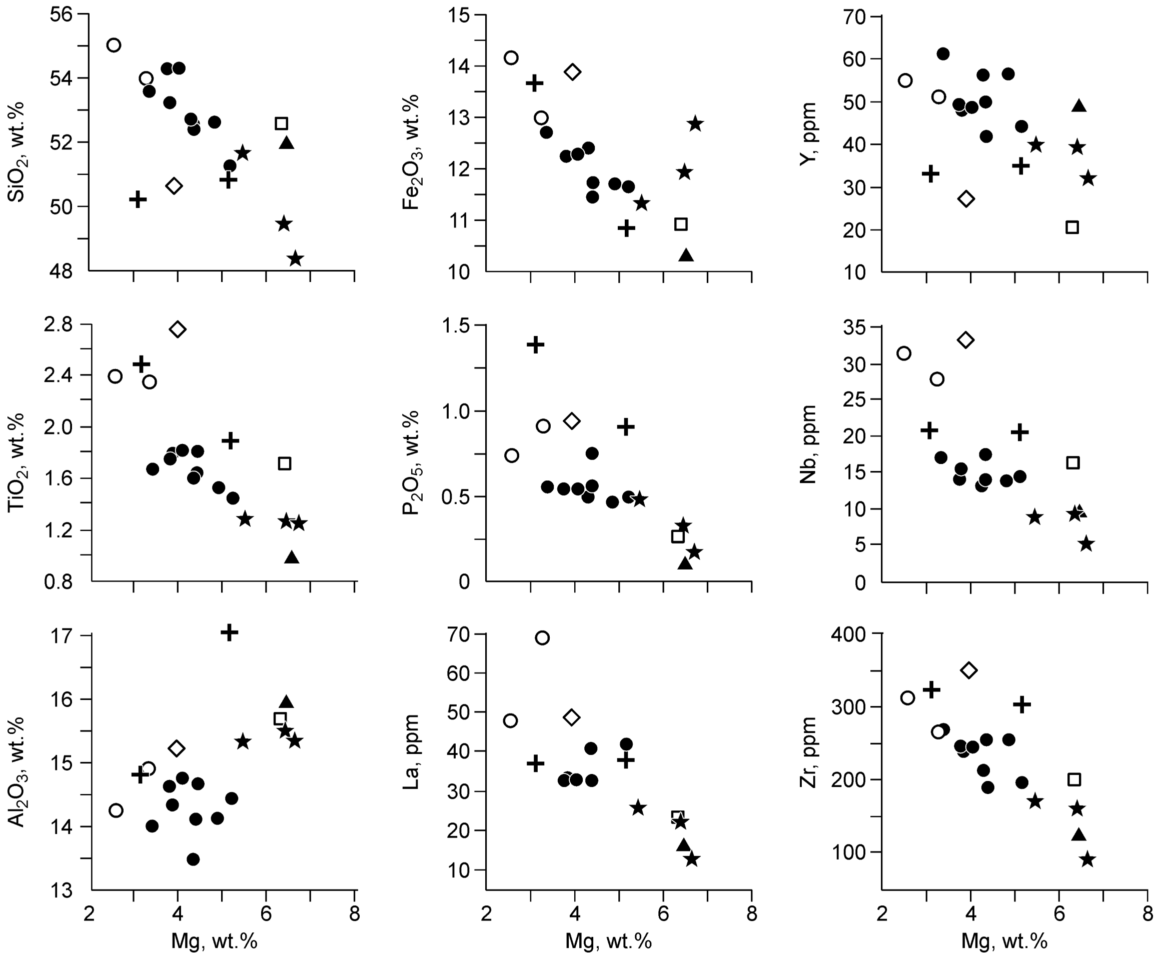

Fig. 5. Major oxides and trace elements versus MgO in basalts of the Kuznetsk Basin (dots), western Siberia (stars; WSB) and eastern Siberia: Nadezhdinsk Formation (triangles), Syverma Formation (squares), and Ivakino Formation (diamonds), after Reichow et al. (2005) and northern Mongolia (crosses) after (Yarmolyuk et al., 1999, 2002) (see also comments in the text "Petrochemistry and geochemistry").

