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^{40}Ar/^{39}Ar dating of Usol'skii sill in the south-eastern Siberian Traps Large Igneous Province: evidence for long-lived magmatism

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ABSTRACT

Main part of the Siberian Traps Large Igneous Province was formed in a short time-span at the Permo-Triassic boundary *c.* 250 Ma. New ^{40}Ar/^{39}Ar dating results for the Usol'skii dolerite sill in south-eastern part of the province indicate its probable emplacement *c.* 6 Myr after the main Permo-Triassic magmatic phase. Compilation of the published ^{40}Ar/^{39}Ar and U-Pb ages implies that basaltic and related magmatism lasted in total as long as 22–26 Myr. Therefore, similar to other large igneous provinces, magmatism of the Siberian Traps combined voluminous short-lived and less prominent long-lived events.

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Introduction

The Siberian Traps Large Igneous Province (STLIP), comprising volcanic and intrusive rocks from the Siberian Platform and the West Siberian Basin (Fig. 1), is the most voluminous ($>10^6$ km^3) among known Phanerozoic large igneous provinces. Tholeiites and alkali basalts with subordinate ultrabasic alkaline, intermediate and acidic rocks make up the STLIP. There has been a long-term debate whether these rocks originated because of impingement of a mantle plume on the base of the lithosphere (Campbell *et al.*, 1992; Lightfoot *et al.*, 1993; Basu *et al.*, 1995; Dobretsov, 2003; Vernikovsky *et al.*, 2003), melting of the lithosphere during passive continental extension without any plume (Zorin and Vladimirov, 1989; Puffer, 2001) or extraterrestrial body impact (Jones *et al.*, 2002). One of the key points of this debate is the timing and duration of the magmatism.

In this paper we provide new ^{40}Ar/^{39}Ar dating results for the Usol'skii dolerite sill located in the Kansk-Taseevskaya basin at the south-eastern part of the STLIP (Fig. 1), which suggest that magmatism in the basin was probably younger than major voluminous phase of the STLIP. Published U-Pb and ^{40}Ar/^{39}Ar ages also confirm the relatively long overall magmatism of the STLIP.

Geological setting

In different parts of the Kansk-Taseevskaya basin, six large, up to 200 m thick, dolerite sills have been identified on the basis of drilling and geological mapping with a total volume of about 67 km^3 (Vasil'ev *et al.*, 2000). Close similarity of the Kansk-Taseevskaya dolerites to basalts of other parts of the STLIP was shown on basis of major element data (e.g. Feoktistov, 1978).

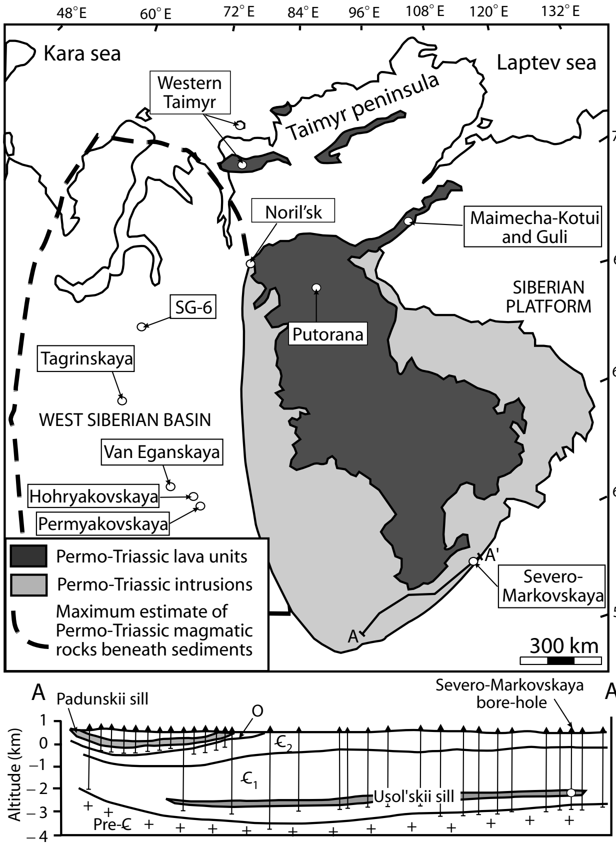

Fig. 1 Geological setting of the dated sections within the STLIP (Reichow *et al.*, 2002) and cross-section through the Kansk-Taseevskaya basin (Feoktistov, 1978).

