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Late Permian palaeomagnetic data east and west of the Urals

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SUMMARY

We studied Upper Permian redbeds from two areas, one between the Urals and the Volga River in the southeastern part of Baltica and the other in north Kazakhstan within the Ural-Mongol belt, which are about 900 km apart; a limited collection of Lower-Middle Triassic volcanics from north Kazakhstan was also studied. A high-temperature component that shows rectilinear decay to the origin was isolated from most samples of all three collections. For the Late Permian of north Kazakhstan, the area-mean direction of this component is $D = 224.3°$, $I = -56.8°$, $k = 161$, $\alpha_{95} = 2.7°$, $N = 18$ sites, palaeopole at 53.4°N, 161.3°E; the fold test is positive. The Triassic result ($D = 55.9°$, $I = +69.1°$, $k = 208$, $\alpha_{95} = 4.2°$, $N = 7$ sites, pole at 57.0°N, 134.1°E) is confirmed by a positive reversal test. The corresponding palaeomagnetic poles from north Kazakhstan show good agreement with the APWP for Baltica, thus indicating no substantial motion between the two areas that are separated by the Urals. Our new mean Late Permian direction for SE Baltica ($D = 42.2°$, $I = 39.2°$, $k = 94$, $\alpha_{95} = 3.5°$, $N = 17$ sites; palaeopole at 45.6°N, 170.2°E) is confirmed as near-primary by a positive tilt test and the presence of dual-polarity directions. The corresponding pole also falls on the APWP of Baltica, but is far-sided with respect to the coeval reference poles, as the observed mean inclination is shallower than expected by $13° \pm 4°$. In principle, lower-than-expected inclinations may be attributed to one or more of the following causes: relative tectonic displacements, quadrupole and octupole terms in the geomagnetic field, higher-order harmonics (incl. secular variation) of the same field, random scatter, non-removed overprints, or inclination error during remanence acquisition and/or diagenetic compaction. Our analysis shows that most mechanisms from the above list cannot explain the observed pattern, leaving as the most likely option that it must be accounted for by inclination shallowing. Comparison with selected coeval results from eastern Baltica (all within Russia) shows that all of them are biased in the same way. This implies that they cannot be used for analysis of geomagnetic field characteristics, such as non-dipole contributions, without a more adequate knowledge of the required correction for inclination shallowing.

Key words: Palaeomagnetic secular variation; Palaeomagnetism applied to tectonics; Asia; Europe.

1 INTRODUCTION

Permian palaeomagnetic results and the corresponding palaeogeographic positions are of importance for such wide-ranging topics as the optimum reconstruction of Pangea (Muttoni *et al.* 2003; Irving 2004; Van der Voo & Torsvik 2004), possible non-dipole contributions to the main field (Van der Voo & Torsvik, 2001), or the detection of errors (such as inclination shallowing) in the recording of the palaeomagnetic field by sedimentary rocks (Tan *et al.* 2007). Because stratified volcanics and palaeomagnetically suitable sedimentary rocks of Permian age are rather abundant in Europe, their results may also reveal secular variation of the Permian field or statistical distributions (Fisherian or otherwise) of large palaeomagnetic collections. We cite these rather well-known issues, because they provide justification for publishing yet one more Permian result from Baltica, as well as another from Central Asia.

Moreover, the Late Permian to Early Triassic characteristics of the palaeomagnetic field in Europe are not very well documented (see Van der Voo & Torsvik 2004, and references therein), and the situation is not much better for North America, despite scores of palaeopoles being available. Also, upon close inspection, the abundance of Permian data from Eurasia is a bit of a fata morgana, as applications of stringent reliability criteria cause the numbers to dwindle rapidly. As an example, we can mention that the initial total of 27 poles traditionally selected from Baltica for the interval of 290–270 Ma reduces to a mere total of three when imprecise age

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determinations, lower demagnetization quality, and the likelihood of inclination shallowing are taken into account (Van der Voo & Torsvik 2004). For the Late Permian (270–250 Ma), about ten poles were considered as sufficiently reliable in recent compilations (Torsvik *et al.* 2001; Van der Voo & Torsvik 2004), but only one (volcanic) result is guaranteed to be free of inclination shallowing. About forty Late Permian palaeomagnetic poles from east Baltica were used by Khramov *et al.* (1982); however, most of them are based on blanket cleaning at 30 mT or 200–300 °C at best and, consequently, they are usually not included in compilations in the international literature. Only a single Late Permian result east of the Urals is available from east Kazakhstan (Levashova *et al.* 2003). Still farther to the south and southeast, several results of this age were obtained in the high mountains of Central Asia (Van der Voo *et al.* 2006, and references therein), but this area was still undergoing deformation in early post-Palaeozoic times, whereas no Late Permian data have yet been reported from other mobile belts that surround the Siberian craton. There is only one well-dated late Early Permian pole from Siberia (275 ± 4 Ma, Pisarevsky *et al.* 2006), whereas there are several reliable poles that were derived from the latest Permian—earliest Triassic traps of the Siberian platform *sensu stricto* (Pavlov *et al.* 2007 and references therein) with well-established ages of about 250 Ma (Baksi & Farrar 1991; Renne & Basu 1991; Mundil *et al.* 2004). These results from the trap basalts are thus somewhat younger than the bulk of Late Permian data from Baltica. It is clear that most attempts to analyse the late Palaeozoic field must essentially be limited to either Baltica alone (Van der Voo & Torsvik 2001, 2004) or to a narrow-time-window comparison of latest Permian palaeomagnetic data from west Baltica and the Siberian trap province (Veselovsky & Pavlov 2006).

Because many scientists are vacillating between inclination shallowing, non-dipole contributions, or tectonic adjustments and a 3500-km megashear (the Pangea-B to Pangea-A transition) as an explanation for the misfit of the reconstruction of Europe, North America, and Gondwana in Pangea-A (Rochette & Vandamme 1993; Van der Voo and Torsvik 2001; Muttoni *et al.* 2003; Veselovsky and Pavlov 2006), it can be argued that any addition to the Late Permian data set of North Eurasia is welcome, in particular results that may help to discriminate between inclination shallowing and non-dipole contributions. This paper adds one Triassic and two Late Permian poles from two areas, separated by the Urals (Fig. 1), to the database and presents a discussion of possible implications to the tectonics of Eurasia and the general reliability of the palaeomagnetic record.

2 GEOLOGICAL SETTING AND SAMPLING

For many decades, the Permian period was subdivided into two epochs (Palmer 1983; Palmer & Geissman 1999), and naturally, all geological and palaeomagnetic data were labelled accordingly. Recently, however, the Permian has been reformed, so that the previous Late Permian interval is now split into Middle and Late epochs (Gradstein *et al.* 2004). Unfortunately, there is no way to directly fit the previous age assignments into the new scale; thus, we had no other option but to use the ‘outdated’ timescale, referring in particular to the Late Permian as consisting of the Ufimian, Kazanian and Tatarian stages (Palmer 1983).

During the late Palaeozoic, Baltica and Siberia had joined into a single landmass and had started to form the Ural orogenic belt (Khain 1977; Puchkov 2000), although further convergent movements are thought to have continued into Triassic time (Khain 1977; Natal’in & Şengör 2005). Parallel to the mountain front, the Ural foredeep started subsiding to the west of this range by the end of Carboniferous time. In contrast, no large impact of this orogenesis is observed in the north Kazakhstan Palaeozoic domain to the east (i.e. in the eastern areas of Fig. 1b). During the first half of the Triassic, some grabens and small basins, which are filled with clastic rocks and volcanics of mostly basaltic composition, formed in the Turgay Basin east of the Urals (Fig. 1b, centre). In some places closer to the Urals, these Triassic rocks are strongly folded and even thrusted, but they are weakly deformed in north Kazakhstan. Later in the Mesozoic, the west Siberian basin and its southwestern arm, the Turgay basin, formed and filled with nearly flat-lying Jurassic and younger sediments (Khain 1977).

Three sedimentation cycles are recognized in the southern part of the Ural foredeep on the European side (also called the Belsky basin in Russian literature) that was formed at the end of the Carboniferous. The oldest one comprises Upper Carboniferous to Lower Permian reef carbonates along the western rim of the foredeep. Evaporites of Kungurian (late Early Permian) age form the second cycle, whereas lagoonal and continental terrigenous rocks, mostly redbeds with some non-marine carbonates, accumulated on the western slope of the foredeep and the adjacent part of the platform in the Late Permian and Early Triassic; the samples for this study came from this part of the section. Hardly any deformation affected the platform, whereas folding in the foredeep took place during most of the Permian and Early Triassic. In particular, deformation at the very end of the Permian (Khain 1977) is likely to have resulted in a regional erosional disconformity between the Upper Permian (Tatarian stage) and Lower Triassic strata (Indian stage). Folding ended in the Middle Triassic, although some local deformation related to salt tectonics is known to have occurred in the later Mesozoic and Cenozoic.