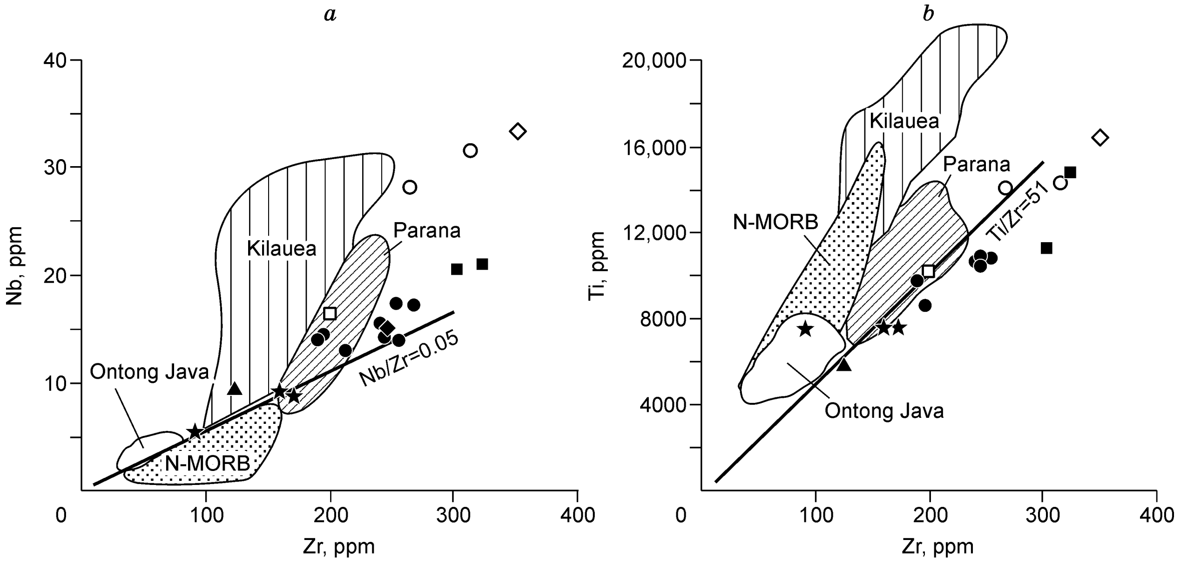

Fig. 6. (*a*) Nb vs. Zr and (*b*) Ti vs. Zr in basalts of the Kuznetsk Basin (dots), western Siberia (stars) and eastern Siberia: Nadezhdinsk Formation (triangles), Syverma Formation (squares), and Ivakino Formation (diamonds) in comparison with Parana, Kilauea, Ontong Java Plateau, and N-MORB fields, after Reichow et al. (2005).

The concentrations of major oxides recalculated to water-free are not widely ranging: SiO_2 spans 51.2 to 53.6; MgO = 3.4–5.2, Fe_2O_{3tot}—11 to 13 wt.%; Mg# = 35–45. The Kuznetsk basalts are less magnesian compared to their "Siberian" analogues, an observation which has been discussed in details in many papers (e.g., Al'mukhamedov 1998, 1999a; Reichow et al., 2005). The concentration of TiO_2 varies from 1.45 to 1.81 wt.%; P_2O_5 = 0.47-0.74 wt.% (Fig. 5) and Al_2O_3 is relatively constant - about 14 wt. %, i.e., below the average value of 17 wt.% for West Siberian basalts. The Kuznetsk basalts are differentiated: #Mg decreases with increasing SiO_2, TiO_2, Fe_2O_3 and Zr; they are characterized by high SiO_2, medium TiO_2, Fe_2O_3, P_2O_5, La, Nb, Zr low Al_2O_3, and compositionally (but not by all elements!) closer to those from the North-Mongolian and Urengoi rifts (Fig. 5).

