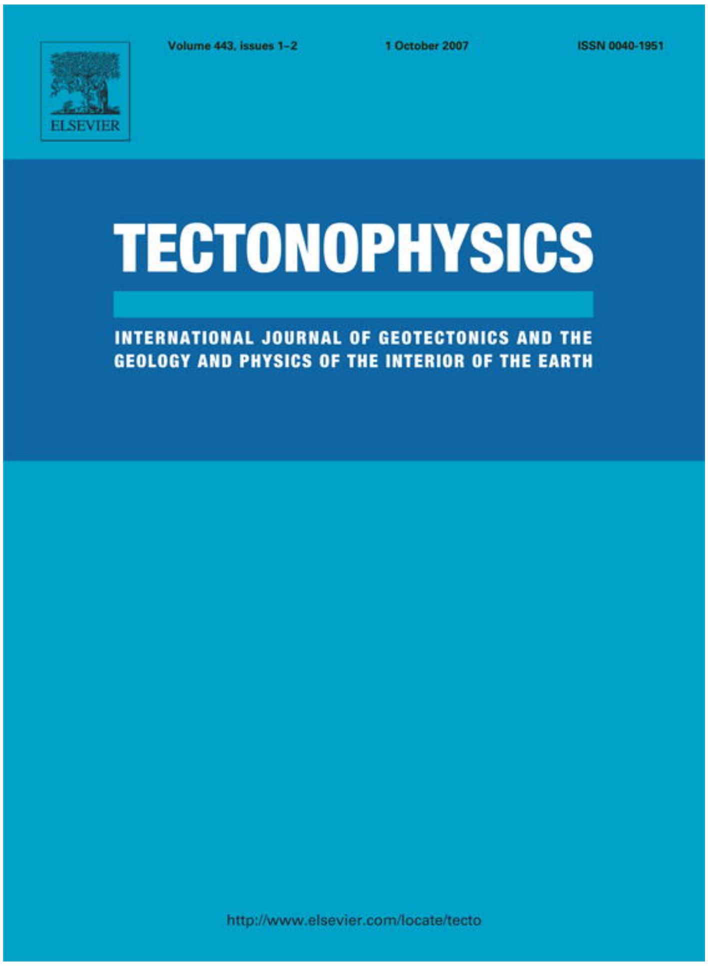
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Paleomagnetism of the Siberian traps: New data and a new overall 250 Ma pole for Siberia

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Abstract

The flood basalt province in Siberia is one of the largest in the world but the number of reliable paleomagnetic data on these volcanics is still limited. We studied lava flows and trap-related intrusions from two areas in the north and west of the Siberian platform. A dual-polarity characteristic component was isolated from most samples with the aid of stepwise thermal and alternating field demagnetization. We then compiled all published paleomagnetic data on the Siberian traps that have been obtained according to modern standards; also included are presumably trap-related overprint directions in Paleozoic rocks. Although these overprints and trap results may locally differ, the corresponding mean poles based on remagnetized sediments and volcanics show excellent overall agreement and justify pooling of both data types. Several ways of data grouping were attempted; the trap mean pole proved to be rather insensitive to statistical treatment. Irrespective of the averaging procedure used, the overall mean poles for the Siberian traps (NSP2: 55.1°N, 147.0°E; $N=8$, $K=123$, $A_{95}=5.0°$ or NSP4: 57.2°N, 151.1°E; $N=8$, $K=192$, $A_{95}=4.0°$) differ slightly, but significantly from the coeval mean poles of Baltica [Torsvik, 2001; Van der Voo, R., and Torsvik, T.H., The quality of the European Permo-Triassic paleopoles and its impact on Pangea reconstructions, in: Timescales of the Paleomagnetic Field, J. E. T. Channell, D.V. Kent, W. Lowrie, and J.G. Meert, eds., AGU Geophys. Monogr., 2004, 135, 29–42]. We consider possible causes for this difference and conclude that it could be explained either by persistent non-dipole terms in the Permo-Triassic geomagnetic field or widespread inclination shallowing in the European data.

Keywords: Siberian traps; Paleomagnetism; Permo-Triassic boundary; Non-dipolarity of the geomagnetic field; Inclination shallowing

1. Introduction

Huge piles of lava flows and associated intrusions of similar age in certain parts of the world are known as flood basalts or traps. Recent developments in laboratory methods, in particular advances in radiometric dating, have led to the realization that the duration of flood basalt events was very short. For instance, it was shown that the main part of the Deccan traps was erupted in less than one million years (e.g., Courtillot et al., 2000). Further increase in interest in continental flood basalt provinces (CFB) comes from understanding that huge eruptions of lava and gases during very short intervals may have led to global environmental crises. There is strong evidence that CFB formation coincided

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with major mass extinctions (e.g. Courtillot and Renne, 2003, for review). Thick successions of lava flows are attractive targets for paleomagnetic studies for additional reasons. One is a possibility to obtain a reliable paleomagnetic pole on well-dated rocks, and it is not surprising that "trap" poles are so prominent in the apparent polar wander paths (APWPs) of many continents. Our knowledge of the ancient geomagnetic field may improve as well, as exemplified by detailed study of polarity transitions (e.g., Heunemann et al., 2004).

One of the largest CFBs in the world lies on and around the Siberian platform (Fig. 1a). Its age had been determined as Late Permian–Early Triassic, with possible extension into Middle–Late Triassic and even Early Jurassic (Zolotukhin and Al'mukhamedov, 1988, and references therein). ^{40}Ar–^{39}Ar data indicate that volcanism overlapped the Permo-Triassic boundary and lasted a few million years, most of the traps being emplaced during one million years or even less (Baksi and Farrar, 1991; Renne and Basu, 1991; Hoffman, 1997; Kamo et al., 2003; Mundil et al., 2004). Unfortunately, there are still too few really reliable ^{40}Ar/^{39}Ar data on the Siberian traps, and most of them are from the region of Norilsk. Paleomagnetic data on the Siberian traps are numerous, but the overwhelming majority of results is based on poorly demagnetized collections (e.g. Lind et al., 1994), which do not satisfy modern standards. Many attempts have been made to select more reliable results from available datasets (Bazhenov and Mossakovsky, 1986; Khramov, 1991; Van der Voo, 1993) and to use them for computation of the Late Paleozoic–Early Mesozoic APWP for the Siberian plate. Such "refined" trap poles have in turn been employed to unravel the tectonic evolution of Asia, but the overall poor quality of the trap data still hampers the credibility of tectonic models.

Recently, several reliable paleomagnetic results on Siberian traps were published (Kravchinsky et al., 2002; Gurevitch et al., 2004; Heunemann et al., 2004) but they are still too scarce, and new trap data are needed for further progress. Below, we present new results from two parts of the Siberian CFB, make a compilation of the most reliable data from and around the Siberian platform, and analyze their tectonic and geomagnetic implications.

2. Geological setting and sampling

The Siberian flood basalt (trap) province occupies several hundred thousand square kilometers in the northwest of the platform, whereas an area about twice as large is blanketed by pyroclastic rocks, which also underlie the flood basalts. Basic intrusions of various dimensions are known within a still larger area, sometimes two thousand kilometers away from the flood basalts (Fig. 1a). To the west, the traps have been found in drill holes and may extend below part of the large West Siberian basin, which may correspond to an aborted attempt at rifting subsequent to trap eruption (e.g. Courtillot et al., 1999). In the Taymyr region to the north, more deformed traps are exposed too (Gurevitch et al., 1995). To the east and southeast, sills extend the total area of the province to at least 1.5×10^6 km^2 (Zolotukhin and Al'mukhamedov, 1988). Recently, Kravchinsky et al. (2002) have shown that many of the kimberlite pipes lying east of the traps actually have the same paleomagnetic direction and age and correspond to early, highly explosive phases of the volcanism. Reichow et al. (2002) have documented a subsurface extension of the traps nearly 1000 km west of the previously known limits of the province, in a drill core from the West Siberian basin. Although the ages of intrusive bodies are rarely firmly established, they are thought to be trap-related and coeval with the flood basalts (Zolotukhin and Al'mukhamedov, 1988). And Lyons et al. (2002) show that magmatism of essentially the same age as the Siberian traps occurred as far South as central Kazakhstan. These suggest an area in excess of 4×10^6 km^2 for the Siberian traps, and a volume in excess of 3×10^6 km^3 and possibly more (Courtillot and Renne, 2003).

Both lava flows and pyroclastic rocks are nearly flat-lying over most of the CFB, but simple folds and gentle monoclines are known along the platform margins, in particular the western one. The age of this deformation is not well established but is generally thought to be synchronous with trap volcanism (Fedorenko et al., 1996). However, trap emplacement occurs in a region of extensional tectonics and many gentle "tectonic" features in traps may be volcanic constructions or loading effects. Gentle tilts are common in host rocks close to and clearly connected with emplacement of intrusive bodies. Finally, gentle folds (on scales of a meter to several tens of meters) and monoclines are observed in some places in bedded Paleozoic sediments intruded by traps; although the age of these structures is not well constrained, some are believed to be trap-related (Myagkova et al., 1963).

An example of an area with widespread intrusions is the valley of the Moyero River in the north-central part of the platform (locality MO, Fig. 1a–b), where such intrusions, composed by dolerites and gabbro–dolerites, cut through a Cambrian to Silurian shallow-water marine

