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Paleomagnetic dating of Phanerozoic kimberlites in Siberia

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ABSTRACT

Diamond bearing kimberlite pipes are exposed across the north-central part of the Siberian platform. Three main time intervals are considered to be the age of emplacement: the Devonian–Early Carboniferous, Triassic, and Cretaceous. However, isotopic age data from of the pipes are scattered and provide a very broad age interval for the magmatic activity. New paleomagnetic poles from four kimberlite pipes (Eastern Udachnaya, Western Udachnaya, International and Obnazhennaya) are obtained to estimate their paleomagnetic age. The mean primary magnetization directions for the pipes are as follows: D = 4.3°, I = −44.5° (k = 29.4, α_{95} = 7.4°, N = 14); D = 340.5°, I = −65.6° (k = 12.9, α_{95} = 19.4°, N = 6); D = 291.1°, I = −78.1° (k = 27.5, α_{95} = 14.9°, N = 5); and D = 306.7°, I = −82.6° (k = 38.4, α_{95} = 5.8°, N = 17), respectively. On the basis of a comparison with the Siberian apparent polar wander path (APWP) we estimate the age of kimberlite magmatism, assuming primary magnetizations in these rocks. The paleomagnetic ages are as follows: 428 ± 13 Ma for Eastern Udachnaya; 251 ± 30 Ma for International pipe; and 168 ± 11 Ma for Obnazhennaya pipe. The Western Udachnaya pipe was remagnetized and no clear paleomagnetic age could be determined. The ages of magmatic activity span the Early Silurian to Middle Late Jurassic. Early Silurian magmatism could be associated with the formation of the Viluy rift. Middle to Late Jurassic magmatic activity is most likely related to subduction related to the accretion of surrounding terranes to Siberia.

1. Introduction

Paleomagnetic data have often been used to estimate the ages of ore deposits and kimberlite fields over the world (Gregory et al., 2006; Hargraves and Onstott, 1980; Jones, 1968; Jones and McElhinny, 1966; Konstantinov and Stegnitskii, 2012; Kravchinsky et al., 2009; Malone et al., 2008; Symons and Arne, 2005; Symons et al., 1999; Wynne et al., 1992; among other studies). Our aim in this contribution is to date four Siberian kimberlite pipes for which radiometric age dating has not provided reliable age estimates. In this paper we also introduce a quantitative method to estate a paleopole's paleomagnetic age with respect to an assumed apparent polar wander path (APWP).

Previous studies (Kravchinsky et al., 2002) reported high quality paleomagnetic data from Siberian kimberlites and confirmed that the magmatism coincided with Late Devonian and Permo-Triassic rifting events. The ages of the kimberlite intrusions are important for the origin of large-scale magmatic events in Siberia and will help industry to search for prospective areas for future diamond exploration.

2. Geologic setting

A chain of Paleozoic to Mesozoic age kimberlites stretches for 1000 km in a SW–NE direction across the north-central part of the Siberian platform, and another trail of Mesozoic kimberlites extends for ~320 km to the northwest from the center of the platform along the eastern boundary of the Anabar Shield (Fig. 1). The Siberian kimberlites are thought to be emplaced during three main epochs: the Devonian–Early Carboniferous, the Triassic, and the Cretaceous (Brakhfogel, 1984). On the eastern side of the Siberian platform, the Devonian Viluy and Kyutungda aulacogens extend into the platform from the ancient passive margin. All Devonian to Early Carboniferous kimberlite exposures are situated between these aulacogens. The Devonian and Triassic kimberlites are associated with Late Devonian–Lower Carboniferous and Permo-Triassic intraplate mafic volcanism (Kravchinsky et al., 2002). Cretaceous kimberlites are exposed in the north Siberian platform on the slopes of the Olenek uplift. They are likely connected with intraplate magmatism in the arctic area as described in Kuzmin et al. (2010). The Viluy aulacogen (Fig. 1) includes 7–8 km of Upper Devonian–Lower Carboniferous evaporite sedimentary rocks and bimodal volcanic rocks. The ~50 km wide Kyutungde aulacogen is filled with Upper Devonian–Lower Carboniferous evaporite rocks (Masaitis et al., 1975; Oleinikov, 1979; Shpount and Oleinikov, 1987).

Isotopic age data and geologic age estimates for the kimberlites have been summarized by Brakhfogel (1984), Krivonos (1997), Griffin et al.

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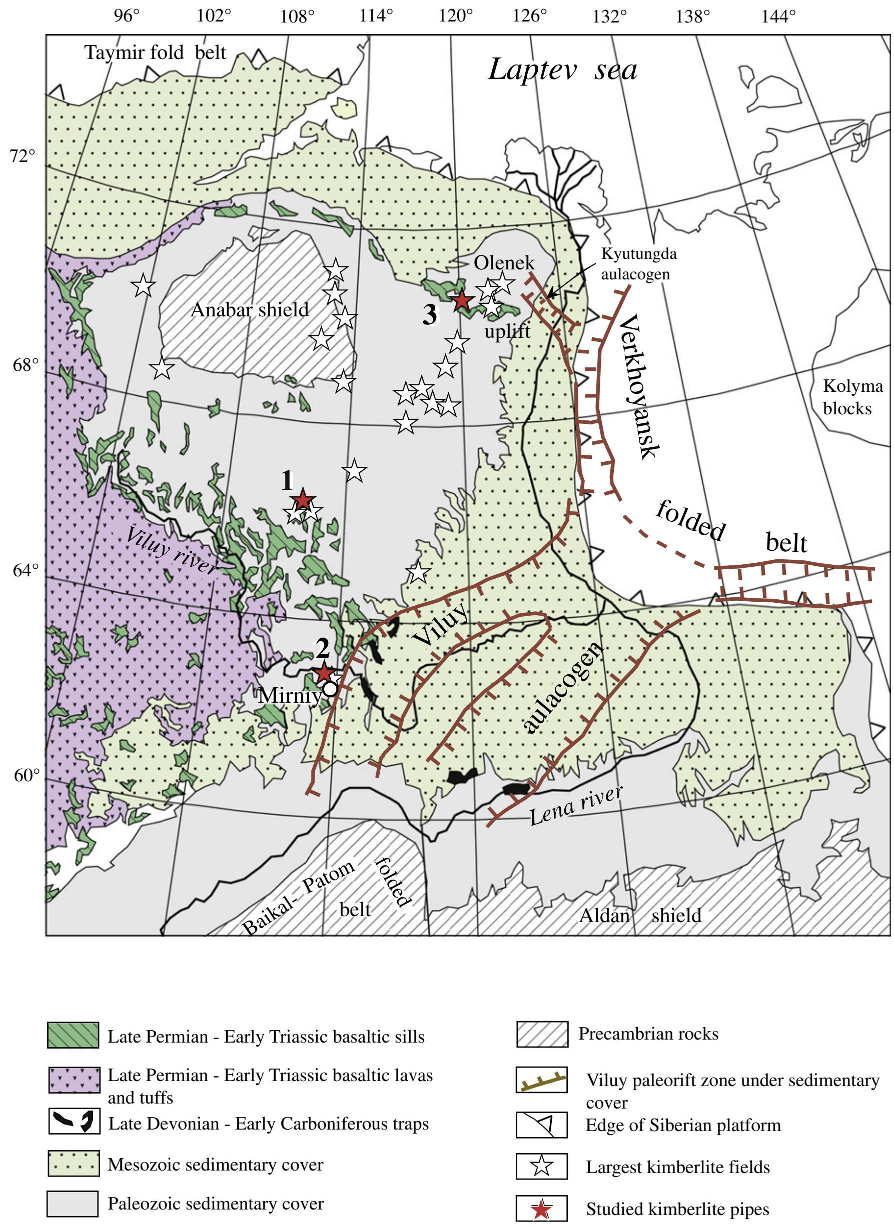

Fig. 1. Simplified equal are projection geological map of the northeastern part of the Siberian platform (Kravchinsky et al., 2002). Sampling localities are as follows: 1 — Daldyn kimberlite pipe field (Eastern and Western Udachnaya pipes); 2 — Malo-Botuoba kimberlite pipe field (International pipe); 3 — Kuoika kimberlite pipe field (Obnazhennaya pipe).

(1999), and Agashev et al. (2004). However, there are major differences among age estimates for a given kimberlite pipe obtained by different methods. Griffin et al. (1999) emphasized this problem for several kimberlite fields. For instance, the authors noted that some age estimates based on K–Ar data were significantly older than estimates by other methods and in several cases they contradicted stratigraphic and paleontologic age estimates, which suggested the presence of excess argon in the K–Ar method. Currently, it is not possible to date every kimberlite pipe because of differences between geologic and absolute age determination methods.

The Udachnaya kimberlite pipes (66°26′N, 112°19′E) are located in the Daldyn kimberlite field (Fig. 1). The field includes a broad band of diamondiferous Devonian to Carboniferous kimberlites that extends from the central to north-central part of the Siberian platform (Ashchepkov et al., 2010). The Udachnaya kimberlite consists of two intersecting intrusions, the smaller eastern and larger western pipes. These pipes cut Cambrian and Ordovician limestones, dolomites, and siltites. Kinny et al. (1997) and Griffin et al. (1999) reported high-resolution ion-microprobe U–Pb perovskite ages of 367 ± 5 Ma for the Eastern Udachnaya pipe and 361 ± 4 and 353 ± 5 Ma for the Western Udachnaya pipe. Other absolute dating methods on various kimberlite pipes in the region yield dates of 364–461 Ma (fission track zircon), 344–358 Ma (U–Pb zircon), 350 ± 13 Ma (Rb–Sr, Svetlaya pipe), and 335–365 Ma (K–Ar, Moskvichka pipe). Recently, Maas et al. (2005) obtained an age estimate of 347 ± 5 Ma using U–Pb isotope dating for the Eastern Udachnaya pipe. Carbonate rock xenoliths with faunas including brachiopods, tetracorallians, tabulates, ostracods, tentaculites, and trilobites of Middle–Late Devonian age were found in the neighboring Alakit–Markha kimberlite field and this age was extrapolated to the Daldyn kimberlite field (Krivonos, 1997). Thus the age of the whole kimberlite field is considered to be Late Devonian–Early Carboniferous.