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The hypsometrically uppermost three sills (Padunskii, Tolstomisovskii and China-Biryusinskii) are visible in limited surface outcrops. Numerous boreholes in the western and eastern parts of the Kansk-Taseevskaya basin suggest that they actually consist of large bodies emplaced mainly within Ordovician and Silurian sediments. These sills may actually represent different parts of the same intrusion but were separated into two different magmatic phases on the basis of K-Ar dating (Feoktistov, 1978). These previously reported K-Ar ages with overall interval between 280 and 180 Ma cannot however be critically evaluated because some of them have been obtained by non-mass spectrometric, so-called volumetric techniques (Starik, 1961), and neither ^{40}K decay constants nor other analytical parameters have been reported. In some areas Padunskii and Tolstomisovskii sills intrude the Ordovician and Silurian sedimentary strata and cut tuffs belonging to the Tutonchanskaya and Korvuchanskaya Early Triassic suites (Domyshev, 1974). The Tulunskii sill has been identified mainly in boreholes within Upper Cambrian to Lower Ordovician sediments. While the Zayarskii and Usol'skii sills recognized as two (probably connected) bodies situated one above another within Early Cambrian sediments (see Fig. 1 for a representative cross-section).

^{40}Ar/^{39}Ar dating

Analytical procedure

For step-heating ^{40}Ar/^{39}Ar dating we used plagioclase separates from two dolerite samples of the Usol'skii sill as exposed in the Severo-Markovskaya bore-hole (Fig. 1). ^{40}Ar/^{39}Ar measurements were performed at Vrije Universiteit Brussel, using a MAP-216 mass spectrometer and double vacuum resistance oven extraction system. Correction for the blanks of the extraction system was performed according a procedure described earlier (Ivanov *et al.*, 2000).

Samples together with LP-6 biotite 40–60 (split from bottle 7-I-D-6) primary standard were irradiated in BR2 nuclear reactor of Belgian Nuclear Center in Mol. Based on dosimetry measurements of an Fe-wire, co-irradiated with the samples in order to control the neutron fluence gradient, error on the J-factor can be estimated to be better than 0.8% (Boven *et al.*, 2001). We used the mass of approximately 15 mg for the LP-6, which lead to maximal subsampling error of about 1.8% because of the inhomogeneity of the standard (Engels and Ingamells, 1977).

McDougall and Roksandic (1974) reported K-Ar age of 127.8 ± 0.7 Ma for the LP6 similar to the age of 127.7 ± 1.4 Ma (Odin *et al.*, 1982) which results from an interlaboratory comparison of K-Ar ages on this standard. This age is again consistent with the relative ^{40}Ar/^{39}Ar age of 127.5 ± 0.03 Ma reported in the most recent paper on intercalibration of ^{40}Ar/^{39}Ar dating standards (Spell and McDougall, 2003) where a revised