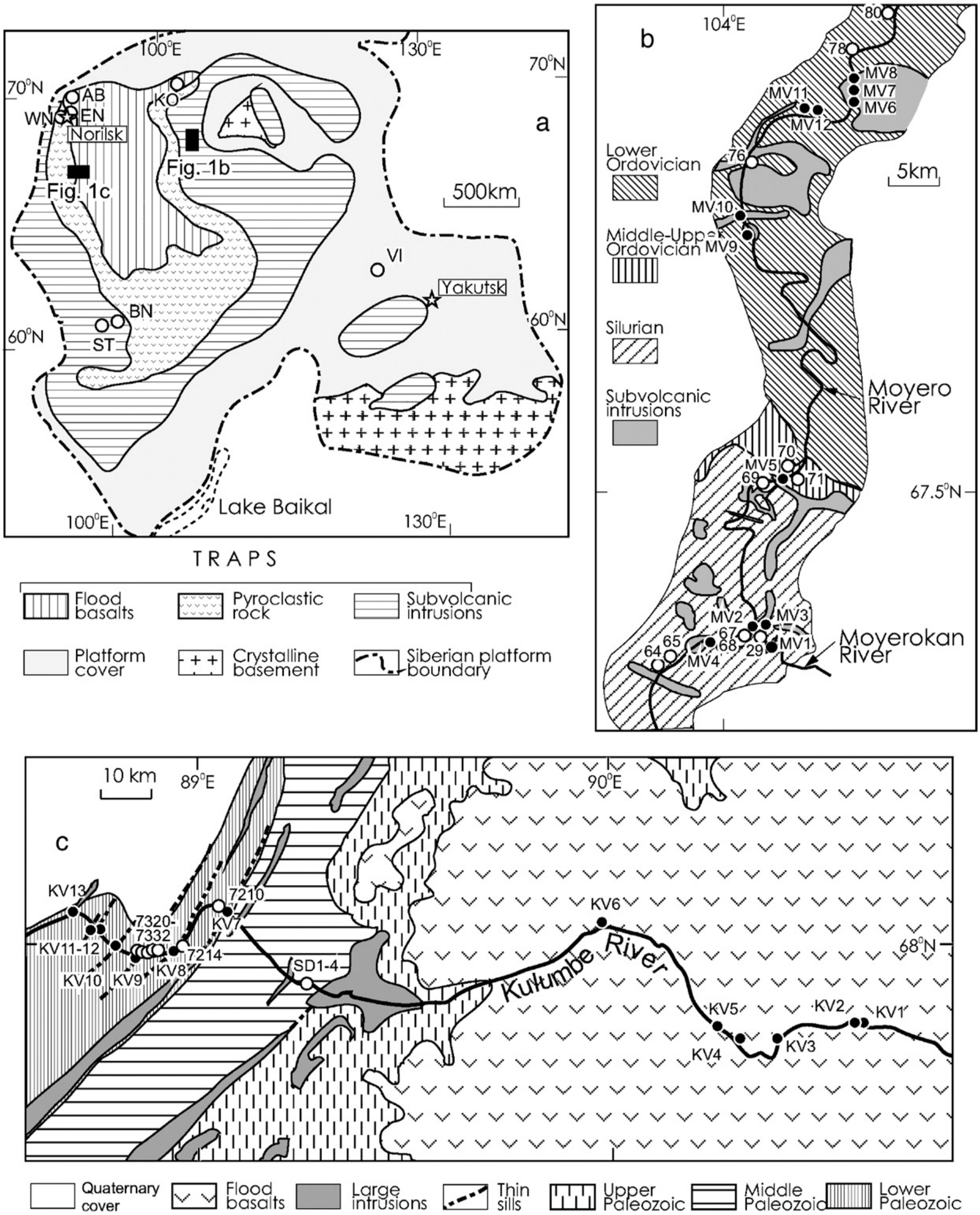


Fig. 1. (a) Sketch map of the Siberian platform showing the distribution of the Siberian traps (after Zolotukhin and Al'mukhamedov, 1988). Open circles, sampling localities in Siberian traps: AB, Abagalagh; EN, East Norilsk, WN, West Norilsk; BN, Nirunda; ST, Stolbovaya; KO, Kotuy; VI, Viluy. (b) Schematic geological map of the Moyero River valley (loc. MO). (c) Schematic geological map of the Kulumbe River valley (loc. KU). Small trap bodies are shown not at scale in b and c. In b and c, our sampling sites (solid dots) and those from other studies (open circles) are labeled as in the text and Tables 1 and 2.

Table 1
Paleomagnetic data on traps from the Moyero River (locality MO)

S	N	In situ				Tilt-corrected			
		D°	I°	k	$\alpha_{95°}$	D°	I°	k	$\alpha_{95°}$
Volcanics [a]									
MV1	10/9	50.1	81.3	69	5.6				
MV2	7/7	103.3	80.0	82	6.7				
MV3	11/9	32.5	76.1	41	8.1				
MV4	12/12	103.4	80.7	216	3.0				
MV5	11/11	66.2	77.6	92	4.8				
MV6	7/6	107.3	75.8	83	7.4				
MV7	7/7	127.6	79.5	156	4.8				
MV8	7/7	100.0	74.5	102	6.0				
MV9	10/9	255.4	−73.1	74	6.0				
MV10	11/10	105.9	79.0	76	5.6				
MV11	7/5	243.8	−71.6	24	15.9				
VOLC	12/11	83.7	78.5	141	3.9				
Remagnetized sediments									
29a	10/8	113.4	79.5	204	3.9	136.2	77.5	124	5.0
29b	10/8	117.3	81.5	165	4.3	142.5	82.4	477	2.5
29c	10/8	116.3	82.6	271	3.4	137.0	82.8	110	5.3
64a	10/7	115.5	80.5	43	9.3	158.3	82.8	31	10.9
64b	11/7	93.9	74.2	38	10.0	112.5	78.4	43	9.3
64c	10/7	106.0	81.0	133	5.2	178.2	87.4	191	4.4
65a	10/7	98.7	83.8	133	5.2	128.1	86.0	46	9.0
65b	10/8	88.8	81.6	33	9.8	163.0	86.4	34	9.6
65c	8/7	121.4	78.9	84	6.6	134.4	81.6	61	7.8
65d	7/6	84.8	82.4	96	6.9	113.5	86.6	177	5.0
67a	10/8	122.3	82.1	154	4.5	135.2	82.0	115	5.2
67b	9/8	110.8	84.3	214	3.8	121.2	82.7	287	3.3
67c	6/3	127.7	76.0	78	14.0	124.0	79.2	128	11.0
67d	10/9	138.5	80.7	192	3.7	144.4	79.8	224	3.4
67e	11/8	111.7	79.6	81	6.2	121.9	79.0	76	6.4
68a	10/6	105.0	86.9	58	8.9	124.4	87.3	70	8.1
68b	9/7	140.1	81.5	92	6.3	146.1	80.6	107	5.9
68c	7/7	81.4	79.6	56	8.1	106.5	80.5	78	6.9
70	15/10	121.8	86.2	52	6.7	118.0	85.0	56	6.5
71	15/5	137.7	81.4	104	7.5	169.7	81.2	86	8.3
75a	11/6	108.8	74.2	37	11.2	108.8	74.2	37	11.2
75b	12/5	117.9	82.4	93	8.0	117.9	82.4	93	8.0
76a	10/9	97.0	84.0	98	5.2	108.5	86.3	150	4.2
76b	11/8	123.2	78.9	60	7.2	118.1	81.8	65	6.9
76c	10/10	121.5	82.4	114	4.5	131.4	84.5	144	4.0
76d	10/9	121.3	80.7	96	5.3	154.4	85.6	48	7.5
76e	10/9	134.1	80.8	166	4.0	132.7	85.1	228	3.4
76f	10/8	133.4	82.2	127	4.9	152.3	84.2	94	5.7
76g	10/7	122.1	81.7	36	10.2	123.8	84.8	26	12.1
78a	10/5	76.4	83.7	84	8.4	104.0	76.5	104	7.5
78b	9/8	92.9	82.2	119	5.1	115.8	79.2	398	2.8
80a	10/9	143.2	83.7	249	3.3	143.2	83.7	249	3.3
80b	9/9	134.3	83.1	89	5.5	148.6	83.4	98	5.2
80c	9/9	126.6	84.2	387	2.6	126.2	84.3	376	2.7
SED	(34)	114.9	81.8	461	1.1	129.5	82.9	417	1.2
Max	(34)					120.2	82.3	552	1.0
Mean	(45)					109.3	81.7	226	1.4

Comments. S, site numbers, the first two digits characterize the number of exposure as in Fig. 1b. VOLC and SED, mean directions on trap bodies and remagnetized sediments, respectively; MAX, mean direction of sediment data at 40% unfolding; MEAN, combined VOLC and MAX; N, the number of studied/accepted samples (sites); D, declination; I, inclination; k, concentration parameter (Fisher, 1953); α_{95}°, radius of the 95% circle of confidence.

[a] No tectonic correction is applied (see text for detail).

sequence. Irregular meter-scale tilts of up to 10°, rarely to 15°, are observed at many exposures of this sequence. The intrusions vary from several meters thick dikes to kilometer size bodies (sills and laccoliths). As the characteristic dimensions of tilted blocks are much smaller than those of intrusions, the tilts are presumably formed during trap emplacement (Myagkova et al., 1963). A regional dip of the Paleozoic strata of 1° to 2° to the southwest appears to be indicated by the geological map (Fig. 1b); this tilt of unknown age, however, cannot be measured at outcrops and has not been taken into account.

Five to twelve samples (105 hand-samples in total) oriented with a magnetic compass were taken at twelve sites from intrusions spread over about 70 km along the Moyero river valley (Fig. 1b, Table 1). Sites MV1, MV5, MV11 and MV12 are from 10 to 30 m thick dikes, whereas sites MV2 and MV3 are from more than 50 m thick intrusions. Sites MV4, MV9 and MV10 are from intrusive bodies several hundred meters in dimensions, and sites MV6–MV8 are from one large intrusion. Apart from the dikes, the exact shape of other intrusions is unknown because of flat relief. Lower Paleozoic to Silurian sedimentary rocks hosting the trap bodies were also sampled from a number of exposures along the same river; these exposures were described in Myagkova et al. (1963), and we use their notation (Fig. 1b, Table 1). At most outcrops, the above-described bedding variation is present but we could not sample approximately homoclinal intervals because of the meter-scale dimensions of this deformation; hence most sedimentary sites are from beds with different attitudes. Primary remanences from these sedimentary rocks have already been published (Gallet and Pavlov, 1996), and only the data that are probably related to trap volcanism are presented here.

Another study area is close to the western margin of the Siberian platform in the valley of the Kulumbe River (locality KU, Fig. 1a,c). From east to west, this river cuts the apparently flat-lying basalt lava flows of the western periphery of the CFB and the Paleozoic sedimentary sequence intruded by numerous trap-related bodies. This sequence is deformed into N–S trending gentle folds and monoclines; in particular, Paleozoic rocks dip E to ESE in the Kulumbe valley. Some authors (Kravtsov, 1967) presume this deformation to be of Carboniferous age and hence to predate trap emplacement. On the other hand, this deformation may be roughly synchronous, at least partly, with volcanism (Malich, 1975), and the regional eastward dips relate to subsidence under the weight of the overlying trap pile (Fig. 1c). Some gentle synclines of similar origin were described in other parts of the Siberian platform (Zolotukhin and Al'mukhamedov, 1988, and references therein).

In the east of KU locality (Fig. 1c), the riverbed consists of long quiet intervals that are interrupted by short gorge-flanked rapids. It is generally assumed that the river runs parallel to the interflow surfaces at quiet intervals, whereas the rapids coincide with the flow sections, which were sampled at six sites (KV1–KV6). The studied flows belong to the Nadezhdinskaya Formation from the middle part of the Norilsk volcanic key section (Geological map of the USSR, 1966). In the west, seven thin dolerite sills with clear baked contacts (sites KV7–KV13) were studied; also sampled were the baked zones at sites KV11 and KV13. There is a general consensus that, judging by similar composition, these minor intrusions belong to the traps too (Geological map of the USSR, 1966). In total, 124 hand-samples of volcanics and baked sediments were taken at 13 sites spread over 150 km (Fig. 1c). Cambrian to Ordovician and Devonian sedimentary host rocks were sampled from 14 sites in the western part of the Kulumbe area (exposures KS1–KS9 and KS10–KS13, respectively; Fig. 1c). Primary remanences from these sedimentary rocks have already been published (Pavlov and Gallet, 1998), and only the data that are probably related to trap volcanism are presented here.

3. Treatment

One to three one-centimeter cubic specimens were cut from a hand-sample. The main part of the collection was studied in the Paleomagnetic laboratory of Institut de Physique du Globe in Paris. Alternative field, AF, cleaning in up to 15 steps was performed with an automated system installed on a 2G cryogenic magnetometer. During thermal demagnetization in up to 15 steps, samples were heated in an oven and then measured on 2G or CTF cryogenic magnetometers. Some specimens were demagnetized in a homemade AF apparatus and measured on a JR-4 spin-magnetometer in the Paleomagnetic Laboratory of the Institute of Physics of the Earth in Moscow. Paleomagnetic components were isolated following Kirschvink (1980). The components isolated from sister-specimens were averaged to obtain sample-mean directions, which were used for further analysis.

4. Results

4.1. Moyero River (loc. MO)

The trap collection was cleaned approximately fifty–fifty by AF and thermal demagnetizations. A lowtemperature to intermediate-temperature component in some samples (Fig. 2a–b) is scattered, and its in situ mean direction ($D=359°$, $I=80°$, $a_{95}=4°$) is close to the present-day dipole field ($I=78°$).