The Eastern Udachnaya pipe consists of massive kimberlite and kimberlite breccias and contains the freshest and most abundant mantle xenoliths from Siberia (Ionov et al., 2010). A recent excavation exposed exceptionally fresh kimberlites at deeper levels in the pit, which is nearly 600 m deep. The kimberlite is free of serpentine, and it contains fresh olivine and "exotic" volatile-bearing minerals (chlorides, carbonates) of inferred magmatic origin (Ionov et al., 2010; Kamenetsky et al., 2009). The Western Udachnaya pipe is composed of altered kimberlite that does not contain fresh minerals.

The Malo-Botuoba kimberlite field consists of several pipes, including Mir, Trubka-1, Amakinskaya, International, and Taezhnaya (Fig. 1). The Paleozoic basement sedimentary rocks of this kimberlite province are exposed close to the Viluy aulocogen in the center of the Siberian platform around the southern Anabar Shield. We sampled the subvertical oval-shaped International kimberlite pipe (coordinates: 62.5°N, 113.0°E) at different levels of a quarry that had reached a depth of 284 m when its excavation was halted in 1980. The gem quality of the International pipe's diamonds is unique in the global market. The pit boundaries of the kimberlite pipe are 90 × 55 m.

Isotopic age data for the Malo-Botuoba kimberlite field are inconsistent (Griffin et al., 1999; Krivonos, 1997). Fission track zircon dates are mainly between 358 and 397 Ma. U–Pb zircon dating gives dates from 344 to 403 Ma. For the Mir pipe the K–Ar age estimate is 403 ± 15 Ma and the Rb–Sr age estimate is 324 ± 11 Ma. Mafic rocks of Late Devonian age are xenoliths (Krivonos, 1997). The pipe cuts across a Late Devonian mafic sill and contains its xenoliths. Conglomerate clasts from these pipes have been found in Carboniferous and Jurassic rocks of the region. Thus, the Late Devonian–Early Carboniferous age of this field is about 340–400 Ma. Kravchinsky et al. (2002) demonstrated that the magnetization of the Mir kimberlite pipe was reset in Permo-Triassic time due to Siberian trap volcanism at the Permo-Triassic boundary.

The Obnazhennaya kimberlite pipe belongs to the Kuoyka kimberlite field. The pipe contains mantle xenoliths of eclogite, pyrope, peridotite, Permo-Triassic flood basalts, Vendian and Cambrian limestones and dolomites as well as Jurassic fossils including a belemnite rostra from the Late Jurassic (Malkov, 2008). Some of the kimberlite pipes of the Kuoyka kimberlite field such as the Piatnitsa and Slyudianka pipes, cut Permian sedimentary rocks and contain xenoliths of Jurassic sediments with poorly preserved fragments of leaves and of Permo-Triassic mafic lavas (Malkov, 2008). U–Pb perovskite age determinations of Kuoyka kimberlites has given 147.7 Ma (Slyudianka pipe), 150.9 Ma (Muse pipe), 151.2 Ma (Tokur pipe), 149.9 Ma (Irina pipe) (Brakhfogel, 1984) and 157 Ma (D'yanga pipe) (Agashev et al., 2004). Zircon has not been detected in the Obnazhennaya pipe. Its age has been determined to be 135 Ma using Rb–Sr whole rock and to range between 128 and 170 Ma using U–Pb method on perovskites nearby picrite bodies (Kinny et al., 1997). Overall, the age of the Kuoyka kimberlite field, including the Obnazhennaya pipe, is commonly considered to be Middle–Late Jurassic.

3. Methods

3.1. Laboratory techniques

We sampled kimberlites as oriented blocks from 58 sites and 17 localities, from which we cut two to five oriented 8 cm^3 cubic specimens, giving a total of four hundred specimens. All samples are oriented in in-situ only coordinate because of the absence of any folding in the central parts of the Siberian platform.

Stepwise thermal demagnetizations and magnetic measurements of the specimens were carried out in the paleomagnetic laboratories at the Physics Department of the University of Alberta, Canada, and at the Russian Academy of Sciences, at Irkutsk.

Thermal demagnetization was performed using an ASC thermal demagnetizer, model TD48-SC, oven housed in three concentric μ-metal shields. The residual field was about 10 nT in the center of the oven. The samples were demagnetized in 10–50 °C steps up to 600–650 °C, and the remanent magnetization was measured with a 2-G Enterprise cryogenic magnetometer (model 755-1.65) and a JR-4 spinner-magnetometer. All the measurements where done in a shielded room. Magnetic susceptibility was measured with a Bartington MS2 magnetic susceptibility meter. Data were processed using Enkin (1996) and Cogné (2003) *PaleoMac* paleomagnetic software. Zijderveld (1967) diagrams were constructed for each sample, and the results were analyzed using principal component analysis (Kirschvink, 1980). The site mean directions were calculated using Fisher (1953) statistics. The combined analysis technique of McFadden and McElhinny (1988) was used when dealing with mixed populations of directions and remagnetization great circles with sector constraints (Halls, 1976; McFadden and McElhinny, 1988).

Isothermal remanent magnetization (IRM) experiments, thermomagnetic curves (Curie point measurements), and hysteresis loop measurements were performed using a Variable Field Translation Balance (VFTB) in the paleomagnetic laboratory at the University of Alberta and at the Munich Institute of Applied Geophysics.

3.2. Paleomagnetic dating techniques

To determine the age of the kimberlites, we compared the estimated pipe mean paleomagnetic poles that we obtained to the Siberian APWP reported in Cocks and Torsvik (2007). We used their APWP spline without the 275 Ma pole of Pisarevsky et al. (2006), i.e., their alternative model B. Cocks and Torsvik (2007) considered model B to be the most probable path. To ensure the quality of the age determination, the angular distance between our resultant pole and every point on the APWP was calculated. The age was estimated based on the minimum angular distance between the analyzed point and the APWP. To perform the calculation, two unit vectors were defined, **S** for the obtained paleomagnetic pole:

$$S_x = \cos(\lambda_s) \times \cos(\varphi_s),$$
$$S_y = \cos(\lambda_s) \times \sin(\varphi_s),$$
$$S_z = \sin(\lambda_s),$$

and **P** for the points on the reference APWP:

$$P_x = \cos\left(\lambda_p\right) \times \cos\left(\varphi_p\right),$$
$$P_y = \cos\left(\lambda_p\right) \times \sin\left(\varphi_p\right),$$
$$P_z = \sin\left(\lambda_p\right),$$

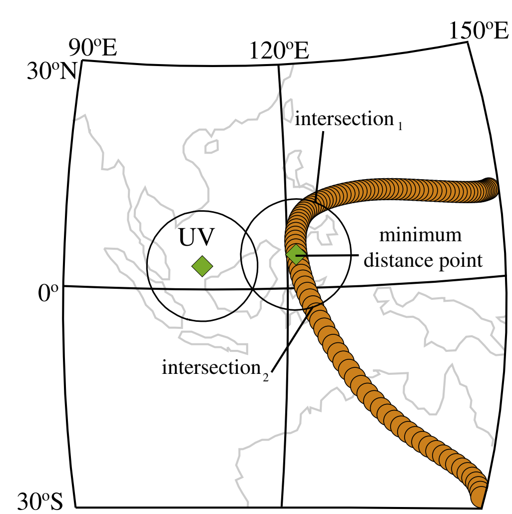

Fig. 2. Procedure used to determine the error in the paleomagnetic age determination. The pole and the circle of confidence are projected over the minimum distance point on the APWP. The intersection points will constrain the error in age. The final uncertainty is given by an average of the two intersection points.

where λ_s and φ_s represent the latitude and the longitude of the obtained paleomagnetic pole and λ_p and φ_p the latitude and longitude of the APWP points. The angular distance ψ is given by the dot product between the two vectors:

$$\psi = \cos^{-1}(\mathbf{S}\cdot\mathbf{P}).$$

To improve the fit of the age determination, we increased the sampling rate of the APWP to 2 Myr by applying a linear interpolation between the points of the path. To calculate the uncertainty in age, the confidence cone angle A_{95} for each of the studied sites was projected at the minimum distance point on the APWP (Fig. 2). The uncertainty is equal to the intersection between the confidence circle and the APWP path. The error was calculated as:

$$\{(i_1 - m) + (m - i_2)\}/2$$

where i_1 and i_2 are the intersection ages and m is the minimum point age.