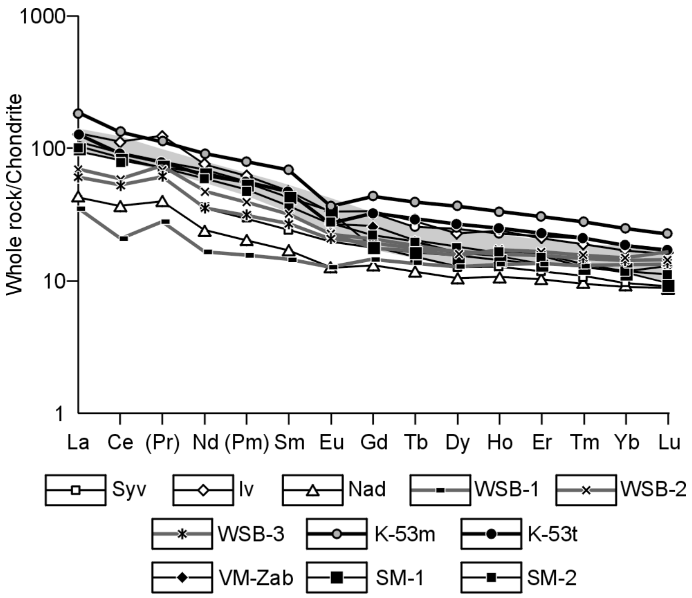

Fig. 7. Chondrite-normalized REE patterns of basalts from the Kuznetsk Basin (grey field). The data for basalts from western Siberia (WSB) and eastern Siberia: Nadezhdinsk Formation (Nad), Syverma Formation (Syv), and Ivakino Formation (Iv), OIB, and N-MORB are presented for comparative purpose, after Reichow et al. (2005). The normalizing values are from (McDonough and Sun, 1995). See comments in the text.

Niobium (14–17 ppm) but not Y (41–50 ppm) shows an increase with decreasing MgO (Fig. 5). The ratio of Nb/Zr (0.05-0.07) is slightly higher than that in basalts of West Siberia and Ontong Java plateau (Table 3, Fig. 6, *a*) (Mahoney et al., 1993; Reichow et al., 2005). The Kuznetsk basalts data plot in the field of Parana basalts in the Zr vs Nb plot (Fig. 6, *a*) and near the Ti/Zr = 51 line in the Zr vs Ti plot (Fig. 6, *b*). Ti/Zr ratios range from 42 to 51, i.e., lower than that of Parana and Nadezhdinsk basalts (Fig. 6, *b*) suggesting different mantle sources, degrees of melting and, possibly, a higher content of Ti-magnetite in the melt. The Kuznetsk basalts have HFSE concentrations close to those in basalts of the Syverma Formation (Siberian Traps) and North Mongolian rift zone (Reichow et al., 2005; Yarmolyuk and Kovalenko, 2003).

The chondrite normalized REE spectra (Fig. 7) of Kuznetsk basalts are similar to those of basalts of the Syverma Formation and North Mongolia and Transbaikalia: they are LREE enriched (La/Sm_n = 2.4–2.5) and have weakly differentiated heavy REE (Sm/Yb_n = 2.3–1.9). The low Eu/Eu* (0.68–0.71) suggest fractionation of plagioclase from the melt (Table 3; Fig. 7). The medium to low Gd/Yb_n (1.4–2.0) in basalts of Kuzbass and other regions are indicative of a mantle source within the spinel zone.

The multi-element spectra normalized to the primitive mantle or BSE (bulk silicate earth) (McDonough and Sun, 1995) of basalts from the Kuznetsk basin and other regions are characterized by increased LILE (Ba, Rb and K) compared to relatively immobile HFSE (Zr, Ti, Y), and negative anomalies at Nb, Ti and Sr (Fig. 8).

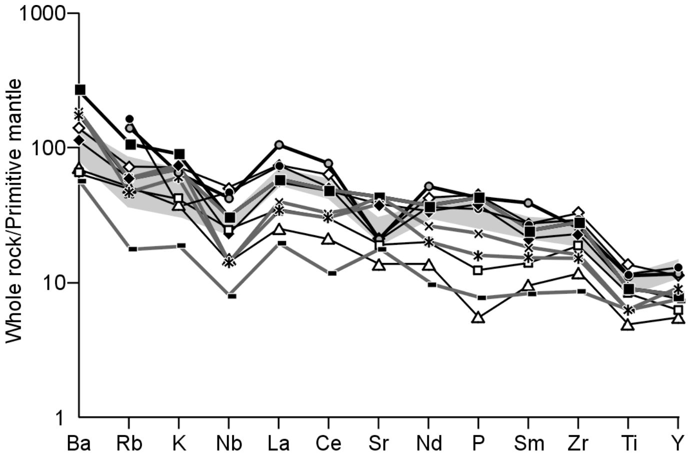

Fig. 8. Primitive mantle normalized multi-component patterns of basalts from the Kuznetsk Basin (grey field) and other regions. The normalizing values are from (McDonough and Sun, 1995). Symbols as in Fig. 7 and see comments in the text.