In the late Palaeozoic, the Dzhezkazgan and Teniz sedimentary basins formed along the western periphery of Kazakhstan (Fig. 1b). Basin-fill consists of clastic rocks with some intercalations of evaporates and non-marine carbonates that either conformably reside on Upper Devonian and Lower Carboniferous marine carbonates or overlie older rocks with major angular unconformity (Litvinovich *et al.* 1974; Khain 1977). In the Teniz Basin, this sequence was accumulating from mid-Carboniferous time until the Late Permian, with the depositional surface extent progressively diminishing with time. Upper Permian redbeds, mostly sandstones, often with well-developed cross-bedding, are known from a limited area in the northern part of the Teniz Basin. The sequence is deformed into large open folds, often of isometric outline, apart from limited areas close to faults. Dips become progressively steeper down-section, and the true thickness of any member of the sequence is lowest in the cores of anticlines and greatest in the synclines. However, no angular unconformities are observed in this mid-Carboniferous—Upper Permian sequence. Thus, these observations have been interpreted as evidence of syn-depositional fold growth (Litvinovich *et al.* 1974). The age of folding of upper Palaeozoic rocks in north Kazakhstan, in the study area in particular, is poorly constrained due to a large gap in the stratigraphic record; still, the general consensus is that deformation occurred at the very end of the Permian or in the Early Triassic. Perhaps the strongest support for this view is an observation that Early-Middle Triassic rocks reside with an angular unconformity on Palaeozoic complexes to the west and north of north Kazakhstan, in the Turgay and the west Siberian Basins, respectively (Kulikov 1974).

West of the Urals, the Upper Permian collection comes from the southeastern part of Baltica (the Kinel River valley) and the

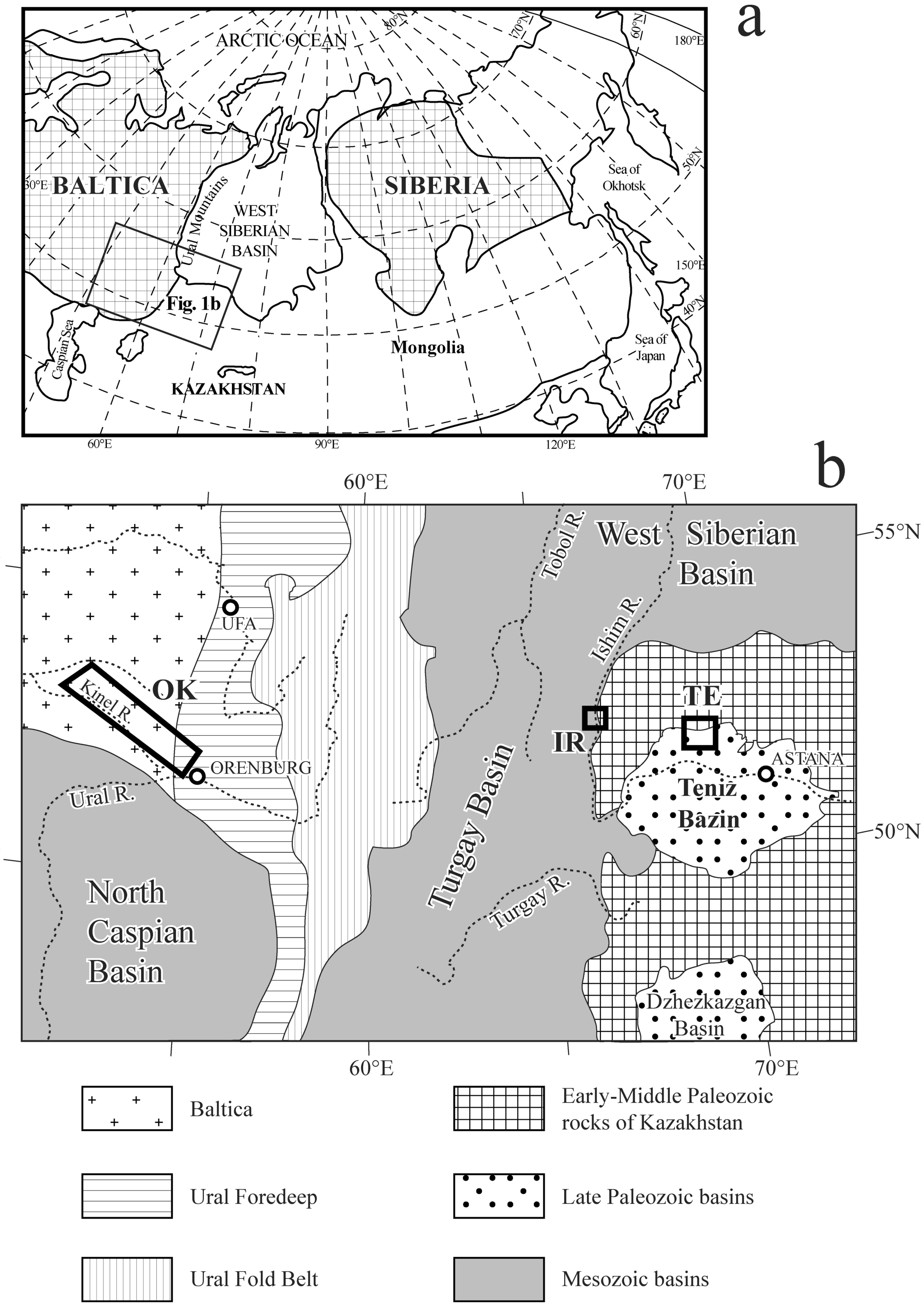

Figure 1. (a) Location map with the outlines of Baltica and Siberia (hatched). (b) Main tectonic units of the South Urals and northwestern Kazakhstan with the positions of the study areas (polygons) labelled (KO, TE and IR) as explained in the text.

adjacent, westernmost part of the Ural Foredeep (around Orenburg City; Fig. 1b). Despite sampling sites being distributed over more than 200 km, it is justified to combine them, as argued below; see the area labelled OK with mean coordinates 53°N, 53°E in Fig. 1(b). Upper Permian redbeds, mostly sandstones and siltstones with some marls, are flat lying on the platform, whereas they were gently deformed into simple folds along the western rim of the foredeep. Initially, the sections were studied for magnetostratigraphy, with sampling intervals spanning as much as several tens of meters. Some sections were treated as a single site, whereas others were divided into two to five non-overlapping sites, depending on the number of samples and the true thickness studied. In total, we examined 238 samples from 18 sites (Table 1), distributed over ten sections.

In the Teniz Basin (area TE, 51.7°N, 67.8°E), Upper Permian red sandstones and siltstones have an age that is assigned mostly on the basis of fresh-water ostracods (Litvinovich *et al.* 1974). The strata outcrop on both limbs of a gentle syncline with dips less than 15°. The stratigraphic thickness studied at each sedimentary site varies from 1 to 3 m. In other parts of the basin, Upper Permian rocks are poorly exposed, outcropping mainly as small sandstone ridges on hilltops, which were avoided because of likely lightning bolts. In

Table 1. Characteristic remanent magnetization (ChRM) directions in Upper Permian sediments (OK collection) from SE Baltica (mean coordinates 53°N, 53°E).

					In situ				Tilt-corrected			
S	Slat	Slon	B	N	$D°$	$I°$	k	$\alpha_{95}°$	$D°$	$I°$	k	$\alpha_{95}°$
Orenburg												
102A	52.0	55.3	175/35	13/13	239.9	−22.6	32	7.6	224.8	−52.6	32	7.6
102B	52.0	55.3	175/35	13/12	239.4	−5.6	28	8.7	232.7	−36.5	28	8.7
105	51.8	55.3	168/6	10/9	236.4	−29.8	44	8.1	234.9	−35.4	44	8.1
104a	51.8	55.3	57/25	11/10	210.4	−32.5	22	10.9	228.1	−40.2	24	10.3
104b	51.8	55.3	50/14	11/11	212.3	−36.5	32	8.4	223.2	−39.6	31	8.5
104D	51.7	54.5	0	19/12	228.7	−35.3	25	9.0	228.7	−35.3	25	9.0
Orenburg				(6/6)	228.6	−27.7	24	13.9	228.9	−40.0	121	6.1
Kinel												
081	53.4	52.4	145/5	18/12	215.2	−37.7	22	9.7	213.7	−42.4	22	9.7
537	53.5	52.1	146/5	12/10	215.9	−39.5	9	17.7	214.3	−44.2	9	17.7
600	53.6	52.7	0	32/14	215.6	−27.8	11	12.7	215.6	−27.8	11	12.7
018	53.4	52.7	0	13/9	226.5	−29.7	36	9.4	226.5	−29.7	36	9.4
088N	53.4	52.6	0	10/9	41.9	34.6	60	6.8	41.9	34.6	60	6.8
088R	53.4	52.6	0	15/11	232.5	−35.7	44	7.3	232.5	−35.7	44	7.3
Y2	52.7	53.4	0	11/9	32.2	48.4	20	11.9	32.2	48.4	20	11.9
Y30	52.7	53.4	0	10/6	37.5	41.0	26	13.4	37.5	41.0	26	13.4
Y58	52.7	53.4	0	11/9	35.8	40.3	30	9.6	35.8	40.3	30	9.6
Y86	52.7	53.4	0	10/0		Scattered						
Y106	52.7	53.4	0	10/8	49.5	40.3	12	16.7	49.5	40.3	12	16.7
Y126	52.7	53.4	0	10/6	30.5	35.9	63	8.7	30.5	35.9	63	8.7
Kinel				(12/11)	39.5	37.6	102	4.5	39.3	38.5	93	4.8
All[a]				(18/17)	42.9	34.2	41	5.7	42.2	39.2	94	3.5

