Available online at www.sciencedirect.com
SCIENCE DIRECT
ELSEVIER
Tectonophysics 379 (2004) 211–226
TECTONOPHYSICS
www.elsevier.com/locate/tecto

# Palaeomagnetism and magnetostratigraphy of the Permian–Triassic northwest central Siberian Trap Basalts ☆

E.L. Gurevitch[a], C. Heunemann[b], V. Rad'ko[c], M. Westphal[d,*], V. Bachtadse[b], J.P. Pozzi[e], H. Feinberg[e]

[a] VNIGRI, Laboratory of Palaeomagnetism and Palaeoreconstructions, Liteiny 39, 191104 St. Petersburg, Russia
[b] Department of Geo-and-Environmental Sciences, Geophysics Section, LMU Munich, Theresienstr. 41, 80333 Munich, Germany
[c] Noril'sk Mining Company, 663255, Talnakh, Box 889, Krasnoyarsk District, Russia
[d] Institut de Physique du Globe, Ecole et Observatoire des Sciences de la Terre, 5 rue Rene Descartes, 67084 Strasbourg Cedex, France
[e] Laboratoire de Géologie, Ecole Normale Supérieure, 24 rue Lhomond, 75231 Paris Cedex 05, France

Received 17 February 2003; accepted 5 November 2003

**Abstract**

A detailed palaeomagnetic and magnetostratigraphic study of the Permian–Triassic Siberian Trap Basalts (STB) in the Noril'sk and Abagalakh regions in northwest Central Siberia is presented. Thermal (TH) and alternating field (AF) demagnetisation techniques have been used and yielded characteristic magnetisation directions. The natural remanent magnetisation of both surface and subsurface samples is characterised by a single component in most cases. Occasionally, a viscous overprint can be identified which is easily removed by TH or AF demagnetisation.

The resulting average mean direction after tectonic correction for the 95 flows sampled in outcrops is $D = 93.7°$, $I = 74.7°$ with $k = 19$ and $\alpha_{95} = 3.3°$. The corresponding pole position is 56.2°N, 146.0°E.

Unoriented samples from four boreholes cores in the same regions have also been studied. They confirm the reversed–normal succession found in outcrops. The fact that only one reversal of the Earth's magnetic field has been recorded in the traps can be taken as evidence for a rather short time span for the major eruptive episode in this region. However, there is evidence elsewhere that the whole volcanic activity associated with the emplacement of the STB was much longer and lasted several million years.


*Keywords:* Palaeomagnetism; Magnetostratigraphy; Siberia; Permian; Triassic; Traps

## 1. Introduction

It as been proposed that large igneous provinces (LIPs) and continental flood basalts (CFBs) may have triggered biological crisis and are responsible for large extinctions like at the Permian–Triassic boundary (see review by Wignall, 2001 and references therein). Yet several questions are still unsolved for the Permian–Triassic event: Are the volcanic activity and the bio-

☆ Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.tecto.2003.11.005.

* Corresponding author. Tel.: +33-3-90-24-00-55; fax: +33-3-90-24-01-25.

*E-mail addresses:* egourev@rambler.ru (E.L. Gurevitch), heunem@geophysik.uni-muenchen.de (C. Heunemann), westphal@eost.u-strasbg.fr (M. Westphal), pozzi@geologie.ens.fr (J.P. Pozzi).

0040-1951/$ - see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.tecto.2003.11.005

logical crisis really synchronous and what are the true interaction mechanisms between volcanic products (lavas, ashes, gases) and the biosphere? To answer these questions very precise ages and thus robust estimates of the duration of the volcanic activity are of vital importance. In combination with radiometric studies, palaeomagnetism and magnetostratigraphy may provide further constraints on the duration.

During the Permian–Triassic crisis, 90% of the species are estimated to have disappeared. The age of this boundary in the Chinese Permian–Triassic type sections is given with $251.2 \pm 3.4$ Ma by Claoué et al. (1991), $249.91 \pm 1.52$ Ma by Renne et al. (1995) and $251.3 \pm 0.3$ Ma by Bowring et al. (1998). The Siberian Trap Basalts (STB), which are coeval within margin of error, are therefore usually associated with the Permian–Triassic mass extinction.

## 2. The Permian–Triassic Siberian traps

Presently, the basalts of Siberian traps cover an area of $0.4 \times 10^6$ km$^2$. If one includes pyroclastics, tuffs and intrusions the area covered increases it up to $1.5 \times 10^6$ km$^2$ (Zolotukhin and Al'Mukhamedov, 1988). Volcanics found on the Taimyr peninsula and in boreholes in Western Siberia are estimated to be of similar age (Gurevitch et al., 1995; Westphal et al., 1998a,b; Reichow et al., 2002) and increase the area covered even more. Estimates of the original volume are highly speculative and range from 1.5 to $4 \times 10^6$ km$^3$ (Fig. 1).

In Central Siberia, the lowermost formations, pyroclastics and tuffs, overlay Late Permian sediments (Kozur, 1998). On Taimyr and in Western Siberia, the traps are in turn overlain by sediments of Early Triassic age (Induan and Olenikian). Five main volcanic regions have been recognised: Noril'sk, Putorana, Tunguska, Taimyr and Maimecha–Kotuy. The 3500-m-thick sequence of volcanic rocks near Noril'sk is thought to be the oldest part of the whole STB province which reaches a total thickness of 6.5 km (Fig. 1). The volcanic rocks consist of alternating sequences of more than 200 lava flows and about 30 tuff layers. Eight varieties of lavas are recognised to be primitive, similar in composition to primary mantle melts; they vary from low-Mg basalts to olivine tholeiites or picrites, with tholeiites dominating. Lavas are of both low-Ti and high-Ti parentage. They are subdivided into four groups (magma types) on the basis of trace element ratios (principally Gd/Yb, Th/U, La/Yb, Ta/La, Ti/Sc and V/Yb) and isotopic data (Fedorenko et al., 1996; Sharma, 1997).

The volcanic activity is subdivided in different stages and suites which can be traced throughout the entire region and share broadly similar chemical features. The lavas were erupted on a very flat topography and their horizontal extension may be very large. Individual flows are a few tens of meters thick and can be identified over tens of kilometres. However, some marker flows are up to 200 m thick and extend over several hundreds of kilometres. Names and average thickness of the Noril'sk suites are given in Table 1a and b, together with the number of samples studied in each section.

Precise $^{39}$Ar/$^{40}$Ar and U–Pb ages are now available (see Wignall, 2001, for a complete description and Reichow et al., 2002). Radiometric age determinations for the lower members of the Noril'sk suite yield consistent ages around 250 Ma ($250.0 \pm 1.6$ Ma, $^{39}$Ar/$^{40}$Ar by Renne et al., 1995 and $251.2 \pm 0.3$ Ma, U–Pb by Kamo et al., 1996) or between 248 and 247 Ma (Venkatesan et al., 1997). Both age clusters suggest a short duration of the volcanic activity. Differences in age of up to 4 Ma are not significant and reflect the use of different standards.

The Putorana and lower Tunguska regions are in the centre and to the south of the main massif. Here the lower Ivakinsky and Syverminsky suites are missing and the volcanic sequence starts with the deposition of 700 m of tuffs and pyroclastics of highly explosive character. On the top of these volcanoclastics a pile of 2 to 3 km of lavas has been deposited. As in the Noril'sk district, the lavas are mostly quartz and olivine tholeiites, sometimes picritic.

Separated from the main Central Siberia Massif by the Yenisey–Khatanga trough, the Taimyr peninsula forms another subprovince where similar lavas are also found. Here the Syradasaysky suite is the oldest suite and is equivalent to the Ivakinsky suite of the Noril'sk area (see in Gurevitch et al., 1995 and references therein).