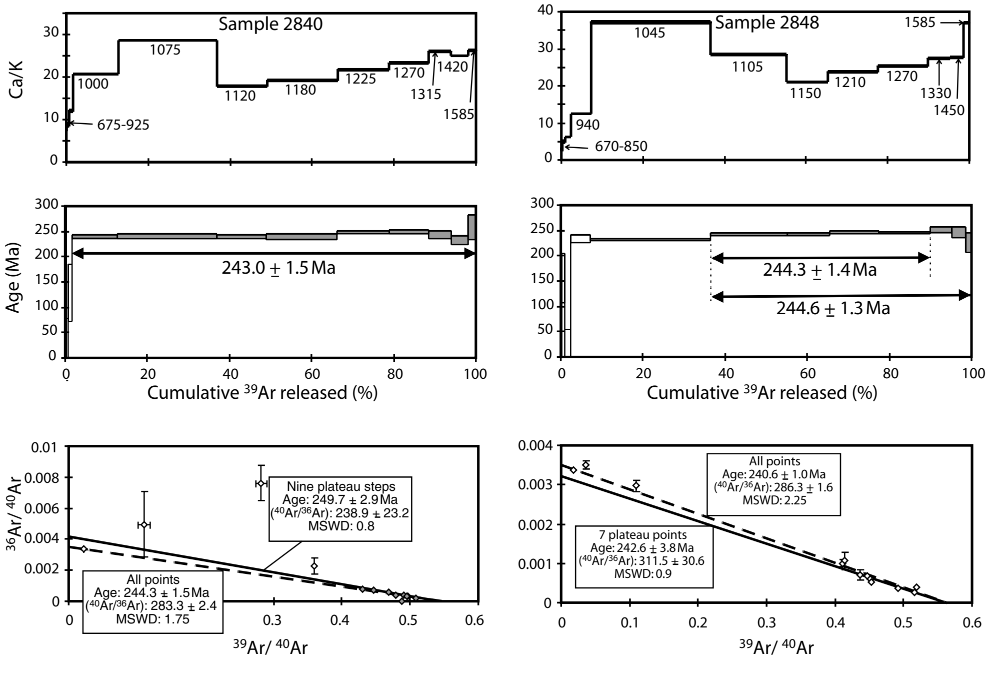

Fig. 2 Stepwise heating argon release spectra and isochrones for plagioclase separates from dolerites 2840 and 2848 of the Usol'skii sill. Studied dolerites are coarse crystalline rocks with large up to few centimetre long plagioclase crystals. As seen in hand specimens, all plagioclases contained altered parts. To separate unaltered plagioclase fragments the samples were crushed, sieved and fractionated using heavy liquids. The final plagioclase separates of around 0.1–0.2 mm size and approximately 10 mg mass were of ultimate cleanness after thorough handpicking of the heavy liquid plagioclase fractions. Step temperatures (in °C) are shown for each step on the upper diagram. All stated errors are at 2 sigma level not taking into account the errors on J-factor, Ca- and K-correction factors. Age plateau is defined as a part of the argon release spectrum with more than three consequent steps of overlapping ages, which make up more than 50% of ^{39}Ar released.

K-Ar age of 98.5 ± 0.8 Ma is recommended for the biotite standard GA-1550 which is used as a primary standard for intercalibration. However an older age of 129.4 ± 0.5 Ma for LP-6 results through comparison with the same primary GA-1550 biotite standard but for which Renne *et al.* (1998) reported a K-Ar age of 98.79 ± 0.96 Ma. For direct comparison of ages with the most recent review of Reichow *et al.* (2002) we applied the latter value for the LP-6.

Using any of the suggested values for the LP-6 standard, all (but Arydzhanskaya suite) $^{40}Ar/^{39}Ar$ ages systematically younger than U-Pb ages from the same units. This small but notable systematic difference between the two isotopic systems indicates the necessity of reconsideration of the ^{235}U, ^{238}U, and ^{40}K decay constants (Begemann *et al.*, 2001; Schön *et al.*, 2004; Ivanov, 2005). It does not affect the conclusions, however, because we do not compare $^{40}Ar/^{39}Ar$ and U-Pb ages directly. Instead we use relative age difference between $^{40}Ar/^{39}Ar$ and U-Pb ages, with the Noril'sk-I intrusion as the reference point. This is possible because this intrusion was dated by both the $^{40}Ar/^{39}Ar$ and U-Pb methods (Renne, 1995; Kamo *et al.*, 1996).