	Mean poles (N)	Plon	Plat	k	A_{95}
Norm	(6)	174.2	48.6	119	6.2
Rev	(11)	168.1	43.9	94	4.7
Oren	(6)	163.9	43.0	153	5.4
Kinel	(11)	173.8	46.9	98	4.6
OK	(18/17)	170.2	45.6	93	3.7

[a] Recalculated from the mean OK pole to the common point at 53°N, 53°E.

S, sites and groups; Oren, Orenburg; Norm and Rev, mean poles of normal and reversed polarity, respectively; Slat (Plat), site (pole) latitude (°N) and Slon (Plon) site (pole) longitude (°E); B, strike/dip angle (0 for horizontal beds); N, number of samples studied/accepted (if for sites, the ratio N is placed in parentheses); D, declination; I, inclination; k, concentration parameter (Fisher 1953); α_{95} (A_{95}), radius of 95 per cent confidence circle around the mean direction (pole).

total, 119 hand-samples could be collected from 18 sites from both limbs of this fold (Table 2).

Triassic volcanics and associated intrusions are known from several small areas in north Kazakhstan, but mostly from boreholes; the outcrops are very rare and small. These rocks are dated as Early-Middle Triassic by Khain (1977), or as Early Triassic by Bekzhanov *et al.* (2000). Note that all information about the age of these and equivalent rocks comes from remote areas. We could sample a single outcrop of Triassic volcanics on the right bank of the Ishim River (area IR, 52.9°N, 66.6°E, Fig. 1b) where all units dip 8°–10° to the ENE. Different coloration and textural features of the flows ensure that each site represents a separate cooling unit, with possible exception of two sites (M8904 and M8910), which may belong to the same flow. Seven sites (45 samples) represent the entire outcrop of about 20 m in stratigraphic thickness.

3 METHODS

All oriented samples were collected as fist-sized blocks and oriented with a magnetic compass. Cubic specimens of 8 cm^3 volume were sawed from the blocks. The collection was studied in the palaeomagnetic laboratories of the Geological Institute of the Russian Academy of Sciences in Moscow and of the University of Michigan in Ann Arbor. In Moscow, specimens were heated in a homemade oven with internal residual fields of approximately 10 nT and measured with a JR-4 spinner magnetometer with a noise level of 0.05 mAm^{-1}. In Ann Arbor, specimens were stepwise demagnetized utilizing an Analytical Services TD-48 thermal demagnetizer; magnetizations were measured with a 2G Enterprises cryogenic magnetometer in a magnetically shielded room. In both laboratories, one specimen from each hand-sample was stepwise demagnetized in 15–20 increments up to 685 °C. No systematic difference was found between the samples that were treated in Moscow or Ann Arbor, and the data have been pooled.

Demagnetization results were plotted on orthogonal vector diagrams (Zijderveld 1967). Visually identified linear trajectories were used to determine directions of magnetic components by Principal Component Analysis (PCA), employing a least-squares fit comprising three or more demagnetization steps (Kirschvink 1980), anchoring the fitting lines to the origin where appropriate. Site-mean directions were computed either using only the PCA-calculated sample directions (Fisher 1953) or combining the latter with remagnetization circles employing the technique of McFadden & McElhinny (1988). Palaeomagnetic software written by Jean-Pascal Cogné (Cogné 2003), Randy Enkin, and Stanislav V. Shipunov was used in the analysis.

Table 2. High-temperature component directions from Upper Permian sediments from the northern part of the Teniz (TE) Basin (51.7°N, 67.8°E).

		In situ				Tilt-corrected			
Site	N	$D°$	$I°$	k	$\alpha_{95}°$	$D°$	$I°$	k	$\alpha_{95}°$
Eastern limb									
M8916	6/6	232.8	−52.9	286	4.0	225.6	−63.4	270	4.1
M8922	7/5	229.6	−43.9	280	4.6	219.5	−57.8	75	8.9
M8929	6/6	240.9	−48.2	90	7.1	234.6	−56.5	52	9.3
M8935	7/6	235.9	−43.0	55	9.1	229.4	−50.7	86	7.3
M8942	7/7	231.4	−63.4	68	7.4	223.1	−59.2	167	4.7
M8970	6/6	221.1	−48.3	61	8.7	224.1	−55.3	80	7.6
M8976	6/6	234.4	−45.9	182	5.0	220.5	−67.4	88	7.2
N3671	6/6	237.7	−46.1	43	10.3	235.1	−53.3	51	9.5
N3677	6/6	226.9	−42.3	30	12.5	223.8	−47.9	47	9.9
N3712	6/6	230.0	−51.9	246	4.3	227.3	−60.9	241	4.3
N3718	7/7	241.8	−58.6	156	4.8	230.3	−58.9	60	7.8
ELimb	(11/11)	232.8	−49.6	109	4.4	226.9	−57.5	168	3.5
Western limb									
M8949	8/8	218.3	−55.5	177	4.2	224.9	−53.8	235	3.6
M8953	8/8	227.9	−58.4	53	7.6	218.0	−58.1	117	5.1
N3691	5/4	236.5	−53.3	57	12.3	232.0	−47.7	251	5.8
M8958	7/7	246.8	−55.8	34	10.4	240.4	−51.3	74	7.1
M8960	7/7	232.5	−50.2	35	10.4	226.0	−57.4	44	9.2
M8964	6/6	244.1	−56.3	106	6.6	242.5	−60.6	91	7.2
M8966	8/8	226.8	−55.2	32	10.0	233.1	−58.6	44	8.4
WLimb	(7/7)	239.3	−55.3	168	4.7	237.0	−55.6	148	5.0
TE	(18/18)	233.0	−51.8	115	3.2	228.5	−56.8	161	2.7
Pole						161.3	53.4		3.2

ELimb and WLimb, means for the eastern and western limb, respectively. Other notation as in Table 1.

4 RESULTS

4.1 Upper Permian redbeds of the southeastern Baltica (OK collection)

This collection included red siltstones, mudstones, marls and sandstones, with a minor amount of grey to greenish-grey varieties of the same rocks. As might be expected, the latter are found not to preserve any stable remanence and were discarded. Also discarded are samples of red sandstone where the remanence displays little or no directional stability during most of the thermal demagnetization steps (not illustrated). In Tables 1–3, the columns labelled ‘N’ list the ratio of samples studied, to samples accepted for the calculation of a site-mean; it can be seen that the number of excluded samples is generally low.

Table 3. ChRM directions from Triassic volcanics of the Ishim River valley (IR, 52.9°N, 66.6°E).

		In situ				Tilt-corrected	
Site	N	$D°$	$I°$	$D°$	$I°$	k	$\alpha_{95}°$
N3638	7/7	197.8	−78.2	232.5	−76.2	346	3.2
N3645	7/7	201.0	−74.7	228.0	−72.8	274	3.7
N3652	6/6	204.1	−69.0	223.6	−67.2	172	5.1
N3658	7/7	214.3	−70.2	233.3	−67.1	119	5.6
N3665	6/4	40.1	66.7	55.4	63.1	66	11.4
M8904	6/6	54.0	74.9	72.5	69.5	235	4.4
M8910	6/4	47.4	70.9	59.2	71.3	96	9.4
MEAN	(7/7)	34.8	72.5	55.9	69.1	208	4.2

Sites are listed from section base upward. Other notation as in Table 1.