The main part of the natural remanent magnetization, NRM, is accounted for by a characteristic component, ChRM, which shows rectilinear decay to the origin and is successfully isolated by both AF and thermal treatments (Fig. 2a–e). ChRM directions are tightly clustered at most sites (Table 1), except for site MV12, which was rejected because of high scatter ($a_{95}>20°$). Two site means of reversed polarity are anti-parallel to nine site means of normal polarity (Fig. 3a). The presence of both polarities implies that emplacement time must have been longer than the typical duration of a reversal (hence larger than say 10^4 years); also, the

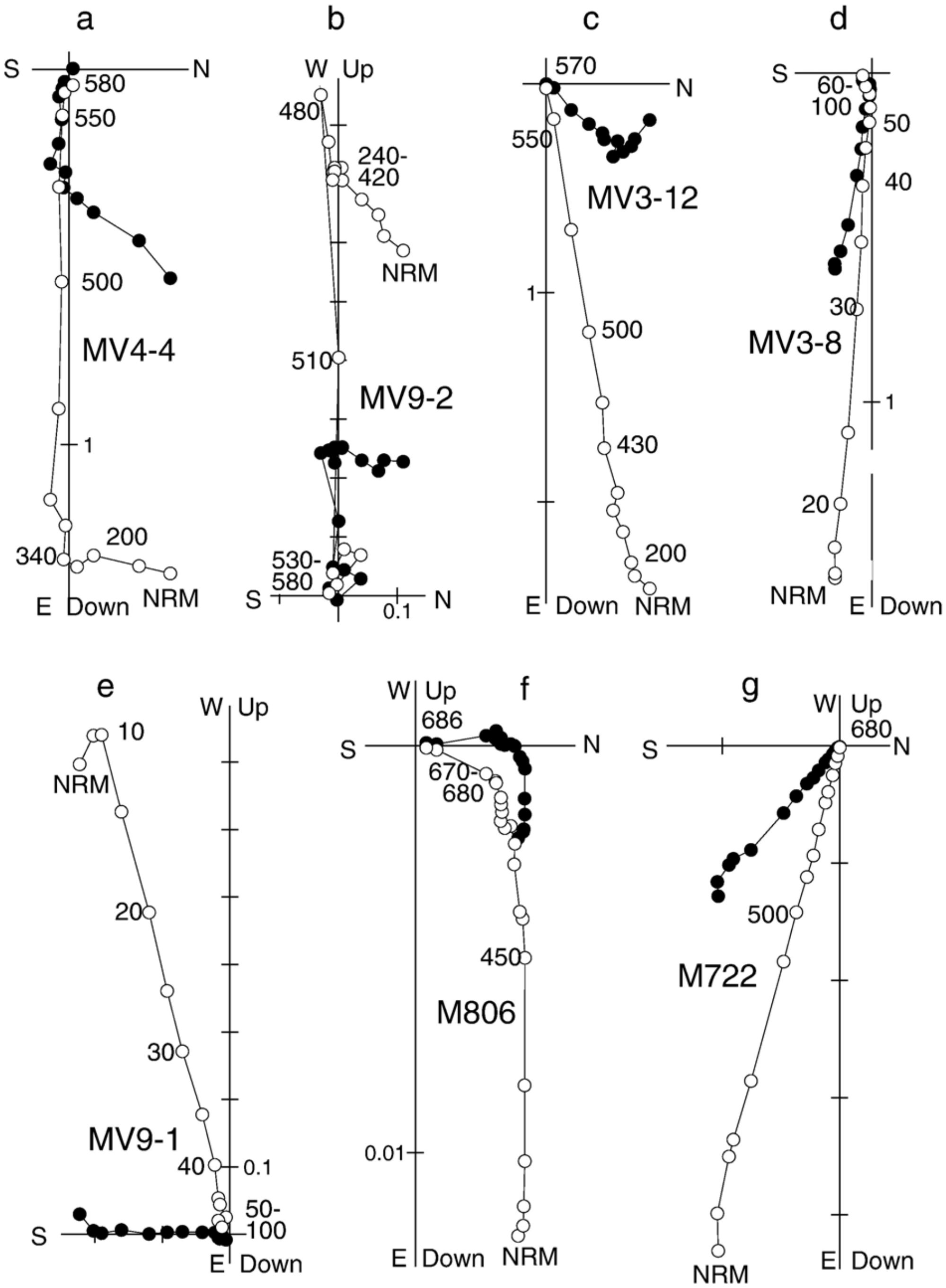


Fig. 2. Representative orthogonal plots of thermally (a–c, f–g) and AF (d–e) demagnetized samples from the Moyero intrusions (a–e) and Paleozoic host rocks (f–g). All data are in situ. Solid (open) symbols are projected onto horizontal (vertical) plane. Temperatures are in degrees Celsius, alternating fields are in mT, and magnetization is in A/m.

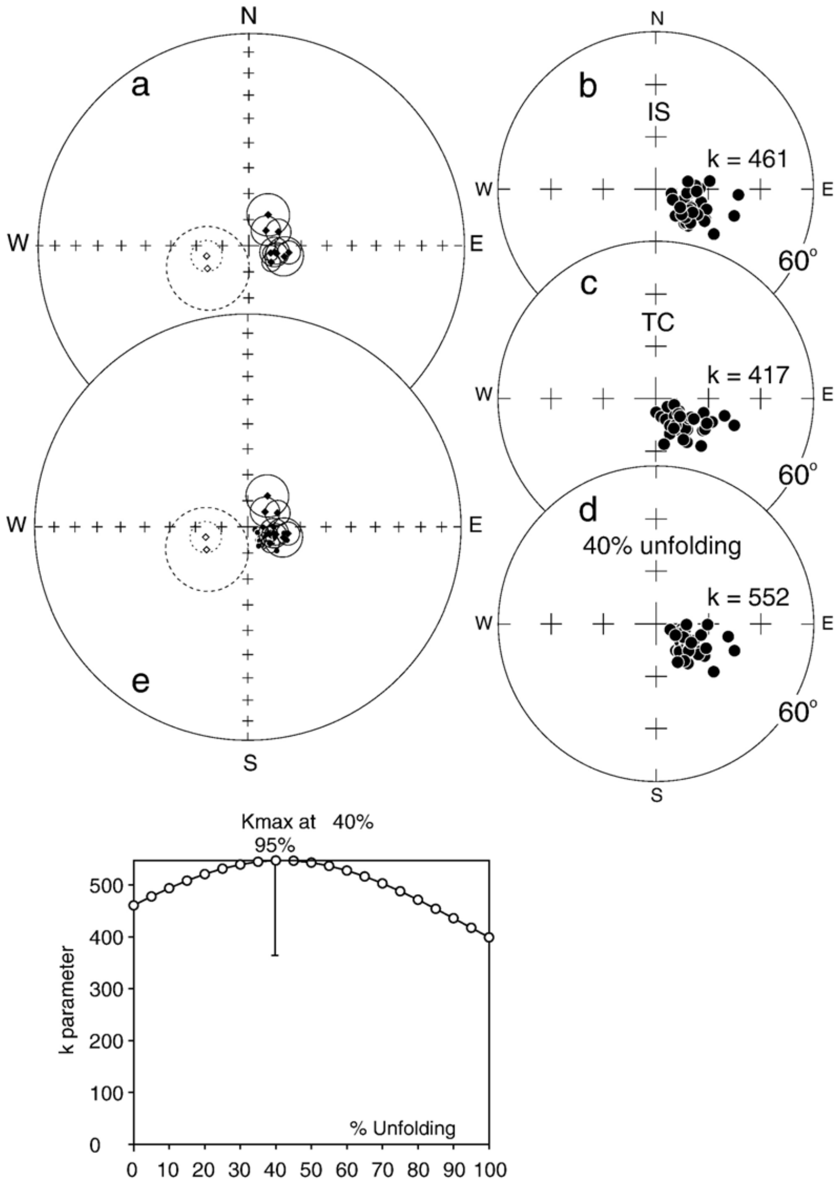


Fig. 3. Paleomagnetic directions from locality MO. (a) Site-means of the ChRM in volcanics (diamonds) with associated confidence circles in situ. (b–d) Overprint site-means (dots) in remagnetized Paleozoic sediments in situ (b), after tilt correction (c), and at 40% unfolding (d) with corresponding values of concentration parameter *k*; note that stereoplots b to d are limited by 60° small circle. (e) volcanic (diamonds) and overprint (dots) data combined as explained in the text; star, overall mean direction. For clarity, confidence circles for overprint means are omitted; the confidence circle of the overall mean is smaller than the symbol (Table 1). Solid (open) symbols and solid (dashed) lines are projected onto lower (upper) hemisphere.

intrusion dimensions (Fig. 1b) and hence cooling times are so different that NRM acquisition must be time-distributed. Hence, secular variation is likely averaged out. As typical dimensions of deformation structures in host sediments are much smaller than intrusions themselves, and the regional tilt could not be determined, no tectonic correction was applied to these data.

At a number of exposures along the Moyero River (Fig. 1b), a steep component of normal polarity was recognized in Paleozoic sedimentary rocks (Gallet and Pavlov, 1996). This remanence is an intermediate-temperature component in some cases (Fig. 2f), while other samples are completely remagnetized (Fig. 2g). Stratigraphic intervals studied and the numbers of samples vary greatly, and we divided each long exposure into a number of “sites”, each site comprising approximately an equal number of consecutive samples (Table 1). Despite minor variation in bedding attitudes and very tight data grouping both in situ and after tilt correction, a maximum of the concentration parameter is observed at 40% unfolding (Fig. 3b–d, Table 1). This maximum is not statistically different from both in situ and tilt-corrected values and hence may not be significant. However, numerical simulation (Watson and Enkin, 1993) shows that optimum untilting falls between 19% and 68% unfolding with 95% probability. Similar maximums at the sample level are observed at intermediate stages of untilting for most exposures too. These observations suggest that the steep component of normal polarity in Paleozoic sedimentary rocks is a synfolding remanence. Hence we used the in situ data from intrusions and sedimentary directions at optimum unfolding for further analysis (Fig. 3e, Table 1).

4.2. Kulumbe River (KU)

Two sister-specimens were available from most volcanic samples, and both AF and thermal demagnetization were applied to the entire collection. The orthogonal plots of AF demagnetized specimens are nearly noiseless; however, many are curved due to joint demagnetization of overlapping components and miss the origin (Fig. 4a), possibly because of acquisition of a gyromagnetic remanence (Roperch and Taylor, 1986). In contrast, thermally demagnetized sister-specimens yield somewhat noisier data but with rectilinear decay to the origin (Fig. 4b); as a result, only thermally demagnetized samples were used for analysis.

Most samples revealed a well-defined ChRM with unblocking temperatures up to 600 °C, which is often the only remanence present (Fig. 4c). A scattered component of probably viscous origin is sometimes identified in the 100 °C–300 °C interval (Fig. 4b, d), except for site KV9 where a normal polarity overprint of unknown age persists up to 400 °C (Fig. 4e) or even more. All flows and one sill are normally magnetized, and the other sills have reversed polarity (Table 2).

A steep reversed ChRM similar to that in the sills is observed in the baked zones at sites KV11 and KV13. Outside of the baked zone, some Lower Paleozoic and Devonian host rocks are also completely remagnetized, whereas this remanence is present as an intermediate-temperature component in others; this pattern is similar to that in the sediments from the Moyero River (Fig. 2f–g). We assume that this steep component is related to trap emplacement and is of the same age everywhere; hence all data are combined. In contrast, a high-temperature remanence with northwesterly declinations and shallow upward inclinations in bi-component samples is interpreted as a primary Early Paleozoic component and is discussed elsewhere (Pavlov and Gallet, 1998).