4. Paleomagnetic results

4.1. Rock-magnetic properties of the studied kimberlites

Three different behaviors (A, B, C) were defined by rock-magnetic experiments (Fig. 3). Behaviors A and B were obtained for all four studied kimberlite pipes. Behavior (C) was observed only in the International pipe. In the first case (sample 11), saturation of IRM was attained at 100–120 mT. The thermomagnetic curves are almost reversible with a Curie temperature of 580 °C. The shape of the hysteresis curve is compatible with a relatively narrow distribution of single or pseudosingle domain magnetite grains. We inferred that this sample was dominated by magnetite or low-titanium titanomagnetite. The magnetization of sample 3 (type B) is saturated in a relatively high field (250 mT). In

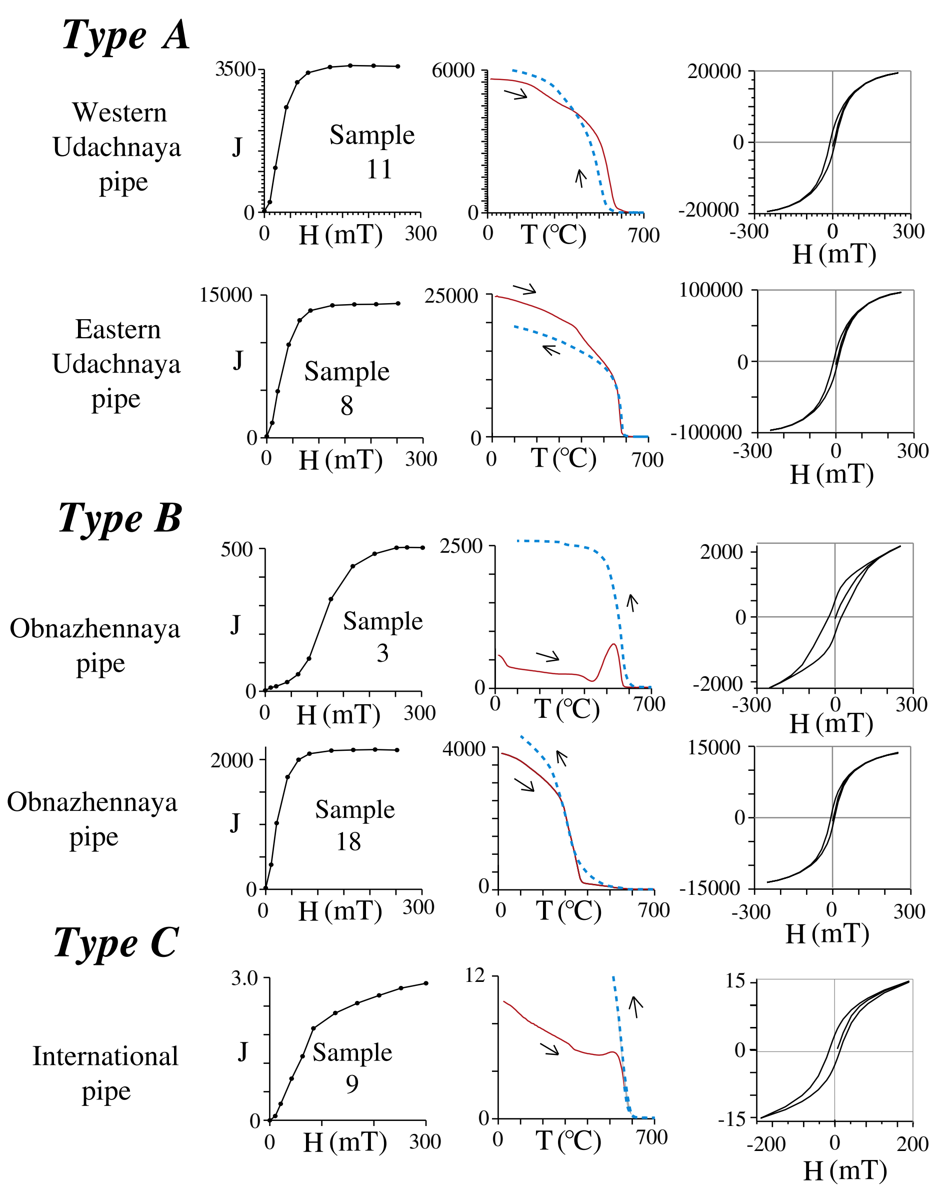

Fig. 3. Typical results of rock magnetic experiments for kimberlite samples from the Eastern Vostochnaya, Western Udachnaya, International, and Obnazhennaya pipes. Isothermal remanent magnetization (IRM) acquisition curves (left), Curie point thermomagnetic curves Js (T) (center), and hysteresis loop (right). J is the isothermal remanence intensity (10^{-4} $Am^2 \times m^3/kg$), H is the magnetizing field intensity in millitesla, T is the temperature in Celsius degrees.

contrast, sample 11 showed a marked increase of magnetization beyond 400 °C, which is typical of titanomagnetite being transformed into magnetite. Titanomagnetite is identified in Eastern Udachaya by mineralogical studies (Kamenestsky et al., 2004). During transformation, the parent spinel breaks down into magnetite and the Curie point rises (Dunlop and Özdemir, 1997). Saturation isothermal remanent magnetization (SIRM) acquisition of type C sample 9 indicated the presence of two components with medium and high coercitivity, respectively. These could be related to the presence of sulfides like pyrrhotite. The thermomagnetic results show the formation of a strongly magnetic component, presumably magnetite, during cooling. Because the primary magnetization may not be carried by magnetite, the natural remanent magnetization (NRM) results from the International pipe must be considered with caution.

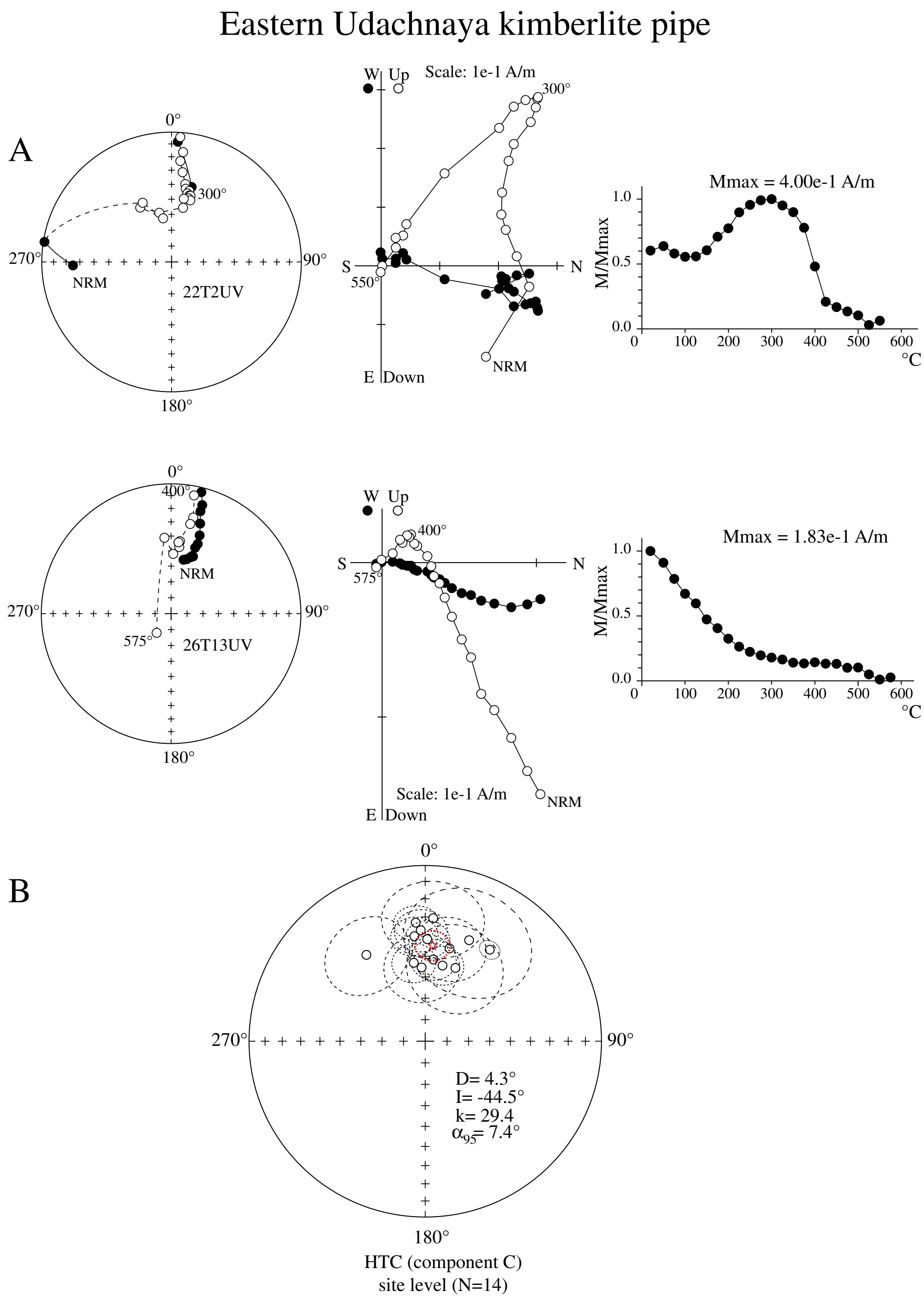

Fig. 4. (A) Typical equal-area projections illustrating demagnetization paths during experiments, and thermal demagnetization orthogonal vector plots in-situ coordinates (Zijderveld, 1967) for samples from the Eastern Udachnaya pipe. Closed (open) symbols in orthogonal plots represent projections onto the horizontal (vertical) plane; temperature steps are indicated in Celsius degrees (°C). NRM: natural remanent magnetization. M/Max: ratio of the measured magnetization respect to the maximum magnetization value (in amperes per meter). (B) Equal-area projections of site-mean directions of high temperature (HTC) component, with circles of 95% confidence. Open symbols: upward inclinations. Star: mean formation direction D: declination, I: inclination, k: precision parameter, α_{95}: radius of the 95% probability confidence circle, N: number of specimens at site level.

4.2. Kimberlites from the Eastern Udachnaya pipe

Two characteristic components were identified in the 14 sites from the Eastern Udachnaya kimberlite pipe (Fig. 4). The low temperature component (LTC), isolated between room temperature and 300 °C, has an average direction: D = 356.9°, I = 72.2° (k = 65.9, α_{95} = 5.1°, N = 13 sites) (Table 1). This direction is close to the Earth's present field direction in the region (D = 352°, I = 81.8°) which we interpret to be a present-day viscous magnetization overprint. The high temperature component (HTC) was isolated between 200–300 °C and 550 °C and converged toward the origin of orthogonal demagnetization diagrams. Most of the samples demonstrated behavior identical to 22T2UV and 26T13UV during demagnetization (Fig. 4). Only a few samples did not display long linear segments at high temperatures and for them the HTC was evaluated using remagnetization circle analysis. The mean direction of the HTC is D = 4.3°, I = −44.5° (k = 29.4, α_{95} = 7.4° N = 14 sites) (Fig. 4, Table 1). There is no folding in the central part of the Siberian platform, and therefore no fold test could be applied.