After removal of a low-temperature component (LTC) at 200–350 °C, some samples revealed a well-defined dual-polarity characteristic component (ChRM) that shows rectilinear decay to the origin (Figs 2 a and d). In most samples, however, additional rectilinear segments can be recognized (Figs 2b and e–h), or the trajectories are curved (Fig. 2c). This reveals an intermediate-temperature component, which is destroyed at 500–600 °C (Figs 2b, f and h) but may persist up to 670 °C (Fig. 2g). This component has very scattered directions (crosses in Fig. 2i). In some cases (but not always!), demagnetization characteristics of this scattered remanence resemble what one may expect in the case of lightning bolts; this remanence, however, is too common in the collection to render this assumption likely. Note also, that most sampled sections are from river banks and dry ravines, where numerous lightning bolts are not very likely. It is known that artificial anhysteretic remanence at moderate fields can be rather resistant to thermal cleaning but should be easily destroyed by alternating field (af). This, however, is not the case for this component, because af cleaning of pilot samples proved to be inefficient as well. Finally, if all three components are recognized in a sample, their directions do not fall on the same great circle. Hence, the intermediate-temperature remanence cannot be a sum of unresolved LTC and ChRM. We can suggest no credible explanation of the intermediate-temperature component.

Despite this shortcoming, the ChRM was successfully isolated, and the number of rejected samples is low (Table 1), the exceptions being sites 600 and Y86, where many grey varieties were included in the sample collection. Characteristic site-mean directions were calculated by combining direct observations and remagnetization circles (McFadden & McElhinny 1988). The ChRM in all samples from the western rim of the Ural foredeep is reversed (Orenburg in Table 1), whereas both polarities are found in the platform (Kinel in Table 1). Because the area-mean directions and poles (not illustrated) are in agreement (Table 1), the data from the two areas within polygon OK were pooled.

In this combined set, the site-means are less scattered after tilt-correction than *in situ* coordinates (Figs 3a and b), with k increasing from 41 to 94, which implies a statistically significant and positive tilt test at the 99 per cent confidence level [$N = 18$ (McElhinny 1964; McClelland Brown 1983)]. The minimum scatter is reached upon full untilting. Although tilting did not end until the Middle Triassic, considerable uplift and folding likely took place around the Permo-Triassic boundary (Khain 1977); hence it is safe to conclude that this remanence is older than ∼251 Ma. The mean poles of normal and reversed polarity (Fig. 3c) differ by 6.4° ± 6.2°, which is marginally significant. However, the difference between the mean poles is small and very close to the critical value. We argue that this apparently inconclusive reversal test is likely to stem from the too-limited statistics, not in the least because of the small number of normally magnetized sites (Table 1). We conclude that the pre-tilting origin of the dual-polarity remanence suggests that it is (near-) primary and thus of Late Permian age. This conclusion is further reinforced by region-wide observations of polarity zones in Upper Permian rocks throughout the eastern half of Baltica and the Ural foredeep (Khramov & Sholpo 1967; Molostovsky and Khramov 1997; Molostovsky 2005).

The anisotropy of magnetic susceptibility (AMS) ranges from 1.016 to 1.078, with an average value of 1.044. The maximum and intermediate axes of the AMS ellipsoid are nearly uniformly distributed along the stereonet perimeter, while the minimum axes are vertical (Fig. 3d). Such an oblate pattern is common for sediments, in which grain alignment did not occur because neither currents during deposition nor subsequent deformation were strong enough

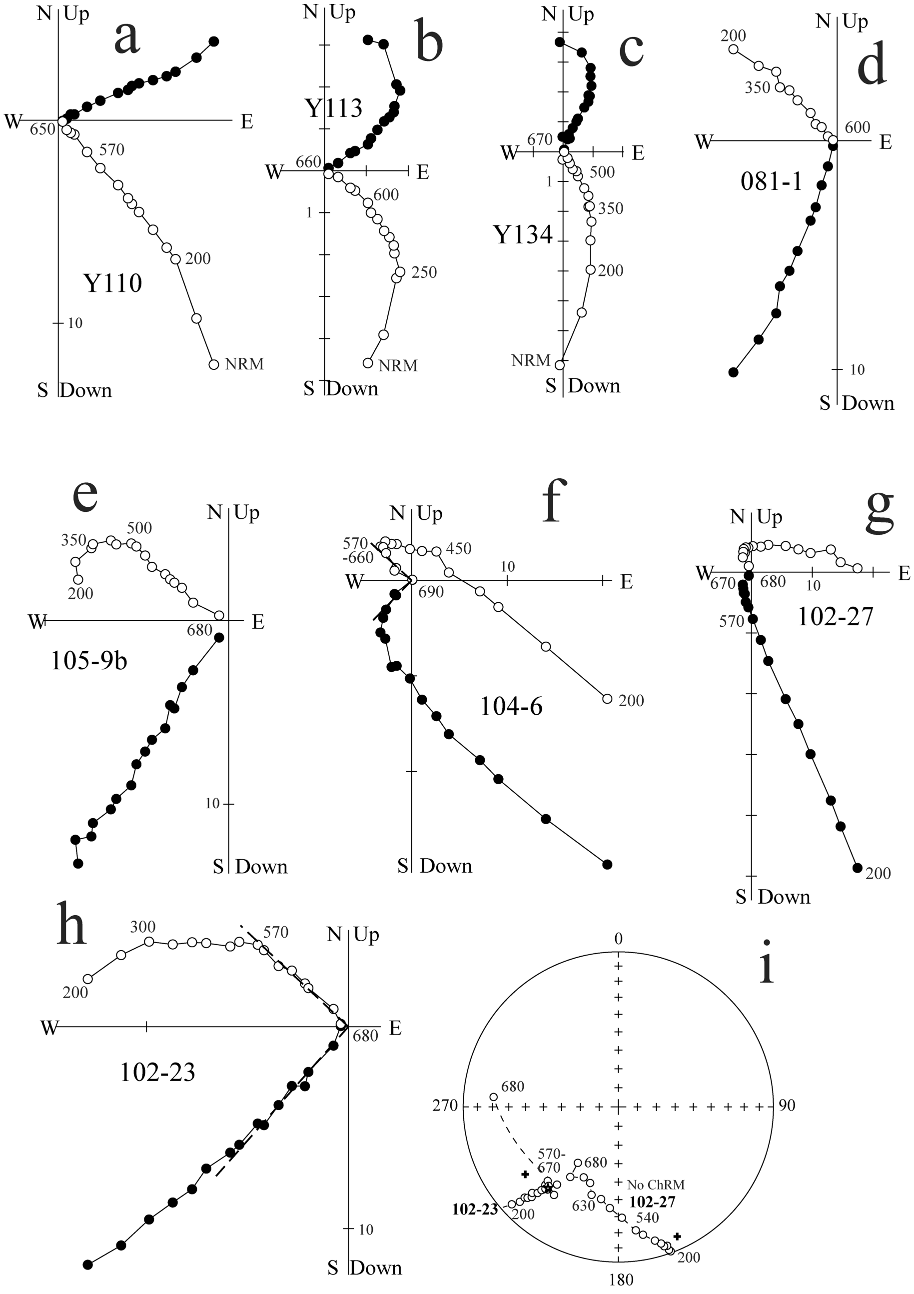

Figure 2. Palaeomagnetic results from the Upper Permian redbeds from SE Baltica (OK area). (a–h) Representative thermal demagnetization plots for (a–c) normal and (d–h) reversed samples in stratigraphic coordinates. Full (open) dots represent vector endpoints projected onto the horizontal (E–W vertical) plane. Temperature steps are in degrees Celsius. Magnetization intensities are in mA m^{-1}. Thick dashed lines on some plots denote isolated components. NRM points are deleted from some plots for clarity. (i) Stereoplot of vector end-point trajectories in stratigraphic coordinates for two samples. '+' symbols denote the directions of the low-temperature component, whereas the best estimate of the ChRM direction is at the intersection of the two trajectories (approximately the average of the two points labelled 670 °C). Solid (open) symbols and solid (dashed) lines are projected onto the lower (upper) hemisphere.

to bring this about. We note also that no correlation is observed between AMS values and inclinations.

4.2 Upper Permian redbeds of the Teniz basin, north Kazakhstan (TE collection)

The last traces of a weak and scattered LTC are removed by 300–400 °C, followed by isolation of single ChRM in most samples (Figs 4a–c). In fewer than ten samples, an intermediate-temperature component can be recognized (e.g. Fig. 4d, 200–540 °C); its mean direction, however, is very close to (and statistically indistinguishable from) the mean direction of the ChRM. The ChRM is not eliminated until 670 °C, and therefore, must reside in hematite, as is expected for redbeds, of course.