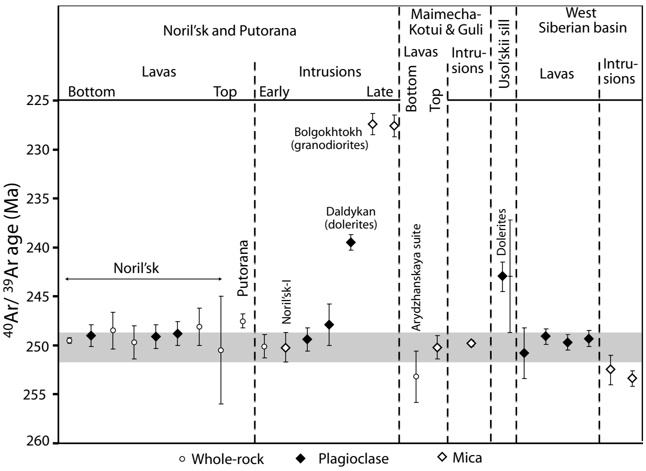

Fig. 3 Compilation of $^{40}Ar/^{39}Ar$ ages for the STLIP. Data are from: Noril'sk and Putorana (Renne and Basu, 1991; Dalrymple *et al.*, 1995; Renne, 1995; Venkatesan *et al.*, 1997), Maimecha-Kotui and Guli (Basu *et al.*, 1995; Dalrymple *et al.*, 1995), West Siberian Basin (Reichow *et al.*, 2002), sill of Kansk-Taseevskaya basin (present study). Selected $^{40}Ar/^{39}Ar$ plateau ages, if not discussed in the text, statistically coincide with the isochron ages. Shaded field represent $^{40}Ar/^{39}Ar$ age of the Noril'sk-I intrusion, which is coeval with the Permo-Triassic boundary (Renne *et al.*, 1995). All ages are relative age of 98.79 Ma for standard GA-1550 (Renne *et al.*, 1998). Large error bar close to the Usol'skii sill dolerite represents the maximal possible error including uncertainty on the LP-6 inhomogeneity.

Dating results

The plagioclase separate from sample 2840 yields plateau with nine of the 12 steps accounting for 98.3% of the total ^{39}Ar released (Fig. 2). The weighted average age for this plateau is 243.0 ± 1.5 Ma. An isochron age of 249.7 ± 2.9 Ma is obtained when retaining only the plateau steps. This age is older than the plateau age and yields very low initial $^{40}Ar/^{36}Ar$ of 238.9 ± 23.2. The isochron age of 244.3 ± 1.5 Ma for all steps is consistent with the plateau age.

The plagioclase separate from sample 2848 yields a slightly disturbed age spectrum (Fig. 3). Despite this, four and seven consequent steps, which account for 53.5% and 63.5% of the total ^{39}Ar released, define equivalent weighted plateau ages of 244.3 ± 1.4 Ma and 244.6 ± 1.3 Ma, respectively. An isochron age of 240.6 ± 1.0 Ma with an initial $^{40}Ar/^{36}Ar$ value of 311.5 ± 30.6 is obtained when retaining all steps. This age is slightly younger than both plateau ages. The isochron for seven plateau steps yields atmospheric initial $^{40}Ar/^{36}Ar$ and age of 242.6 ± 3.8 Ma, which is in agreement with the plateau ages.

It has been shown that multigrain samples, which experienced minor irregular radiogenic argon losses, may yield reproducible but meaningless plateau ages (e.g. Min *et al.*, 2000). In the case of alkali feldspar of 1.1 Ga Palisade rhyolite (Min *et al.*, 2000), the true $^{40}Ar/^{39}Ar$ ages are characterized by high amount of radiogenic argon in comparison with lower apparent ages. Samples 2840 and 2848 exhibit older ages at temperature steps of 1225–1270 °C and 1330 °C, respectively, and slightly younger ages at both the lower and higher temperature steps (Fig. 2). This age pattern does correlate neither with Ca/K ratio, nor with amount of radiogenic argon (Table 1). For example, the 1270 °C step age of 249.3 ± 4.4 Ma, the highest value among measured for the sample 2840, is characterized by 94.1% of radiogenic argon. The temperature step of 1105 °C with 92.3% of radiogenic argon, the highest value among measured for the sample 2848, is characterized by age of 242.1 ± 2.7 Ma. Taking into account that both dolerites were sampled from the same sill and the $^{40}Ar/^{39}Ar$ plateau ages of the two dated dolerites are concordant with each other, we consider that slight deviation of measured ages for individual steps reflect rather analytical errors than minor radiogenic argon losses. Therefore, a mean value of 243.9 ± 1.0 Ma is obtained as the age of the final magmatic event in the Kansk-Taseevskaya basin. To compare our $^{40}Ar/^{39}Ar$ results with the previously published $^{40}Ar/^{39}Ar$ ages for the STLIP we have to account for an uncertainty in calculation of the J-factor. Overall age estimate for the emplacement of the Usol'skii sill is 243.9 ± 1.4 Ma and, if the subsampling problem for the LP6 standard considered, it is 243.9 ± 5.8 Ma.

