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Permian palaeomagnetism of East Kazakhstan and the amalgamation of Eurasia

Natalia M. Levashova,[1] Kirill E. Degtyarev,[1] Mikhail L. Bazhenov,[1] Adam Q. Collins[2] and Rob Van der Voo[2]

[1] *Geological Institute, Academy of Sciences of Russia, Pyzhevsky Lane,* 7, *Moscow,* 109017, *Russia*
[2] *Department of Geological Sciences, University of Michigan Ann Arbor, MI* 48109-1063, *USA. E-mail: voo@umich.edu*

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SUMMARY

Most of Kazakhstan belongs to the Ural–Mongol belt, the tectonic evolution of which is poorly understood as demonstrated by disparate tectonic models suggested thus far. We undertook a palaeomagnetic study of Upper Permian basalts and andesites from two localities in east Kazakhstan in order to evaluate the final stages of the evolution of this belt and Eurasian amalgamation. Thermal demagnetization revealed a single pre-tilting characteristic component of ubiquitously reversed polarity from all samples. The mean declination of this remanence from one locality agrees rather well with the Permian European palaeomeridian, whereas that from the other is clockwise rotated by $28° \pm 8°$. The overall mean inclination of $-49° \pm 4°$ differs by $9.7° \pm 4.2°$ from the reference inclination calculated, for our localities, from the Eurasian mean pole for the 245–260 Ma interval and is in agreement with 260–275 Ma data. We account for the observed pattern by either a slightly erroneous rock age (lithologies are somewhat older than indicated by geological data) or non-dipole (octopole) components of the geomagnetic field. Because significant relative motion of the study area with respect to Eurasia is not demonstrated, we conclude that welding of Kazakhstan, Europe and Siberia was essentially completed by Mid-Permian time.

Key words: Eurasia amalgamation, Late Permian, palaeomagnetism, Ural–Mongol fold belt, vertical–axis rotations.

INTRODUCTION

The Ural–Mongol fold belt is the largest mobile belt of Eurasia. It stretches for approximately 10 000 km from the Arctic Ocean through Central Asia almost to the Pacific and fills the space between the European platform in the west, the Siberian platform in the northeast, and the Tarim block and Mesozoic–Cenozoic mobile belts in the south (Fig. 1a). Kazakhstan, located in the central part of the Ural–Mongol belt, is composed of many tectonic units, separated by ophiolites, and is likely to be its structurally most complex part.

It has been proposed that the major tectonic units of Kazakhstan amalgamated into a single block during the Silurian, with only relatively minor internal deformation since that time (Zaytsev 1984; Mossakovsky *et al.* 1993), followed by the closure of the Ural Ocean and welding of Kazakhstan to Europe in the Late Palaeozoic (Mossakovsky *et al.* 1993). In contrast, Sengör & Natal'in (1996) hypothesize large-scale displacements of up to 2000 km along strike-slip faults within and around Kazakhstan until the end of the Permian. Post-Palaeozoic motions have also been hypothesized within Kazakhstan and even for areas further north in Eurasia (Khramov *et al.* 1982; Bazhenov & Mossakovsky 1986; Cogné *et al.* 1999). Lyons *et al.* (2002) demonstrated, however, that no large displacements occurred after the Early Triassic.

To a large degree, these disparate views on the evolution of Kazakhstan stem from different estimates of the timing, magnitude and direction of horizontal movements; thus, palaeomagnetic data could resolve many controversies. The data, however, are still very scarce, often of low reliability, and very unevenly distributed through space and geological time. Whereas several authors have reported Late Palaeozoic (Permian?) remagnetizations from Kazakhstan (Pechersky & Didenko 1995; Grishin *et al.* 1997), no reliable primary Permian data exist for this region. In this paper, we report new Late Permian palaeomagnetic data from eastern Kazakhstan and discuss their implications for the Late Palaeozoic evolution of this part of the world.