The Maimecha–Kotuy province represents a fifth volcanic region within the STBs. The volcanics exposed here differ in geochemistry from the ones described so far and consist mostly of alkaline to ultrabasic lavas, filling a graben 3 km deep. Based

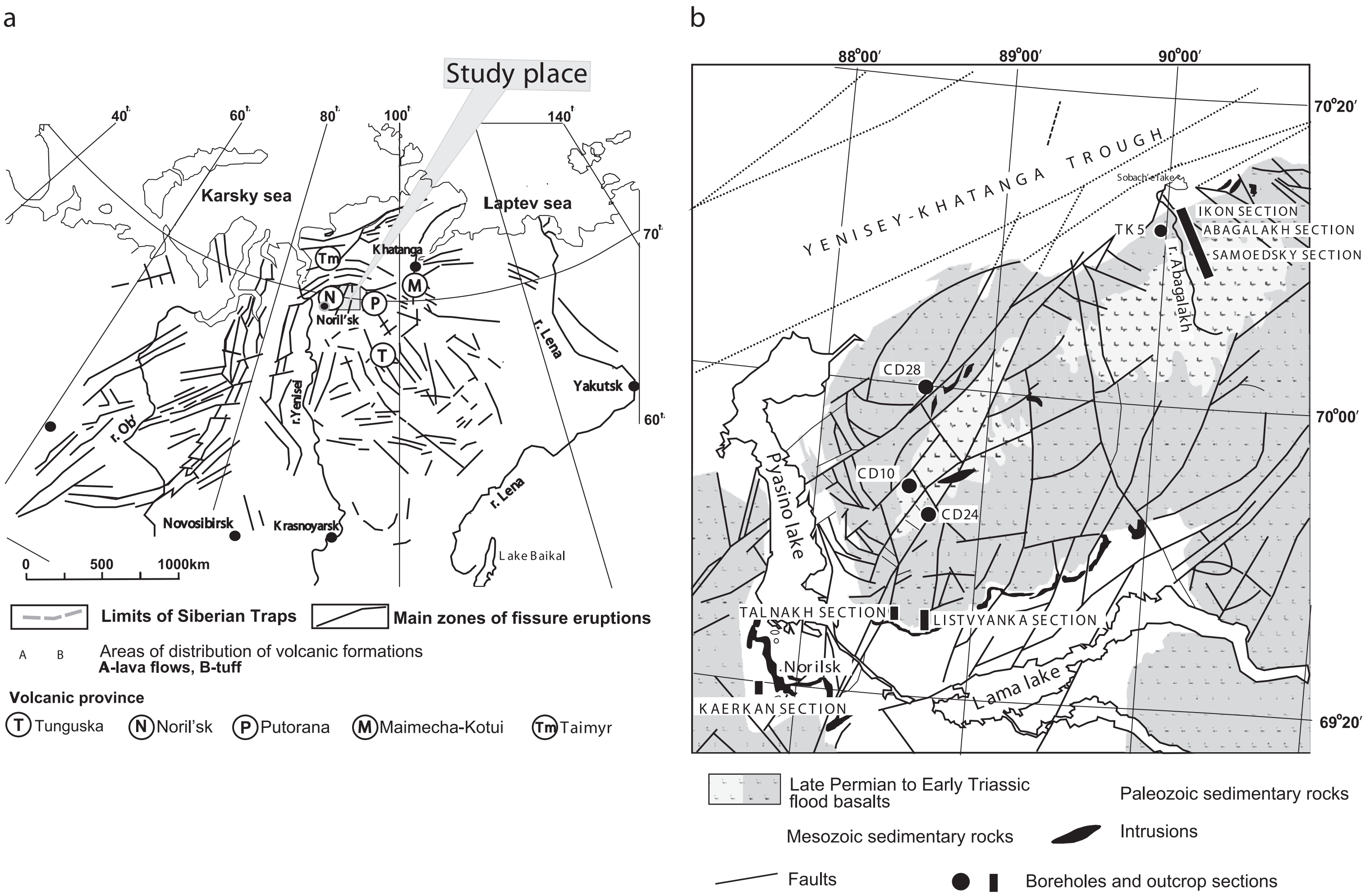



Fig. 1. (a) General outline showing the position of the Central Siberia basalt province with the main regions (from Masaitis, 1983). (b) Detailed map of the Noril'sk–Abagalakh region showing the position of sections and boreholes sampled.

Table 1

(a) Suites in Noril'sk region, sampled in outcrops

| Suite | Abbr. | Petro | Thickness (m) | Abagalakh 70.33°N 90.13°E | Talnakh 69.46°N 88.50°E | Listvyanka 69.47°N 88.72°E | Kaerkan 69.29°N 87.72°E |
|---|---|---|---|---|---|---|---|
| Average bedding plane (strike and dip) | | | | 55–65/10–15 | 279/11 | 279/10–12 | 170/10 |
| Samoedsky | sm | Th | 340–360 | 33 | | | |
| Kumginsky | km | Th | 160–220 | 35 | | | |
| Kharaelakhsky | hr | Th, ASA | 380–480 | 42 | | | |
| Mokulaevsky | mk | Th | 250–600 | 77 | | | |
| Morongovsky | mr | Th, ASA | 400–500 | 65 | | | |
| Nadezhdinsky | nd | Th, ASA, Tf | 230–650 | 115 | | | |
| Tuklonsky | tk | Th | 20–200 | 37 | | | |
| Khakanchansky | hk | Th | 0–20 | | | 4 | |
| Gudchikhinsky | gd | Th, P | 80–290 | | | 46 | |
| Syverminsky | sv | Th, ASA | 0–170 | | 36 | 69 | 5 |
| Ivakinsky | iv | ASA, Th, Tf | 40–210 | | 30 | 31 | 5 |
| Total | | | | 404 | 66 | 150 | 10 |

(b) Suites in Noril'sk region, cores of boreholes sampled

| Suite | Petro | Thickness (m) | CD10 69.75°N 88.55°E | CD24 69.66°N 88.66°E | CD28 70.00°N 88.58°E | TK5 70.33°N 90.10°E |
|---|---|---|---|---|---|---|
| Kumginsky | Th | 160–220 | 27 | | | |
| Kharaelakhsky | Th, ASA | 380–480 | 3 | 37 | | 35 |
| Mokulaevsky | Th | 250–600 | | 51 | | 24 |
| Morongovsky | Th, ASA | 400–500 | | 38 | | 36 |
| Nadezhdinsky | Th, ASA, Tf | 230–650 | | 27 | | 21 |
| Tuklonsky | Th | 20–200 | | 9 | 9 | 3 |
| Gudchikhinsky | Th, P | 80–290 | | 12 | 20 | |
| Syverminsky | Th, ASA | 0–170 | | 10 | 3 | |
| Ivakinsky | ASA, Th, Tf | 40–210 | | 19 | 17 | |
| Total | | | 30 | 203 | 49 | 119 |

Abbr. indicates the current abbreviations for the different suites used here. Petro: ASA: Alkaline to subalkaline basalts, P: picrites, Tf: tuffs, Th: tholeiites.

on an alternation of low and high-Ti lavas, they are correlated to the middle part of the main Noril'sk sequence: Morongovsky and Mokulaevsky suites by Fedorenko and Czamanske (1997). However, this lithostratigraphic correlation is not supported by precise radiometric ages. Basu et al. (1995) obtained an age of 253.0 ± 2.6 Ma for the base and of 250.4 ± 1.3 Ma for the top of this section and it is important to note that these last ages have been obtained in the same laboratory and with the same standard than the age of 250.0 ± 1.6 Ma for the basal formations of Noril'sk by Renne et al. (1995). These authors consider then that they are directly comparable and that the bottom of the Maimecha–Kotuy section is significantly older than the lowermost lavas from Noril'sk. U–Pb and U–Th–

Table 2

Siberian traps, mean directions and poles averaged by regions

| Region | $N$ | $D_m$ | $I_m$ | $k$ | $\alpha_{95}$ | Lat. | Long. | $K$ | $A_{95}$ |
|---|---|---|---|---|---|---|---|---|---|
| Noril'sk | 12 | 95.1 | 78.3 | 79 | 4.9 | 58.9 | 134.3 | 26 | 8.6 |
| Putorana massif | 10 | 101.6 | 69.6 | 561 | 2.0 | 45.0 | 149.8 | 173 | 3.7 |
| West Taimyr | 7 | 121.9 | 71.2 | 282 | 4.0 | 44.9 | 126.5 | 76 | 6.9 |
| Central Taimyr | 6 | 121.0 | 69.1 | 65 | 8.3 | 45.0 | 148.3 | 29 | 12.4 |
| Maimecha–Kotuy | 8 | 101.9 | 69.2 | 233 | 3.6 | 45.2 | 158.0 | 97 | 5.6 |
| SE kimberlites | 5 | 101.5 | 77.0 | 63 | 9.6 | 53.7 | 153.0 | 17 | 18.7 |
| Average | 49 | 106.4 | 73.0 | 90 | 2.1 | 49.9 | 144.8 | 29 | 3.8 |

$N$: number of results; $D_m$, $I_m$: mean declination and inclination; $k$, $\alpha_{95}$: Fisher concentration and precision parameter; Lat., long., $K$, $A_{95}$: mean pole and precision parameters.

