40Ar/39Ar 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 40Ar/39Ar 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 40Ar/39Ar 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.

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 (>106 km3) 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 40Ar/39Ar 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 40Ar/39Ar 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 km3 (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).
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 40K 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 (Domyshov, 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).

### 40Ar/39Ar dating

**Analytical procedure**

For step-heating 40Ar/39Ar dating we used plagioclase separates from two dolerite samples of the Usol’skii sill as exposed in the Severo-Markovskaya bore-hole (Fig. 1). 40Ar/39Ar 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).

**Fig. 2** Stepwise heating argon release spectra and isochrons 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 39Ar released.

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 40Ar/39Ar age of 127.5 ± 0.03 Ma reported in the most recent paper on intercalibration of 40Ar/39Ar dating standards (Spell and McDougall, 2003) where a revised...
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 Arydzhan et al., 2014) 40Ar/39Ar 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 238U, 238U, and 40K decay constants (Begemann et al., 2001; Schön et al., 2004; Ivanov, 2005). It does not affect the conclusions, however, because we do not compare 40Ar/39Ar and U-Pb ages directly. Instead we use relative age difference between 40Ar/39Ar and U-Pb ages, with the Noril’sk-I intrusion as the reference point. This is possible because this intrusion was dated by 40Ar/39Ar and U-Pb methods (Renne, 1995; Kamo et al., 1996).

**Dating results**

The plagioclase separate from sample 2840 yields plateau with nine of the 12 steps accounting for 98.3% of the total 39Ar 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 40Ar/39Ar 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 39Ar 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 40Ar/39Ar 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 40Ar/36Ar 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 40Ar/39Ar 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 40Ar/39Ar 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 40Ar/39Ar results with the previously published 40Ar/39Ar 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 40Ar/39Ar and U-Pb ages**

40Ar/39Ar ages

On basis of 40Ar/39Ar 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.
Ar dating of Usol’skii sill in the south-eastern Siberia after all mentioned in the text of 253.3 ± 2.6 Ma (here and there-40Ar/39Ar ages for biotites from olivine 40Ar/39Ar ages are recalculated to the c. 250 Ma). Recently published
40Ar/39Ar 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 40Ar/39Ar age of 253.3 ± 2.6 Ma (here and thereafter after all mentioned in the text 40Ar/39Ar 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 40Ar/39Ar 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 40Ar/39Ar 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 40Ar/39Ar plagioclase age of 239.5 ± 0.8 Ma for the Dalldyk 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-I 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 40Ar/39Ar 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 geochronologically 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

Table 1 Summary of 40Ar/39Ar analytical data

<table>
<thead>
<tr>
<th>Temp. (°C)</th>
<th>40Ar* (%)</th>
<th>40Ar*+39ArK</th>
<th>Age (±2 s)</th>
<th>39Ar/40Ar</th>
<th>36Ar/40Ar</th>
<th>39Ar/40Ar</th>
<th>Ca/K</th>
</tr>
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<tbody>
<tr>
<td>Sample 2840 (J = 0.07988 relative to LP6 age of 129.4 Ma)</td>
<td></td>
<td></td>
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<tr>
<td>675</td>
<td>0.1</td>
<td>0</td>
<td>16.4 ± 61.7</td>
<td>0.003375(33)</td>
<td>0.01100(88)</td>
<td>10.2</td>
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<tr>
<td>765</td>
<td>0.3</td>
<td>0</td>
<td>12.89 ± 56.0</td>
<td>0.002256(51)</td>
<td>0.03591(40)</td>
<td>12.1</td>
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<tr>
<td>855</td>
<td>0.7</td>
<td>0.3</td>
<td>0.0111(22)</td>
<td>0.000563(41)</td>
<td>0.4693(15)</td>
<td>20.7</td>
<td></td>
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<tr>
<td>925</td>
<td>1.7</td>
<td>33.3</td>
<td>0.93(21)</td>
<td>239.4 ± 3.4</td>
<td>0.000419(49)</td>
<td>0.4905(23)</td>
<td>28.6</td>
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<tr>
<td>1000</td>
<td>12.7</td>
<td>83.4</td>
<td>1.7761(13)</td>
<td>2401.0 ± 3.9</td>
<td>0.000263(38)</td>
<td>0.5008(12)</td>
<td>21.8</td>
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<tr>
<td>1075</td>
<td>36.9</td>
<td>87.6</td>
<td>1.7861(15)</td>
<td>2476.0 ± 2.9</td>
<td>0.000784(66)</td>
<td>0.4312(23)</td>
<td>19.3</td>
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<tr>
<td>1120</td>
<td>49.0</td>
<td>79.4</td>
<td>1.7761(16)</td>
<td>2493.0 ± 4.4</td>
<td>0.000919(58)</td>
<td>0.5075(20)</td>
<td>26.0</td>
</tr>
<tr>
<td>1180</td>
<td>66.2</td>
<td>76.8</td>
<td>1.782(23)</td>
<td>2438.3 ± 7.3</td>
<td>0.000510(97)</td>
<td>0.4754(22)</td>
<td>25.0</td>
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<tr>
<td>1225</td>
<td>78.8</td>
<td>92.2</td>
<td>1.842(12)</td>
<td>232.3 ± 1.6</td>
<td>0.000381(81)</td>
<td>0.5190(12)</td>
<td>37.2</td>
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<tr>
<td>1270</td>
<td>88.5</td>
<td>94.1</td>
<td>1.855(17)</td>
<td>2401.0 ± 5.9</td>
<td>0.000604(15)</td>
<td>0.4916(87)</td>
<td>27.4</td>
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<tr>
<td>1315</td>
<td>94.0</td>
<td>90.9</td>
<td>1.811(29)</td>
<td>2476.0 ± 2.9</td>
<td>0.000263(38)</td>
<td>0.5008(12)</td>
<td>21.8</td>
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<td>1420</td>
<td>98.1</td>
<td>82.1</td>
<td>1.728(35)</td>
<td>232.3 ± 1.6</td>
<td>0.000381(81)</td>
<td>0.5190(12)</td>
<td>37.2</td>
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<tr>
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<td>100</td>
<td>92.9</td>
<td>1.927(98)</td>
<td>258.3 ± 24.6</td>
<td>0.00024(32)</td>
<td>0.4819(29)</td>
<td>26.2</td>
</tr>
</tbody>
</table>

Values in parentheses indicate error of the two last meaningful digits.
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 magmatic event. 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 Permian-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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