Geochronology

The first $^{40}Ar/^{39}Ar$ data for Kuznetsk basalts were obtained in the IGM SB RAS. Amphibole ages of 246.2 ± 1.4 and 249.0 ± 1.8 Ma for the Syrkashev Sill (Fedoseev, 2004) are close to the Permian–Triassic boundary. The new plagioclase and biotite $^{40}Ar/^{39}Ar$ ages were obtained in the Massachusetts Institute of Technology and briefly reported in (Reichow et al., 2009) (Table 2; Fig. 9). Fig. 3 shows the position of these sampling points. The plagioclase separate from sample S4.1, the Karakan Sill, yielded a plateau age of 250.3 ± 0.7 Ma. Sample FGS-8 from the Osinovka drill core provided a concordant age of 250.7 ± 0.6 Ma also from plagioclase. The biotite ages of samples FGS-1 and FGS-5 from the Syrkashev Sill are 251.5 ± 0.3 and 250.6 ± 0.4 Ma, respectively. All these ages correspond to the uppermost Permian. For the details of heating experiments and calculations see (Reichow et al., 2009).

Discussion

Types of magmatic bodies

A very important yet unsolved problem of Kuznetsk traps is their origin: volcanic or subvolcanic. Many researchers have pointed out the difficulty in differentiating lavas flows from sills (e.g., Luchistkiy, 1960; Sobolev, 1936, 1986), however in practice the conclusions has been that the majority are volcanically derived (lava flows). A reason for this could be several special criteria, such as vitreous texture, amygdaloidal structure, association with tuffs, absence of secondary (daughter) dykes, columnar cleave, etc., which have long time been regarded as typical features of volcanic, not subvolcanic, bodies (Boulter, 1993; Krasnov and Fedoseev, 2000; Menyailov, 1962; Raymond and Murchison, 1988; Shuzhanov and Sergieva, 1991).

Most of the walls in open-pits of the Kuznetsk basin show lower contacts of mafic bodies, which are commonly parallel to the bedding of the underlying sediments (Fig. 4, *a*). Such a feature is seen in many exposures located several kilometers apart and suggests rather “hot” than “cold” contact. Besides, the rocks are characterized by the absence of voids and amygdules at the contact and by the presence of layered segments, compositionally analogous to contact rocks, at a distance away from the contact. The absence of bubble textures and unbroken bedding suggest a limited presence of gaseous phase in magma and relatively slow/calm movement of melt.

The upper contacts of basalt-dolerite bodies are poorly seen in natural exposures, including river banks where they are covered by modern sediments. We studied the only clear upper contact in the Kyrgai open-pit (Fig. 4, *b*), which is characterized by a strongly wavy surface with a lot of both basaltic and sedimentary bays, pockets and swells. The largely variable thickness of the bounding sedimentary bed, 0 to 1.5 meters, indicates the “flowing” of carbonate-mudstone-sandstone material during melt intrusion. Later, post-magmatic tectonic movements probably resulted in the wedging out of this bed. No signatures of significant “hot” effect of basalts on sedimentary rocks and no secondary dykes have been found. Therefore, we suggest that those near-contact macro-textures resulted from a strong flow of magma, which, on the last stage of sill formation, was followed by small-scale brittle deformation, which affected both the basalts and the hosting sedimentary rocks. The volume of magma and its temperature were probably not enough to “detach” it from the main body and this led to formation of the wavy\sinuous surface of sill upper contact.

More evidence for the sill nature of basaltic rocks comes from the two parallel basalt stratum-like bodies, which trace the contour of the Bungorap trough (Fig. 3). Moreover, the dolerite-basalt body in the northwestern part of the Bungorap trough splits into two, that is also indicative of its subvolcanic origin.

On the other hand, we must admit that the thermal effect of Kuzbass sills on the sedimentary rocks is much lower than is usually expected for intruding basic magmas. Probably, this is an exotic case typical of shallow and thin sills only (Krasnov and Fedoseev, 2000). Many researches of Kuzbass mentioned the apparent low thermal effect and used it as a vital argument in favor of the volcanic origin of Kuzbass traps (Neiburg, 1940). Several geologists, e.g., M.A. Usov (1935) and V.A. Khakhlov (1935), also supported the idea of volcanic eruptions. Later, A.M. Kuzmin (1969) presented an idea about the intrusive nature of the Kuzbass traps, which suggested a laccolite with several stratum-like satellites in the place of the formerly proposed volcanic edifice. All those researchers regarded the absence of exogenic or post-magmatic crust, which usually cover lava flows, as a main argument of subvolcanic origin of traps, i.e., sills.