Compilation of published $^{40}Ar/^{39}Ar$ and U-Pb ages

$^{40}Ar/^{39}Ar$ ages

On basis of $^{40}Ar/^{39}Ar$ dating of representative samples from a volcanic sequence in the Noril'sk area, Renne and Basu (1991) proposed a short time-span of the STLIP magmatism at the Permo-Triassic boundary (i.e.

Table 1 Summary of ^{40}Ar/^{39}Ar analytical data

Temp. (°C)	^{39}**Ar**$_{cum}$ **(%)**	^{40}**Ar* (%)**	^{40}**Ar*/**^{39}**Ar**$_K$	**Age (±2 s)**	^{36}**Ar/**^{40}**Ar**	^{39}**Ar/**^{40}**Ar**	**Ca/K**
Sample 2840 (J = 0.07988 relative to LP6 age of 129.4 Ma)							
675	0.1	0	–	–	0.0036(20)	0.1101(88)	10.2
765	0.3	0	–	–	0.0089(15)	0.2822(83)	7.7
855	0.7	0.3	0.11(22)	16.4 ± 61.7	0.003375(33)	0.02233(34)	8.7
925	1.7	33.3	0.93(21)	128.9 ± 56.0	0.00226(51)	0.3591(40)	12.1
1000	12.7	83.4	1.776(13)	239.4 ± 3.4	0.000563(41)	0.4693(15)	20.7
1075	36.9	87.6	1.786(15)	240.6 ± 3.9	0.000419(49)	0.4905(23)	28.6
1120	49.0	79.4	1.776(16)	239.4 ± 4.0	0.000698(47)	0.4470(16)	17.8
1180	66.2	76.8	1.782(23)	240.1 ± 5.9	0.000784(66)	0.4312(23)	19.3
1225	78.8	92.2	1.842(12)	247.6 ± 2.9	0.000263(38)	0.5008(12)	21.8
1270	88.5	94.1	1.855(17)	249.3 ± 4.4	0.000199(58)	0.5075(20)	23.3
1315	94.0	90.9	1.811(29)	243.8 ± 7.3	0.000310(97)	0.5017(24)	26.0
1420	98.1	82.1	1.728(35)	233.3 ± 8.9	0.00060(11)	0.4754(22)	25.0
1585	100	92.9	1.927(98)	258.3 ± 24.6	0.00024(32)	0.4819(29)	26.2
Sample 2848 (J = 0.08036 relative to LP6 age of 129.4 Ma)							
670	0.3	0	–	–	0.003505(51)	0.03558(52)	2.9
790	1.0	12.3	1.12(18)	155.8 ± 48.5	0.002969(68)	0.10934(29)	4.9
850	2.4	0.1	0.07(15)	10.1 ± 44.3	0.0033800(92)	0.017795(38)	6.3
940	7.3	70.4	1.715(31)	233.0 ± 8	0.001002(43)	0.41040(54)	12.5
1045	36.5	88.7	1.7099(63)	232.3 ± 1.6	0.0003810(81)	0.5190(12)	37.2
1105	55.1	92.3	1.787(11)	242.1 ± 2.7	0.000261(17)	0.5164(11)	28.4
1150	65.4	80.0	1.790(14)	242.5 ± 3.5	0.000678(21)	0.44666(54)	21.0
1210	77.5	82.2	1.818(10)	246.0 ± 2.6	0.000604(15)	0.45204(75)	23.8
1270	90.0	89.2	1.813(10)	245.4 ± 2.5	0.000367(16)	0.49166(87)	25.3
1330	95.3	84.4	1.865(23)	252.0 ± 5.8	0.000527(35)	0.45265(73)	27.4
1450	98.5	79.4	1.817(44)	245.9 ± 11.0	0.000699(64)	0.43670(98)	27.6
1585	100	68.7	1.661(79)	226.1 ± 20.2	0.00106(11)	0.41360(97)	37.1