The ChRM directions are well clustered at the within-site level, with most site-means having confidence limits less than 10° (Table 2). These site-means are better clustered after tilt correction than *in situ* (Figs 4e and f), whereas the best grouping (k = 198) is attained at 65-per cent unfolding; however, the entire range of values of the precision parameter k during incremental unfolding

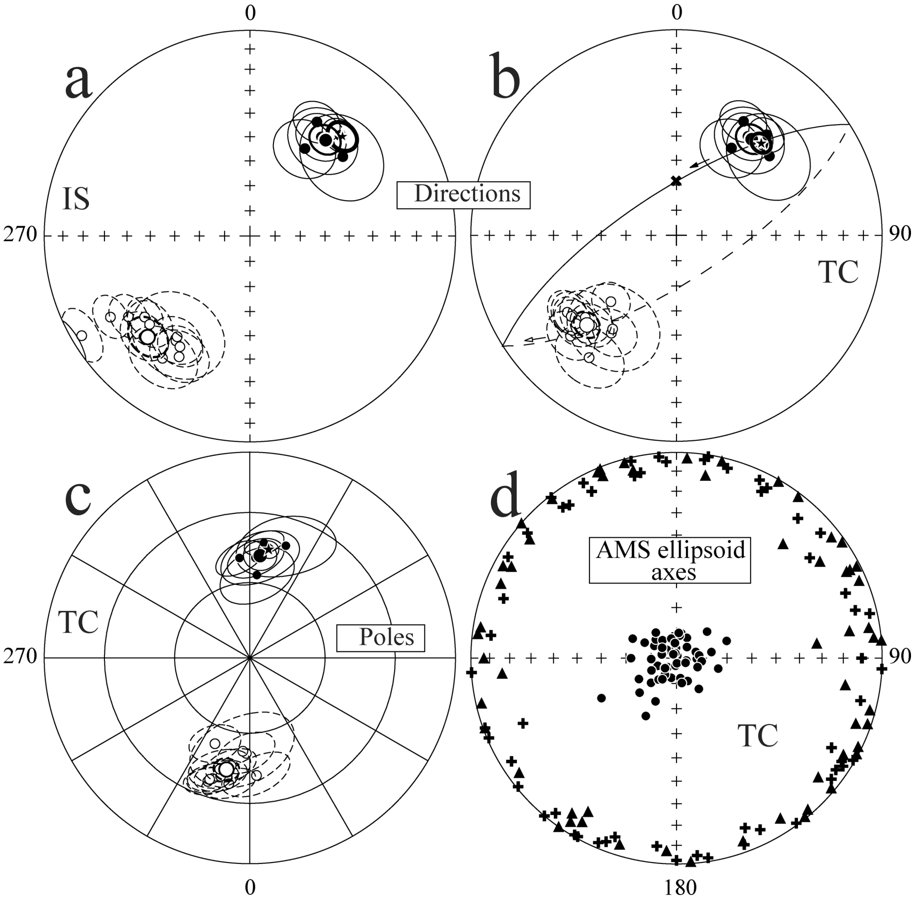

Figure 3. Palaeomagnetic results from Upper Permian redbeds from SE Baltica (OK area). (a and b) Stereoplots of ChRM site-mean directions with associated 95 per cent confidence circles (thin lines) *in situ* (a) and after tilt correction (b). Larger circles are polarity-means with associated 95 per cent confidence circles (medium-thick lines). Stars are the NE/downward overall ChRM mean directions with associated 95 per cent confidence circle (thickest line). Oblique cross and great circle in (b) are the present-day dipole field direction and the best fitting line through two polarity-means and this present-day direction. Small arrows indicate the direction of bias, if a ChRM mean direction would be contaminated by an undetected present-day field (PDF) overprint. (c) Stereoplot of tilt-corrected unit poles (circles), polarity-mean poles (larger circles) and overall mean pole (star) with associated 95 per cent confidence circle (with line thicknesses as in b). (d) Lower-hemisphere stereoplot of maximum (plusses), intermediate (filled triangles) and minimum (filled circles) axes of the anisotropy ellipsoid after tilt correction. Solid symbols and solid lines are projected onto the lower or northern hemisphere, whereas open symbols and dashed lines are projected onto the upper or southern hemisphere.

shows statistically insignificant variations. We calculated the means for the eastern and western limbs separately and applied another version of the fold test (McFadden & Jones 1981). The calculated values of F-statistics are 3.25 and 0.9 before and after tilt correction, respectively, while the 95- and 90-per cent critical values are 3.29 and 1.59, respectively. Thus the tilt-corrected means definitely agree, whereas the *in situ* ones differ at a level of significance slightly less than 95 per cent. With minor reservation, we conclude that the ChRM in these Upper Permian redbeds is pre-folding. Taking into account that deformation in the study area is not much younger than the rocks themselves, the pre-folding origin of the ChRM is nearly equivalent to it being primary.

AMS values range from 1.012 to 1.054, 1.025 on average; minimum axes are normal to bedding and maximum and intermediate ellipsoid axes are forming a girdle, as is typical for undeformed sedimentary rocks (Figs 4g and h). It is well known that such a pattern can be the sum of paramagnetic and ferromagnetic fractions. The studied collection shows a strong development of hematite coating (=red pigment), which is unlikely to produce the oblate pattern of AMS axes. Hence we conclude that the fabric reflects non-ferromagnetic materials in these Upper Permian redbeds of the Teniz basin.

4.3 Triassic volcanics of north Kazakhstan (collection IR)

In the Triassic volcanics, a LTC is clearly present in some samples (Fig. 5a) but it is usually very small (Fig. 5b) or absent altogether (Fig. 5d). Its mean direction based on 26 samples from all sites ($D = 10^\circ$, $I = 78^\circ$, $\alpha_{95} = 13^\circ$; not illustrated) does not differ significantly from the present-day geocentric co-axial dipole field ($I = 69^\circ$) or the total field ($D = 11^\circ$, $I = 71^\circ$) in the study area, and the LTC is likely to be a viscous overprint and/or unstable remanence due to weathering.

After LTC removal, a well-defined ChRM, showing rectilinear decay to the origin, is isolated from more than 90 per cent of the samples (Figs 5a, b and d). Judging by the predominant unblocking temperatures up to ∼580 °C, with occasional continuations up to ∼640 °C (Fig. 5e), the ChRM resides either in pure magnetite (e.g. Fig. 5c) or its partly oxidized variety (Fig. 5e). The directions are tightly grouped at both within- and between-sites levels (Table 3; Figs 5f and g).

This remanence is reversed at four structurally lower sites and has normal polarity at the upper three. The two polarity-means are nearly antipodal, differing by 173.2° (6.8°) ± 7.1°, thus rendering