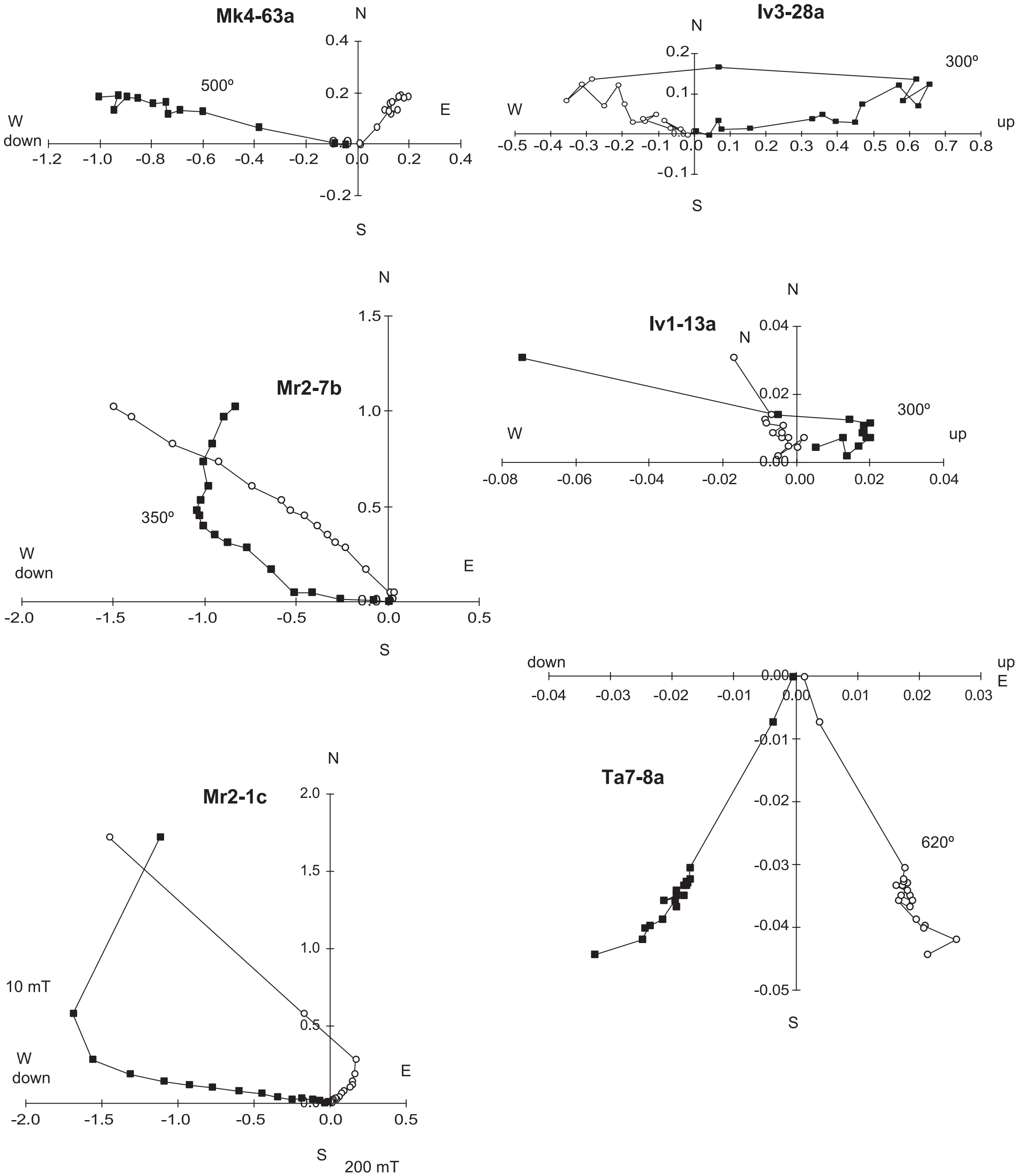



Fig. 2. Representative demagnetisation behaviour of several samples. Open circles: projection on the horizontal plane; full squares: projection on the north–south vertical plane. Characteristic temperatures or alternating magnetic field values of individual demagnetisation steps are given.

Pb ages on zircons, baddeleyites and perovskites (Kamo et al., 2000) are in the same range of 254.8 ± 5.8 and 250.4 ± 0.4 Ma.

In the West Siberia basin, new results obtained from borehole samples have given indistinguishable ages around 250 Ma (Reichow et al., 2002). Unfortunately, the precise stratigraphic position of the samples is not known and moreover borehole SG6 where we have a reliable magnetostratigraphy has not been dated yet (Westphal et al., 1998a,b). Finally, several kimberlite pipes southeast of the main massif provided data from similar ages (Kravchinsky et al., 2002).

## 3. Previous palaeomagnetic and magnetostratigraphic results

The Siberian traps basalts have been studied for almost 40 years, but the older results do not meet modern experimental standards (incomplete demagnetisations mostly). With the question of the possible correlation between high volcanic activity and large biological crises, these formations received a renewed interest. A query of the Global Palaeomagnetic Database (GPMDB, McElhinny and Lock, 1996), completed with some recent results (Gurevitch et al., 1995; Solodovnikov, 1995; Kravchinsky et al., 2002) yields 49 results with demagnetisation code equal to or higher than 2 not including duplicate and combined data. Mean directions and poles for different regions of the Trap Basalts are given in Table 2 and in more detail in on-line data tables. Grouping the results from Noril'sk region by suites (Lind et al., 1994) reveals differences in declination for the Syverminsky ($D = 143°$) and the Gudchikinsky ($D = 122°$) suites with slightly shallower inclinations than the stratigraphically higher suites.

The typical magnetostratigraphic succession from bottom to top found in the Central Siberia traps is from reverse to normal (R–N). Samples of reverse polarity are found in the Ivakinsky suite in the Noril'sk area and in the stratigraphically equivalent Syradasaysky suite on Western Taimyr. The major part of the overlying lava succession is of normal polarity. Only at the top of Noril'sk section (Samoedsky suite) and on Western Taimyr (Verhnetamsky suite), directions of reverse polarity are identified occasionally (Lind et al., 1994; Gurevitch et al., 1995). Dykes and intrusives in the Noril'sk area, which are younger, show both polarities.

The magnetostratigraphic succession identified in borehole SG6 in Western Siberia is N–R–N–R–N (Westphal et al., 1998a,b). As only the upper part of about 2 km of lavas has been cored and studied, it is very likely that this section is younger than those outcropping in the Noril'sk region and that the first normal polarity zone is equivalent to the Noril'sk normal polarity interval.

For the Maimecha–Kotuy district, the succession given by Fedorenko and Czamanske (1997) is N–R (Gusev et al., 1967). The base (1 km thick) is of normal polarity and the upper part (3 km) of the pile is of reverse polarity. The implications of this result will be discussed further down.

Table 3
Mean directions from the Noril'sk region, averaged by suites (Lind et al., 1994)

| Suite | $N$ | $D_m$ | $I_m$ | $k$ | $\alpha_{95}$ | Lat. | Long. | $A_{95}$ |
|---|---|---|---|---|---|---|---|---|
| Samoedsky | 12 | 76 | 77 | 46 | 5.9 | 62 | 152 | 11.9 |
| Samoedsky (rev. s.)[a] | 10 | 288 | −65 | 11 | 13.2 | 38 | 145 | 23.0 |
| Kumginsky | 17 | 55 | 76 | 115 | 3.2 | 68 | 169 | 6.0 |
| Kharaelakhsky | 74 | 82 | 76 | 62 | 2.1 | 59 | 151 | 3.8 |
| Mokularevsky | 48 | 95 | 77 | 48 | 2 | 57 | 140 | 5.5 |
| Morongovsky | 40 | 89 | 83 | 28 | 4.2 | 66 | 126 | 8.9 |
| Nadezhdinsky | 18 | 72 | 79 | 55 | 4.4 | 66 | 148 | 8.9 |
| Tuklonsky | 15 | 38 | 76 | 29 | 6.7 | 74 | 184 | 13.3 |
| Khakanchansky | 1 | 100 | 79 | – | – | 58 | 130 | – |
| Gudchikhinsky | 15 | 122 | 73 | 47 | 5.3 | 45 | 129 | 9.7 |
| Syverminsky | 14 | 143 | 68 | 64 | 4.7 | 34 | 117 | 7.7 |
| Ivakinsky | 22 | 244 | −67 | 13 | 8.2 | 54 | 180 | 14.1 |
| Average | 276 | 85 | 77 | 31 | 1.5 | 60 | 144 | 9.1 |

[a] Samoedsky (rev. s.) gives the mean direction of the reverse samples found in this suite (Lind et al., 1994, Table 3, p. 1146).