4.3. Sediments near the Eastern Udachnaya kimberlite pipe

The Eastern Udachnaya pipe intrudes through the carbonate and fine sandstone sediments of the Early Ordovician Oldondinskaya Formation with a Tremadocian–Arenigian age of 505–478 Ma. The Oldondinskaya samples were taken 500 m away from the contact of 400 × 350 m^2 kimberlite pipe. The formation's bedding is horizontal, and the kimberlite pipe cuts the horizontal strata. The LTC component calculated for 21 samples (D = 342.3°, I = 77.3°, k = 255.6, α_{95} = 2.0°; Fig. 5, Table 1) was easily removed below to 300 °C and coincided with the present-day Earth's geomagnetic field. We interpreted it to be the present day overprint.

Although the magnetization of the host sedimentary rocks is four orders of magnitude weaker than that of the kimberlites, about 65% of the samples studied revealed a high temperature component between 300 °C and 400–450 °C. Above this temperature oxidation occurred during heating and magnetic susceptibility increased radically, indicating severe mineralogic changes. The brownish color of the sedimentary rocks that appeared during heating likely indicates the transformation of magnetite to hematite. The mean direction for the high temperature component, calculated from 21 samples, is D = 6.1°, I = −12.4° (k = 26.6, α_{95} = 6.3°; Fig. 5, Table 1). This direction differs radically from that of the Eastern Udachnaya kimberlite and, therefore, we conclude that the area was not reheated by metamorphism related to the Permo-Triassic traps. Therefore we infer that both the kimberlites and sedimentary rocks most likely preserve a primary magnetization associated with kimberlite emplacement.

4.4. Kimberlites from the Western Udachnaya pipe

The Western Udachnya pipe is situated beside the Eastern Udachnaya kimberlite pipe. The LTC from <300 °C gives a direction of D = 325.5°, I = 73.8° (k = 25.0, α_{95} = 5.0°, n = 34 samples) (Table 1, Fig. 6). The HTC demagnetization response is very similar to that of the Eastern Udachnya kimberlite. The mean direction isolated between 300 and 550–580 °C is D = 340.5°, I = −65.6° (k = 12.9, α_{95} = 19.4°, N = 6 sites) (Table 1, Fig. 6). The direction differs noticeably from the mean value of the Eastern Udachnya kimberlite, which may indicate a different age of magnetization for Eastern and Western kimberlite pipes.

4.5. Sedimentary rocks from the baked contact of the Western Udachnaya kimberlite pipe

Sedimentary rocks along a perpendicular profile to the Western Udachnaya kimberlite pipe's contact were sampled to perform a baked contact test. The agreement between the primary magnetization direction of the pipe and the adjacent baked rocks provides confidence with respect to the stability of the primary natural remanent magnetization of the intrusive body (Butler, 1998). Sediments from the contact are harder and visibly metamorphosed. Only the HTC is well-preserved from room temperature to 380–440 °C (Fig. 7). Magnetic susceptibility and NRM intensity increased rapidly. When the samples were heated above 440 °C the heating was accompanied by a change in color towards red, indicating the likely transformation of magnetite to hematite. Mean HTC directions for the seven sites are scattered, ranging from shallow to steeper inclinations. The mean site direction is as follows: D = 29.3°, I = −28.3° (k = 15.8, α_{95} = 15.7°, N = 7 sites) (Table 1). This direction is very different from those of the kimberlites and host sedimentary rocks. The result implies that regional remagnetization did not occur in either the sediments or kimberlites by Permo-Triassic traps because they all possessed different HTC directions. The mean direction from the baked contact sedimentary rocks is likely the unresolved superposition of the primary magnetization of the host rocks by partial remagnetization caused by the kimberlite intrusion.

4.6. International kimberlite pipe

Twenty-two samples from 14 sites were subjected to progressive thermal demagnetization. The LTC, unblocked below 200 °C, has a mean direction of D = 17.3°, I = 83.8° (*k* = 56.7, α_{95} = 4.2°, n = 22 samples) (Table 2, Fig. 8), which is close to the present magnetic field of the region of D = 350.7°, I = 78.9°. Therefore the LTC is deemed to

Table 1
Site mean paleomagnetic directions for the high temperature components for the Eastern Udachnaya pipe (66.9°N, 112.5°E); the Western Udachnaya pipe (66.9°N, 112.5°E); and the host sediments and sediments from the baked contact zone.

Site/unit	n	D (°)	I (°)	k	α_{95} (°)	Notes
Eastern Udachnaya pipe						
UV_01	11	355.4	−32.8	28.7	9.1	3d + 8cc
UV_02	3	35.1	−36.5	741.6	4.5	3d
UV_03	5	5.6	−51.4	59.0	10.0	5d
UV_04	8	325.8	−40.3	10.0	18.8	5d + 3cc
UV_05	7	14.6	−44.6	15.3	15.9	7d
UV_06	6	12.8	−53.6	51.6	9.4	6d
UV_07	5	22.3	−52.8	14.3	21.5	4d + 1cc
UV_08	6	357.2	−55.4	17.0	16.7	6d
UV_09	11	23.4	−37.4	3.6	27.5	5d + 6cc
UV_10	5	3.7	−30.5	15.4	20.7	4d + 1cc
UV_11	10	357.7	−36.9	20.9	10.9	8d + 2cc
UV_12	9	354.1	−39.7	29.6	9.9	5d + 4cc
UV_13	9	1.1	−41.5	30.7	9.5	8d + 1cc
UV_14	10	351.7	−52.8	26.1	9.6	10d
UV mean	14 sites	4.3	−44.5	29.4	7.4	
Western Udachnaya pipe						
UZ-1	7	7.9	−75.1	25.5	12.2	7d
UZ-2	6	31.9	−76.1	17.3	16.6	6d
UZ-3	8	8.7	−63.4	13.2	15.9	7d + 1cc
UZ-4	9	358.9	−62.8	15.7	13.8	5d + 4c
UZ-5	9	312.1	−65.5	22.1	11.2	9d
UZ-6	6	308.5	−28.8	15.9	17.7	1d + 5cc
UZ mean	6 sites	340.5	−65.6	12.9	19.4	
Host sediments	21 samples	6.1	−12.4	26.6	6.3	14d + 7cc
Baked contact zone	7 sites	29.3	−28.3	15.8	15.7	

n: number of directions for samples or sites accepted for calculation; D (I): declination (inclination) of the characteristic component of NRM in geographic coordinates; k: precision parameter; α_{95}: radius of the 95% probability confidence circle. Entry d or cc in notes means number of directions or great circles accepted for calculations; if there is no entry this means that only directions were accepted for the calculation.

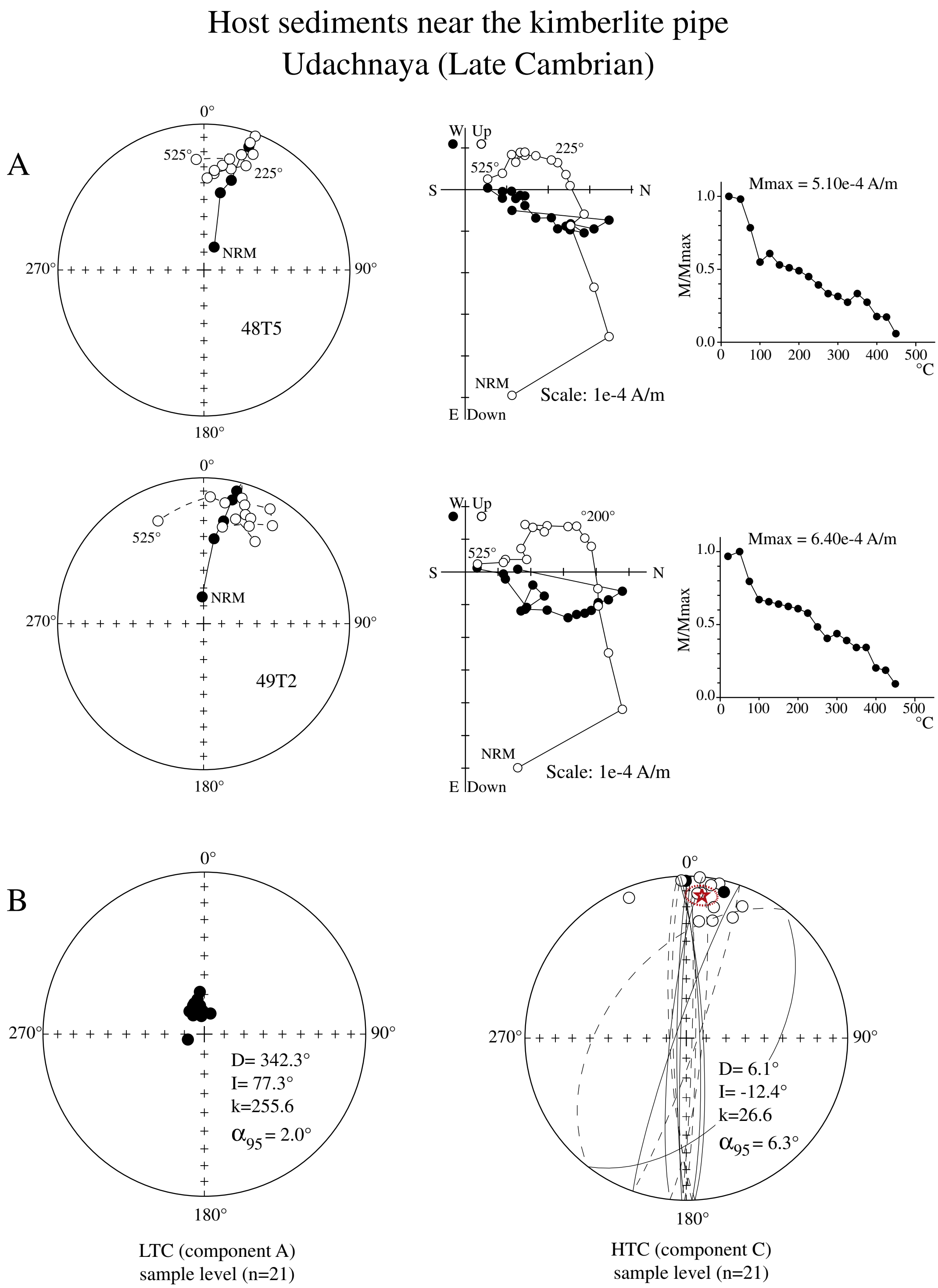

Fig. 5. (A) Typical equal-area projections, orthogonal vector plots and remanence intensity decay plots for the host sediments near the kimberlite pipe Udachnaya. Plotting conventions as in Fig. 4A. (B) Equal-area projections of the low temperature component (LTC) and high temperature component (HTC) for the host sediments. Plotting conventions as in Fig. 4B, except n: number of specimens at sample level.