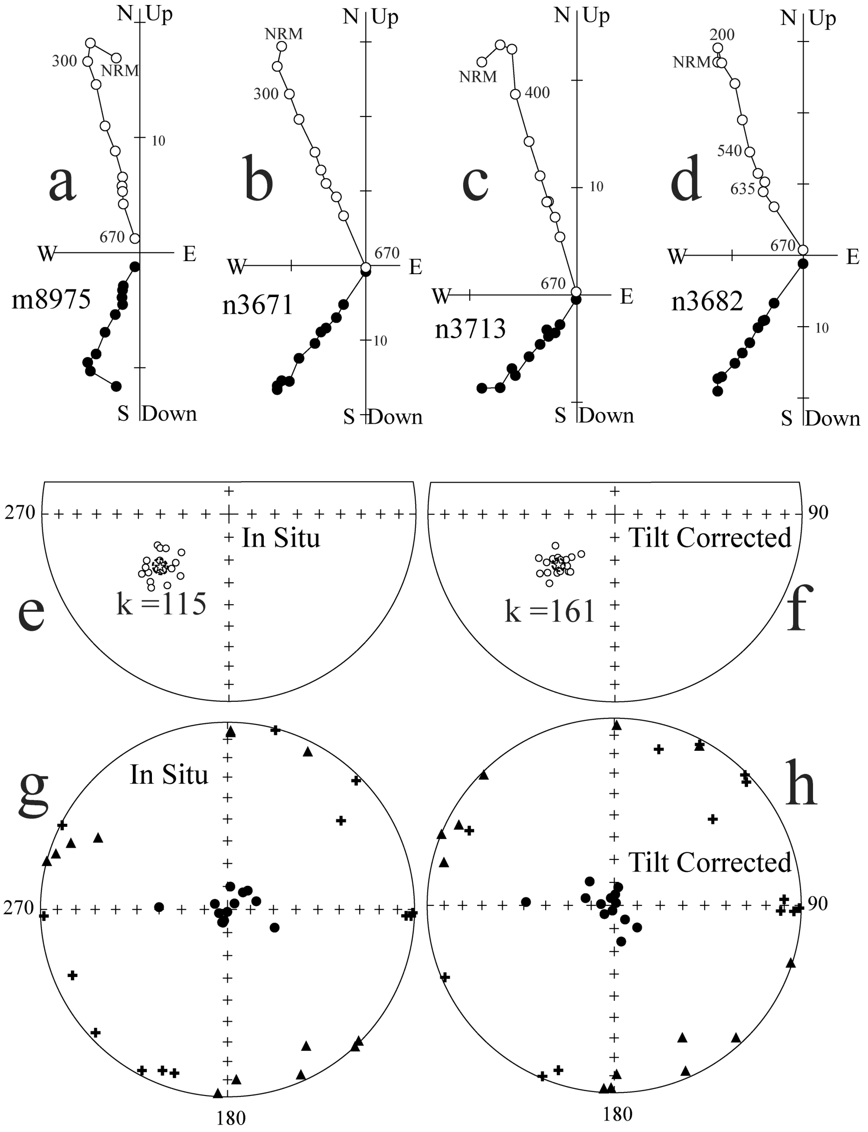

Figure 4. Palaeomagnetic results from Upper Permian redbeds from north Kazakhstan (TE area). Symbols and conventions as in Figs 2 and 3. (a–d), Representative thermal demagnetization plots in stratigraphic coordinates. (e and f) Stereoplots of ChRM site-mean directions (open circles) *in situ* (e) and after tilt correction (f); for clarity, 95 per cent confidence circles are not shown. (g and h) Stereoplots of the axes of the AMS ellipsoid (as in Fig. 3d) *in situ* (g) and after tilt correction (h).

the reversal test positive. Bedding attitude is uniform for the entire studied section, and there is, therefore, no fold test. It could be argued that the directional clustering is too tight, indicating either incomplete averaging of secular variation or severe overprinting. Both caveats, however, do not look applicable, because of antipodal normal and reversed directions and a sharp transition between magnetozones, as well as the colinearity of the directions carried by Ti-free magnetite and its partly oxidized partners. Thus we prefer to interpret the ChRM in these Triassic volcanics as being of primary origin.

5 INTERPRETATION AND DISCUSSION

5.1 Comparison of palaeomagnetic data from north Kazakhstan with APWP for Baltica

The Late Permian Teniz (TE) and Triassic (IR) poles from north Kazakhstan can be compared with the APWP for Baltica for the 200–300 Ma interval (Torsvik *et al.* 2001) in Fig. 6. The confidence oval for the IR pole overlaps the 235–220 Ma reference poles, in agreement with the estimated Early–Middle Triassic age of these volcanics. With respect to those extrapolated from the 230 Ma reference pole, the IR mean directions differ by $\Delta I = -1.2° \pm 5.2°$ and $\Delta D = 5.2° \pm 14.1°$, using the method and terminology of Demarest (1983). The TE pole also agrees well with its coeval (255–260 Ma) reference poles, and insignificantly differs by $\Delta D = 4.2° \pm 5.9°$ and $\Delta I = -2.9° \pm 3.3°$ from the directions calculated for the TE Basin from Baltica's 260 Ma pole. These findings indicate that if any relative motion took place between Baltica and north Kazakhstan since the Late Permian, the magnitude of this motion (in terms of relative rotation and latitudinal displacement) was well within the error limits of the data. Of course, the possibility of latitude-parallel motion (i.e. in a SE–NW direction in our case) exists and cannot be evaluated with palaeomagnetic data. With this reservation in mind, we can conclude that the amalgamation of Baltica and north Kazakhstan into a single landmass is likely to have been completed

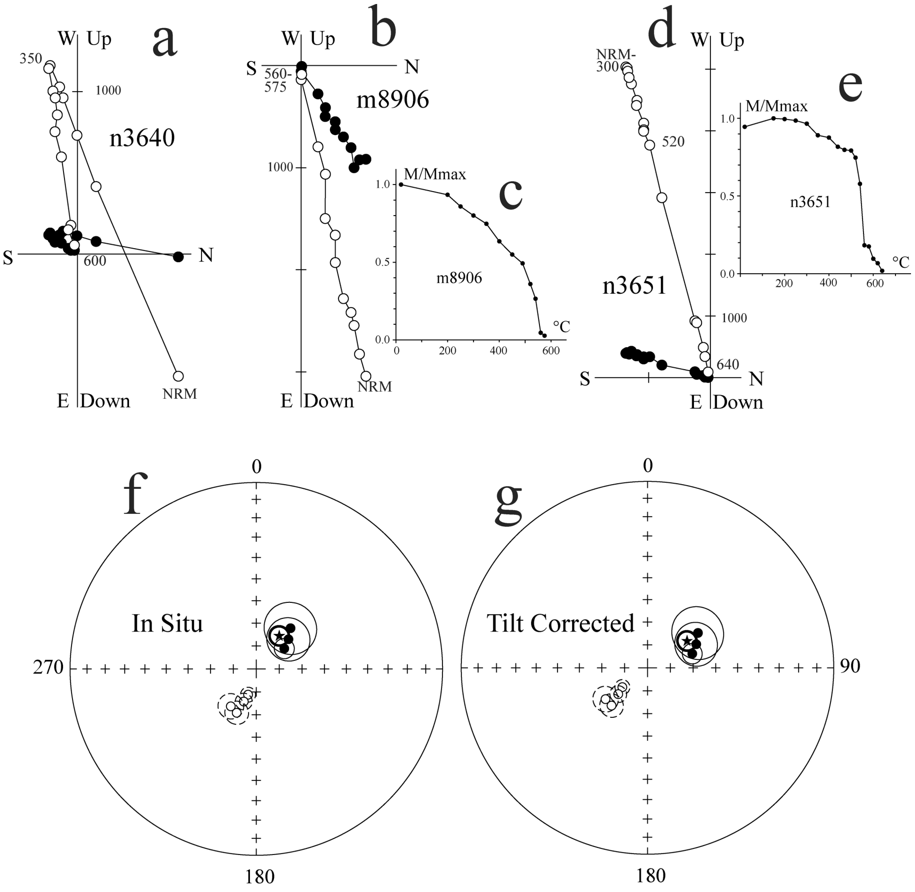

Figure 5. Palaeomagnetic results from the Triassic volcanics of north Kazakhstan; symbols and conventions as in Fig. 2 and 3. (a,b and d) Representative thermal demagnetization plots in stratigraphic coordinates. (c and e). Plots of normalized NRM intensity versus temperature. (f and g) Stereoplots of ChRM site-mean directions (filled and open circles) with associated 95 per cent confidence circles (thin lines) of the Triassic rocks *in situ* (f) and after tilt correction (g). The star represents the ChRM formation-mean with its associated 95 per cent confidence circle (thick line).

by Late Permian time, in accord with geological data (e.g. Chuvashov 1999).

The above conclusion also agrees with the general view on the orogenesis of the Ural foredeep and fold belt before the end of the Permian. Several researchers, however, have argued for large-scale post-orogenic strike-slip movements, which parallel the structural pattern of the Ural belt or cut it at a very acute angle (Plyusnin 1971; Puchkov 2000; Buslov *et al.* 2004; Windley *et al.* 2007). In particular, these motions are thought to be responsible for the deformation of the Triassic volcano-sedimentary sequence in small grabens along the eastern slopes of the Urals. Hetzel & Glodny (2002), for instance, advocated a Triassic (248–229 Ma) orogen-parallel dextral displacement of some 15–43 km along the Kyshtym and adjacent faults. Other geological evidence in support of regional strike-slip displacements, however, is scarce and controversial; for instance, Plyusnin (1971) advocates predominantly sinistral displacements, while Buslov *et al.* (2004) attributes the opposite sense to this motion.

Because such Ural-parallel displacements are rather oblique with respect to the Late Permian grid, as can be judged from the geometry of Fig. 6(a), the possibility of palaeomagnetic detection is greatly diminished. Our results show that, irrespective of the sense, a displacement largely exceeding 1000 km would have spoiled the observed fit of our new Kazakhstan poles and the Baltic APWP, while smaller and geologically more probable motion remains within the error limits.

Another palaeomagnetically detectable form of deformation, often associated with strike-slip displacements, consists of rotations. The best-studied example is the San-Andreas fault, which traverses a region of rotated blocks of various sizes (Hornafius 1985; Luyendyk 1989); a complex pattern of rotations has also been presented for the area next to the North Anatolian fault (Piper *et al.* 1996; Tatar *et al.* 2002). The lack of rotation of the north Kazakhstan data with respect to Baltica is not persuasive simply because the IR and TE sampling areas are too far removed from any proposed shear zones. However, numerous palaeomagnetic studies revealed widespread post-folding remagnetization of Palaeozoic rocks in the Ural fold belt (Danukalov *et al.* 1983; Shipunov 1998). This overprint is of predominantly reversed polarity, is thought to be of Permian age, and generally agrees with the Permian reference values for Baltica. In summary, the overall consistency of Permian declinations, both along and across the Urals, shows that post-Permian rotations associated with strike-slip faults in this region have thus far escaped detection, if any ever occurred. This stands in sharp contrast with the area of southern Kazakhstan and adjacent Tien Shan and Tarim, where many Late Permian rotated declinations have been documented (Van der Voo *et al.* 2006 and references therein).