REGIONAL TECTONIC SETTING

Typical orogenic belts, such as the Urals, North American Cordillera and Andes, display a more or less clear linear structure. In contrast, no prevailing structural trend can be observed in Kazakhstan, and Early Palaeozoic major structural domains often form T- or Y-junctions. The most widespread Early Palaeozoic structures are the fragments of subduction-related (calc-alkali volcanic) zones, accretionary wedges, flysch basins and Precambrian microcontinents with Early Palaeozoic terrigenous-carbonate cover. Such a

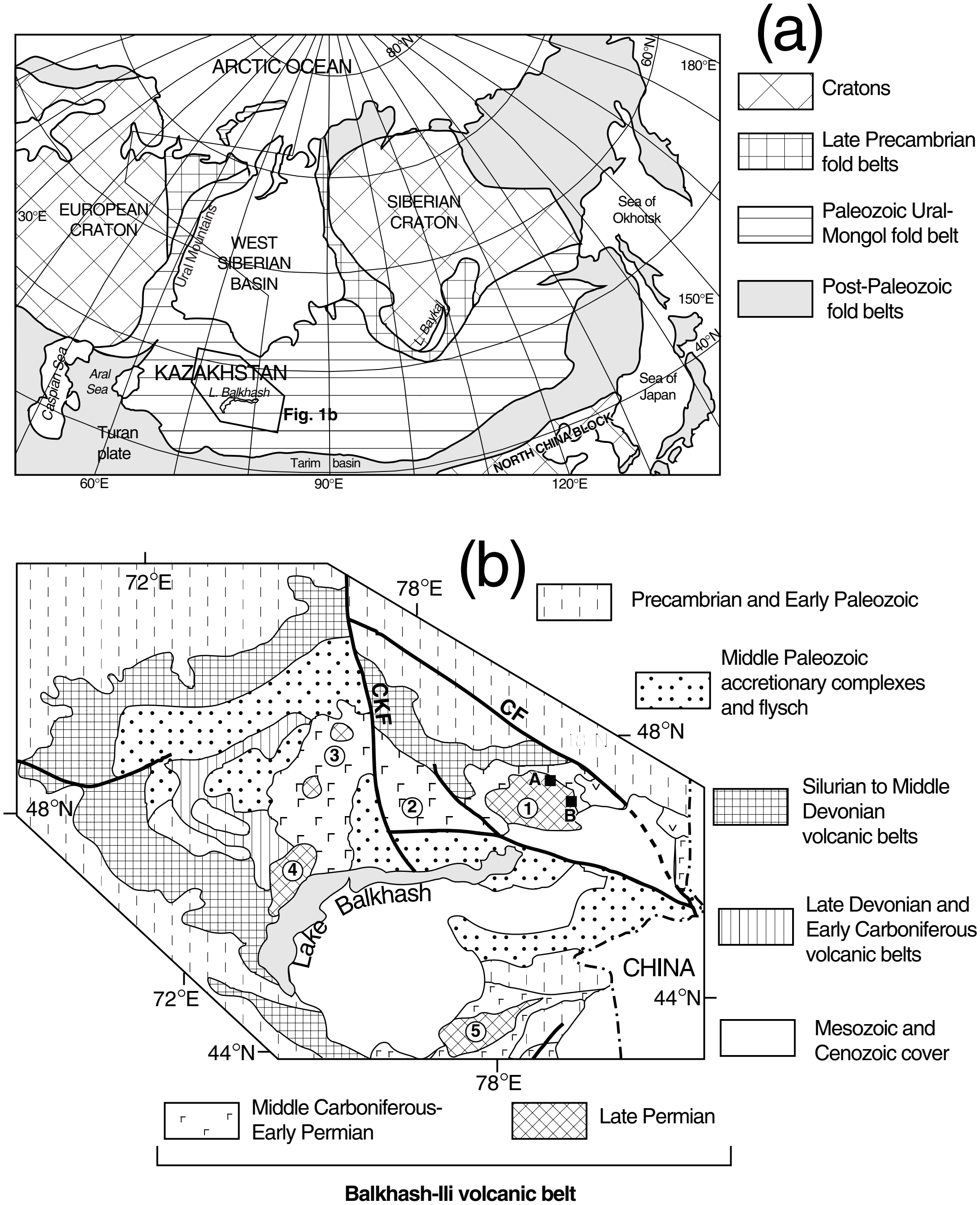

Figure 1. (a) Location map of the Ural–Mongol fold belt. (b) Distribution of volcanic complexes of different ages in Central and East Kazakhstan. Encircled numbers, main basins filled with Upper Palaeozoic volcanics in the Balkhash–Ili belt: (1), Bakanas basin, (2), North Balkhash basin, (3), North Tokraus basin, (4), South Tokraus basin, (5) Ili basin. Thick solid lines, major faults: CKF, Central Kazakhstan Fault, CF, Chingiz Fault. Solid squares, sampling localities A (Fig. 2a) and B (Fig. 2b).

composite structure has no counterparts among other Phanerozoic fold belts, with the possible exception of the Variscan belt in Western Europe.