be a present-day overprint. The HTC is unblocked between almost 130 °C and 658 °C. As expected from the rock-magnetic experiments, the primary components of magnetization were not well defined and often did not trend to the origin of the Zijderveld diagrams, thus requiring the use of remagnetization circles for several samples. The average HTC direction, obtained from combining the directions and great circles, at the site level is as follows: D = 291.1°, I = −78.1° (k = 27.5, α_{95} = 14.9°, N = 5) (Table 2). However, because of the mineralogy characteristic of the samples, this result should be considered with caution.

4.7. Obnazhennaya kimberlite pipe

Thermal and alternating field (AF) demagnetization was applied to samples from 17 sites in the Obnazhennaya kimberlite pipe (Table 2, Fig. 9). Two magnetization components were isolated in most of the samples. The LTC is completely removed above 250 °C and by 50 mT, giving an average direction of D = 302.5°, I = 87.0° (k = 110.9, α_{95} = 3.4°, N = 17 sites). This direction is close to the present field direction in the region (D = 347.0°, I = 83.1°) and is interpreted to be a

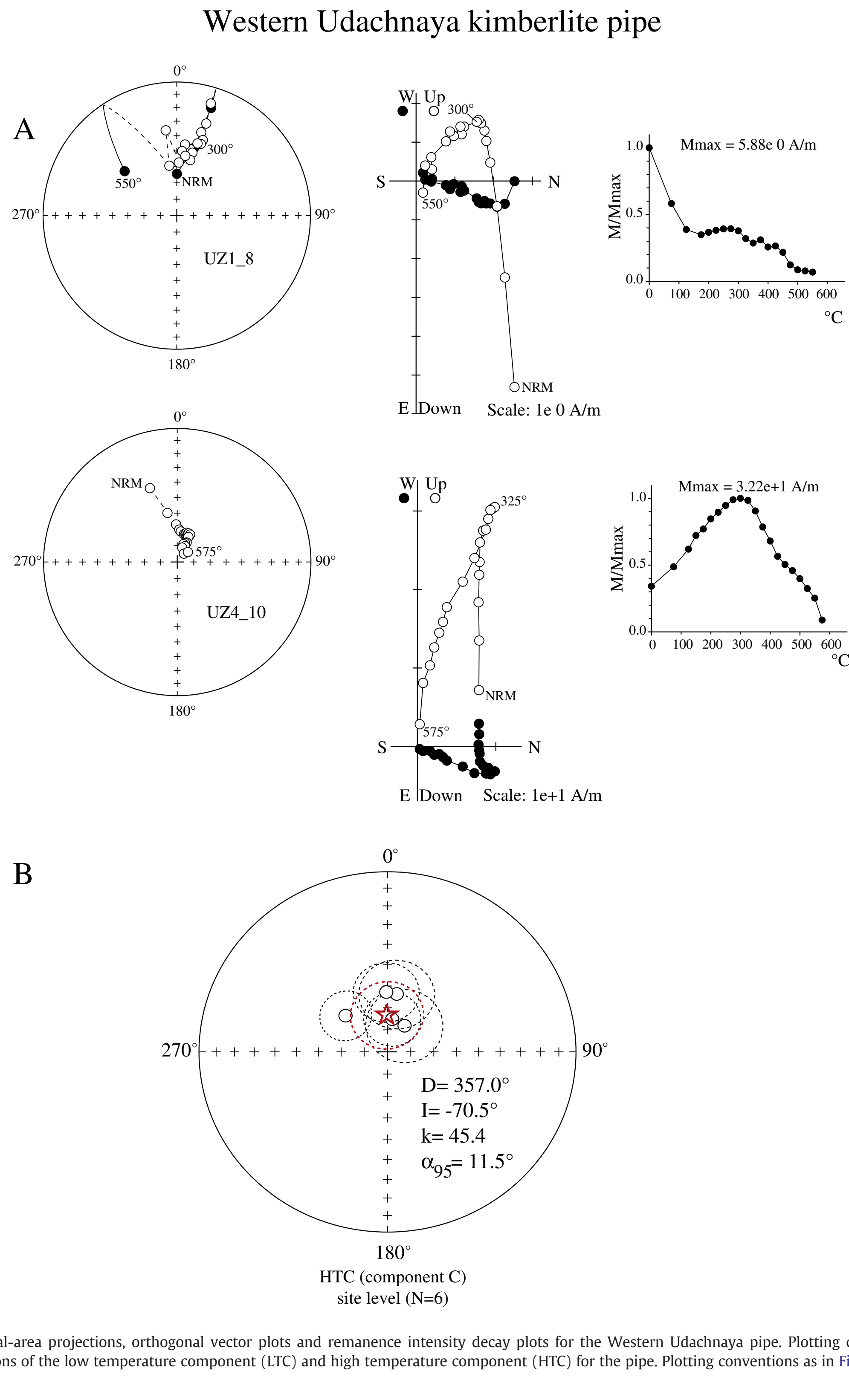

Fig. 6. (A) Typical equal-area projections, orthogonal vector plots and remanence intensity decay plots for the Western Udachnaya pipe. Plotting conventions as in Fig. 4A. (B) Equal-area projections of the low temperature component (LTC) and high temperature component (HTC) for the pipe. Plotting conventions as in Fig. 4B.

present-day overprint. The high temperature/high AF component is isolated between 350 °C and 575 °C and 125 mT and 350 mT. During heating to higher temperatures, some samples demonstrate a substantial increase in magnetic susceptibility, indicating thereby a possible oxidation of titanomagnetite. For this reason, using a combination of the stable end point directions and great circle analysis (McFadden and McElhinny, 1988), we found an average HTC direction of D = 306.7°, I = −82.6° (k = 38.4, α_{95} = 5.8°, N = 17 sites) (Table 2).