Grouping of the data from sills and remagnetized sediments is similar in situ and after tilt correction but has a maximum at about 50% stepwise unfolding (Fig. 5; Table 2). This maximum is not statistically different from both in situ and tilt-corrected values, but 95% confidence limits of optimal unfolding do not include both 0 and 100% unfolding (Watson and Enkin, 1993). Remagnetization that is much younger than trap volcanism looks unlikely because of the positive contact test and the presence of both polarities in the sills. Note also that trap volcanism and related deformation was the last non-trivial tectonic event in the studied part of the Siberian platform; post-Triassic deformation is known only in the Yenisey–Khatanga Basin more than 500 km to the north. Thus there is no process that might have completely remagnetized both intrusions and sediments. One might suppose that trap emplacement and related remagnetization took place

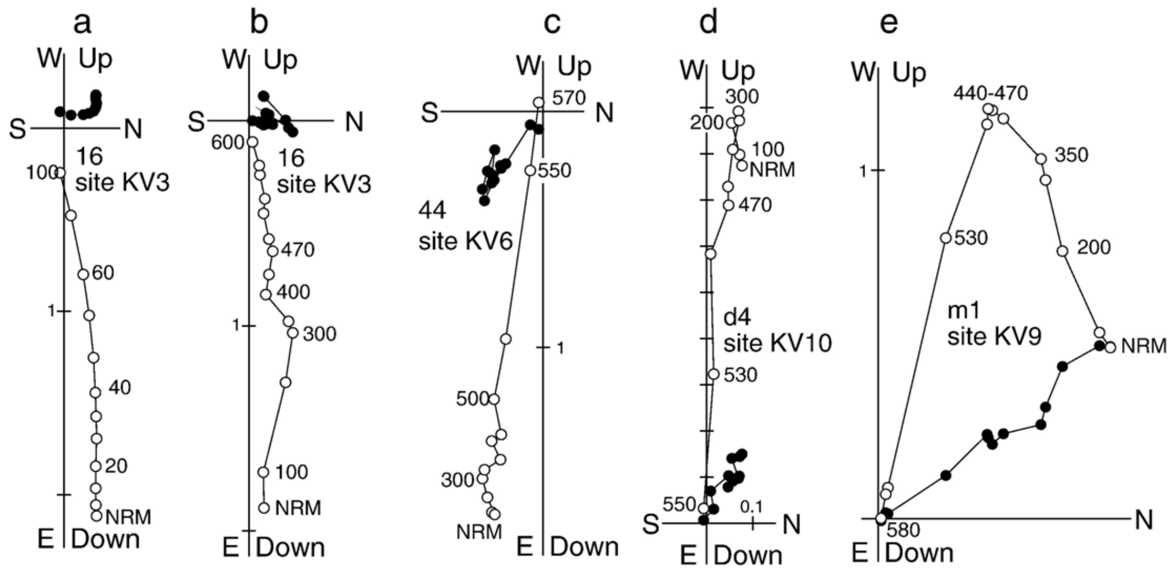


Fig. 4. Representative orthogonal plots of AF (a) and thermally (b–e) demagnetized samples from the Kulumbe volcanics. Other notations as in Fig. 2.

Table 2
Paleomagnetic data from the Kulumbe River (locality KU)

S	N	B	In situ				Tilt-corrected			
			D°	I°	K	A95°	D°	I°	K	a95°
KV1	7/7	0/0	62.9	83.4	253	3.8	62.9	83.4	253	3.8
KV2	4/4	0/0	86.9	76.0	211	6.3	86.9	76.0	211	6.3
KV3	9/8	0/0	42.5	70.6	119	5.1	42.5	70.6	119	5.1
KV4	8/7	0/0	21.6	78.1	116	5.6	21.6	78.1	116	5.6
KV5	9/9	0/0	39.8	66.8	134	4.5	39.8	66.8	134	4.5
KV6	9/9	0/0	134.8	72.3	134	4.5	134.8	72.3	134	4.5
Flows	(6/6)		62.0	77.7	47	9.9	62.0	77.7	47	9.9
KV7	8/6	118/19	31.2	88.3	63	8.5	112.9	70.8	63	8.5
KV8	10/10	130/17	299.5	−82.1	85	5.3	306.6	−65.2	85	5.3
KV9	7/7	122/19	329.7	−81.2	307	3.6	323.6	−61.2	307	3.6
KV10	7/7	118/21	334.2	−80.5	96	6.2	313.0	−62.5	96	6.2
KV11 [a]	20/20	122/15	319.5	−82.3	78	3.7	308.1	−67.3	81	3.6
KV12	9/9	116/14	317.1	−77.6	372	2.7	306.2	−64.1	372	2.7
KV13 [a]	17/17	133/10	306.7	−74.7	96	3.7	309.1	−65.1	87	3.8
Sills	(7/7)		315.4	−81.4	236	3.9	309.4	−65.4	274	3.7
SD1	27/24	146/10	255.8	−77.3	154	2.4	285.0	−71.5	151	2.4
SD2	11/11	119/12	232.4	−79.3	86	5.0	267.4	−71.1	86	5.0
SD3	7/7	124/10	249.2	−80.2	54	8.3	275.6	−72.9	50	8.6
SD4	10/3	115/8	281.3	−69.3	83	13.6	284.8	−61.9	126	11.0
KS7	33/17	123/17	96.0	87.2	81	5.1	119.1	70.3	87	4.9
7214 [b]	51/9	117/16	319.1	−59.1	29	9.8	312.6	−44.2	26	10.2
7320	14/4	119/24	284.2	−81.3	42	14.3	294.8	−57.8	36	15.5
7322	16/4	114/17	25.6	−80.8	20	21.3	323.6	−70.9	24	19.1
7323	36/8	122/20	309.4	−81.5	46	8.3	304.4	−61.0	52	7.7
7324	12/6	111/23	12.5	−80.3	20	15.4	313.0	−63.9	22	14.6
7325	21/11	121/18	341.8	−76.5	45	6.9	319.2	−60.6	44	7.0
7332	32/10	121/22	243.1	−85.4	150	4.0	291.6	−65.5	136	4.2
KS8	16/16	118/23	337.3	−83.1	58	4.9	306.9	−61.3	69	4.5
KS9	13/13	115/24	302.8	−79.6	58	5.5	297.6	−55.9	55	5.6
SED	(14/13)		295.7	−83.0	92	4.3	298.3	−65.7	88	4.4
SED+Sill	(21/20)		303.6	−82.6	117	3.0	302.2	−65.7	110	3.1
Max	(21/20)						302.6	−75.8	132	2.9
Mean	(27/26)						112.1	76.0	61	3.7

B is azimuth of dip/dip angle. Mean is combined Flows and Max. Other notations as in Table 1.
[a] Results on baked sedimentary rocks are included.
[b] This anomalous direction was excluded.

at an intermediate stage of "deformation"; if so, the best estimate of the paleofield is the overall mean of the data on sills and sediments at optimal unfolding and lava flows in situ (Fig. 5c; Table 2).

5. The Siberian trap mean pole

The usual complaint of paleomagnetists is that paleomagnetic results are too scarce for conclusions they wish to derive from them. In contrast, we have a rare case of overabundance for the Siberian traps, with several ten entries in the database of McElhinny and Lock (1990). According to modern standards, most published data, however, are of insufficient quality, being based on NRM measurements, time-cleaning technique, or blanket cleaning at low to moderate temperatures or alternative fields at best. Although many samples in our collections do not show directional changes during cleaning, there are many that do (Figs. 2 and 4), and discriminating between "good and bad samples" is only possible a posteriori. Many trap results exist as catalogue entries, and the evaluation of their quality is a problem. Also, it is often impossible to determine to which degree the datasets of unit poles overlap. Hence we adopted two *sine qua* non-criteria of data acceptance: a result must be published in sufficient detail to allow independent evaluation of its quality, and it must be based on complete stepwise demagnetization and principal component analysis. Also, it is worth noting that extensive rock-magnetic studies of the traps all over the Siberian CFB province demonstrated that magnetite and low-titanium titanomagnetite are the

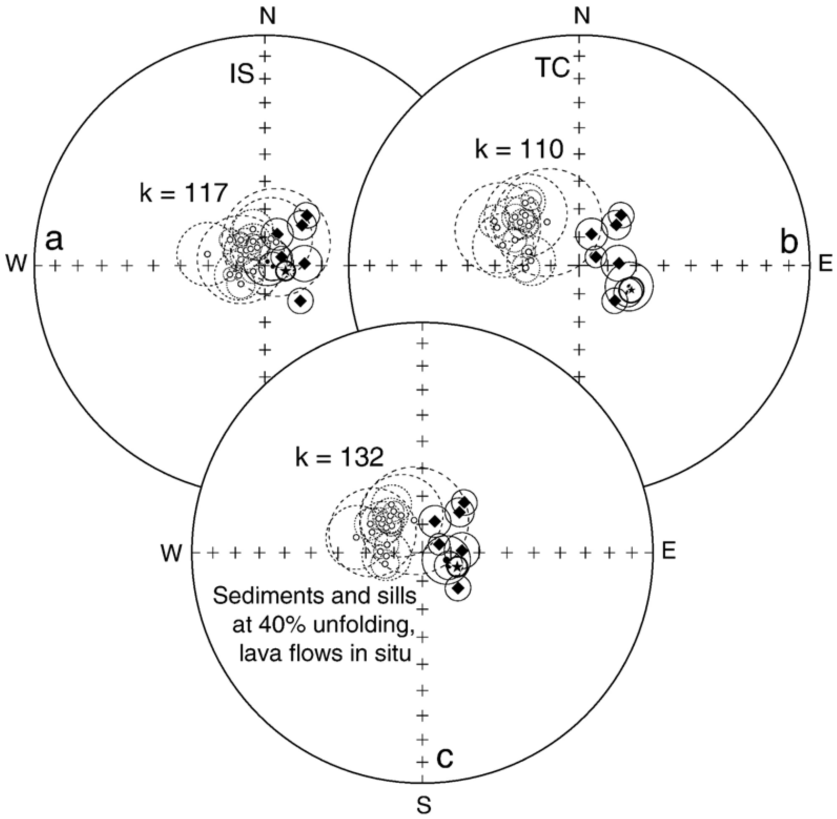


Fig. 5. Site-mean directions in lava flows (diamonds) and sills and remagnetized Paleozoic sediments (dots) with associated confidence circles from locality KU in situ (a), after tilt correction (b), and combined as explained in the text (c). The values of concentration parameter k are calculated for the data from sills and host sediments only. Other notations as in Fig. 3.

main NRM carriers in these rocks (Gusev, 1971; Lind et al., 1994).

Several paleomagnetic results, which satisfy the above criteria, have been published during the last decade. These data came from lava flows, minor intrusions such as dikes and sills, and large intrusive bodies, as well as trap-remagnetized older rocks. Below, we present a brief summary description or comment of these data (Fig. 1a; Table 3):

1. East Norilsk (EN). There are 35 sites on lava flows and minor intrusions from three adjacent sections (Gurevitch et al., 2004). Both polarities are found, but the polarity-means are significantly non-antipodal. The unit poles are dispersed (k=6.5), and the fold test is inconclusive. Heunemann et al. (2004) assumed that an R-N polarity transition is recorded in this section, and just three lowermost cooling units probably represent the steady-state field. We preferred to exclude all EN data from computation of the mean pole.
2. Abagalakh (AB). Sixty lava flows from three adjacent sections are studied (Gurevitch et al., 2004). All data are of normal polarity; the fold test is inconclusive. As above, Heunemann et al. (2004) are of opinion that 16 lower cooling units represent the final stage of the same R-N polarity transition, while the steady-state field is recorded by the 44 remaining units. Following this interpretation, the overall mean for the upper 44 units is used further on.
3. West Norilsk (WN). Seven sites from lava flows and minor intrusions are available (Pavlov et al., 2001). Both polarities are found; no fold test can be performed.
4. Big Nirunda River (BN). One site from a large intrusion and 11 sites from three Paleozoic sedimentary sections are available (Veselovsky et al., 2003). All rocks are of reversed polarity. The data on sediments are least scattered at 90% unfolding, and the upper confidence limit on degree of optimum untilting coincides with 100% unfolding (Watson and Enkin, 1993). Veselovsky et al. (2003) concluded in favor of a clearly positive fold test and hence that the sediments were remagnetized at the very beginning of deformation; here, site-means after 90% unfolding were used for computation of the area-mean pole (Table 3).