Middle to Late Palaeozoic Kazakhstan geology is dominated by several strongly curved volcanic belts (Fig. 1b), which overlie all older structures with stratigraphic and angular non-conformities. The Silurian volcanic belt occupies the outer position and is represented by volcano-sedimentary rocks (Degtyarev & Ryazantsev 1993). The Early to Middle Devonian volcanic belt occupies more or less the same area as the Silurian one, but its inner front is slightly shifted inward. In the Frasnian, volcanic activity shifted approximately 150 km to the south and southeast in the northern part of the area and continued there during the Famennian–Tournaisian. Further inward migration of volcanic activity occurred during the Carboniferous, followed by the last manifestations of volcanism in the Late Permian and, locally, in the Triassic. The lateral shift of volcanism is negligible in the southern arms of the volcanic belts, is noticeable in their northern arms, and is greatest in the central parts (Fig. 1b). This volcanic activity and inward migration of its fronts lasted for approximately 150 Ma, while sedimentation, mostly of terrigenous rocks, continued in the inner parts of the loop-like belts. As a result, Late Devonian–Early Carboniferous volcanics overlap the Silurian and Early Devonian flysch series and accretional wedges.

Several deformation phases affected these belts, but their intensities show large spatial variation. Generally, the volcanics are not strongly deformed except for limited areas close to large faults. All volcanic belts comprise rhyolite, andesite–dacite and andesite–basalt complexes. Within each belt, the composition of the volcanic series varies strongly, but everywhere progresses from basalt to andesite and dacite and then to rhyolites (Tectonics of Kazakhstan 1982). Between the Silurian and the Early Permian the volcanics are all of calc-alkali affinity and are considered to be subduction-related (Kurchavov 1994).

Taken at face value, and assuming that the present-day geometry represents the original configuration (which we think is unlikely!), the available data would imply that a nearly circular subduction zone formed an active continental margin that surrounded a basin with oceanic crust. Subduction would have slowly propagated inward while preserving its loop-like form, and a steadily shrinking oceanic basin must have existed for approximately 150 Ma until its complete extinction. Such a configuration, however, is hardly possible within the plate-tectonic concept and has no counterparts in the present-day world. A better solution is to assume oroclinal bending of an originally nearly linear structure (Sengör *et al.* 1993). The subduction-related volcanism ended before the Late Permian. The Permian (Balkhash–Ili) volcanic belt is the innermost and tightest one; thus, the structure, i.e. the continental margin, had to bend no earlier than the very end of the Early Permian. According to all existing data, the European, Siberian and Tarim platforms did not move significantly with respect to each other after the beginning of the Triassic. Thus, there was a very short time interval when this huge structure could have been bent. *A priori* this solution does not look realistic either, but at this time we lack information concerning possible rotations. As recently as 2002 April, Tevelev (*pers. comm.*) summarized the available geological data and came to the conclusion that they alone impose no constraint on the origin of the curved volcanic belts. Ongoing research by our own group (Bazhenov *et al.* 2002; Van der Voo *et al.* 2002) is aimed at resolving the origin of the curvature and will be presented in future publications.

GEOLOGICAL SETTING AND SAMPLING

The youngest and innermost Balkhash–Ili volcanic belt is composed of five large basins; these are the Bakanas, North Balkhash, North and South Tokraus, and Ili basins (labelled 1–5 in Fig. 1b). These basins overlap older structures and, locally, are bounded by strike-slip faults (Tectonics of Kazakhstan 1982).

The Balkhash–Ili volcanic belt comprises Middle Carboniferous to Upper Permian volcano-sedimentary rocks. The volcanics range in composition from rhyolite to andesite–dacite and andesite–basalt. The pre-Late Permian volcanics belong to the calc-alkali series and are typical of subduction-related formations (Kurchavov *et al.* 1994; Kurchavov *et al.* 1999). The Upper Permian volcanics are more localized, mainly in the Ili, South Tokraus and Bakanas basins (Fig. 1b), and usually form the cores of large synclines. These volcanics comprise alkali basalt and andesite with subordinate acidic lava and intrusions and thus differ from the older formations (Tectonics of Kazakhstan 1982; Sal'menova & Koshkin 1990). This drastic change in the volcanism character most probably results from a change in tectonic regime and may indicate the termination of subduction in the Early Permian. Note, however, that the spatial distribution of Late Permian volcanism inherits, albeit locally, that of the more widely distributed older volcanics.