## 4. New palaeomagnetic sampling

Samples were taken from outcrops and boreholes in Noril'sk area and 150 km northeast. The locations of the sections sampled are given in Table 1a and b and in Fig. 1. Outcrop sampling was carried out along Abagalakh river, which cuts approximately 60 lava flows from the Tuklonsky up to the Samoedsky suites. The lower suites (Ivakinsky up to Khakanchansky) were sampled closer to Noril'sk in three additional sections: Listvyanka, Talnakh and Kaerkan. The Listvyanka section starts with an intrusion of Ergalasky type in Late Permian sediments covered by four flows of the Ivakinsky suite, 11 lavas from the Syverminsky, seven from the Gudchikinsky and a single flow from

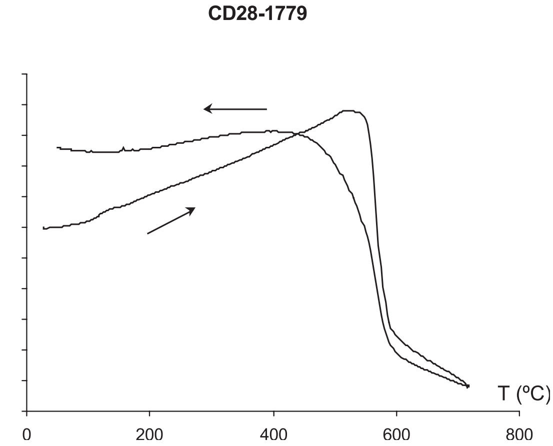



Fig. 3. Susceptibility variations with temperature of a sample from borehole CD 28.

the Khakanchansky suites. One flow from the Ivakinsky and one from the Syverminsky suites were sampled in Kaerkan. Section Talnakh is composed of four flows from the Ivakinsky and three from the Syverminsky suites.

Samples from outcrops (at least six per flow) were taken with a petrol-powered portable drill and were orientated using a magnetic compass and, whenever possible, additionally with a sun compass. Bedding planes are horizontal or gently dipping toward to the north in the Talnakh and Listvyanka sections, to the west in the Kaerkan and to the southeast in the Abagalakh section. The maximum dip angle is 15°. Combining Abagalakh, Listvyanka, Kaerkan and Talnakh sections yields a complete coverage from the Late Permian to the top of the STB sequence.

Four hundred samples of borehole cores were taken from old core collections. Here only the up and down orientation is known, but, as the direction of the Permian and Triassic field was always steep, inclinations alone can provide unambiguous polarity results.

The samples were studied in the St. Petersburg, Paris, Strasbourg and Munich palaeomagnetic labora-

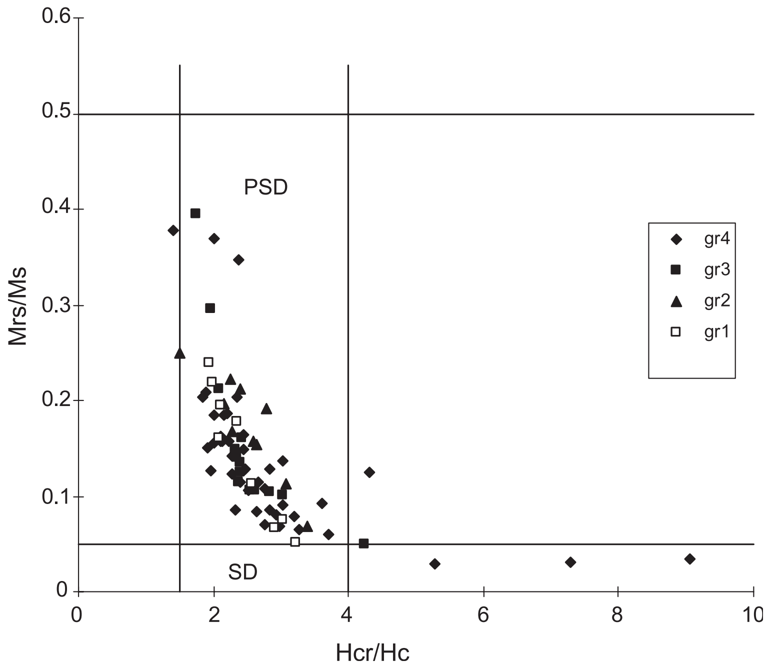



Fig. 4. Day plot of samples from Abagalakh and Talnakh sections. There is not any significant difference between the different directional groups.

tories using JR4, JR5 and Molspin spinners, and CTF and 2G cryogenic magnetometers. All samples have been demagnetised stepwise either thermally up to their respective Curie point or by alternating fields (AFs) up to 200 mT with an average of 15 steps. Principal component analysis (Kirschvink, 1980) was performed and the precision of the directions was calculated with the Kent et al. (1983) algorithm. Interlaboratory comparisons proved the very good coherence of the results.

### 4.1. Rock-magnetic characteristics

Ninety percent of the samples are characterised by a single component (Fig. 2, sample Mk4-063a). Only occasionally a secondary overprint of viscous origin was observed. Maximum blocking temperatures of the hard component are between 520 and 590 °C, characteristic for low-Ti titanomagnetite and magnetite. The soft component, if present, has a blocking temperature between 200 and 400 °C. For a few samples, the primary component could not be clearly identified by the demagnetisation process. For instance, sample Mr2-7b was thermally demagnetised, whereas sample Mr2-1c from the same flow, was demagnetised by alternating fields up to 200 mT. In this case, AF seems more efficient than the thermal method and the intermediate component between 350 and 500 °C does not have any geomagnetic significance (Fig. 2).

The magnetisations of Ivakinsky and Syverminsky samples are often complex. Sample Iv3-28a from Ivakinsky suite shows two components: a soft normal and a hard reverse polarity component above 300 °C. Thermal demagnetisations display often erratic behaviour above 400 or 500 °C with a Curie temperature about 530 °C. The reverse component is not always very well defined as shown by sample Iv1-013a, it may even be completely hidden (Fig. 2).

The bottom intrusion (denoted iv-intr, Ergalasky type) in the Listvyanka section is of normal polarity, but the four flows from Ivakinsky suite overlying it

Table 4
Mean results, averaged by suites, all outcrop sections combined

| Suite | $N$ | Geographic coord. | | Stratigraphic coord. | | $k$ | $\alpha_{95}$ | PGV | |
|---|---|---|---|---|---|---|---|---|---|
| | | $D_{mg}$ | $I_{mg}$ | $D_{ms}$ | $I_{ms}$ | | | Lat. | Long. |
| sm | 2 | 63.4 | 70.3 | 81.3 | 69.5 | 25 | – | 51.7 | 162.8 |
| km | 7 | 34.3 | 72.1 | 63.2 | 73.1 | 173 | 4.6 | 62.1 | 171.9 |
| hr | 7 | 68.0 | 73.2 | 94.3 | 68.7 | 34 | 10.4 | 46.7 | 153.5 |
| mk | 13 | 47.3 | 77.9 | 95.4 | 74.2 | 85 | 4.5 | 53.5 | 145.7 |
| mr | 11 | 19.5 | 78.0 | 90.5 | 80.0 | 164 | 3.6 | 62.5 | 136.2 |
| nd | 15 | 6.5 | 60.8 | 28.1 | 70.6 | 69 | 4.6 | 70.2 | 217.0 |
| tk | 5 | 8.2 | 65.0 | 36.9 | 74.0 | 95 | 7.8 | 71.9 | 195.6 |
| hk | 1 | 108.5 | 57.5 | 90.3 | 57.6 | – | – | 35.5 | 165.0 |
| gd | 7 | 129.2 | 62.3 | 107.3 | 66.0 | 30 | 11.0 | 39.0 | 143.0 |
| sv | 15 | 157.1 | 43.5 | 150.9 | 52.6 | 199 | 2.7 | 15.7 | 112.8 |
| iv (R) | 9 | 264.8 | – 74.7 | 235.5 | – 70.9 | 32 | 9.1 | 62.0 | 180.2 |
| iv (N) | 6 | 162.0 | 57.5 | 150.5 | 66.7 | 18 | 15.8 | 30.7 | 110.5 |
| All flows | 95 | 79.4 | 78.3 | – | – | 10.3 | 4.5 | | |
| | 95 | – | – | 93.7 | 74.7 | 18.8 | 3.3 | | |
| Mean pole | 95 | 54.6°N | 146.0°E | $K = 7.6$ | $A_{95} = 5.3$ | | | | |
| *Mean results, averaged by groups* | | | | | | | | | |
| Group 4 | 55 | 60 | 78 | – | – | 30 | 3.5 | – | – |
| | 55 | – | – | 90 | 74 | 53 | 2.6 | 54.8 | 149.7 |
| Gr 3 (tk5–nd5) | 14 | 4 | 57 | 20 | 68 | 265 | 2.5 | 68.6 | 234.0 |
| Gr2 (sv) | 16 | 157 | 44 | 151 | 53 | 199 | 2.6 | 16.1 | 113.2 |
| Gr1 (iv) | 9 | 265 | – 75 | 236 | – 71 | 32 | 9 | 62.0 | 180.2 |