Table 3
Paleomagnetic poles on the Siberian traps

Area	N	Coordinates		Pole			Ref
		φ°N	λ°E	Φ°N	Λ°E	K	A_{95}°	
Siberian platform								
AB[a]	44/0	70.3	90.1	58.0	149.9	25	4.4	1
NW	7/0	69.3	87.9	52.4	159.5	55	8.2	2
BN	1/11	62.0	95.3	54.3	143.0	83	5.0	3
BN-is	1/11	62.0	95.3	44.0	151.6		11.1	5
BN-tc	1/11	62.0	95.3	56.2	141.6		5.2	5
BN[b]	1/3	62.0	95.3	54.4	143.8	60	12.0[b]	3
ST	4/10	62.1	91.5	53.3	150.2	56	5.3	3
ST[b]	1/4	62.1	91.5	55.3	148.7	68	11.2	3
KO	5/0	73.0	102.4	52.7	148.4	31	13.9	3
VI	3/0	66.1	111.5	57.5	162.7	19	29.3	4
MO	11/34	67.6	104.1	58.5	134.5	66	2.7	5
MO-is	11/34	67.6	104.1	58.7	137.0		2.7	5
MO-tc	11/34	67.6	104.1	58.5	130.8		3.1	5
MO[b]	11/0	67.6	104.1	60.8	153.5	42	7.1	5
KU	13/13	68.0	89.0	50.1	129.1	21	6.6	5
KU-is	13/13	68.0	89.0	60.5	119.9		6.7	5
KU-tc	13/13	68.0	89.0	40.5	134.3		7.3	5
KU[b]	9	68.0	89.0	64.9	140.3	16	13.2	5
SED	0/68			54.9	134.5	51	2.4	
VOL	29/0			57.3	139.8	22	5.8	
NSP1	88/67			56.4	141.7	30	2.1	
NSP2	(8)			55.1	147.0	123	5.0	
NSP3	(6)			57.0	148.1	159	5.3	
NSP4	(8)			57.2	151.1	192	4.0	
Peri-Siberian mobile belts								
WT	29	72.9	84.0	59.0	149.7	16	15.7	6
ET	19	75.2	100.0	49.6	128.8	–	8.5	7
EK	15	50.1	79.6	56	139	25	7.9	8
KB	9	54.5	86.9	60.2	174.1	70	6.2	9
Mean	4			57.3	146.2	49	13.2	

is(tc)—poles calculated for BN, MO and KU areas in assuming prefolding (postfolding) age of magnetization.

Study areas are labeled as in Fig. 1a; VOL, SED, means of volcanic sites and remagnetized host rocks, respectively, from areas BN, KU, MO, and ST, where both rock types were studied; NSP1, overall mean of all site-mean poles; NSP2, overall mean of all area-mean poles; NSP3, overall mean of all region-mean poles; NSP4 — the same as NSP2, but calculated using alternate poles (see text); Mean, mean of four poles from the mobile belts around Siberian platform (see text). N, number of volcanic/host rock sites (the number of mean poles in brackets). φ, λ, mean latitude and longitude of sampling area, respectively. Φ, Λ, mean latitude and longitude of paleomagnetic pole, respectively; K, concentration parameter. A_{95}, radius of confidence circle.

Ref, references: 1, Gurevitch et al. (2004); 2, Pavlov et al. (2001); 3, Veselovsky et al. (2003); 4, Kravchinsky et al. (2002); 5, this paper; 6, Gurevitch et al. (1995); 7, Torsvik and Andersen (2002), 8, Lyons et al. (2002); 9, Metelkin and Bragin (2000). Other notations as in Table 1.

[a] Transitional poles as recognized by Heunemann et al. (2004) are excluded.

[b] Alternate poles, explanation in text.

5. Stolbovaya River (ST). Four sites from a large intrusion and ten sites from three sections of flat lying Paleozoic sediments are available (Veselovsky et al., 2003). All sediments reveal reversed remagnetization directions, while both polarities are found in the intrusion.
6. Kotuy River (KO). Five sites on lava flows are available (Veselovsky et al., 2003). Both polarities are found; no fold test can be performed.
7. Viluy area (VI). Three trap units were studied (Kravchinsky et al., 2002); although several sites are available from each unit, the corresponding unit means are considered as site-means here. The data on two remagnetized Paleozoic pipes (Kravchinsky et al., 2002) are rejected as these objects are several hundred kilometers away from the nearest studied trap units, and the relation of remagnetization to trap emplacement is unclear.
8. Moyero River (MO). Eleven sites from intrusions of different dimensions and 34 sites from eleven sedimentary sections are available (this study; Gallet and Pavlov, 1996). Paleomagnetic data on remagnetized sediments show best grouping at 40% unfolding.
9. Kulumbe River (KU). Six lava flows, seven sills, and 13 sedimentary sections were studied (this study; Pavlov and Gallet, 1998). Paleomagnetic data on sills and remagnetized host sediments show best grouping at 50% unfolding.

We have argued for a synfolding origin of the remanences in MO sediments and KU sills and sediments; also, our analysis indicates a probable synfolding origin for the BN sediment data. This conclusion, however, is not very robust since improvement in data grouping is not statistically significant for each of the three datasets. So we compared the corresponding mean poles in different coordinates. The values of concentration parameter k for these three poles are 40 and 62 in situ and after tilt correction, respectively, whereas $k=188$ after optimum unfolding (Fig. 6a–c). Such a sharp increase in grouping confirms the synfolding origin of the remanences at these localities, and forms a positive test at the regional scale (the distances between MO, KU and BN are on the order of 1000 km).

Different sampling policies were used in these studies, and the number of independently oriented samples varies from 5 or 6 for a dyke or a flow up to about 100 for a sedimentary section (exposure). As a result, in most cases, except for the AB locality where a sequence of lava flows was studied, it is not immediately obvious which group of samples should be taken as an

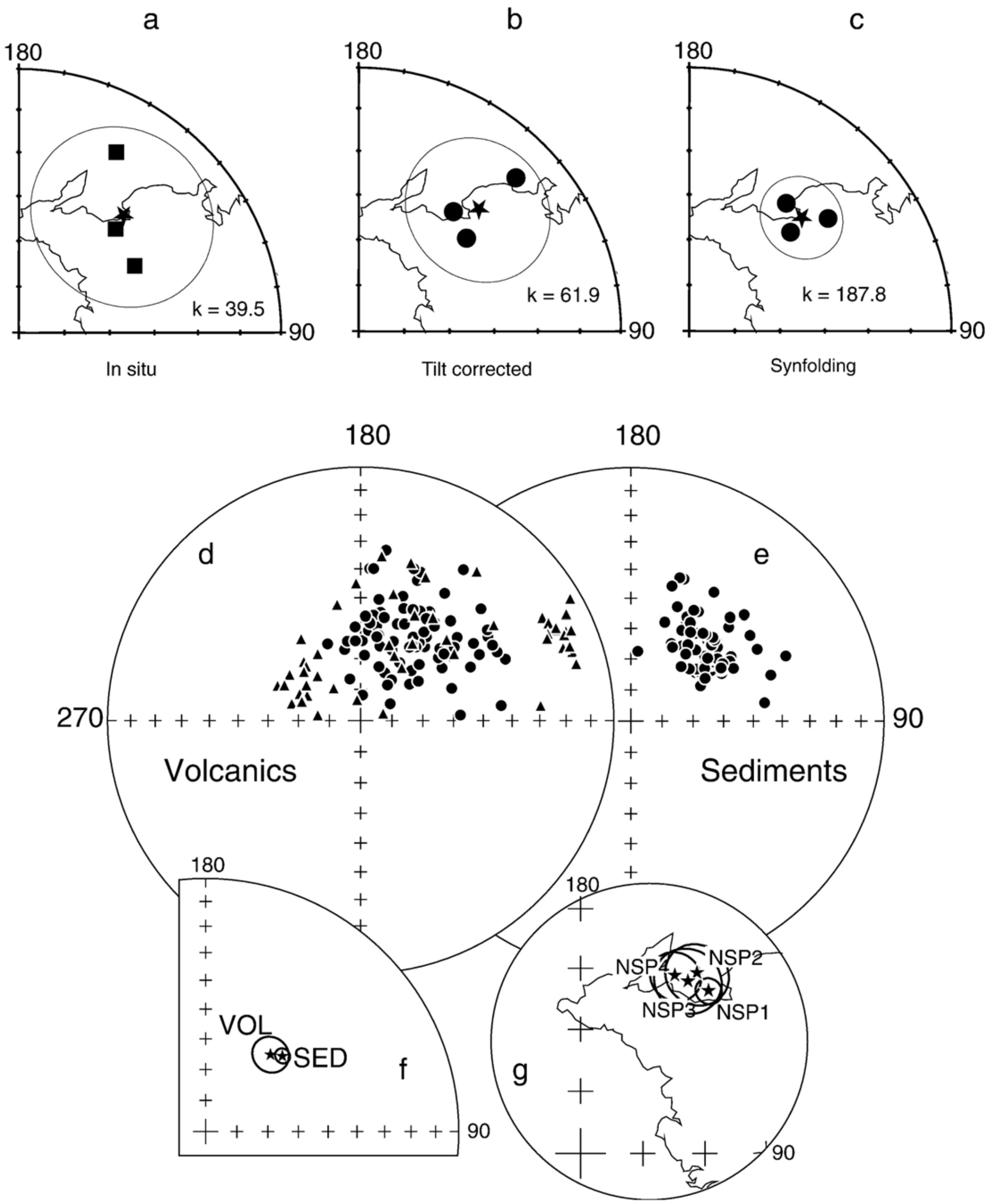


Fig. 6. a–c, Comparison of poles MO, BN, and KU calculated from (a) in situ; (b) tilt-corrected and (c) synfolding directions. d–e, Site mean poles on trap volcanics (d) and remagnetized sediments (e). Dots, data used for computation of the Siberian mean pole; triangles, transitional poles from localities EN and AB (see text for more detail). (f) Mean poles for volcanic (VOL) and sedimentary (SED) sites from localities BN, KU, MO, and ST (see text for more detail). (g) Four overall mean trap poles (zoomed; see text for more detail). Other notations as in Fig. 3.

independent spot-reading of the ambient field. For instance, a group of minor intrusions could intrude simultaneously, or a large intrusion may be a single sill of limited thickness. Similar ambiguities exist for sediments where remagnetization could be either related to a short outburst of brines or slow cooling. Thus there is a statistical problem of how to better average the data to obtain the mean pole. We therefore tried several approaches, and the corresponding set of the New Siberian Poles (NSP with a digit) is presented below.

First, all samples from a flow, dyke, or sill were considered as a site (i.e. unit vector/pole for further analysis), irrespective of the number of samples and sites from such a cooling unit. Different outcrops within a large intrusion were considered as separate sites, because slow cooling can be assumed. Finally, as the number of samples per remagnetized sedimentary section varies from 6 to >100, long sections were sometimes divided into a number of sites (with the important case of the Kulumbe river sediments further discussed below), each comprising several consecutive samples (6–15). The site-means based on <3 independently oriented samples and/or with confidence circles of >20° were rejected.