One of the main structures of the Bakanas basin is the large Berictas syncline, dominated by Upper Carboniferous–Lower Permian acid volcanics, with Upper Permian rocks in its core (Sal'menova & Koshkin 1990). Locally, a horizon of tuffaceous rocks with rare acid volcanic flows is present at the base of the Upper Permian section. Pollen and spores date this horizon as straddling the Early to Late Permian boundary (Sal'menova & Koshkin 1990). The upper part of the section is composed of basalt and andesite–basalt with several flows of trachy-rhyolites and rare layers of sandstones, conglomerates and limestones. The remnants of mollusks in the limestones and flora in the sandstones indicate that the upper member of the section (the sampled Bakalin Formation) accumulated in the Late Permian (Sal'menova & Koshkin 1990). The thickness of the Bakalin Formation varies from 600 to 2600 m.

Multiple deformational events affected the volcanic belt sequences during the Middle and Late Palaeozoic. The youngest folding of Middle to Late Permian age is of limited extent; in particular, no angular non-conformity of this age is present in the study area. Terrigenous and often coal-bearing Triassic to Lower Jurassic sediments overlie, without angular non-conformities, the Upper Permian volcanics of the Bakalin Formation. During the Late Triassic to Early Jurassic, the eastern half of Kazakhstan was dissected by NW–SE-trending dextral strike-slip faults, such as the Central Kazakhstan Fault (Koshkin 1969) and the Chingiz Fault (Samygin 1974). In particular, the Chingiz Fault is close to the study area in the northeast (Fig. 1b), and complexes as young as the Early Jurassic are deformed and displaced by this fault (Samygin 1974). Post-Middle Jurassic rocks are flat-lying or tilted by only a few degrees in all the parts of East Kazakhstan that are far away from Cenozoic mountains of the Junggar Range and Tien Shan. Thus the volcanics of the Bakalin Formation were tilted not later than the Middle Jurassic.

Volcanics of the Bakalin Formation were sampled from two parts of the Berictas syncline; at both localities sampling started at the base of this formation. A 600 m thick section of interbedded black basalts and violet-red to black andesites with a few intercalations of red tuffaceous sandstone was studied in the northwestern part of the syncline (locality A, Fig. 2a). 69 samples were taken from seven sites in two sections with different strikes, with each site covering 10–20 m of the true thickness. In addition, nine samples (site A2) were taken from a layer, approximately 10 m thick, of yellow-white sandstone, which overlies the volcanics in this area. The exposures form a system of 5–10 m high ridges separated by shallow-bottom valleys. The tops of ridge crests were avoided because of possible lightning strikes. However, strongly magnetized rocks, which affected the compass readings, were noted at ridge foothills and in the valleys; these rocks were avoided in our sampling. Therefore, no sections of the outcrop appear to be inaccessible to lightning. We will discuss the possibility of plunging fold axes when we describe the palaeomagnetic results.

An approximately 1500 m thick homoclinal section of the Bakalin Formation was studied in the eastern part of the Berictas syncline (locality B, Fig. 2b). 81 samples of black basalt and violet-red to black andesite were more or less uniformly spaced (eight sites) through the section in an attempt to perform a magnetostratigraphic study. The exposed area consists of a series of strike-parallel