Reverse polarity directions were inverted for the calculation.

are of reverse polarity with steep inclinations. The lowest flow from the Talnakh section shows characteristic remanent magnetisations (ChRM) of both polarities (ta1-2 N and R). We suppose that this normal direction is the result of a remagnetisation by a later normal Triassic field. The mean directions of the ChRM for lava flows of the Ivakinsky suite in the Talnakh, Kaerkan and Listvyanka sections are similar. The flows from the Syverminsky suite are of normal polarity, but with a lower inclination as determined by Lind et al. (1994) for the same suite (Tables 3 and 4).

The presence of magnetite or low-Ti titanomagnetites as the main carrier of the magnetisation is confirmed by the temperature dependence of the low field susceptibility measured with a KLY kappabridge. The curves show an increase of susceptibility just below 580° and almost no hematite present (Fig. 3). Ms(T)-curves measured with a Variable Field Translation Balance (VFTB) yield similar results. In some cases, alterations were observed when samples were heated over 600 °C resulting in an increase of susceptibility. Measurements of the coercive force and the remanence coercivity (Hc and Hcr), of the saturation magnetisation and the saturation remanent magnetisation (Ms and Mrs) for samples of the whole section were also done. A plot of the Hcr/Hc against Mrs/Ms (Day et al., 1977) indicate that the magnetic grains are mainly in the pseudo-single-domain (PSD) range (Fig. 4). All these different rock-magnetic properties show a great uniformity along the whole section.

### 4.2. Results from outcrop sections

The soft component has usually a steep normal direction, but shallow and even negative inclinations are occasionally found. The mean characteristic directions for all the flows from the different sections are given in Table 4 for suite averages and detailed in online data tables. Differences in bedding orientation within the sections are too small for internal fold tests. However, combining all data, a regional fold test is possible. After corrections for bedding, the precision

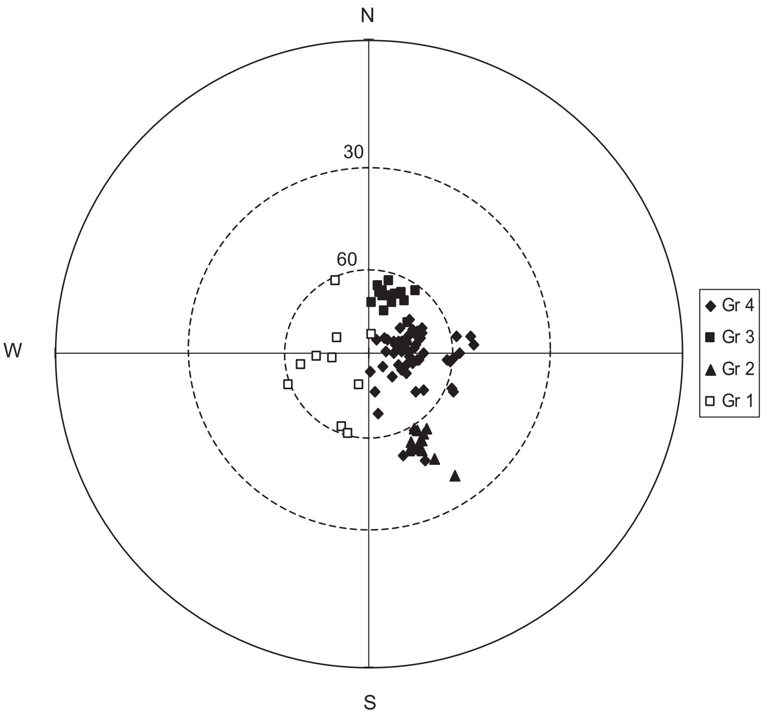



Fig. 5. Stereogram of the characteristic mean flow directions after tectonic corrections and showing the different directional groups (see text).

parameter $k$ of the overall mean (calculated with reverse directions inverted to normal) increases from 10.3 to 18.8, which is statistically significant. This is in favour for a prefolding origin of the magnetisation.

A comparison of previously published results given in Table 3 and our new data shows systematic differences in poles positions by a few degrees very likely reflecting incomplete demagnetisation of the older data set (Lind et al., 1994).

Four directional groups of directions can be readily identified on the stereogram after bedding correction (Fig. 5). These groups are formed by successive flows allowing us to distinguish them statistically. Group (Gr 1) is formed by all the flows of reverse polarity from the Ivakinsky suite ($D=236$, $I=-71$). A second group (Gr 2) clusters around $D=151°$ and $I=54°$ and is formed by the flows from Syverminsky suite up to flow gd1. A less obvious third group (Gr 3) appears around $D=20°$ and $I=68°$. It corresponds to flows tk5 to nd5 covering the upper half of Tuklonsky and the lower half of Nadezdinsky suites. The remaining flows, mainly the upper part of the complete section, form the last group. The respective mean directions are given in Table 4.

Groups 2 and 3 display very low scatter ($k=199$ and 265) and are interpreted to be either transitional directions and a post transitional excursion, respectively. The very low scatters indicate either a long period with a very low secular variation or more probably that these two series of 14 to 15 flows were emplaced in a time period too short for averaging secular variation. In order to obtain a better view of the directional deviation between these groups, we calculated the best-fit great circle plane passing through all the directions. Taking this plane as a reference, each direction has an apparent inclination and declination. The apparent inclination corresponds to the out of plane scatter and the apparent declination shows the shift along this plane against the depth of a composite Abagalakh–Listvyanka section (Fig. 6). The reversal between Ivakinsky and Gudchikhinsky lavas is clearly visible. Gr 2 and Gr 3 appear as offset groups with low scatter.

### 4.3. Boreholes samples

Cores obtained from boreholes provide continuous sections of the lava pile. Borehole TK5 is close to Abagalakh section and penetrates the same formations. Boreholes CD24 and CD28 are closer to Noril'sk and overlap stratigraphically with the Abagalakh and Listvyanka sections.

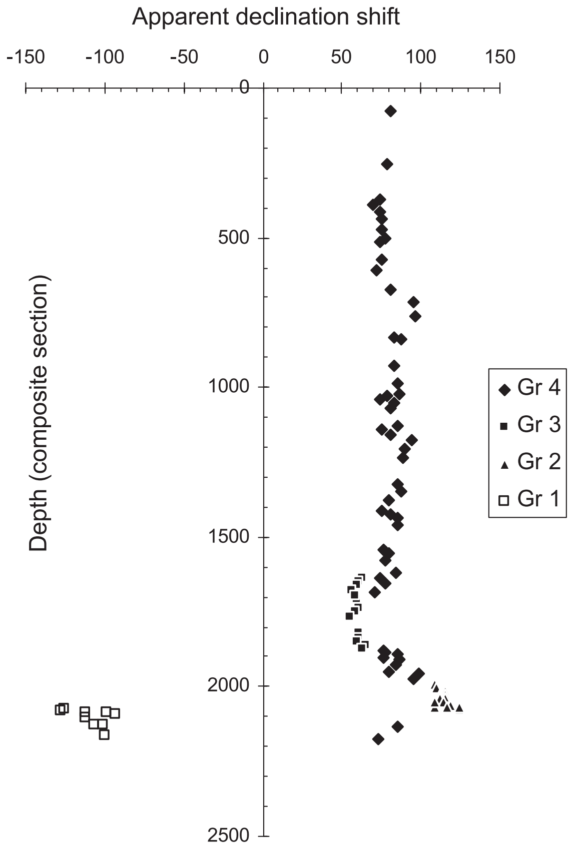



Fig. 6. Apparent declination shift of all flow mean directions versus depth (composite Abagalakh–Listvyanka section) when compared to the best-fit great circle plane passing through all the directions. The directional groups as defined in the text are indicated.