In total, we obtained 139 sites from trap bodies and 68 sites from remagnetized host rocks. When all volcanic site poles are plotted together, 51 presumably transitional poles from the EN and AB areas are more scattered than, and generally fall outside of the remaining rather well clustered data (Fig. 6d), in agreement with the conclusions of Heunemann et al. (2004). In contrast, the data on remagnetized sediments form a compact distribution on the stereonet (Fig. 6e). We excluded the transitional data, and 88 volcanic sites and 67 sedimentary sites were retained for further analysis.

So far, the hypothesis that Paleozoic sediments were remagnetized during trap emplacement is fully confirmed only for the sills and host rocks from the KU area. We separately calculated the mean poles on volcanics and Paleozoic sediments from localities BN, KU, MO, and ST, where both data types are available. The latter two poles (entries VOL and SED, Table 3) are in perfect agreement, the more precisely defined SED pole with its confidence circle lying within the confidence circle of the VOL pole (Fig. 6f). Hence the hypothesis of trap-related remagnetization of Paleozoic sediments is confirmed, and the results on sedimentary and volcanic rocks can be combined. This agreement of the SED and VOL poles, as well as the reasonable clustering of unit sedimentary poles, indicates that remagnetization of sediments in general encompassed a sufficiently long time interval for secular variation to be averaged out.

Similar reasoning in relation to volcanic data means that secular variation is largely averaged out too, despite the limited number of sites at some localities (Table 3). Thus the mean Siberian pole can be calculated at the site level as the overall mean of 155 volcanic and sedimentary sites (NSP1: 56.4°N, 141.7°E, N=155, K=30, A_{95}=2.1°; Fig. 6g and Table 3).

The statistics at the site level, however, has several shortcomings. One stems from the plain fact that more than half of the sites come from just two localities AB and MO, and any error in one of these data sets, e.g. unaccounted-for primary tilts, will bias the Siberian mean pole. Another drawback is that we do not know if all sites are independent spot-readings of the field, as already pointed out. This may bias the mean pole too and adversely affect its precision. So, we followed a second, traditional approach: site-means from limited areas (localities) are combined to compute area-mean poles, which are in turn used to calculate the Siberian mean pole. Eight area-mean poles defined in this way are reasonably well clustered and the corresponding Siberian mean pole is well constrained (pole NSP2, 55.1°N, 147.0°E, N=8, K=123, A_{95}=5.0°; Fig. 6g and Table 3).

This “traditional” approach is not flawless either, because it gives the same weight to better and worse defined area-mean poles (Table 3). Still another statistical scheme involves multi-level averaging, going from sites to exposures/large intrusions, then to sub-areas (e.g., localities AB, WN, ST and BN were treated as such), then to regions, then to Siberia as a whole (we abstain from presenting all detail for the sake of brevity). This third approach yields six regional means, which are Norilsk, Moyero, Kulumbe, Kotuy, Viluy, and Tunguska (Fig. 1a), from which the overall mean pole NSP3 was derived (57.0°N, 148.1°E, N=6, K=159, A_{95}=5.3°; Fig. 6g and Table 3). Unfortunately, the latter approach cannot remedy the simple fact that two poles based on the smallest datasets (VI and KO, Table 3) have to be used in parallel with better defined results. Still other averaging schemes could be proposed; yet, all mean poles we calculated for the Siberian traps are statistically identical.

One point remains to be discussed. We see on Fig. 7a and b (NSP2 option) that the eight trap poles now available after careful selection and obtaining the new data presented in this paper actually form a non-Fisherian, elliptically elongated cloud with an aspect ratio on the order of 3. Bivariate statistics (Le Goff, 1990) are more appropriate for such a distribution, yielding pole NSP2b (55.3°N, 146.9°E, N=8, K_x/K_y=497/83, A_{95x}/A_{95y}=2.2/5.4°; and confirming an elongation of 2.5. This elongation may in part come from the KU and MO poles. We have seen that tilt correction on the triplet of poles KU, MO and BN produced a positive fold test. But this deserves further discussion.

As far as KU is concerned, one can suggest on the strength of geological evidence that the magnetization of all remagnetized rocks and sills (KV8–KV13) from the lower part of Kulumbe river (below site 7214, Fig. 1c) was caused by a single short-lasting event (emplacement of a nearby intrusion). The remarkable

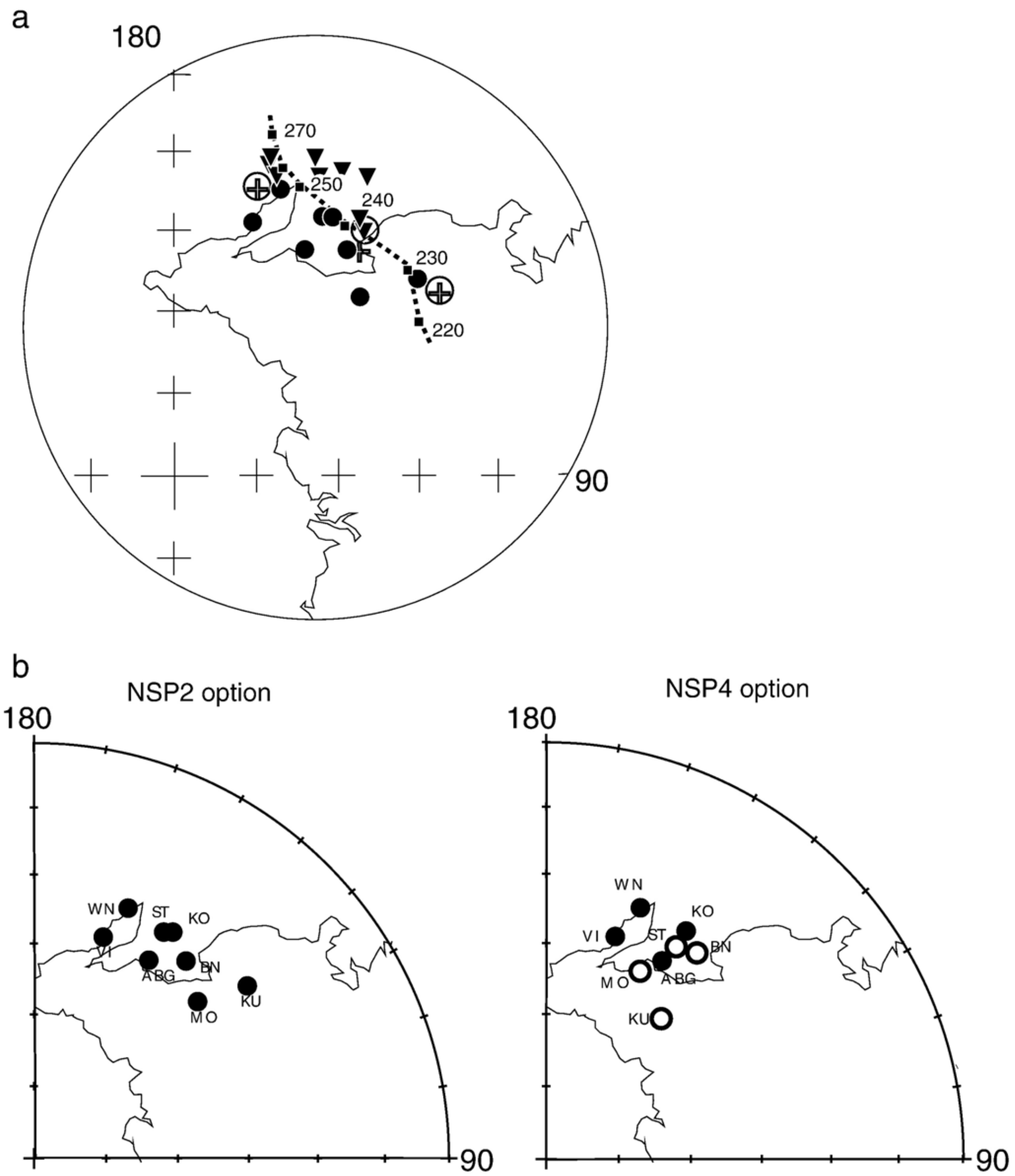


Fig. 7. (a) Comparison of the area-mean poles for the Siberian traps (solid circles) with Late Permian (inverted triangles) and Early–Middle Triassic (crosses) unit poles from Western Europe. Also shown are a segment of the Baltican APWP (dotted line) and mean Baltic poles (solid squares) for different ages (Torsvik et al., 2001). West European data on volcanics are circled. Ages of poles are in Ma. (b) Comparison of distribution of poles for NSP2 and NSP4 options (see text). Empty circles indicate alternate poles. Note that there is no elongation in the case of the NSP4 option.

similarity of corresponding paleomagnetic directions (precision parameters are close to 200) supports this suggestion. In that case, the weight given to this large set of data should not be overestimated and all of that part of the KU section can be averaged to yield a single (unit weight) direction. When such the averaging procedure is applied, the KU pole moves significantly closer to other trap poles (Fig. 7b (NSP4 option)).

In fact, there may also be some problems with interpretation of the paleomagnetic directions of remagnetized rocks from Moyero valley. First, because of a distinct difference of their mean with respect to the volcanic rocks mean; second, because of very tight grouping of mean directions ($k>400$); third, because of unclear (in situ, synfolding or post-folding) remagnetization age, these directions can be considered as somewhat suspicious. If so, it will not be unreasonable to discard them when calculating the overall MO average direction. Finally, instead of dividing the large outcrops of remagnetized rocks of BN and ST areas into several sites, as done above, we can treat all studied outcrops of remagnetized rocks with unit weight, as done by Veselovsky et al. (2003). When these remarks are implemented, the alternate poles for KU, MO, BN and ST areas yield a mean pole NSP4 (57.2°N, 151.1°E, $N=8$, $K=192$, $A_{95}=4°$, see Figs. 6g, 7b and Table 3); with these alternate KU, MO, ST and BN, the clustering of regional Siberian poles is slightly improved (α_{95} is reduced from 5° to 4°), and the 8 poles comprising the "trap cloud" now form a Fisherian distribution.

Therefore, different statistical procedures result in slightly different but statistically similar poles, thus