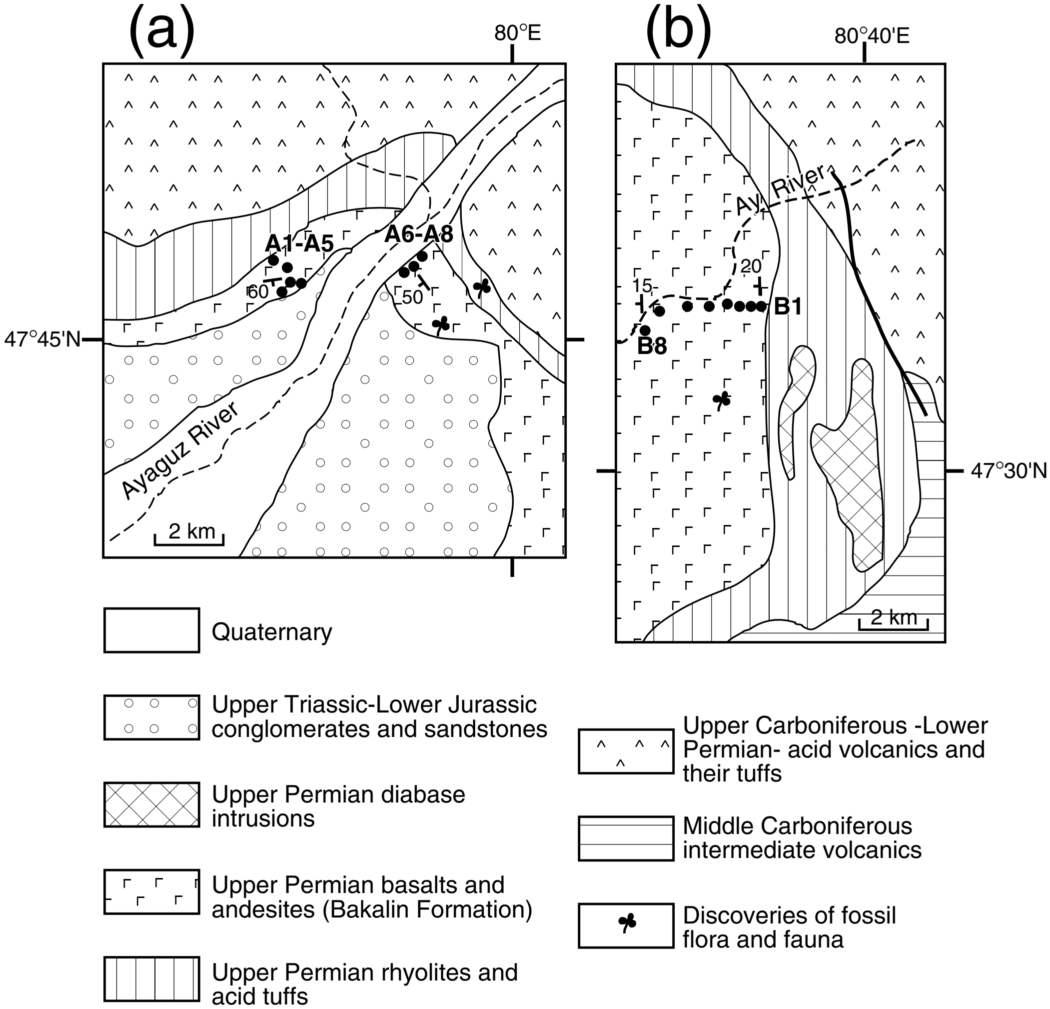

Figure 2. Geological maps of localities A (a) and B (b) and location of palaeomagnetic sites (solid dots). Faults are shown by thick solid lines.

ridges up to 100 m in height, which form a set of well-defined westward-dipping questas. The samples were taken from hypsometrical lows, and no indication of lightning strikes was observed in the field.

Hand samples were oriented with a magnetic compass. Within the two limbs of the structure at locality A (Fig. 2a), the bedding of several sedimentary layers inside the volcanic units proved to be similar through a given section, and their mean was taken as the attitude of the entire section. Metre-scale variation in bedding was found in the overlying sandstone layer. However, this variation does not extend into the volcanics. We found no sedimentary layers at locality B. The strikes were determined accurately from far-sight measurements in the field and topographic maps. Far-sight measurements of dip angles varied from 30° to 10°, with a tendency to become gentle to the section top. Similar values for locality B dips are also shown on detailed geological maps (1:200 000 and 1:50 000). Owing to nearly complete exposure at this locality and sharp relief, overall bedding of the rocks could be determined from mean strike and dip orientations of multiple structural triangles. This was done by transferring stratigraphically equivalent features from stereographic aerial photographs on to topographic maps; the mean dip values thus derived for structural correction have uncertainties of ±3°.