Values in parentheses indicate error of the two last meaningful digits.

c. 250 Ma). Recently published ^{40}Ar/^{39}Ar and U-Pb dates for the different STLIP localities (Fig. 1), are in accordance with this idea. But, some significantly older and younger ages have also been published (Basu *et al.*, 1995; Dalrymple *et al.*, 1995; Reichow *et al.*, 2002; Fig. 3). For example, Basu *et al.* (1995) reported an ^{40}Ar/^{39}Ar age of 253.3 ± 2.6 Ma (here and thereafter all mentioned in the text ^{40}Ar/^{39}Ar ages are recalculated to the age of 98.79 Ma for GA-1550 standard) on a plagioclase separate from an olivine nephelinite (Arydjansky suite), which represents the initial phase of magmatism in the Maimecha-Kotui area. These authors used the same standards and correction factors as in Renne and Basu (1991), hence their ages are directly comparable on basis of internal uncertainty. Reichow *et al.* (2002) and Dalrymple *et al.* (1995) obtained comparable Late Permian ^{40}Ar/^{39}Ar ages for biotites from olivine gabbros of the Van Eganskaya borehole within the West Siberian Basin (253.4 ± 0.8 and 252.5 ± 1.5 Ma) and for Noril'sk-I intrusion (254 ± 1 Ma) respectively. The latter age was in disagreement with ages obtained for plagioclases. After a careful ^{40}Ar/^{39}Ar laser stepwise heating study of a biotite from the Noril'sk-I intrusion the Late Permian age of 254 ± 1 Ma was considered as being too old because of the presence of excess argon (Renne, 1995). Other older ages for biotites (Reichow *et al.*, 2002) have not been confirmed neither disproved, so far. On basis of palaeomagnetic data (Kazanskii *et al.*, 2000) lavas in the SG-6 borehole within the West Siberian Basin were considered to have erupted from the Late Permian (Late Tatarian) to the Early-Middle Triassic (Olenekian-Anisian; the boundary between these two epochs corresponds to 241.7 ± 4.7 Ma; Gradstein and Ogg, 1996).

Dalrymple *et al.* (1995) determined ^{40}Ar/^{39}Ar plagioclase age of 239.5 ± 0.8 Ma for the Daldykan dolerite intrusions as weighted average of the two aliquots and biotite ages of 227.4 ± 1.1 Ma and 227.6 ± 1.1 Ma for the Bolgokhtokh granodiorite intrusion in the Noril'sk area. These ages are analytically robust and do not contradict with any of the geological relationships. The latest Bolgokhtokh intrusion is 22.7 ± 2.3 Ma younger than the Notril'sk-I intrusion.

U-Pb ages

In Fig. 4 we summarize all U-Pb ages obtained for the STLIP (Campbell *et al.*, 1992; Kamo *et al.*, 1996, 2000, 2003; Vernikovsky *et al.*, 2003). Despite slight systematic differences between ^{40}Ar/^{39}Ar and U-Pb ages, they are almost consistent with each other. For example, the U-Pb age for the Bolgokhtokh granodiorite intrusion is 22.3 ± 0.6 Ma younger than the Noril'sk-I intrusion. Kamo *et al.* (2003) argued that the Bolgokhtokh intrusion was not related to the STLIP magmatism. However, there are many geochemically similar Permo-Triassic anorogenic-type intrusions within or close to the STLIP (Dobretsov, 2003; Vernikovsky *et al.*, 2003). One example is given by granodiorites and syenites from the Western Taimyr Peninsula and nearby islands of the Kara Sea (Fig. 1). These intrusive rocks yield concordant U-Pb zircon