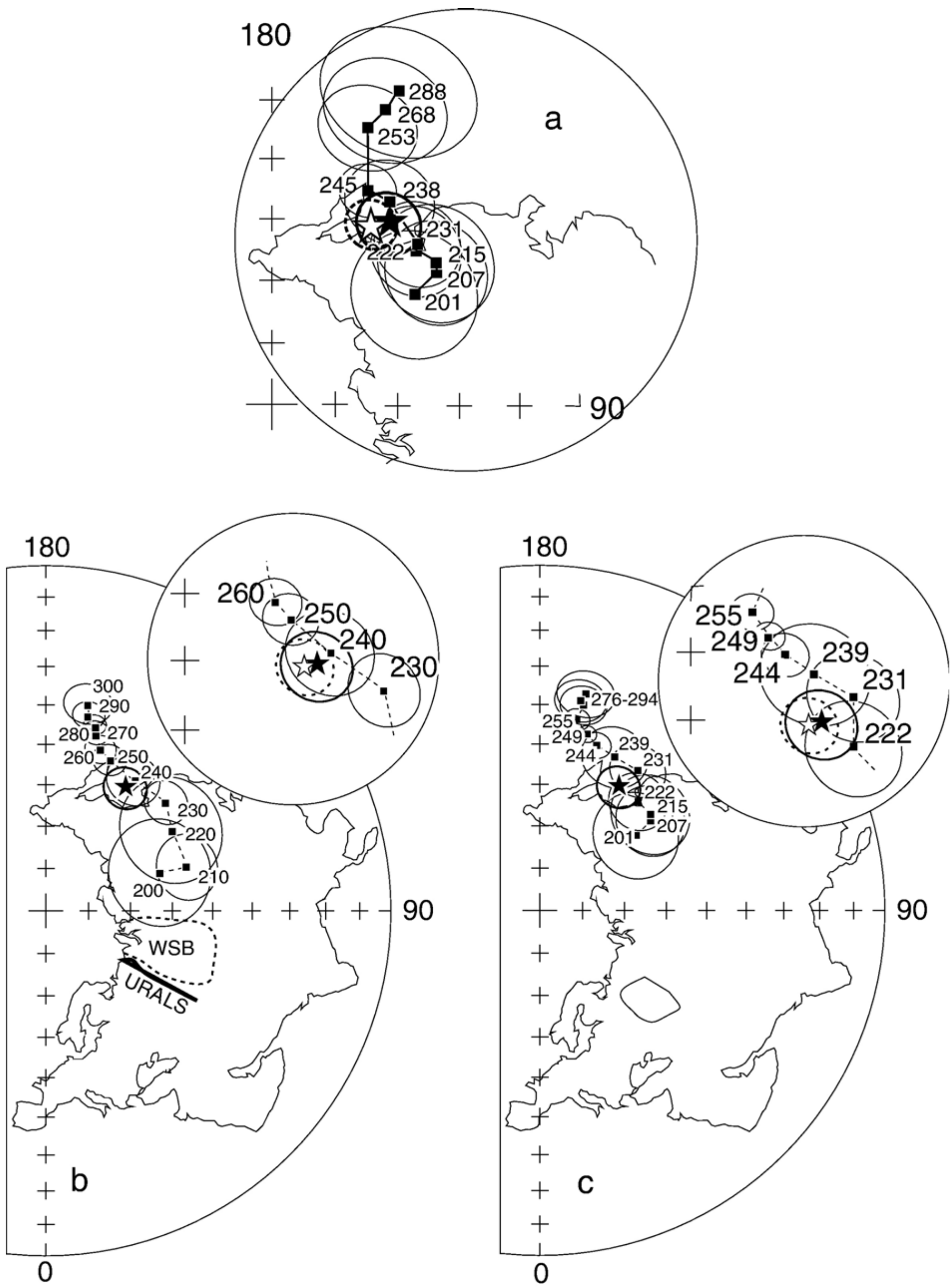


Fig. 8. Comparison of the overall mean trap pole with the APWPs for (a) Siberia (Molostovsky and Khramov, 1997), (b) Western Europe (Torsvik et al., 2001), and (c) the northeastern part of European Russia (Molostovsky and Khramov, 1997). Inserts in b and c show zoomed parts of the corresponding figures. Solid star and thick solid circle: NSP2 pole with its confidence limits; open star and dotted circle: NSP4 pole with its confidence limits. Squares, mean poles for different ages (connected with thin dotted line) with associated confidence circles (thin solid lines). Ages are in Ma; those closest to the age of the Siberian traps are bold-faced. WSB, West Siberian Basin. Outlined patch in European Russia (Fig. 8c) is the area where the results came from.

constituting a kind of robustness test (NSP1 to NSP4, Table 3; Fig. 6g). Although the above mean poles may be considered equally reliable, we have selected for the discussion below the NSP2 pole, which is based on the most widely used statistical treatment, and the NSP4 pole, which has the strongest clustering upon bedding correction and yields the most Fisherian trap pole distribution.

6. Siberia versus Baltica

As stated above, we used only fully published and completely demagnetized data for computation of the Siberian mean pole and rejected all results, which do not meet these two criteria. In their version of the Siberian APWP, Molostovsky and Khramov (1997) used the time scale of Harland et al. (1990), where the Permo-Triassic boundary is placed at around 245 Ma, while the age now ascribed to the Siberian traps is ca. 250 Ma to (e.g., Renne et al., 1995; Kamo et al., 2003; discussion in Courtillot and Renne, 2003; Mundil et al., 2004). Hence, we assume that the NSP poles are coeval with the 245 Ma pole of Molostovsky and Khramov (1997). The NSP2 and NSP4 poles, however, seem to fall on a younger APWP segment: close to 238 Ma (Fig. 8a). Nevertheless, the difference between these poles and the 245 Ma pole of Molostovsky and Khramov (1997) is not significant $-\gamma/\gamma_c$ values (McFadden and McElhinny, 1990) are 6.2°/6.6° and 5.9°/6.1° respectively. We note, however, that the NSP4 pole falls slightly closer to the expected (Siberian APWP) reference pole of the corresponding age.

Several versions of the APWP for Baltica have recently been compiled; these paths differ in data treatment and selection criteria of unit poles. In particular, some authors discarded the Russian data as being based on inadequate demagnetization and hence unreliable (e.g., Torsvik et al., 2001), while Molostovsky and Khramov (1997) used them. Despite these differences in the underlying datasets, these two APWPs are similar (Fig. 8b–c).

The NSP2 and NSP4 poles (and for that matter all other NSP poles) fall rather close to both Baltican APWPs (Fig. 8b–c): the nearest coeval poles of Torsvik et al. (2001) and Molostovsky and Khramov (1997) are younger by some 10 Ma and 5–20 Ma, respectively The angular distances between NSP2 and NSP4 poles and the 250 Ma European pole of Torsvik et al. (2001) are 7.7°±5.9° and 7.6°±5.4°. When comparing these poles with a recently published European 250 Ma mean pole (Van der Voo and Torsvik, 2004), angular differences remain significant (8.4°±8.0° and 8.3°±6.8°). A larger difference of about 11.2°±5.6° (resp. 11.0°±5.0°) and 14.5°±4.5° (resp. 14.1°±4.0°) is observed with respect to the 244 Ma (resp. 249 Ma) pole of Molostovsky and Khramov (1997).

The NSP2 and NSP4 poles are only slightly near-sided with respect to the Baltican data (Fig. 9a), nevertheless the offset in both cases is significant.

Several authors have hypothesized relative motions between Siberia and Baltica (Khramov et al., 1982; Bazhenov and Mossakovsky, 1986; Cogné et al., 1999). Despite differences in these hypotheses, which we abstain from discussing here, all require an increase in distance between these cratons since the Late Permian; in other words, there had to be considerable extension between Siberia and Baltica. These models were supported by a network of Early–Middle Triassic NS trending rifts and grabens under the sedimentary cover of the West Siberian Basin (WSB in Fig. 8b) to the west of the Siberian platform (e.g., Zonenshain et al., 1990). Negating this, however, the observed relationship between the NSP2 and NSP4 poles and the Baltican APWPs requires EW convergence between these two blocks (if it is a consequence of tectonic motion).

The only post-Paleozoic locus of compression between them is the Urals (Fig. 8b), where some Cenozoic tectonism is indeed known. This deformation, however, may account for convergence of no more than a few kilometers (Bachmanov et al., 2001) and not for the far-sidedness of Baltican poles (Fig. 9a). Hence, we can rule out tectonic motion as a possible explanation for the misfit of the coeval Baltican and Siberian poles.

It has been suggested that the Paleozoic geomagnetic field departed from a purely geocentric axial dipole (g1, GAD) geometry and might have included significant quadrupole (g2) and/or octupole (g3) terms (Kent and Smethurst, 1998; Van der Voo and Torsvik, 2001). If so, non-dipole terms in the field could have resulted in moderate inclination shallowing in the West European data with respect to the Siberian ones. In other words, the European poles could be far-sided with respect to the trap pole, as indicated by the observed data (Fig. 9a). The offset of the NSP2 and 250 Ma Baltican pole (Van der Voo and Torsvik, 2004) could be accounted for, for instance, by a g3/g1 contribution of −30%. The offset of the NSP4 and 250 Ma Baltica pole (Torsvik et al., 2001) could be accounted for by a g3/g1 contribution of +30% and g2/g1 contribution of −15% (Fig. 9b). However, Besse and Courtillot (2002) and Courtillot and Besse (2004) have shown that the global paleomagnetic database supported only a small quadrupole and no significant octupole contribution to the field in the past 200 Ma. The situation for the Permo-Triassic boundary field remains unclear.

This explanation, however, is non-unique (e.g. Cogné et al., 1999; Gilder et al., 2001). Most Late Permian–Early Triassic poles from Western Europe are from sediments, where inclination errors during remanence acquisition and/or compaction are possible (Van der Voo and Torsvik, 2004). Using the formula $\tan I_{obs} = f^* \tan I_{field}$, where I_{obs} is observed inclination and I_{field} is dipole inclination of the ambient field (King, 1955; Barton and McFadden, 1996), it is possible to compute the angular difference for different values of parameter f. The observed difference between the Siberian and European mean poles could be accounted for by values of shallowing between 0.5 and 0.9, with a best fit at about 0.65 (Fig. 9c). The existence of inclination error could be tested by comparing with data on igneous rocks of Baltica of similar age. There are the 243±5 Ma pole on the Lunner dykes (Torsvik et al., 1998) and the 261 Ma pole on the Esterel volcanics (Zijderveld, 1975), and their mean is close to the Siberian mean poles on traps. Despite, just two poles with disparate ages do not constitute a conclusive test. Thus, the issues of non-dipole contribution vs. inclination shallowing (with other options still possible, including overprinting) cannot be resolved at this stage with available data.

Finally, could the misfit between the NSP and the coeval Baltican poles stem from differences in ages? Reliable trap ages fall into a narrow interval centered on 250 Ma but come mostly from the Norilsk area (Renne and Basu, 1991; Renne et al., 1995; Kamo et al., 2003; Mundil et al., 2004). Thus the synchronicity of all traps, intrusive bodies in particular, is either based on indirect evidence or inferred. The area-mean poles used in calculating NSP2 (Table 3) appear to be smeared along the Baltican APWPs (Fig. 7a), which could reflect some age differences. However, the MO pole falls close to the Middle Triassic APWP segment (Fig. 7a,b), while $^{39}Ar/^{40}Ar$ ages on several samples from intrusive bodies in the Moyero River valley are centered around 250 Ma too (Hoffman, 1997; unpublished data). These ages indicate that the unit trap poles are indeed coeval, and that their scatter is not due to age differences. Moreover, the discussion on NSP4 shows that elongation may be due to improper averaging. When another statistical scheme is applied, elongation disappears and is therefore not a problem anymore.