PALAEOMAGNETIC STUDY

Methods

One cubic specimen from each hand-sample was subjected to progressive thermal demagnetization in 15–20 steps up to 685 °C. The specimens were thermally demagnetized in a home-made oven with internal residual fields of approximately 10 nT and measured with a JR-4 spinner magnetometer with a noise level of 0.05 mA m^{-1}. Demagnetization results were plotted on orthogonal vector diagrams (Zijderveld 1967), and linear trajectories were used to determine directions of magnetic components by a least-squares fit comprising three or more measurements (Kirschvink 1980). The characteristic remanent magnetization, ChRM, was determined without anchoring the final linear segments to the origin of vector diagrams. Components isolated from samples were used to calculate site means. Palaeomagnetic software written by Randy Enkin and Stanislav V. Shipunov for the IBM PC and by Jean-Pascal Cogné for the Macintosh were used in the analysis.

Palaeomagnetic results

At locality A, the intensity of natural remanent magnetization (NRM) ranges from 0.7 to more than 10 A m^{-1} in volcanics and

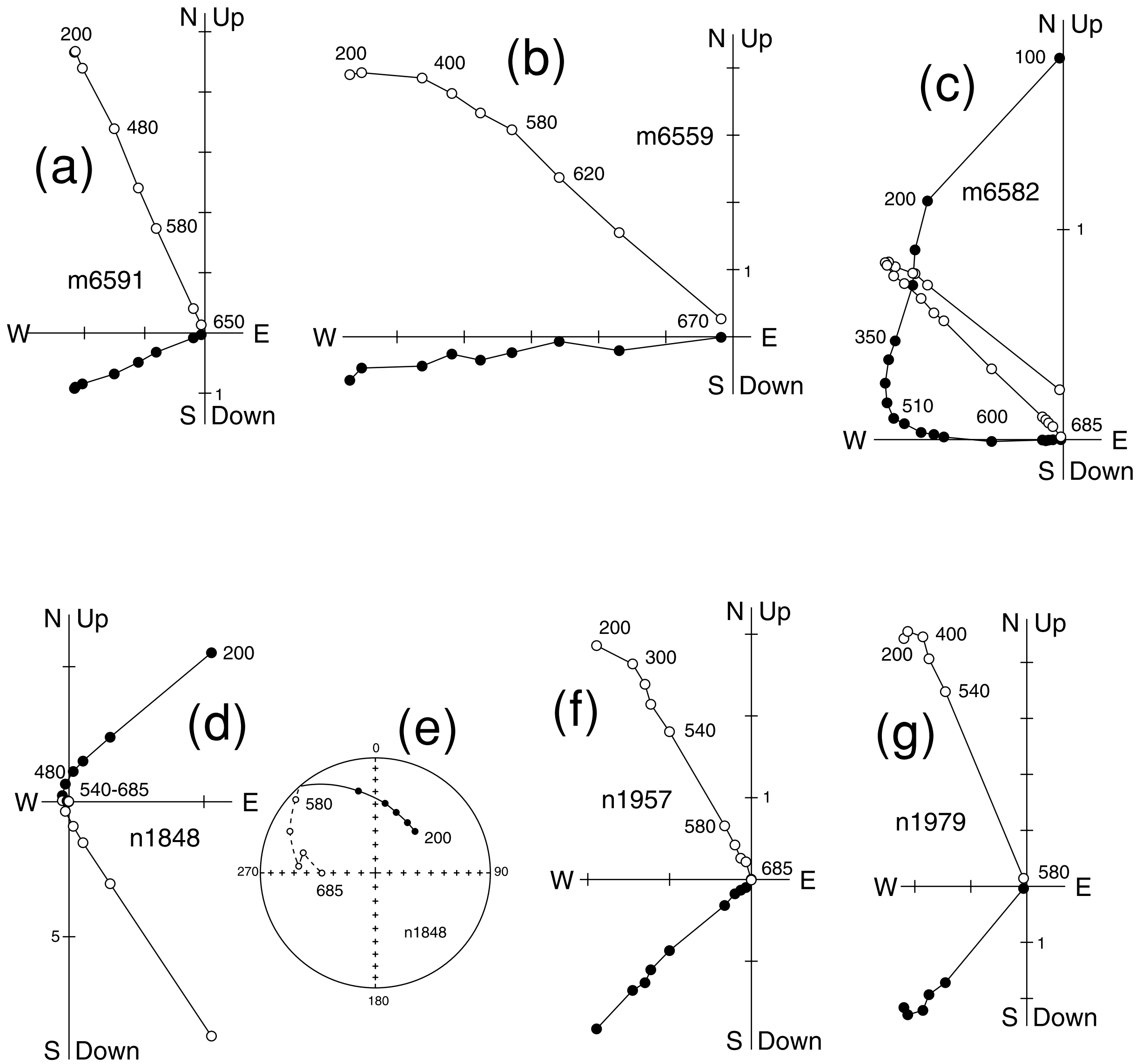

Figure 3. Representative thermal demagnetization plots (a–d, f–g) and directional changes of palaeomagnetic vector (e) of Upper Permian volcanics from localities A (a–e) and B (f–g) in stratigraphic coordinates. Full (open) dots represent vector endpoints projected on to the horizontal (vertical) plane. Temperature steps are in degrees celsius. Magnetization intensities are in A m^{-1}. For clarity, NRM points are omitted.

from 0.1 to 0.4 A m^{-1} in sediments. A single characteristic component, ChRM, was readily isolated from most lava samples after removal of a weak dispersed remanence at 200–400 °C (Fig. 3a and b). In some samples a much stronger overprint persisted well above 500 °C (Fig. 3c) or could not be removed until 685 °C as demonstrated by continuously curved orthogonal plots (Fig. 3d) and remagnetization circles on stereonets (Fig. 3e). Strongly overprinted samples often had initial NRM intensities of more than 10 A m^{-1}, and the directions of the lower-temperature component show no grouping either *in situ* or after tilt-correction. We attribute this overprinting to lightning strikes, which are likely in this area.

Basalts and andesites at locality B (Fig. 2b) show very similar characteristics to those from locality A, and a well-defined ChRM was isolated from most samples (Fig. 3f and g). A lightning-induced remanence was found in only a few samples from the low-relief section top.