The palaeomagnetic components are comparable to those of outcrops samples and display one or two components. Samples of the borehole CD10 (Kumginsky suite) are an exception. They have complex magnetisations with up to three components indicating overprinting unlike the parallel part of Abagalakh section. No visible magnetostratigraphic succession can be identified in this section.

It was shown that for steep inclinations, the arithmetical mean $I_m$ is a biased estimation (too shallow) of the true mean $I_o$. Mean inclinations for the unoriented borehole cores have been calculated according to the Westphal et al. (1998a) procedure. This method was

Table 5
Results from boreholes (arithmetical means and corrected inclinations)

| Borehole means component | $N/N_o$ | $I_m$ | $\sigma$ | $I_o$ | $k$ | Paleolat. |
|---|---|---|---|---|---|---|
| Abag. (Fisher) | 200 | | $\alpha_{95} = 1.6$ | 76.9 | 39.0 | 65.0 |
| Abag. (incl. alone) | 200 | 73.5 | 8.2 | $77.9 \pm 0.8$ | $43.1 \pm 7.1$ | 66.8 |
| TK 5 N | 113 | 74.1 | 7.8 | 87.0 | 21.9 | 84.0 |
| CD 10 N | 18/19 | 71.4 | 8.8 | 74.7 | 85.5 | 61.3 |
| CD 24 N | 170 | 73.8 | 8.3 | 79.2 | 37.7 | 69.1 |
| CD 24 R | 15/18 | − 66.5 | 25.8 | − 89.6 | 30.5 | 86.7 |
| CD 28 N | 30 | 60.0 | 13.7 | 65.5 | 12.4 | 47.6 |
| CD 28 R | 9 | − 69.8 | 5.9 | − 71.5 | 77.3 | 56.2 |
| All N | 313/321 | 72.6 | 9.7 | 88.3 | 19.4 | 86.6 |
| All R | 34/38 | − 73.7 | 8.5 | − 80.9 | 26.3 | 72.2 |

N and R represents normal and reverse components, respectively; $I_m$ and $\sigma$ are the arithmetical mean and standard deviation of the inclinations; $I_o$ and $k$ are the estimations of the true mean inclination and of the $k$ value (Westphal et al., 1998a).

first tested with the characteristic directions from the Abagalakh section (all samples of normal polarity after bedding corrections). Calculated with the Fisher statistics, the mean inclination is $76.9 \pm 1.6$ and $k = 39.0$. The arithmetical mean $I_m$ of the inclinations alone is 73.5 (with $\sigma = 8.2$) and the corrected inclination $I_o$ is $77.9 \pm 0.8$ with $k = 43.1 \pm 7.1$. The two estimations are similar within margin of errors. The method was then applied to the different boreholes data and is summarised in Table 5.

### 4.4. Pole positions

The mean pole positions are given in Table 6 and in Fig. 7. The mean poles from Ivakinsky samples, Abagalakh and Western Taimyr, are similar and close to the mean poles calculated by Torsvik et al. (2001) for 250 and 240 Ma, but slightly offset counterclockwise. The mean pole from Maimecha–Kotuy province (Table 1) fits better for ages around 260 Ma. As borehole SG6 (Westphal et al., 1998b) provided only inclination values, the corresponding pole should plot on a small circle intersecting the apparent polar wander path (APWP) between 210 and 220 Ma. If we assume that the age of 253 Ma for the base of the Maimecha–Kotuy province is true, the trend of the poles is parallel to the trend of the APWP.

Table 6
Mean poles

| | Latitude | Longitude | $A_{95}$ |
|---|---|---|---|
| All flows | 56 | 146 | 6 |
| Group 4 | 55 | 150 | 4 |
| Tk5–Nd5 (group 3) | 69 | 234 | 4 |
| Sv (group 2) | 16 | 113 | 2 |
| Iv (group 1) | 62 | 180 | 17 |
| W. Taimyr (Gurevitch et al., 1995) | 59 | 150 | 11 |

## 5. Magnetostratigraphy

Fig. 8 summarises the inclination variations as a function of the stratigraphic position of the outcrop section and boreholes. The large majority of the samples carry a positive, normal inclination. Negative inclinations are only identified in the lowermost part (Ivakinsky suite). All flows of the Abagalakh section are of normal polarity. Isolated samples having a negative inclination are found rarely above the Ivakinsky suite, mainly in borehole CD24 (13 samples), TK5 (6 samples) and only three (not shown) in the Abagalakh outcrop section. These apparently reverse polarity samples cannot be correlated between boreholes or outcrop sections. The most probable explanation is that some samples were mishandled and inverted during sampling or storage and that other ones may derive from unrecognised intrusions of younger age.

In borehole CD10 (mainly Kumginsky suite), both polarities occur. This core is the shortest and penetrates only the uppermost suites. There is no significant succession of positive or negative inclinations allowing for the definition of polarity intervals. Moreover, the parallel outcrop in the Abagalakh section does not

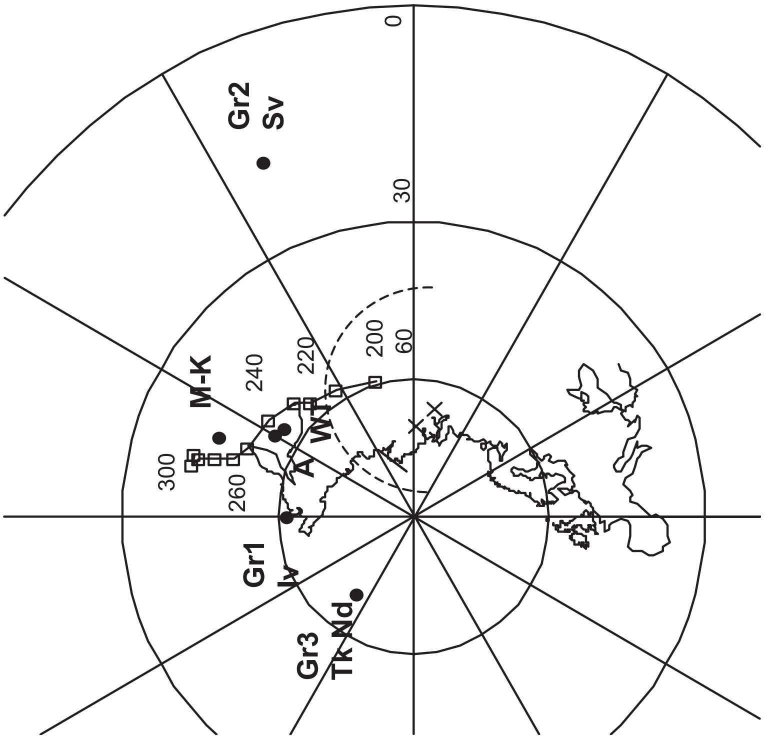



Fig. 7. Polar wander curve from Torsvik et al. (2001) in Eurasian co-ordinates between 300 and 200 Ma (squares). Circles indicate the position of the paleopoles of the Ivakinsky (Iv), Syverminsky (Sv), Tuklonsky to Nadezhdinsky (Tk–Nd) suites and the remaining group (A) mean poles. The Maimecha–Kotuy province (M–K), West Taimyr (WT) mean poles are also shown. Noril'sk and borehole SG6 localities are indicated by small crosses. The broken line denotes the possible position of the paleopole obtained from the inclinations of borehole SG6.