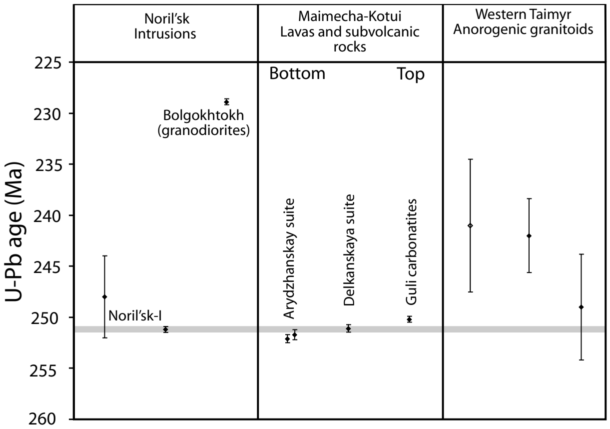

Fig. 4 Compilation of U-Pb ages for the STLIP. Data are from Campbell *et al.* (1992); Kamo *et al.* (1996, 2000, 2003); Vernikovsky *et al.* (2003). Shaded field represents U-Pb age of the Noril'sk-I intrusion. According to the $^{40}Ar/^{39}Ar$ data the Noril'sk-I intrusion is coeval with the Permo-Triassic boundary. It is also the case for U-Pb system if the U-Pb age of 251.4 ± 0.3 Ma for zircons from beds 25–26 of the Meishan stratotype section D is accepted for the boundary (Bowring *et al.*, 1998). However, older age of 252.6 ± 0.2 Ma was recently obtained by Mundil *et al.* (2004) on zircons from the same beds after removing zircon parts, which experienced losses of radiogenic lead. This inconsistency shows further need of precise geochronology in the Meishan stratotype section D and search of other suitable Permo-Triassic sections for the dating.

ages of 241.0 ± 6.5, 242.0 ± 3.6, and 249.0 ± 5.2 Ma (Vernikovsky *et al.*, 2003).

Kamo *et al.* (2000) reported the U-Pb perovskite age of 252.1 ± 0.4 Ma for olivine nephelinite from the Arydjansky suite of the Maimech-a-Kotui area. Later, these authors corrected the same U-Pb data for another initial lead isotopic composition and suggested a new slightly younger U-Pb age of 251.7 ± 0.4 Ma (Kamo *et al.*, 2003). Any of this two ages are close to the Permian–Triassic boundary, despite which of the two U-Pb ages are accepted for the boundary (see captions to Fig. 4).

Discussion and conclusions

The critical point for discussing the impact model of the STLIP origin is timing of the magmatism initiation. If the Late Permian ages of 253.4 ± 0.8 and 252.5 ± 1.5 Ma for the intrusions and lavas of the West Siberian Basin and interpretation of palaeomagnetic data for initial phase of the volcanism in the same basin are correct then the impact model of the STLIP origin (Jones *et al.*, 2002) can be ruled out and discussion should be restricted to evaluation of the terrestrial magmatic processes.

The geochronological information alone is insufficient for choosing plume (Campbell *et al.*, 1992; Lightfoot *et al.*, 1993; Basu *et al.*, 1995; Dobretsov, 2003; Vernikovsky *et al.*, 2003) or non-plume (Zorin and Vladimirov, 1989; Puffer, 2001) models. When coupled with geological and geochemical observations one should be aware, however, that not all magmatism was restricted to the short time-span of 1–2 Ma at the Permo-Triassic boundary (Renne *et al.*, 1995). Based on results of our $^{40}Ar/^{39}Ar$ study we infer that dolerites in the Kansk-Taseevskaya basin are most likely younger than the main magmatic event. Probably they are coeval with dolerites of the Daldykan intrusions in the Noril'sk area, which are *c.* 10 Ma younger than the main magmatic event (Dalrymple *et al.*, 1995). The overall duration of magmatism of the STLIP is estimated to be 22–26 Ma long. In this respect, the STLIP does not differ from other large igneous provinces for which precise $^{40}Ar/^{39}Ar$ ages are available (e.g. Ethiopian Traps, Hofman *et al.*, 1997; Deccan Traps, Sheth *et al.*, 2001a,b; Central Atlantic Magmatic Province, Baksi, 2003). So, probably it is a general feature of large igneous provinces to combine rapid voluminous phases with less prominent disperse continuous phases of magmatism.

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