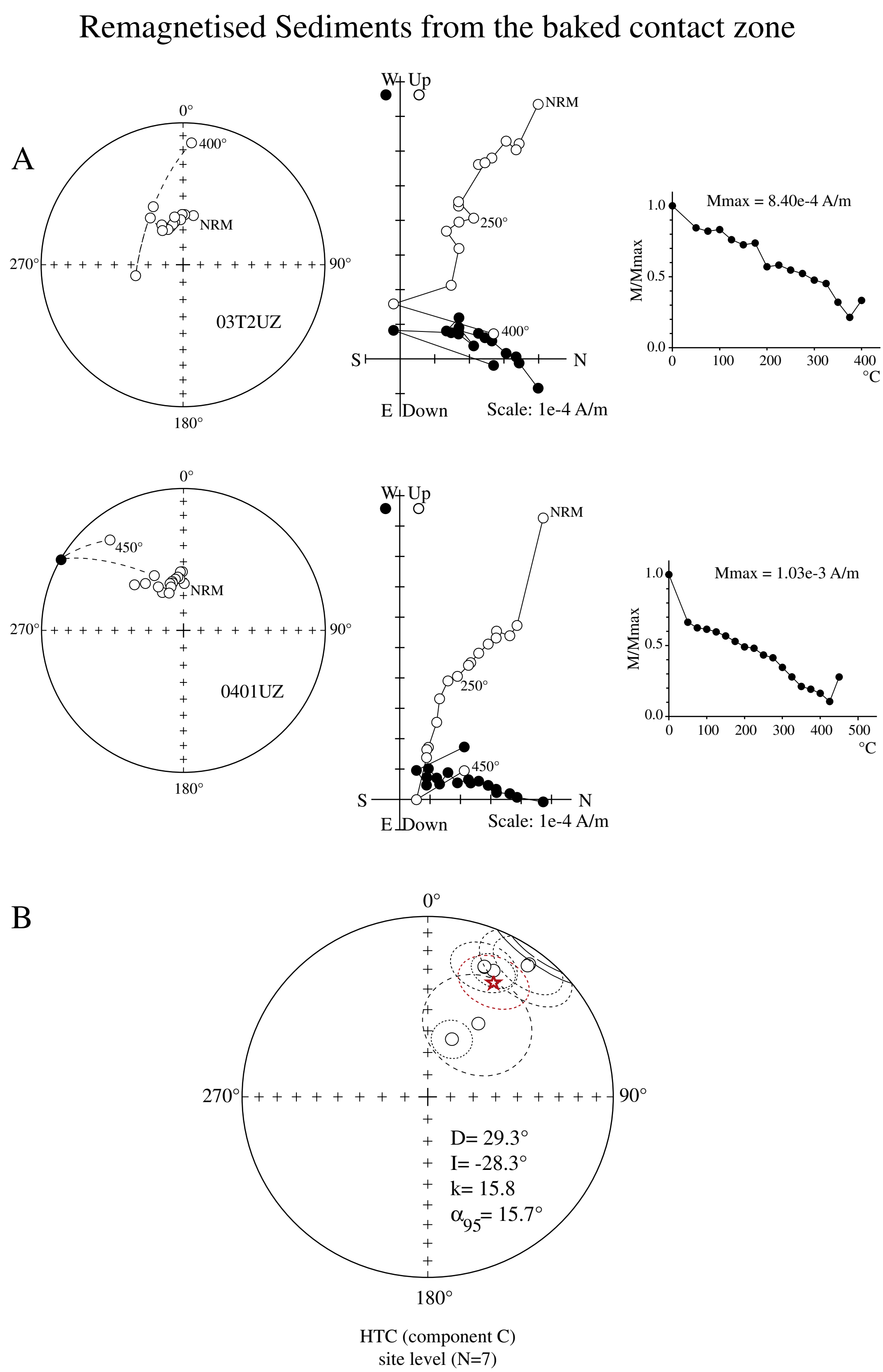

Fig. 7. (A) Typical equal-area projections, orthogonal vector plots and remanence intensity decay plots for the remagnetized sediments from the baked contact zone. Plotting conventions as in Fig. 4A. (B) Equal-area projections of the low temperature component (LTC) and high temperature component (HTC) for the remagnetized sediments. Plotting conventions as in Fig. 4B.

5. Discussion

We have identified both low and high laboratory unblocking temperature magnetization components in the studied kimberlite pipes and sedimentary rocks. HTC directions for the pipes are summarized in Fig. 10. Only high temperature components were found in the contact zone sedimentary rocks of the Western Udachnaya pipe. In all other cases the LTC can be interpreted as either a present day or a Cenozoic

Table 2
Paleomagnetic high temperature components mean directions for the International pipe (62.4°N, 113.7°E) and the Obnazhennaya pipe (70.5°N, 120.5°E).

Site number	n	D (°)	I (°)	k	α_{95} (°)	Comment
International pipe						
IN-1	5	267.8	−83.2	17.1	19.0	5d
IN-2	4	298.3	−64.3	9.7	35.8	2d+2cc
IN-3	4	222.7	−67.0	4.9	52.7	2d+2cc
IN-4	4	348.5	−80.4	783.1	6.3	4cc
IN-5	4	334.4	−71.7	18.0	25.7	2d+2cc
IN mean	5 sites	291.1	−78.1	27.5	14.9	
Obnazhennaya pipe						
Obn-02	9	2.8	−76.6	7.4	20.6	5d+4cc
Obn-04	4	156.3	−77.7	144.9	7.7	4d
Obn-06	11	70.1	−85.8	36.8	7.6	11d
Obn-08	12	281.4	−78.1	60.8	5.6	10d+2cc
Obn-10	12	153.3	−79.4	7.8	16.7	11d+1cc
Obn-12	10	319.7	−82.2	27.6	9.4	10d
Obn-14	6	302.6	−71.1	72.4	7.9	6d
Obn-16	10	31.4	−82.1	59.7	6.3	10d
Obn-18	3	326.5	−71.7	78.5	14.0	3d
Obn-20	5	317.3	−73.5	154.2	6.2	5d
Obn-22	6	119.4	−86.0	68.8	8.1	6d
Obn-24	8	336.4	−78.5	52.6	7.7	8d
Obn-26	6	256.8	−71.9	21.9	14.6	6d
Obn-28	8	322.0	−66.1	28.3	10.6	8d
Obn-30	5	38.7	−82.7	28.1	14.7	5d
Obn-32	6	304.0	−75.3	33.4	11.6	6d
Obn-34	5	248.8	−63.9	25.6	15.4	5d
Obn Mean	17 sites	306.7	−82.6	38.4	5.8	All sites

Same abbreviation as in Table 1.

geomagnetic field overprint. The individual HTC paleomagnetic poles for the kimberlite pipes and sedimentary rocks are listed in Table 3 and plotted in Fig. 11. The pole locations do not exactly match the current APWP for Siberia because the reliable poles used by Cocks and Torsvik (2007) to construct the APWP are few in number and paleomagnetic data are not available for many geologic time periods.

Cooling rates of kimbelite magma depend on the magma emplacement temperature, size of the body and depth of the sampling level. McFadden and Jones (1977) and McFadden (1977) found that cooling of some small South African kimberlite bodies took place over on the order of a few hundreds to first few thousands of years from the maximum temperature of 350 °C. Fontana et al. (2011) estimated from thermomagnetic analysis done on Southern Africa kimberlite pipes that the basaltic clasts in the layered and massive vent-filling pyroclastic deposits in the center of the pipe were emplaced at >570 °C (some even >760–920 °C), and the temperatures near the edges were as low as 200–440 °C. Van Fossen and Kent (1993) reported a polarity reversal recorded in one kimberlite dyke in the US. They estimated an emplacement temperature of ~700 °C and cooling rates between 10^3 and 10^7 years. The sizes of the kimberlite pipes we studied are in the order of 100 m in diameter and the present day sampling surface is estimated to be at least few hundred meters below the ancient surface. Our preliminary estimate of the cooling temperature rate using the method of Van Fossen and Kent (1993) is at least 10^4 and 10^7 years in the center of the kimberlite bodies. We sampled at the different levels across the kimberlite pipes and therefore consider that geomagnetic secular variations are most likely averaged in our study.

The poles for the Eastern Udachnaya and Western Udachnaya kimberlites are situated far apart from each other at 3.1°N/108.6°E and 25.6°N/126.9°E, respectively (Fig. 11). The Eastern Udachnaya kimberlite pole lies among the group of the Late Ordovician–Early Silurian Siberian poles, and gives a paleomagnetic age of 428±13 Ma (Fig. 11). This pole is close to the paleomagnetic pole for the host Early Ordovician sedimentary rocks. The pole for the host sedimentary rocks at 16.7°S/106.2°E with A_{95}=4.6° is very well defined, although no fold test or reversal test could be applied, and gives an Early Silurian paleomagnetic age of 441±3 Ma that is situated near the Late Ordovician Siberian pole of 450 Ma. The age of the sedimentary rocks is well defined paleontologically as Early Ordovician; therefore we interpret the pole to record either an overprint of the host sedimentary rocks of the Udachnaya area by the Eastern Udachnaya kimberlite magmatic event or to record secular variation that was not averaged out during magnetization acquisition.

The primary nature of the HTC was inferred based on the proximity of the pole's position to the Ordovician group of poles and the result of the baked contact test. The pole calculated for the baked sedimentary rocks is notably different from the kimberlite or sediment poles and is situated farther west in the center of the Indian Ocean at 5.2°S/84.2°E, A_{95}=12.7° (Fig. 11). We interpret this pole to record the partial overprinting of the original remanence in the Early Ordovician sedimentary rocks by a thermoremanent magnetization from the intrusion of the Udachnaya kimberlite pipes.

The Early Silurian paleomagnetic age of the Eastern Udachnaya kimberlite differs radically from the inferred Late Devonian age inferred from radiometric dating (Griffin et al., 1999; Kinny et al., 1997; Maas et al., 2005). This discrepancy may be caused by several factors. Although the Siberian APWP has the most poles from the Ordovician period, these poles are very scattered. The Silurian is poorly represented, and there are no poles with ages between 435 and 365 Myr. The APWP for this time interval has been reconstructed by interpolation. The low resolution and precision of the Siberian APWP invite speculation and undoubtedly affect the accuracy of the paleomagnetic dating attempted in this study substantially. However, if we assume the inferred paleomagnetic age to be reasonable, we can conclude that kimberlite magmatism in the Siberian platform started much earlier than the Late Devonian. Kravchinsky et al. (2002) discussed the then available radiometric ages and paleomagnetic data, and suggested that the Alakit–Markha kimberlite field magmatism located south of the Anabar Shield was associated with the eruption of the Late Devonian–Early Carboniferous Viluy traps. The Eastern Udachnaya pipe is from the Daldyn kimberlite field, which appears to be older than the Alakit–Markha kimberlite field. Kuzmin et al. (2010) discussed the early Paleozoic large scale magmatism to the south of the present day Siberian platform in the Altay–Sayan terrane and the Viluy rift. They found that Siberia was located above the large African low shear wave velocity zone throughout the Paleozoic. The earliest igneous rocks in the Viluy rift are tephrites, trachybasalts, trachytes, phonolites, and ultrabasic alkali rocks with carbonatites (Gaiduk, 1987), which corresponds to the earliest arch-uplift stage of development of the Viluy rift. The intrusion of the Eastern Udachnaya kimberlite pipe could be provisionally associated with this early arch uplift.

The Western Udachnaya kimberlite pole at 25.6°N/126.9°E, A_{95}= 28.5° is distinct from of all other poles obtained in this study and from the Siberian APWP. We interpret the anomalous location of this pole to be a result of remagnetization during later alteration. The Western Udachnaya pipe is composed of altered kimberlite; such alteration could take place either gradually or quickly at any time after kimberlite intrusion. The pipe's paleomagnetic pole is located between the Early Paleozoic and Mesozoic segments of the APWP but does not match well with any specific poles. Most likely the HTC is a combination of a primary and a viscous magnetization, which could be related to gradual alteration processes related to hydrothermal fluids. The regional remagnetization by the Permo-Triassic trap magmatic event is unlikely because the host sedimentary rocks and the Eastern Udachnaya pipe paleopoles coincide with the early Paleozoic segment of the APWP.