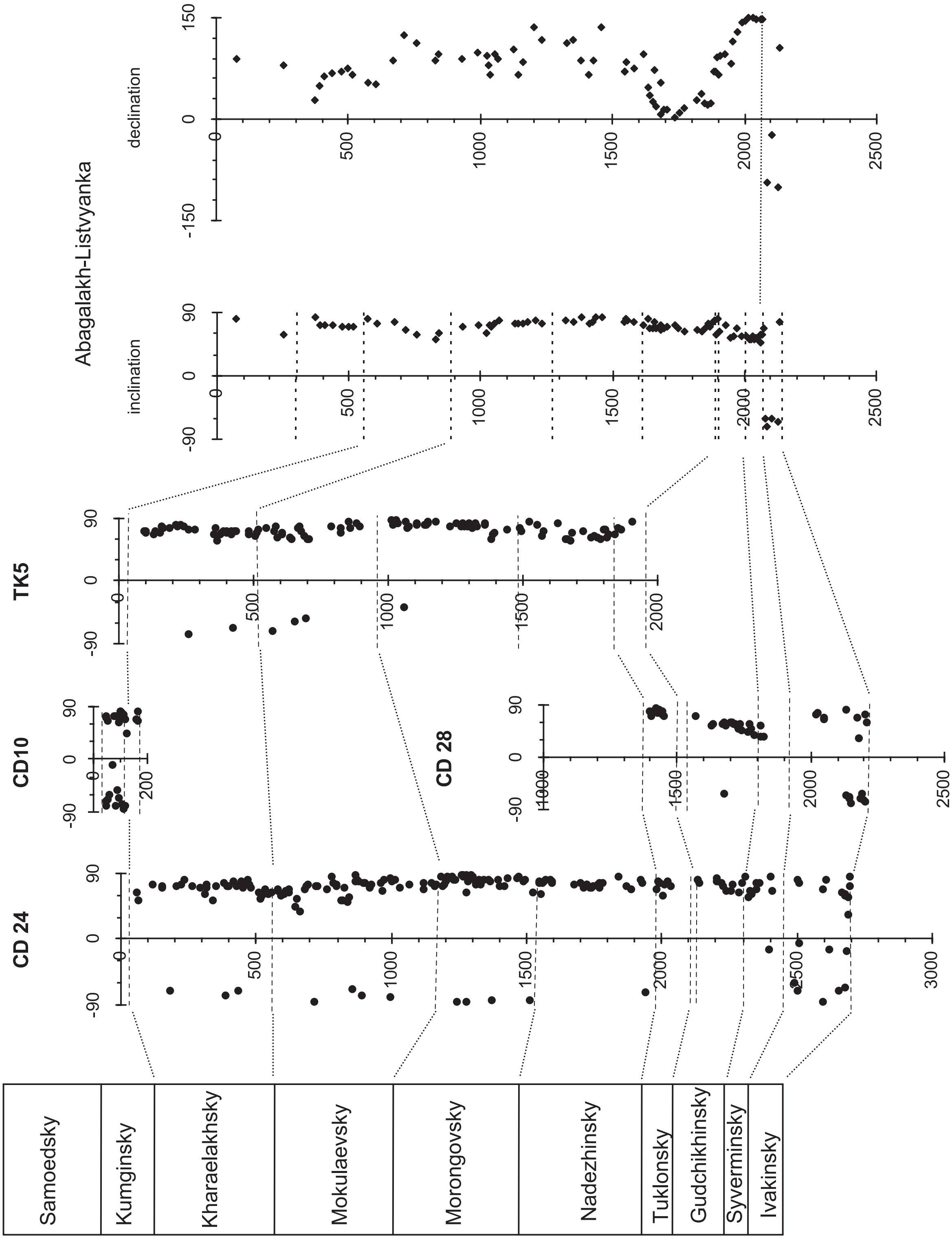
show any evidence for reversals. We suspect that remagnetisations affecting the top formations not covered and protected by later flows are the cause of theses complex magnetisations. Lind et al. (1994) states also that occasional reverse directions exist in the uppermost formations of the Noril'sk (see Table 2). Both polarities are also found at the top of the Western Taimyr section studied by Gurevitch et al. (1995).

The transitional directions found by Lind et al. (1994) in the Syverminsky and the Gudchikhinsky suites are confirmed by our results from the Talnakh, Kaerkan and Listvyanka sections.

In contrast to outcrop sampling, boreholes CD 24 and CD 28 provide a continuous coverage of the lava pile between Nadezhdinsky and Gudchikinsky suites assuring that no magnetostratigraphic gap exists in our study. The magnetostratigraphic succession for the whole Noril'sk area is therefore R–N.

The polarity succession from Maimecha–Kotuy (M–K) district is N–R. Based on chemical comparisons, Fedorenko and Czamanske (1997) correlated the Kogotsky suite from the M–K section with the Noril'sk Morongovsky and Mokulaevsky suites. In this case, the top of the M–K section must be younger than the top of the basalts in the Noril'sk area. Alternatively, Basu et al. (1995) consider their ages as true and that the M–K region is therefore significantly older. Thus, the N–R succession may represent one of the Illawara reversals preceding the Permian Triassic boundary. This is in agreement with a slightly

Fig. 8. Magnetostratigraphic correlations between outcrops and boreholes. The column on the left-hand side represents the succession and average thickness of the suites in the Noril'sk area. For boreholes, individual sample inclinations are shown. For the composite Abagalakh–Listvyanka section flow mean directions are given.


Abagalakh-Listvyanka
declination
inclination
TK5
CD10
CD 28
CD 24
Samoedsky
Kumginsky
Kharaelakhsky
Mokulaevsky
Morongovsky
Nadezhinsky
Tuklonsky
Gudchikhinsky
Syverminsky
Ivakinsky

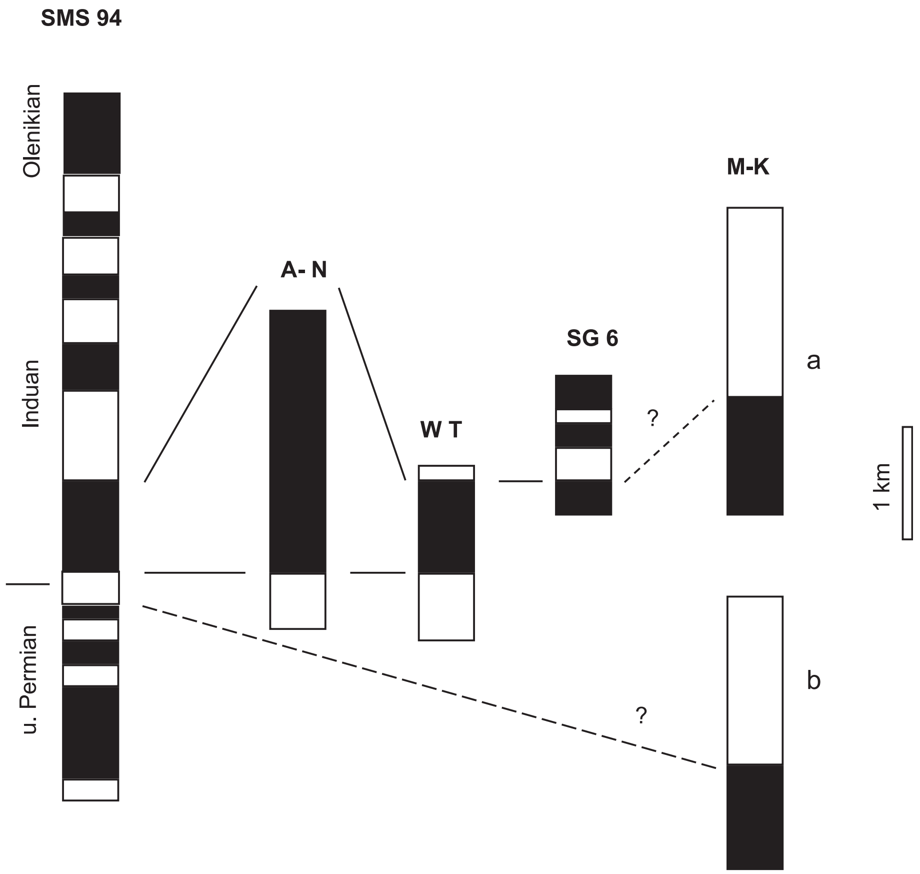



Fig. 9. Proposed general magnetostratigraphic correlation of the Siberian traps with the global Permian–Triassic magnetostratigraphy. Magnetostratigraphic scales: black: normal polarity, white: reverse polarity. SMS94: Steiner et al. (1994) scale; A–N: composite Abagalakh–Noril'sk section; WT: western Taimyr; SG6: western Siberia borehole; M–K a and b: alternative correlations for the Maimecha–Kotuy section.

older age (260–270 Ma) of the M–K volcanics derived from the comparison of their palaeopole position to the APWP for Baltica used as reference (Fig. 7). However, this pole (Table 2) has to be regarded as being less reliable due to still incomplete demagnetisations. The two alternative correlations are presented in Fig. 9. A new palaeomagnetic study is now in process and may help to solve this ambiguity.