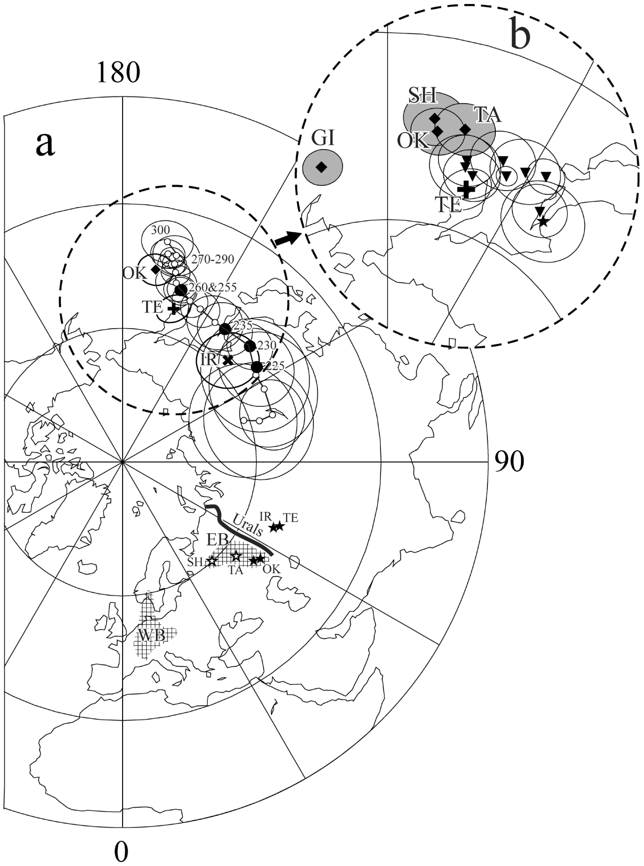

Figure 6. (a) Comparison of the APWP of west Baltica (filled and open circles) (Torsvik *et al.* 2001) with our new palaeopoles from east Baltica (OK, diamond) and from north Kazakhstan (IR, cross and TE, plus-sign). The mean poles from the APWP that are compared with our results are shown as larger filled circles, whereas the other mean poles are shown as smaller open ones. All poles are shown with their confidence circles. The locations of our study areas in east Baltica and north Kazakhstan are shown as stars on the map; also shown are the localtities of two previously published Late Permian results from east Baltica (SH and TA), open stars. The west (WB) and east Baltica (EB) regions where the reference poles come from are cross-hatched. The Urals are shown as a thick solid line. (b) Zoomed part of (a) showing the distribution of our two new Late Permian poles (KO, TE) and the reference poles from Baltica derived from sediments (inverted triangles) and volcanics (star). Three previously published Late Permian poles from east Baltica (SH, TA, GI; diamonds, with shaded cones of 95 per cent confidence) are also shown.

5.2 Comparison of Late Permian data from west and east Baltica

In contrast to the Kazakhstan data, the OK pole falls on the APWP for Baltica but in an older part marked by well-dated Early Permian (270–290 Ma) and tightly clustered reference poles. The age of the OK-rocks, however, is definitely younger, as documented from the local stratigraphy and supported by the observation of normal (presumably post-Kiaman) magnetic polarity. With respect to the coeval 260 Ma reference pole for Baltica, the observed inclination of OK is significantly shallowed ($\Delta I = 8.1^\circ \pm 3.8^\circ$), while the declination is statistically the same ($\Delta D = 3.0^\circ \pm 5.3^\circ$). Calculating a direction by extrapolation from the TE pole to the OK study area (53°N, 53°E) yields $D = 41.8^\circ$, $I = 51.2^\circ$, $\alpha_{95} = 3.0^\circ$, which is significantly steeper by $12.0^\circ \pm 3.7^\circ$ than the coeval observed OK inclination. Clearly these mismatches require an explanation.

Before presenting this, we must briefly review the existing other Late Permian palaeomagnetic data from the eastern part of Baltica (i.e. the former Soviet Union). As has already been noted, about forty Late Permian palaeomagnetic poles from east Baltica were used by Khramov *et al.* (1982); nearly all poles, however, are based on either a 'time-cleaning' technique (i.e. a storage test) or, at best, blanket 'cleaning' with maximum steps of 30 mT or 200–300 °C; besides, many results are available as entries in the pole lists only. Our OK collection clearly demonstrates that such limited treatment is insufficient for complete removal of overprints, and hence we are not convinced that these older results are reliable. We discard them regardless of whether they agree with more reliable results or not. Unfortunately, this greatly reduces the number of poles that can be used; apart from the OK pole, we are aware of only three Late Permian poles from east Baltica that have been obtained with modern demagnetization methods (Fig. 6a). These are:

(1) The SH pole (Plat = 44°N; Plong = 171°E; $A_{95} = 4^\circ$) obtained from Upper Permian (Tatarian) redbeds from the Sukhona River valley (north European Russia), which is based on six sites of normal polarity and ten reversed sites and confirmed by a positive fold test (Khramov *et al.* 2006).

(2) The TA pole (Plat = 44.3°N; Plong = 165.1°E; $A_{95} = 4.2^\circ$) from Upper Permian (Tatarian) redbeds from the Volga region (centraleast European Russia), which is based on four sites of normal polarity and eleven reversed sites. This pole is also confirmed by a positive fold test as well as a positive reversal test (Shatsillo *et al.* 2006).

(3) The GI pole (Plat = 50.6°N; Plong = 194.4°E; $A_{95} = 2.8^\circ$) has been obtained by Gialanella *et al.* (1997) from rocks in the same

area as the TA result. The authors performed a magnetostratigraphic study of the Upper Permian section and published a mean pole giving unit weight to samples. Although the directions of the two polarities look antipodal, and results from an additional section yield a positive fold test, the location of the pole is far removed from Baltica's APWP, for possible reasons that will be discussed next.

Our OK and the SH and TA area-mean poles are very tightly grouped ($k = 1100$), whereas the GI pole deviates by $\sim 20^\circ$ (Fig. 6b). The mean direction for the auxiliary section of Gialanella *et al.* (1997, their fig. 2d) is $D = 24.7^\circ$, $I = 43.2^\circ$, $\alpha_{95} = 5.8^\circ$ (12 samples), whereas the mean directions from exactly the same outcrop obtained by Shatsillo *et al.* (2006) is $D = 46.8^\circ$, $I = 44.3^\circ$, $\alpha_{95} = 9.3^\circ$(five sites). Comparing these two results, we find that $\Delta I = 1.1^\circ \pm 8.8^\circ$ is negligible, but that $\Delta D = 22.1^\circ \pm 12.2^\circ$. It is not possible to attribute the discrepancy to orientation error with any certainty, but we note that if the local magnetic declination of a decade ago was used with the wrong sign, the deviation disappears. Also, close inspection of the GI data (fig. 2b in Gialanella *et al.* 1997) shows that many clearly anomalous (transitional?) unit directions are included into the statistics, so that their mean pole may be biased. All in all, we discard the GI pole from further analysis. In the following paragraphs we will successively examine various possible causes of the far-sidedness of the three Late Permian poles SH, OK and TA.

5.2.1 *Erroneous ages*

The redbeds at the TE locality in N. Kazakhstan are dated less precisely than the Late Permian sediments of the OK area, but they are definitely of Permian age (Litvinovich *et al.* 1974). It is therefore, possible for the TE pole to fall on an older part of the APWP than the OK pole, but that is not what we observe, as the TE pole falls on a younger segment (Fig. 6a). As already noted, the OK pole cannot be of Early Permian (Kiaman) age. We can rule out erroneous ages as an explanation of the observed pattern.

5.2.2 *Post-Permian movements between Asia and Europe*

The Ural fold belt separates the OK and TE areas and relative movements of the two sides could create an inclination discrepancy between these two results. Today, these areas are separated by about 900 km in a direction that is nearly orthogonal to the Ural fold belt (Fig. 6a). Taking this into account by calculating (by extrapolation) the palaeolatitudes from the two results for the same location we find that they differ by 9.7° ± 3.0°, i.e. *ca.* 1100 ± 350 km. This indicates a more than two-fold shortening between the study areas in the latest Permian or Mesozoic. However, we recall that the Kazakhstan and west Baltica results (where the Baltica reference poles come from) show good agreement for the Permian. In contrast, it is the poles from east and west Baltica that form two distinct groups (Fig. 6b), unlikely belonging to one general population. Thus the pattern is such that the OK+SH+TA areas from east Baltica had to move simultaneously with respect to north Kazakhstan and west Baltica, while there was no discernible movement (neither convergence nor divergence) between the latter two regions. Such an 'independent' motion of east Baltica with respect to its eastern and western neighbours finds no support from any available geological data from Eurasia. Hence, tectonic motions as an explanation can be ruled out as well.