The ChRM is reversed everywhere and the directions are tightly clustered at each site at locality A, with well-defined corresponding site means (Table 1). The only exception is sediments at site A2 where direct observations and remagnetization circles were combined (McFadden & McElhinny 1988). In order to calculate the locality means on the same statistical level, the magnetostratigraphic section at locality B was divided into eight groups of nine to 12 consecutive samples, and the corresponding groups were treated as sites (Table 1). The fold test (McFadden & Jones 1981) is positive at the 95 per cent confidence level indicating a pre-folding age for the ChRM at locality A (Fig. 4a and b, Table 1). Bedding attitudes at locality B are very uniform, thus rendering any fold test inconclusive. The mean declinations for localities A and B differ by approximately 30°, while the mean inclinations are statistically identical (Table 1), therefore the results from localities A and B can only be compared with inclination-only statistics (McFadden & Reid 1982). The inclination-only test shows the best data grouping in stratigraphic coordinates; hence we conclude that the ChRM is of pre-folding origin at both localities (Fig. 4c; Table 1).

Table 1. Palaeomagnetic data from Upper Permian rocks (localities A and B).

Site	N/N_0	A/d	*In situ*				Tilt corrected			
			D (deg)	I (deg)	k	α_{95}	D (deg)	I (deg)	k	α_{95}
Locality A										
A1	7/8	160/59	211.8	−36.1	150	4.3	279.8	−55.2	157	4.2
A2*	8/9	137/51	193.7	−49.7	8	21.2	261.6	−49.0	55	8.0
A3	10/10	167/57	219.3	−27.3	144	3.7	264.2	−44.9	148	3.6
A4	11/13	172/59	225.0	−24.0	66	5.2	267.7	−43.5	66	5.2
A5	5/5	170/56	205.3	−33.0	133	5.4	269.0	−61.4	168	4.8
A6	7/13	239/48	249.1	−4.4	28	10.0	254.7	−51.6	28	10.1
A7	7/7	239/48	250.8	−3.6	61	6.8	257.1	−50.4	61	6.8
A8	9/13	239/48	258.9	0.8	107	4.5	266.7	−43.9	110	4.5
Mean	64/78		232.4	−19.6	11	5.5	265.2	−48.9	49	2.6
Mean	(8/8)		229.5	−24.5	8	17.2	264.9	−50.2	107	4.8
$F_{(2,12)} = 3.89$			$f = 28.81$				$f = 0.99$			
Locality B										
B1	9/10	265/20	241.2	−33.7	82	5.2	232.2	−51.2	82	5.2
B2	9/10	265/20	245.0	−30.8	56	6.2	237.9	−49.0	55	6.3
B3	9/10	265/20	243.5	−25.1	108	4.5	237.5	−43.2	103	4.6
B4	10/10	265/20	243.7	−28.4	128	3.9	235.7	−46.3	127	3.9
B5	8/9	265/20	245.9	−28.6	96	5.1	239.7	−47.0	95	5.1
B6	9/9	265/20	244.0	−20.5	62	5.7	239.3	−38.8	68	5.7
B7	10/11	265/15	244.6	−42.2	48	6.4	237.3	−55.8	48	6.4
B8	10/12	265/17	242.9	−36.6	60	5.7	235.8	−51.4	75	5.1
Mean	74/81		243.7	−31.0	52	2.2	237.0	−48.0	61	2.1
Mean	(8/8)		243.8	−30.7	140	4.2	237.0	−47.9	216	3.4
INCL	(16/16)			−27.4	17	8.8		−49.3	102	3.6