Borehole SG6 gave an N–R–N–R–N succession. Taking all the results together yields a minimum of five to seven polarity zones for the complete magnetostratigraphy of the STB. The eruptive cycles were initiated before the Permian–Triassic boundary and proceeded long after into the Early Triassic (Induan–Olenikian). Nevertheless, the major part of the volcanic formations erupted around 249–251 Ma ago.

## 6. Conclusions

The VGP obtained from the outcrop sections (54.7°N, 146.0°E) is close to the mean pole from Taimyr (Gurevitch et al., 1995) (59°N, 150°E). The borehole samples yield corrected inclinations which seem too high compared to the results of outcrop sections. The palaeolatitudes deduced from the corrected inclinations are about 46° to 85°N, whereas the palaeolatitudes deduced from the mean inclination from outcrop sections is about 59° to 62°N.

The magnetostratigraphy of the STB in the Noril'sk area compiled on the basis of results of different outcrop sections and boreholes confirms the presence of a zone of reverse polarity (R) at the bottom the volcanic sequence (Ivakinsky suite). All higher formations are of normal polarity (N). Some isolated samples randomly distributed in the borehole samples are of reverse polarity. However, they could not be correlated between the sections and boreholes and do not allow to define further intervals of reverse polarity. The simple R–N magnetostratigraphic succession of the bulk of the Siberian traps confirms the rather short duration of the main eruptive cycle.

## Acknowledgements

We greatly appreciate the help of D. Krása and V. Vodovozov during field work. Grants from the Centre National de la Recherche Scientifique (CNRS) allowed French participants' visits to Russia and Russian ones to come to France several times. C.H. was supported through a grant of the Deutsche Forschungsgesellschaft (Priority program "Geomagnetic Variations", Grant So72/66-1 1 2). E.L.G. received a grant from the RFFI (00-05-64008).

## References

Basu, A.R., Poreda, R.J., Renne, P.R., Teichmann, F., Vasiliev, Y.R., Sobolev, N.V., Turrin, B.D., 1995. High-3He plume origin and temporal spatial evolution of the Siberian flood basalts. Science 269, 822–825.

Bowring, S.A., Erwin, D.H., Jin, Y.G., Martin, M.W., Davidek, K., Wang, W., 1998. U–Pb zircon geochronology and tempo of the end-Permian mass extinction. Science 280, 1039–1045.

Claoué, J.C., Zichao, Z., Guogan, M., Shaohua, D., 1991. The age of the Permian–Triassic boundary. Earth Planet. Sci. Lett. 105, 182–190.

Day, R., Fuller, M., Schmidt, V.A., 1977. Hysteresis properties of titanomagnetites: grain-size and compositional dependence. Phys. Earth Planet. Inter. 13, 260–267.

Fedorenko, V., Czamanske, G., 1997. Results of new field and geochemical studies of the volcanic and intrusive rocks of the Maimecha–Kotuy area, Siberian flood-basalt province (Russia). Int. Geol. Rev. 39, 479–531.

Fedorenko, V., Lightfoot, P.C., Naldrett, A., Czamanske, G., Hawkesworth, C., Wooden, J., Ebel, D., 1996. Petrogenesis of the flood-basalt sequence at Noril'sk, north Central Siberia. Int. Geol. Rev. 38, 99–135.

Gurevitch, E.L., Westphal, M., Daragan-Suchov, J., Feinberg, H., Pozzi, J.P., Khramov, A.N., 1995. Paleomagnetism and magnetostratigraphy of the traps from Western Taimyr (northern Siberia) and the Permo-Triassic crisis. Earth Planet. Sci. Lett. 136 (3–4), 461–473.

Gusev, B.V., Metallova, V.V., Fainberg, F.S., 1967. Magnetism of Rocks of the Trap Formation of the Western Part of the Siberian Platform. Nedra Press, Leningrad. 129 pp. (in Russian).

Kamo, S.L., Czamanske, G.K., Krogh, T.E., 1996. A minimum U–Pb age for the Siberian flood-basalt volcanism. Geochim. Cosmochim. Acta 60 (18), 3505–3511.

Kamo, S.L., Czamanske, G.K., Amelin, Y., Fedorenko, V., Trofimov, V., 2000. U–Pb zircon and baddeleyite and U–Th–Pb perovskite ages for Siberian flood volcanism, Maymecha–Kotuy area, Siberia. Goldschmidt2000 . J. Conf. Absr. 5 (2), 569.

Kent, J.T., Briden, J.C., Mardia, K.W., 1983. Linear and planar structure in ordered multivariate data as applied to progressive demagnetization of palaeomagnetic remanence. Geophys. J. R. Astron. Soc. 75, 593–621.

Kirschvink, J.L., 1980. The least square line and plane and the analysis of paleomagnetic data. Geophys. J. R. Astron. Soc. 62, 699–718.

Kozur, H.W., 1998. Some aspects of the Permian–Triassic boundary (PTB) and of the possible causes for the biotic crisis around this boundary. Palaeogeogr. Palaeoclimatol. Palaeoecol. 143, 227–272.

Kravchinsky, V.A., Konstantinov, K.M., Courtillot, V., Savrasov, J.I., Valet, J.P., Cherniy, S.D., Mishenin, S.G., Parasotka, B.S., 2002. Palaeomagnetism of East Siberian traps and kimberlites: two new poles and palaeogeographic reconstructions at about 360 and 250 Ma. Geophys. J. Int. 148, 1–33.

Lind, E.N., Kropotov, S.V., Czamanske, G.K., Grommé, S.C., Fedorenko, V.A., 1994. Paleomagnetism of the Siberian flood basalts of the Noril'sk area: a constraint on eruption duration. Int. Geol. Rev. 36, 1139–1150.

Masaitis, V.L., 1983. Permian and Triassic volcanism of Siberia. Zap. Vseross. Mineral. Obsestva CXII (4), 412–425 (in Russian).

McElhinny, M.W., Lock, J., 1996. IAGA paleomagnetic databases with access. Surv. Geophys. 17, 575–591.

Reichow, M.K., Saunders, A.D., White, R.V., Pringle, M.S., Al'Mukhamedov, A.L., Medvedev, A.I., Kirda, N.P., 2002. $^{40}Ar/^{39}Ar$ dates from the West Siberia basin: Siberia flood basalt province doubled. Science 296, 1846–1849.

Renne, P.R., Zichao, Z., Richards, M.A., Black, M.T., Basu, A.R., 1995. Synchrony and causal relations between Permian–Triassic boundary crises and siberian flood volcanism. Science 269, 1413–1416.

Sharma, M., 1997. Siberian traps. In: Mahoney, J.J., Coffin, M.E. (Eds.), Large Igneous Provinces: Continental, Oceanic and Planetary Flood Volcanism. Geophysical Monograph (AGU), vol. 100, pp. 273–295.

Solodovnikov, G.M., 1995. Paleointensity of the early Triassic geomagnetic field. Phys. Solid Earth 30, 813–821.

Steiner, M.B., Morales, M., Shoemaker, E.M., 1994. Magnetostratigraphic, biostratigraphic, and lithologic correlations in Triassic strata of the Western United States. Applications of Paleomagnetism to Sedimentary Geology, SEPM Special Publ., vol. 49, pp. 41–57.

Torsvik, T.H., Van der Voo, R., Meert, J.G., Mosar, J., Walderhaug, H.J., 2001. Reconstructions of the Continents around North Atlantic and about the 60° parallel. Earth Planet. Sci. Lett. 187, 55–69.

Venkatesan, T.R., Kumar, A., Gopalan, K., Al'Mukhamedov, A.I., 1997. $^{40}$Ar–$^{39}$Ar age of the Siberian basaltic volcanism. Chem. Geol. 138, 303–310.

Westphal, M., Gurevitch, E.L., Pozzi, J.P., 1998a. On the estimation of the true mean inclinations when declinations are unknown. Geophys. Res. Lett. 25 (10), 1569–1572.

Westphal, M., Gurevitch, E.L., Samsonov, B.V., Feinberg, H., Pozzi, J.P., 1998b. Magnetostratigraphy of the lower Triassic volcanics from borehole SG6 in Western Siberia. Evidence for long lasting Permo-Triassic volcanic activity. Geophys. J. Int. 134, 254–266.

Wignall, P.B., 2001. Large igneous provinces and mass extinctions. Earth-Sci. Rev. 53, 1–33.

Zolotukhin, V.V., Al'Mukhamedov, A.I., 1988. Traps of the Siberian platform. In: Macdougall, J.D. (Ed.), Continental Flood Basalts. Kluwer Academic Publishers, Dordrecht, pp. 273–310.