The internal structure and rock assemblages of the Late Permian Karakan Sill indicate magma intrusion at depths of several hundred meters, possibly, into water-saturated rocks,

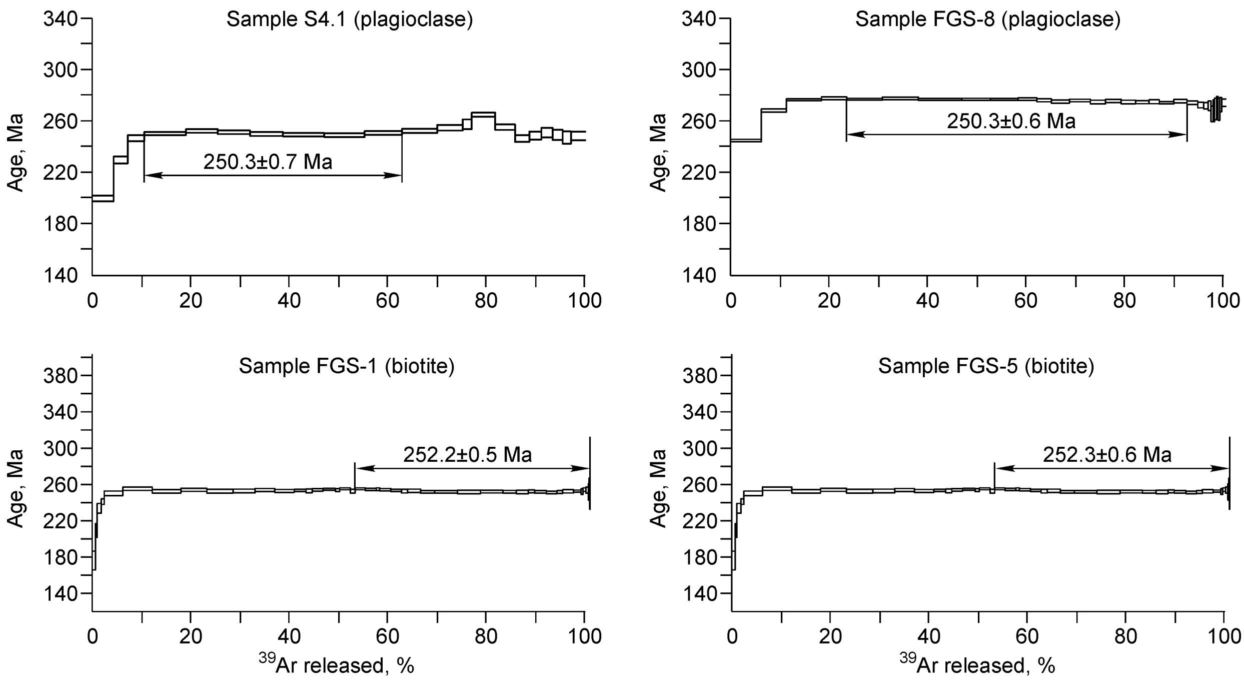

Fig. 9. $^{40}Ar/^{39}Ar$ ages of Kuznetsk basalt and gabbro obtained in the Massachusetts Institute of Technologies (Reichow et al., 2009).

which resulted in pressure-affected rapid cooling and quenching. The Late Permian Syrkashev Sill consists of gabbro-dolerite and monzo-diorite, which are geochemically and geochronologically comagmatic to the Late Permian sills of the Saltymakov complex. But the Saltymakov sills are hosted by Upper Carboniferous-Lower Permian sediments and occur at depths of several kilometers.

The wide occurrence of tuffs in the Abinskaya Series suggests a paleo-volcano. More evidence for this idea comes from the geological and geophysical data from geological survey reports (e.g., Lavrenov et al., 2008a,b). The proposed volcano is recorded by a gravitational anomaly in the northern Bungorap trough and by the maximal thickness of the Abinskaya Series (up to 2000 m), which there includes seven stratum-like basaltic bodies up to 103 meters thick each. The thickness of the tuff-sedimentary sequences abruptly decreases to zero away from the proposed volcano. The Jurassic sediments overlap the Permian deposits in the southern and northern parts of the Kuznetsk Basin suggesting a volcanic construction rather then an extended plateau. The clastic material of the Jurassic terrogeneous rocks contain products of basalt alteration (Kutolin, 1963; Lavrenov et al., 2008a,b), which could have been derived from the paleo-volcano material.