5.2.3 *Systematic bias in one set of directions from an overprint*

Combining two non-antipodal polarity directions is often believed to cancel a distortion due to overprinting, but this is not quite correct (e.g. Khramov & Sholpo 1967). Combining normal (N) and reversed (R) directions tacitly assumes that a non-removed overprint creates the same angular bias for both polarities. The latter is only true if the overprint direction is (nearly) orthogonal to the bi-polar remanence. Usually, the overprint direction is much closer to one polarity than to the other; in our case of the OK-result, the present-day field (PDF) is 35° and 140° away from the means for normal and reversed polarity, respectively (Fig. 3b). Moreover, a perfect cancellation of an overprint is achieved only if the numbers of normal and reversed directions are approximately the same; otherwise, one polarity and its bias will predominate in the overall mean. This is common for Permian data from all of Baltica where reversed polarity prevails. Hence, a PDF overprint will cause less deviation for N than for R results, leading to inclination shallowing if the reversed directions predominate, which is the case for the Late Permian data set. Therefore, pooling the two polarities does not cancel the overprint completely. On the other hand, this error cannot exceed half of the angular difference between the N and inverted R mean directions. In the OK case, this results in a difference of just 6.4° ± 6.2°, which is barely significant and less than the observed inclination anomaly of 8.1° ± 3.8° with respect to west Baltica and much less than the difference of 12.6° ± 3.7° between the OK and TE mean inclinations.

5.2.4 *Zonal non-dipole fields*

The magnitude of a zonal quadrupole contribution to the total field is typically expressed as the ratio (G2) of the Gaussian coefficients g_2/g_1, and the zonal octupole field is similarly denoted G3. Non-zero G2 and G3 can create a deviation of the observed inclination from that predicted by the dipole formula (Merrill *et al.* 1996). In particular, the non-dipole terms lead to inclination shallowing in the northern hemisphere, if they are of the same sign ('polarity') as the dipole term. If the non-dipole field was in existence with the same sign for, say, a good part of an epoch, then the reference APWP as well as individual palaeopoles may be inaccurate. Thus, the question is whether a likely configuration of G2 or G3 can explain the difference in inclinations between our two study areas and between east and west Baltica. We performed the calculations for various G2 and G3 values and found that the observed difference in inclinations for TE and OK from our two study areas cannot be achieved by any values in the full range of 0.0–1.0 without greatly disturbing the agreement between TE and west Baltica. In other words, no contribution of quadrupole and/or octupole fields can yield the observed inclination gradient of about 1°/100 km in Russia without destroying the good agreement of the TE and coeval Baltican poles. Hence, we maintain that we can reject the hypothesis that the observed difference in inclinations stems from non-dipole terms alone.

5.2.5 *Secular variation and higher-order non-dipole fields*

The inclination of the modern reference field also deviates from that predicted by the dipole formula because of higher-order non-dipole fields, which can be related to varying magnetic fluxes from the core. For instance, the deviations in inclination between the total field and the geocentric co-axial dipole field are up to 5° around a present-day Siberian anomaly, whereas a similar anomaly in the equatorial

Atlantic reveals an inclination deviation of more than 20°, so that the modern inclination gradient around this anomaly can be as high as 2°/100 km. It is therefore, theoretically possible that the observed TE-OK difference is related to such a feature. The general belief, however, is that such anomalies are transient features (e.g. Merrill *et al.* 1996), whereas the consistently low inclinations of the OK sites indicate that their cause persisted over two polarity chrons at least, which may well imply a duration of some 10^6 yr. Moreover, N and R directions can remain antipodal only if this higher-order feature preserves its location with respect to the globe and, importantly, reverses synchronously with the main dipole field. To sum up, in order to account for our Late Permian data by a higher-order field or secular variation feature, one must assume that such an anomaly in the Ural region was stationary with respect to the globe, existed for about one million years, and reversed synchronously with the dipole field. Any such single condition is not impossible, but when combined together these requirements make this hypothesis very unlikely.

5.2.6 *Sedimentary inclination shallowing*

This process is the only one that can fully account for the difference in inclinations between OK and TE results, provided that we can assume that some sediments are more affected than others. We also recall that a component of inclination shallowing already discussed above may be related to imperfect averaging of unremoved overprints, which is, of course, not due to sedimentary processes.

Using the standard formula $\tan I = f \tan I_0$, where I is the measured inclination, I_0 is the inclination of the ambient field, f is flattening factor (King 1955), we obtain $f = 0.66$ for the OK result, which is close to what was found in other redbeds (Tauxe 2005). Moreover, judging by the very good agreement of the three selected Late Permian poles from eastern Baltica (Fig. 6b), it is logical to assume that all three results are similarly affected by this process.

We acknowledge that no direct evidence for inclination shallowing is available from our data. Similar distributions of AMS ellipsoid axes (Figs 3d and 4h) and similarly small AMS values are found for the TE results, which appear to show no shallowing, and the OK data, where the inclination anomaly seems largest. We found that no correlation exists between AMS values and inclinations for the OK data. In general, detecting inclination shallowing, let alone qualitatively evaluating it, remains a difficult problem, despite considerable effort spent on solving it. There is a laboratory method of inclination error evaluation (Jackson *et al.* 1991), but it is very complex and time-consuming. In some cases, researchers have concluded that this bias was successfully established and corrected-for (e.g. Kodama & Davi 1995; Hodych *et al.* 1999), but this has been typically for magnetite-bearing rocks. In other cases, for redbeds in particular, the success has been limited; a very detailed study of redbeds from north Tarim, for instance, did not establish any measurable parameters to detect shallowing, despite a very large inclination anomaly of about 25° (Tan *et al.* 2003). The most convincing evidence (becoming actually more abundant recently) for sedimentary inclination flattening has come from comparisons between the inclinations of extrusive volcanics and sediments (Stamatakos *et al.* 1995; Vlag *et al.* 1997; Van der Voo & Torsvik 2004; Tan *et al.* 2007). A useful test has been proposed by Tauxe & Kent (2004), who suggested the use of the distribution of site-mean directions in order to evaluate quantitatively its distortion from an initial Fisherian one. However, their method requires >100 sites, or additionally even >20 samples per site for a more robust test. These conditions cannot be met with the available OK collection, nor do the SH and TA collections from east Baltica offer this option, but we can nevertheless allow the conclusion that inclination shallowing, due to sedimentary processes as well as imperfect averaging of undocumented overprint components, is a likely explanation for the observed inclination anomalies. We might add that the good fit between the palaeomagnetic data from north Kazakhstan and west Baltica does not mean that either is free of inclination bias, given that it is suspected for the latter (Van der Voo & Torsvik 2004).

6 CONCLUSIONS

Upper Permian redbeds from SE Baltica and north Kazakhstan, about 900 km apart, and a limited collection of Triassic volcanics from north Kazakhstan reveal high-temperature components that show rectilinear decay to the origin from most samples of all collections. Mean directions have good precision (Tables 1–3), and their primary origin is indicated by positive fold and/or reversal tests. The Late Permian and Triassic palaeomagnetic poles from Kazakhstan show good agreement with the APWP for Baltica, indicating that substantial post-Permian motion between the areas separated by the Ural fold belt are not called for. We also found no palaeomagnetic evidence for post-Permian rotations possibly associated with large-scale strike-slips within, or close to, this fold belt.

In contrast to the north Kazakhstan data, the pole from SE Baltica falls on the APWP on a segment that is too old for the age of the OK rocks. The pole is, therefore, called far-sided with respect to the coeval reference poles. We analysed possible causes for the deviating inclination and found that errors in ages, relative tectonic displacements, non-dipole terms, or secular variation of the geomagnetic field, cannot account for the observed difference in inclinations between SE Baltica and either west Baltica or north Kazakhstan. By a process of elimination, we therefore, conclude that inclination error during or shortly after remanence acquisition or due to imperfect averaging of unrecognized overprints in the data from SE Baltica is the only viable explanation. A very good fit between our result from SE Baltica and two coeval poles from other parts of east Baltica implies that similar inclination errors are of regional extent.

To obtain useful information about the correction needed to remedy the inclination shallowing, large (>100) sets of palaeomagnetic site-mean directions are required (Tauxe & Kent 2004). This will require multiple and extensive field seasons targeting Late Permian formations in European Russia, which is planned for future work.

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