The paleomagnetic pole for the International kimberlite pipe is located at 48.8°N/147°E (A_{95}=27.2°; Table 3, Fig. 11). This pole agrees with the Permo-Triassic NSP3 paleomagnetic pole for the Siberian traps of 57.0°N/148.1°E, A_{95}=5.3° as reported by Pavlov et al. (2007). Our rock-magnetic data show that the initial primary magnetization is not carried by magnetite and could be associated with secondary minerals. The magnetizations from four of the five sites did not preserve

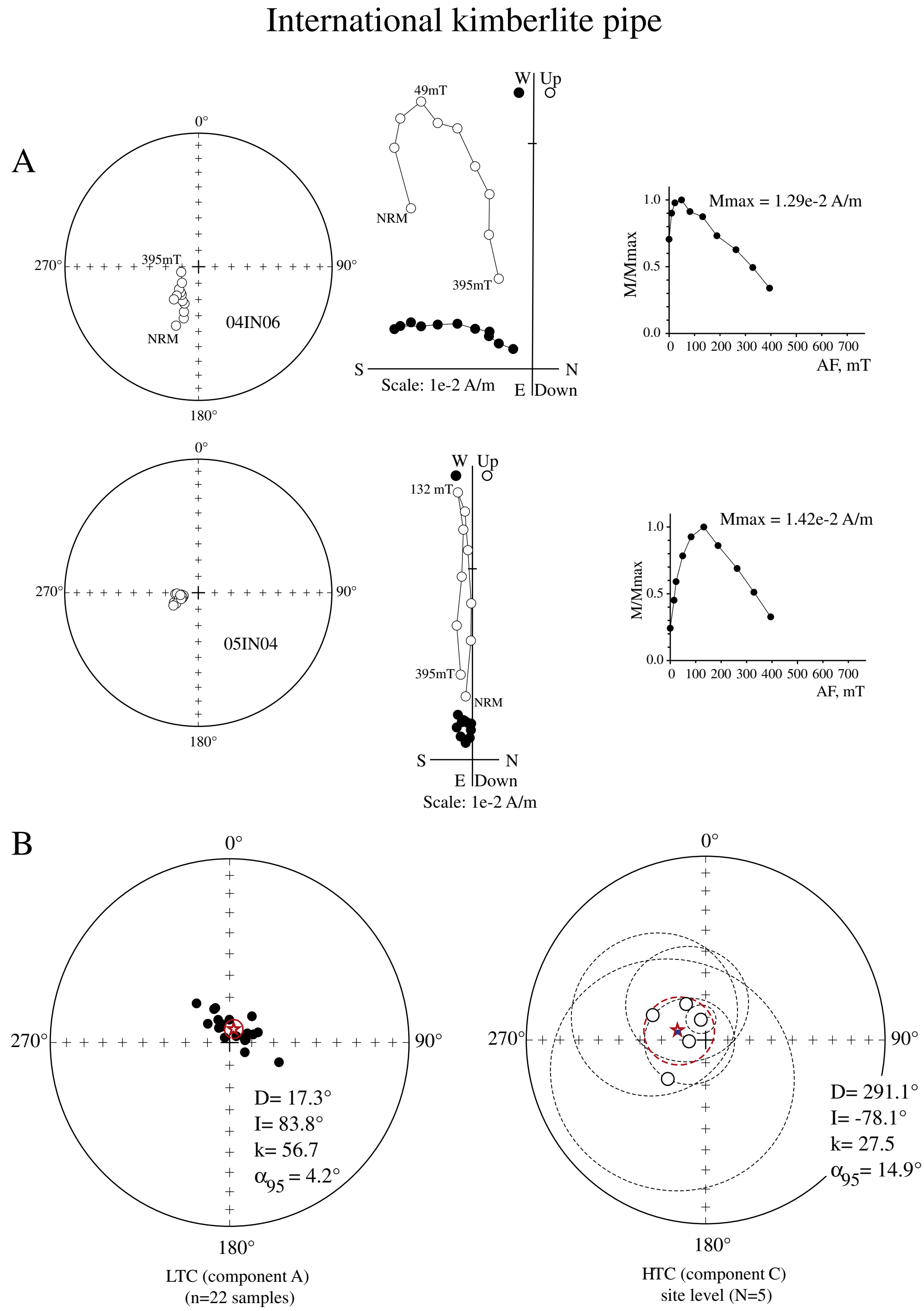

Fig. 8. (A) Typical equal-area projections, orthogonal vector plots and remanence intensity decay plots for the International pipe. Plotting conventions as in Fig. 4A. (B) Equal-area projections of the low temperature component (LTC) and high temperature component (HTC) for the pipe. Plotting conventions as in Fig. 4B, except n: number of specimens at sample level.

linear segments of the high temperature component and they could be evaluated only by using remagnetization circle analysis. The paleomagnetic age is determined as 251 ± 30 Ma. The HTC magnetization in these rocks is secondary and likely corresponds to the age of the major remagnetization event in the area — the Siberian traps eruption.

The paleomagnetic pole for the Obnazhennaya kimberlite pipe at 59.6°N/143.9°E (A_{95} = 11.2°; Table 3, Fig. 11) is also located near the Permo-Triassic NSP3 paleomagnetic pole of Pavlov et al. (2007) for Siberian traps at 57.0°N/148.1°E, A_{95} = 5.3°. The pipe's mean direction is based on HTC directions and some remagnetization circles. The kimberlite is fresh and rock-magnetic data suggest that magnetite/titanomagnetite is the major carrier of what we assume is a primary thermoremanent magnetization. Radiometric, paleontological, and stratigraphic ages for this pipe suggests Middle–Late Jurassic. For this period of time, the Siberian APWP is not well defined and the Eurasian APWP is used to describe the motion of Siberia (Besse and Courtillot, 2002; Schettino and Scotese, 2005). For this reason we used the Eurasian APWP of Besse and Courtillot (2002) and the most recent Eurasian APWP of Torsvik et al. (2008) for the past 200 Ma. We estimate a

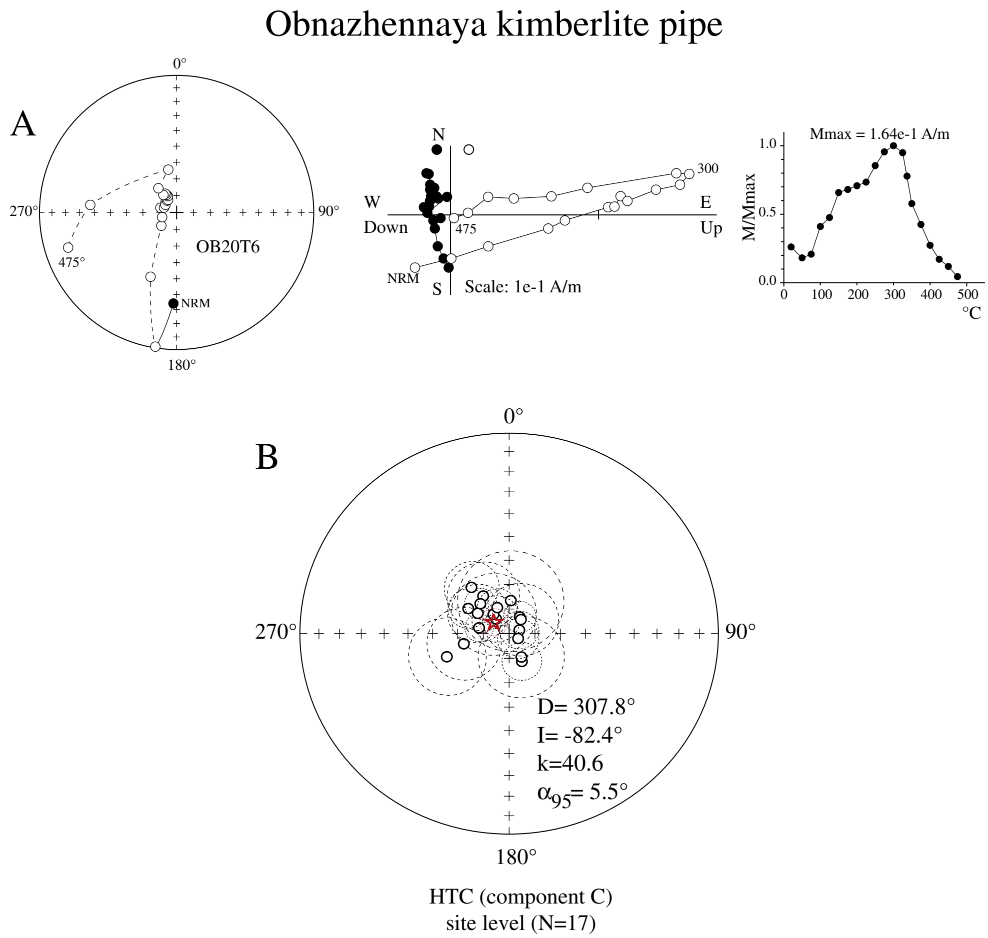

Fig. 9. (A) Typical equal-area projections, orthogonal vector plots and remanence intensity decay plots for the Obnazhennaya kimberlite pipe. Plotting conventions as in Fig. 4A. (B) Equal-area projections of the low temperature component (LTC) and high temperature component (HTC) for the pipe. Plotting conventions as in Fig. 4B.

paleomagnetic age of 168 ± 11 Ma with the APWP of Besse and Courtillot (2002) and 151 ± 14 Ma with the APWP of Torsvik et al. (2008). Both results agree within error and the difference might be related to the data selection of Besse and Courtillot (2002) and Torsvik et al. (2008) for the APWP construction, different Euler rotation parameters, and degree of smoothing used to construct the APWP (Torsvik et al., 2008). The Obnazhennaya age results are consistent with the geologic constraints and with the published radiometric dating data; thus we confirm the Middle–Late Jurassic age of the Obnazhennaya pipe.