The Abinskaya Series consists of coarse-clastic alluvial deposits in its lower and upper parts, Mal'tsevo and Yaminskaya Formations, respectively, and tuff-bearing basin sediments with lime matrix in the middle part (Mal'tsevo and Sosnovka Formations). The varying thickness and the facial diversity of Abinskaya beds both suggest subsidence of the Kuznetsk Basin in Triassic time, which is also recorded by the beginning of the Late Permian plume-related magmatism. During the Triassic, the basin probably was an extension structure, which developed coevaly with the formation of the riftogenic structures currently present in the basement of the West Siberian sedimentary basin (Fig. 1).

The paper has presented the geological, lithological, stratigraphic, geochronological and petrological-geochemical data, which are indicative of the occurrence of basaltic sills, i.e., subvolcanic bodies, in the Abinskaya Series on one hand, and suggest a paleovolcano on the other hand. To come to a conclusion on the type of basaltic emplacement we need to perform a detailed study of core samples of Abinskaya Series tuff-sedimentary rocks and their hosted basalts in the northern Bungorap trough. Special attention should be paid to contacts and thicknesses of basaltic bodies and their geochronological dating.

Interpretation of geochemical data

According to previous investigators (Kruk et al., 1999; Kutolin, 1963) the Kuzbass basalts are geochemically transitional between tholeiitic and subalkaline. They are dominated by olivine-normative (5–8%) and quart-normative (2–11%) tholeiites; $SiO_2 = 48–49.5\%$ and 51.3–53.5%, respectively. The Triassic basalts of the Urengoi Rift in the basement of the West Siberian Basin and of the North-Mongolian rift system possess similar geochemical characteristics (Fig. 5). Compared to the East Siberian flood basalts, the Kuzbass traps have higher silica, phosphorus, alkali and iron (Al'mukhamedov et al., 1998, 1999a; Kruk et al., 1999). Figs. 5 and 6 show two groups of Kuzbass basalts, which are characterized by different concentrations of TiO_2, Fe_2O_3, La, and Nb. We suggest that the lower-Ti group, which also has lower Fe_2O_3, La and Nb, was contaminated by continental crust material. More evidence for this idea comes from higher than average Th concentrations in the low-Ti group compared to the high-Ti one (Table 3) (Kruk et al., 1999; Puchtel et al., 1997).

The primitive mantle normalized multi-component diagrams are characterized by negative anomalies at Nb, Ti and Sr (Fig. 8). Since the continental crust is generally depleted in Nb and Ti (McDonough and Sun, 1995), the Nb and Ti negative anomalies can be due to crustal contamination. On the other hand, Nb and Ti are compatible with Ti-magnetite, and therefore its crystallization at high oxygen fugacity conditions could have resulted in those anomalies. However, the latter case is less probable because the concentrations of Ti in Kuzbass basalts is much higher than those in subalkaline and calc-alkaline island-arc basalts (Frolova and Burikova, 1997), which form at a high oxygen fugacity achieved during melting of subducted oceanic slab containing water-rich minerals (Figs. 5, 8; Table 3). The Sr anomalies can be due to fractional crystallization of plagioclase in an intermediate chamber. Secondary alteration processes as a factor of low Sr concentrations are less probable, because Kuzbass basalts are relatively fresh and have rather lower L.O.I. (wt.%) compared to those of the West Siberian Basin (4-5 wt.%). The contamination of basaltic magmas by continental crust material is quite probable due to a combination of low Nb and high La/Sm_n (2.45), Th/Ta (5.3–6.5), Th/Ce (0.6) and Th (4.4–11) (Figs. 7, 8; Table 3) (Arndt and Jenner, 1986; Puchtel et al., 1997).

Our obtained new data on the major and trace element composition of Kuzbass basalts are indicative of their similarity to plateaubasalts (low MgO, negative anomalies at Nb and Ti in the multi-component spectra; Fig. 8), medium-Ti basalts of the Syverma Formation of the East Siberian flood basalt province, which are located in the middle part of the Norilsk section, and to the basalts of the Urengoi rift (West Siberian Basin) and North-Mongolian rift system.

Age of magmatism and position of the Permian–Triassic boundary in the Kuznetsk Basin

Our obtained and the recently published data show that the magmatism in Kuzbass was active in the Late Permian–Middle Triassic and was related to a mantle plume (Kruk et al., 1999; Reichow et al., 2009). We compared the age and geochemical composition of Kuzbass basalts, dolerites and gabbros and suggested that they all are related to a global event at the Permian–Triassic boundary, which affected a huge territory of East and West Siberia, Southern and Polar Ural, Taimyr, Mongolia and Transbaikalia. Most researchers agree that the Permian–Triassic basalt eruptions were the largest event of continental magmatism during the whole history of the Earth, which resulted in abrupt climatic changes and their related mass extinction of biota in that vast region (Erwin, 1994; Wignall, 2001).