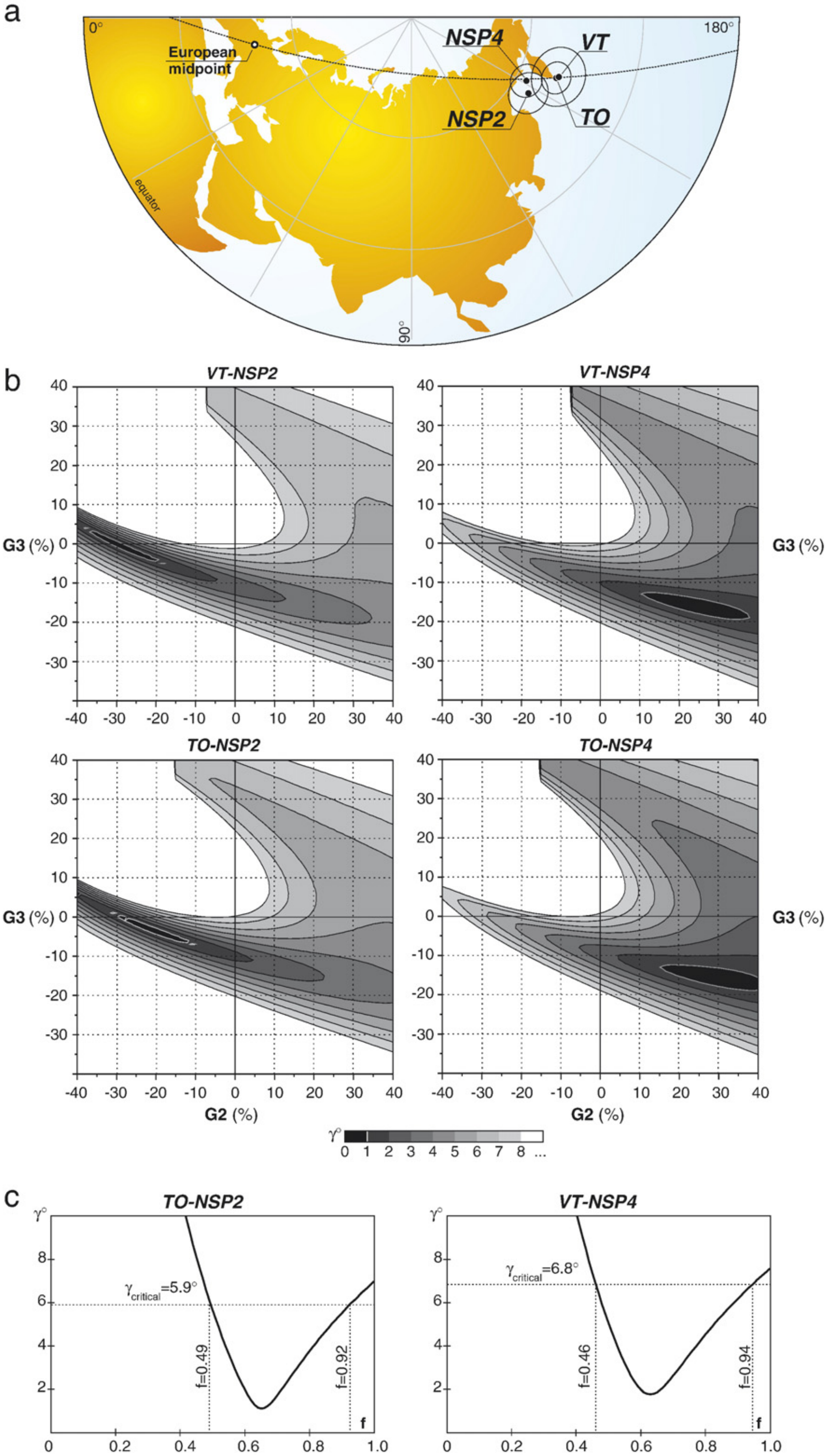
7. Craton versus fold belts

Coeval paleomagnetic data are available from the mobile belts around the Siberian platform (Fig. 10a; Table 3). To the north of Siberia, there are results on the West Taymyr traps, WT (Gurevitch et al., 1995), and on remagnetized Paleozoic rocks from East Taymyr, ET (Torsvik and Andersen, 2002). Some presumably trap-related volcanics are locally known to the southwest of Siberia, in the Kuznetsk Basin to the south of the Siberian craton (KB, Table 3). Still further away from Siberia, Lyons et al. (2002) reported new ages of about 249 Ma and a paleomagnetic pole on the Semeitau volcanic series from NE Kazakhstan (EK, Table 3). Of these results, the WT and EK poles fall close to the center of the Siberian trap poles distribution and show agreement with the NSP poles (Fig. 10b). Hence the WT and EK poles refute 1) any possible rotation/translation between the West Taimyr area and the craton and any considerable shortening/extension in the Yenisey–Khatanga basin between the Siberian platform and the Taimyr fold belt since the Early Triassic; 2) post-Permian left-lateral motion in the shear zones between Siberia and Kazakhstan, thus further supporting the conclusions of Lyons et al. (2002).

In contrast, the ET and KB unit poles are significantly different from the NSP2 and NSP4 mean poles and further increase the elongation of the Siberian trap pole distribution. The ET pole nearly coincides with the KU pole, calculated according to the NSP2 option, and thus, could fall within the cloud of the cratonic poles (Fig. 10b). Torsvik and Andersen (2002) attributed the deviation of the ET pole from the Siberian traps mean pole to the fact that “magmatism in Taimyr could therefore, at least in part, be considerably younger than that of Central Siberia Traps”. Our analysis indicates that this conclusion could be called into question.

The KB pole (Metelkin and Bragin, 2000) falls at the other end of the distribution, though not far from the VI and WN poles from the Siberian platform, and its authors advocated a tectonic origin for the misfit between their result and Siberian data. With respect to the NSP2 pole, KB would seem to indicate counterclockwise rotation by 18°±12° and northward motion by 10°±6°. Note, however, that whereas rotation can be attributed to some (local?) deformation, poleward

Fig. 9. (a) Far-sidedness of European poles with respect to Siberian ones. VT and TO, the poles from (Van der Voo and Torsvik, 2004) and (Torsvik et al., 2001) respectively. (b) Plot of angular difference γ between the NSP2 and NSP4 poles for Siberia and 250 Ma mean pole for Baltica (Torsvik et al., 2001; Van der Voo and Torsvik, 2004) versus different values of input of quadrupole (G2 = g2/g1) and octupole (G3 = g3/g1) terms (in percent of dipole term). The areas where $\gamma > \gamma_{critical}$ (McFadden and McElhinny, 1990) are not shaded. The scale (in degrees) for the gamma parameter (grey) contours is included at the bottom of b. (c) Plot of angular difference γ (defined as above) versus shallowing parameter f (Barton and McFadden, 1996). TO-NSP2 and VT-NSP4, the plots for corresponding pairs of poles.


a
0°
180°
European midpoint
NSP4
VT
NSP2
TO
equator
90°
b
VT-NSP2
VT-NSP4
TO-NSP2
TO-NSP4
G3 (%)
G2 (%)
γ°
c
TO-NSP2
VT-NSP4
γcritical=5.9°
γcritical=6.8°
f=0.49
f=0.92
f=0.46
f=0.94
f

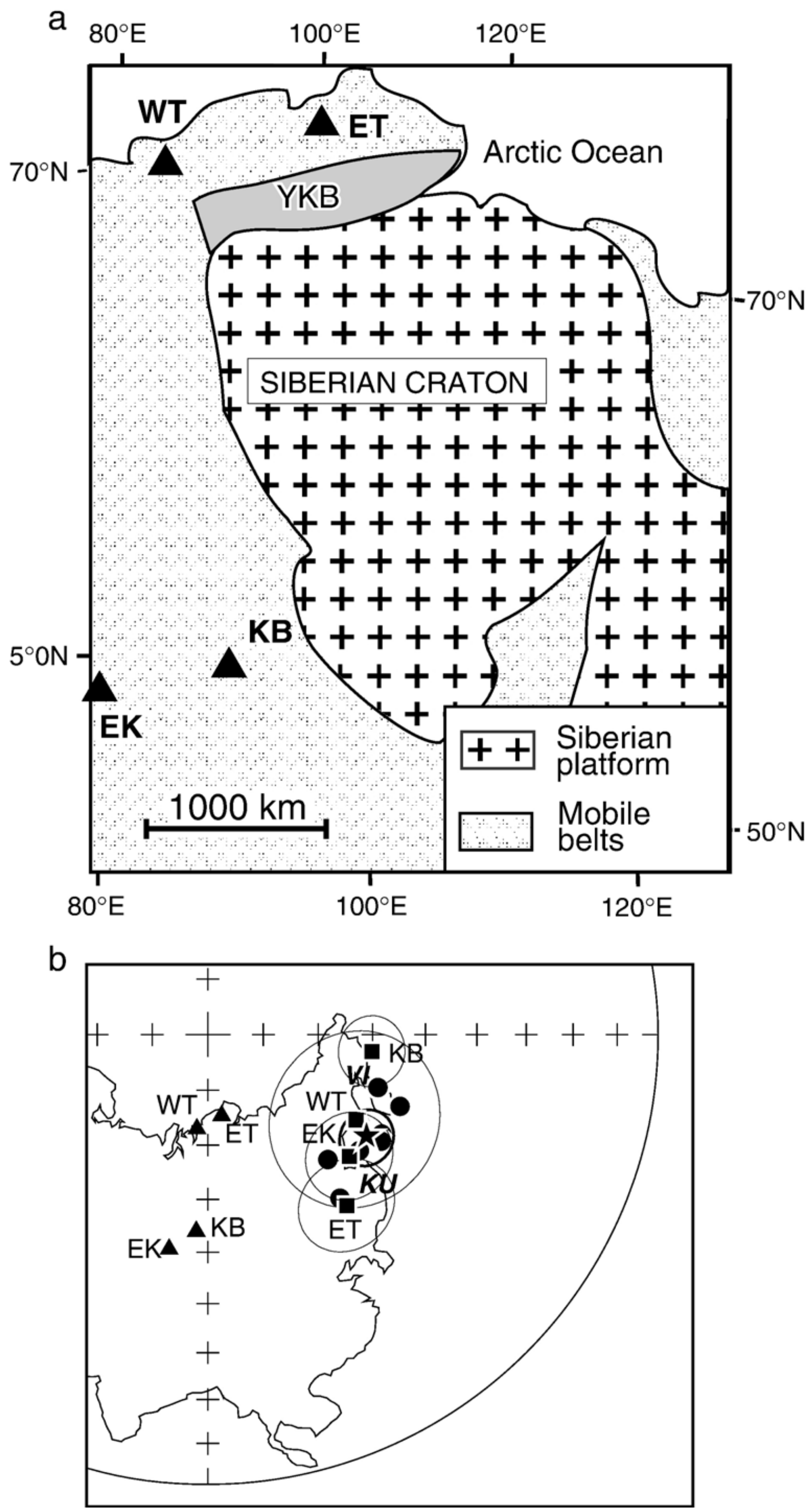


Fig. 10. (a) Cartoon showing the Siberian craton, surrounding mobile belts, and sampling locations within these belts (solid triangles labeled as in Table 3 and the text) within these belts. The Yenisey–Khatanga basin (YKB), located between the craton and the Taimyr fold belt is shaded. (b) Comparison of the area mean poles from the craton (large solid circles; not labeled except for poles KU and VI, which are specifically referred to) and the poles from the mobile belts (squares; labeled as in Table 3 and text). For clarity, confidence circles (thin solid lines) are shown only for the poles from mobile belts. Solid star and thick solid circle, the NSP2 pole with its confidence limits.

motion of the Paleozoic fold belts by 1100 km ± 700 km is not compatible with the geology of this region. Besides, the KB result should be considered in parallel with the EK data from North Kazakhstan (Lyons et al., 2002), which shows no motion with respect to Siberia. This inconsistency between the Siberian mean pole and KB result seems rather enigmatic and would require further investigations.

8. Conclusion

We performed a paleomagnetic study of Siberian trap-related volcanics and remagnetized host rocks from two localities and isolated a bi-polar characteristic remanence from most sites. Two new results complement the global database and furnish useful references for stable Siberia at 250 Ma. We have combined them with other fully published data based on completely demagnetized collections. Whereas the trap-related poles for the entire province scatter in an elongated fashion (with an elongation factor larger than 2), parallel to the APWP of Siberia, we show that admission of other, also permissible, averaging procedures for four areas improves the consistency of the overall data set and eliminates the elongation, restoring a Fisherian distribution of the unit poles.

The overall mean pole for the Siberian traps differs slightly from previously published coeval mean poles of Baltica and Siberia. In the case of Siberia, the angular difference between the mean poles lies within error bars; on the other hand, the difference between our new Siberian poles and the corresponding Baltic ones is significant. This difference could have resulted from: 1) relative tectonic motions between the two cratons; 2) systematic differences in ages of the data; 3) persistent non-dipole terms in the geomagnetic field or 4) widespread inclination shallowing in the European data. Available geological and geochronological data, however, do not support first two hypotheses. This leaves open the possibility of non-dipolar behavior of the geomagnetic field close to the Permo-Triassic boundary or of inclination shallowing in European data, which deserves further study.

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