6. Conclusions

We have obtained new paleomagnetic poles for the Eastern Udachnaya, Western Udachnaya, International, and Obnazhennaya kimberlite pipes of the Siberian platform. The poles are compared to the Siberian APWP (Cocks and Torsvik, 2007) for the Paleozoic interval and to Besse and Courtillot (2002) and Torsvik et al. (2008) for the Mesozoic interval to estimate the ages of the studied pipes. The ages of the kimberlites fall into three groups spanning the Early Silurian to the Late Jurassic.

1. Two kimberlite pipes were studied from the Udachnaya field. The Western Udachanya pipe has been remagnetized by post-intrusion alteration so that no clear age could be determined. The Eastern Udachnaya pipe provides a well-defined, most likely primary, thermoremanent magnetization that gives an Early Silurian age of 428 ± 13 Ma. We consider that magmatism corresponds to the earliest stage of the Viluy rift formation. This age contradicts previously published Late Devonian radiometric ages. An alternative interpretation is that the paleomagnetic age could be inaccurate because of the imprecision of the Paleozoic segment of the Siberian APWP that was used as the reference path for the age estimates.
2. For the International kimberlite pipe, magnetic mineralogy and paleomagnetic data provide evidence that the samples have been remagnetized. The estimated paleomagnetic age of 251 ± 30 Ma is likely related to the Permo-Triassic trap magmatism that was a major remagnetization event affecting the Malo-Botuoba kimberlite field. The previously studied Mir kimberlite pipe was remagnetized by the same magmatic event (Kravchinsky et al., 2002).
3. Comparison of the Obnazhennya paleomagnetic pole with the Eurasian APWP (Besse and Courtillot, 2002; Torsvik et al., 2008) yields a Middle–Late Jurassic age for the kimberlite, which corresponds to previously reported radiometric, paleontologic, and stratigraphic age estimates.

Paleomagnetic techniques applied to dating Siberian kimberlite magmatism reveal a large span of kimberlite ages, from the Early Silurian to Middle–Late Jurassic. Early Silurian to Late Devonian ages are most likely related to magmatism during the early and main stages of formation of the Viluy rift. Middle–Late Jurassic magmatism could be associated with subduction processes that took place on the present day northeast margin of the Siberian platform during this time period, associated with the accretion of the Omolon, Kolyma, and surrounding terranes. The Omolon block accreted to the Siberian platform in the post–Late Jurassic (Savostin et al., 1993). Recent numerical models have demonstrated that low-angle subduction can

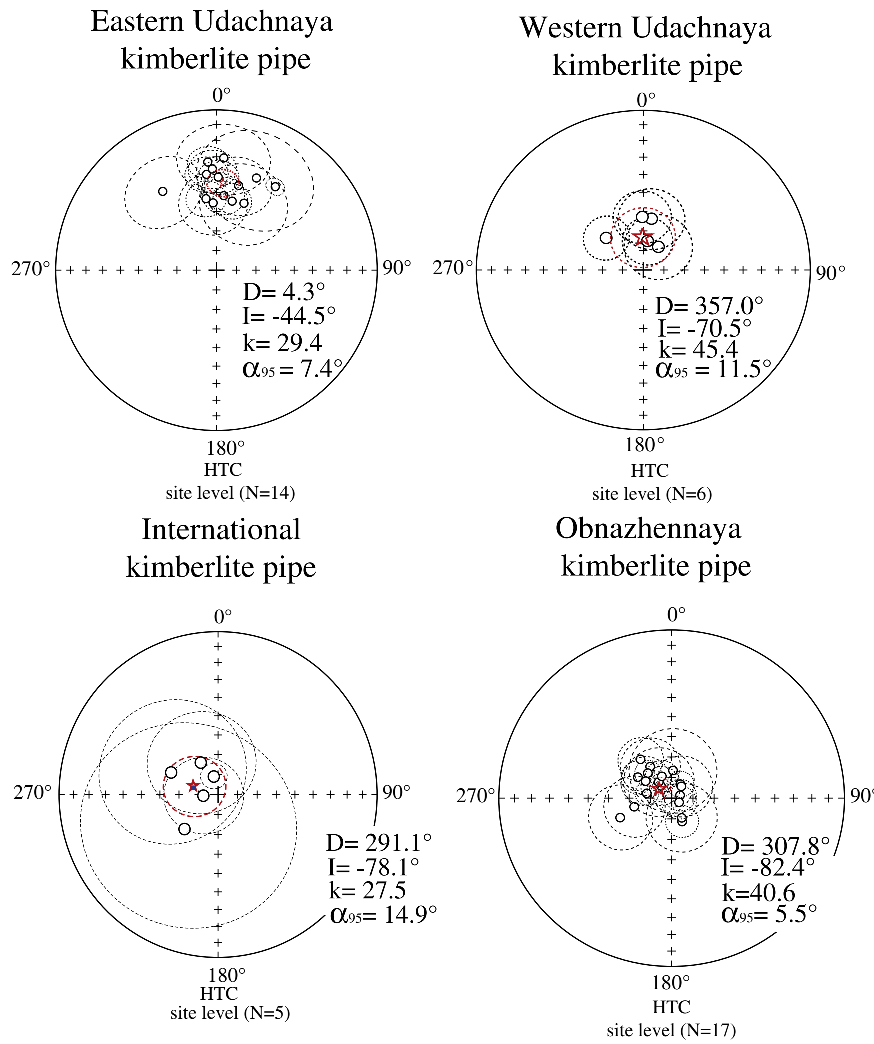

Fig. 10. Equal-area projections of site-mean directions of high temperature (HTC) components for each studied pipe, with circles of 95% confidence. Open (close) symbols: upward (downward) inclinations. Star: mean formation direction. D: declination, I: inclination, k: precision parameter, α_{95}: radius of the 95% probability confidence circle, N: number of specimens at site level.

result from high plate convergence velocities that have triggered partial melting and kimberlite/lamproite magmatism far into North American continent by more than 1200 km from the subduction trench (Currie and Beaumont, 2011). Geochemical studies on some kimberlite pipes in Siberia also suggest that subduction is involved in the formation of some kimberlite fields (Ashchepkov et al., 2010).

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Table 3
Paleomagnetic poles and estimated ages for the studied pipes.

Studied object	Site coordinates		Paleomagnetic pole coordinates		dp/dm (A_{95})	N	Paleolatitude (°)	Paleomagnetic age (Ma)
	Lat °N	Long °E	Lat °N	Long °E				
Udachnaya Eastern kimberlite pipe	66.9	112.5	3.1	108.6	9.3/5.9 (7.4)	14 sites	26.2 ± 9.3	428 ± 13
Udachnaya Western kimberlite pipe	66.9	112.5	25.6	126.9	31.6/25.7 (28.5)	6 sites		
Baked contact test (BCT)	66.9	112.5	−5.2	84.2	17.2/9.4 (12.7)	7 sites		
Early Ordovician host sediments	66.9	112.5	−16.7	106.2	6.4/3.3 (4.6)	21 samples	6.3 ± 6.4	Remagnetized
International kimberlite pipe	62.4	113.7	48.8	147.0	28.1/26.4 (27.2)	5 sites		251 ± 30
Obnazhennaya kimberlite pipe	70.5	120.5	59.6	143.9	11.3/11.1 (11.2)	17 sites	75.4 ± 11.3	168 ± 11[a] 151 ± 14[b]

Lat (long): latitude (longitude) of the sampling sites of paleomagnetic pole. dp/dm: semi-axes of the oval of 95% confidence of the paleomagnetic pole; A_{95}: radius of the 95% confidence circle.

[a] The age determined using APWP of Besse and Courtillot (2002).

[b] The age determined using APWP of Torsvik et al. (2008).

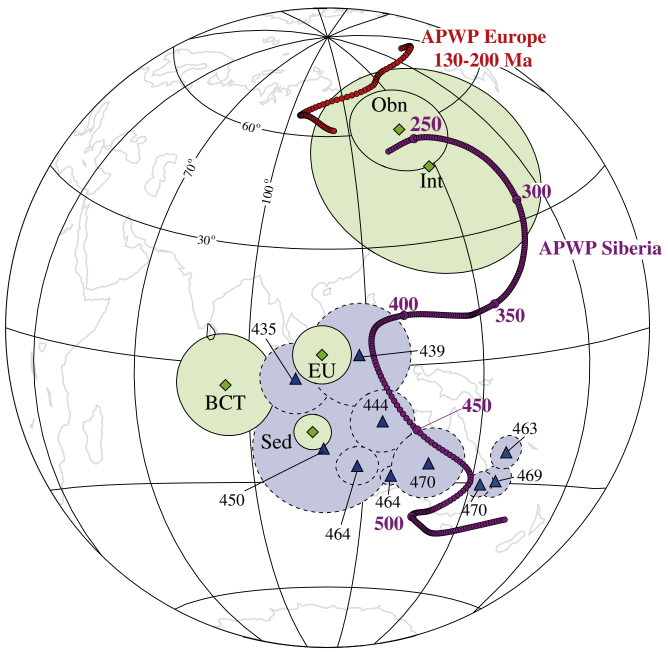

Fig. 11. Equal area projection of paleomagnetic poles from kimberlites pipes and sediments (diamonds) with ellipses of 95% confidence (shadow areas). Triangles represent the Siberian platform poles between 430 and 470 Myr with their corresponding 95% confidence ellipses (dashed ellipses). Circles represent the Siberian APWP of Cocks and Torsvik (2007) interpolated to 2 Myr intervals and the European APWP of Besse and Courtillot (2002) between 130 and 200 Ma interpolated to 2 Myr intervals. Obn: Obnazhennay pipe paleomagnetic pole; Int: International pipe paleomagnetic poles; EU: Eastern Udachnnaya pipe paleomagnetic pole; BCT: baked contact test paleomagnetic pole; Sed: sediments near the Eastern Udachnya kimberlite pipe paleomagnetic pole. The Western Udachnaya paleomagnetic pole is not illustrated.

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