Before interpreting the obtained geochronological data we should discuss the precise age of the Permian–Triassic boundary. In the International Stratigraphic Chart, which was ratified by the International Commission on Stratigraphy, this boundary is shown at 251.0 ± 0.4 Ma based on the U-Pb dating of zircons from Meishan Beds 25 and 28 bracketing the Permian–Triassic boundary (Gradstein et al., 2004). On the other hand many authors mentioned divergences between the age data obtained for the same layers by the U-Pb and Ar-Ar methods (Reichow et al., 2009 and the references therein). This paper presents the $^{40}Ar/^{39}Ar$ ages and therefore we will compare them with the data on the Meishan Beds 25 and 28 obtained by the $^{40}Ar/^{39}Ar$ method. The recent $^{40}Ar/^{39}Ar$ data place the Permian–Triassic boundary at 249.25 ± 0.14 Ma (Reichow et al., 2009) or at 249.83 ± 0.15 Ma (Renne et al., 1995). The mean average of those two values is 249.54 ± 0.14 Ma

Thus, if we accept the $^{40}Ar/^{39}Ar$ Permian–Triassic boundary of 249.25 ± 0.14, the basaltoids of the Karakan Sill hosted by the lower Abinskaya Series, are Upper Permian because they yielded an age of 250.3 ± 0.7 Ma. Moreover, we must remember that the age of sill is in any case younger than the age of hosting sediments. Therefore, the proposed Permian–Triassic boundary in the Kuzbass stratigraphic column should be revised because, accordingly as the base of the Abinskaya Series (i.e., the Permian–Triassic boundary) is placed 250–300 m below the sill. Our obtained geochronological data and the structural position of Karakan subvolcanics suggest that the Permian–Triassic boundary in the stratigraphic scale of the Kuznetsk Basin can be moved to an upper horizon of the Mal'tsevo Formation, i.e., over the Karakan Sill (Table 1). However, to prove/disprove this proposal more geochronological studies will be necessary.

Structural position and age analogues of Kuznetsk Basin plume-related magmatism in Southern Ural and Northern Mongolia

The 252–248 Ma isotopic age of Kuzbass sills (lower Abinskaya Series) matches the Late Permian–Early Triassic age of the Siberian Flood Basalts (East Siberia) and riftogenic basalts of West Siberia. The upper Abinskaya Series includes pyroclastic rocks and several basaltic flows, which stratigraphically are of equivalent to the Middle Triassic age of riftogenic volcanic rocks in Southern Ural (Ivanov, 1974; Tuzhikova and Kurbezhekova, 1973) and northern Mongolia (Vorontsov et al., 2007; Yarmolyuk and Kovalenko, 2003; Yarmolyuk et al., 1999, 2002).

The occurrences of Late Permian–Middle Triassic magmatic units of Kuzbass and Southern Ural are located around the frame of the East Siberian Flood Basalt Province and at the extension of basement rifts of the West Siberian sedimentary basin (Fig. 1). The basaltic magmatism of the Chelyabinsk graben (Southern Ural) (Ivanov, 1974; Tuzhikova and Kurbezhekova, 1973) resulted in multiple on-land fissure eruptions of linear type with subordinate subvolcanic sill intrusions and formation of tuffs and tuffites. The thickness of the volcanogenic-sedimentary sequence in the central part of the graben reaches 1000 meters and decreases to the west and east. The sequence is located at the base of a Late Triassic coal-bearing sedimentary section. Its Early-Middle Triassic age is constrained from abundant occurrences of palynological complexes and flora remnants. The basaltic bodies from the Chelyabinskaya-7 borehole sampled at depths of 254 and 696.4 meters yielded $^{40}Ar/^{39}Ar$ age of 243.3 ± 0.6 and 242.1 ± 0.6 Ma, respectively (Reichow et al., 2009). Those isotopic ages can match the biostratigraphic data in two cases: 1) if the upper body is a flow and the lower body is a sill or 2) if both bodies are sills. Thus, the geological, biostratigraphic and isotopic age data on South Ural basalts suggest an Early-Triassic event of plume-related magmatism.

Other occurrences of Early–Middle Triassic volcanic units are located in the North-Mongolian rift zone (Vorontsov et al., 2007; Yarmolyuk and Kovalenko, 2003; Yarmolyuk et al., 1999, 2002), which is extended to a distance over 2000 km from the Mongolian Altay in the west to the Vitim plateau in the east (Fig. 1). It consists of a system of depressions and grabens and their separating uplifts and horsts. These structures have been strongly eroded and the rift zone itself is surrounded by occurrences of magmatic rocks.

There are several depressions/trough in Northern Mongolia, which are filled by Early Mesozoic sedimentary-volcanogenic rocks (Vorontsov et al., 2007; Yarmolyuk et al., 2002). The largest Orkhon trough is 150 by 120 km in size, i.e., comparable with the Bungorap trough in the Kuznetsk Basin. The Orkhon trough consists of the Abzog (lower) and Mogod (upper) Formations. The lower formation consists of conglomerate, sandstone and mudstone with Middle-Late Triassic flora. The upper formation is connected with the lower one by gradual facies transition and is dominated by basic and andesitic volcanogenic rocks. The volcanics are trachyandesibasalt (pyroxene and pyroxene-plagioclase porphyric varieties), with rare basalt, trachyandesite and trachyte. The thickness of the volcanogenic-sedimentary sequence reaches 2500 meter in the Urtyngol graben. Locally, there are horizons of pillow-lavas with hyaloclastic matrix, which indicate underwater eruptions. The pillow-lavas alternate with red agglomerates and porous subaerial lavas. The Bat-Tsengel trough is 15 by 30 km in size and filled by a 1200 meters thick volcanogenic section: lavas of pyroxene and pyroxene-plagioclase porphyric volcanics and, to a lesser degree, tuffs. The Upper-Khonui trough includes a 30 by 30 km field of volcanic rocks: lavas and tuffs overlap the Early Mesozoic weathering crust and compositionally are similar to the Late Triassic volcanics of the Bat-Tsengel trough (Map of Geological Formations , 1989).

Conclusions

The geological and stratigraphic data on sedimentary rocks and geochemical and geochronological data on magmatic rocks of the Kuznetsk Basin indicate that mafic sills and dykes formed during a period from 252 to 248 Ma, and the whole section of the Late Permian (?)–Early Triassic Abinskaya Series contains abundant volcano-clastic and volcanogenic-sedimentary rocks as well as stratum-like basaltic bodies of unclear origin (volcanic versus subvolcanic).

The basalts are medium-high-Ti tholeiites, which are enriched in Nb and La and compositionally close to the Early Triassic basalts of the Syverma Formation of the East Siberian Flood Basalt province, to the Urengoi Rift in the West Siberian sedimentary basin and to the Triassic basalts of the North Mongolian rift system. Evidence for their formation in relation to mantle plume activity comes from a combination of negative Nb anomalies in the primitive mantle normalized multi-component diagrams ($Nb/La_{pm} = 0.34–0.48$) and high LREE ($La_n = 90–115$, $La/Sm_n = 2.4–2.6$). The low to medium degrees of HREE fractionation ($Gd/Yb_n = 1.4–1.7$) suggest a spinel facies mantle source.

The composition and age of the studied rocks confirmed the previous hypothesis about the structural and temporal link of Kuzbass basaltic traps with the voluminous eruption of trap basalts in Permian–Triassic time resulting from the Siberian superplume. The variable thickness and lithological composition of the Late Permian(?)–Early Triassic Abinskaya Series suggest its formation in a paleovolcano setting.

Thus, the Late Permian–Early Triassic plume-related magmatism of the Kuzbass can be compared with the formation of the Late Permian–Middle Triassic volcanogenic-sedimentary sequences of the southern Urals and northern Mongolia, which all are indicative of magamtism in an extensional setting. The age of plume-related magmatism changes from Late Permian–Early Triassic in West Siberia, through Late Permian–Middle Triassic in southern Ural and Kuzbass to Triassic in northern Mongolia. Such a tendency can be explained by surface manifestation of the Siberian superplume over the northward migrating Eurasian plate and magmatism localization within strike-slip related extension zones (Allen et al., 2006). Those large-scale strike-slip faults were abundantly formed in the folded area separating the East-European and Siberian continents, which resulted from their Late Paleozoic collision (Buslov et al. 2003, 2004; Dobretsov and Buslov, 2007; Hetzel and Glodny, 2002; Laurent-Charvet et al., 2003).

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