* – ChRM directions and remagnetization circles are combined (McFadden & McElhinny 1988).
Sites are labelled as in the text. N/N_0, the number of samples (sites) accepted/studied; A/d, dip direction/dip angle; D, declination; I, inclination; k, concentration parameter; α_{95}, radius of confidence circle (in deg); F, the 95 − per cent critical value of F statistics with the numbers of degrees of freedom in parentheses; f, calculated value of the same; INCL, overall mean inclination.

The structure at locality A looks like a syncline with an axis that steeply plunges southward at 207°/45° (Fig. 2a). After simple tilt-correction, the two limb means from this locality differ by 6° ± 10°, which is statistically insignificant. A correction for the plunge increases the angular distance between these two means to 26° ± 10°. We tried to vary the azimuth of plunge (from 160° to 248°) but the difference between the two limb means remained statistically significant. Thus we conclude that the structure of locality A did not form by tilting of a fold with an originally horizontal axis, and that the locality-mean after simple tilt correction is the best estimate of the remanence direction. Such a situation has actually been described by Stewart (1995). We should also stress that none of the corrections for plunge significantly improves the declination difference between locality A and locality B.

Magnetite and titanomagnetite are generally found to prevail in fresh basalt and andesite elsewhere (Dunlop & Ozdemir 1997). Instead, ChRM unblocking temperatures in the volcanics from both localities are distributed from below 580° to 685° (Fig. 5). A single magnetic phase appears to be present in some samples (Fig. 5a and c), whereas the presence of two minerals is indicated in others (Fig. 5d). ChRM directions do not correlate with unblocking temperatures, and no change in direction is observed in two-phase samples (Fig. 3f). Such a pattern might result from a complete higher-temperature remagnetization (e.g. because of deep burial or a metamorphic event). However, the limited thickness of less than 1 km of Mesozoic rocks over most of eastern Kazakhstan and the absence of any signs of metamorphism in the studied volcanics argue against a thermal resetting. A few Triassic intrusions occur in this region but are found far away from the study area. These rocks have yielded an Early Triassic palaeopole at 56°N, 139°E, which clearly looks younger on Siberia's Apparent Polar Wander Path (APWP) and differs from ours by more than 20° (Lyons *et al.* 2002). The high reversal rate in the Triassic (Opdyke & Channell 1996) is also difficult to match with the ubiquitous reversed polarity in the Upper Permian volcanics.

We think that the observed blocking-temperature pattern resulted from oxidation of the volcanics soon after eruption. It could have taken place at high temperatures upon initial cooling as demonstrated by numerous levels of red to violet-red andesite at both localities. Another possibility is oxidation at lower temperatures under subaerial conditions.

The positive fold test indicates that the ChRM is of pre-Middle Jurassic age. The reversed polarity of this component over considerable stratigraphic intervals suggests a pre-Triassic acquisition time. The lack of overprints, apart from the lightning-induced one, and the absence of any signs of metamorphism make any younger remagnetization of these rocks unlikely. Basaltic lava flows have typically low viscosity, and generally do not accumulate on surfaces inclined by more than 5°. Therefore, unaccounted for primary tilts can hardly have introduced a noticeable error in the mean directions. Thick stratigraphic intervals and tight grouping of tilt-corrected site means imply that secular variation is adequately averaged. Thus we arrive at the conclusion that the overall mean inclination in the studied rocks is an accurate estimate of the ancient Permian geomagnetic field.

Implications for the age of the studied rocks

Judging by palaeontological data, the Bakalin Formation accumulated in the Upper Permian (Sal'menova & Koshkin 1990). It is

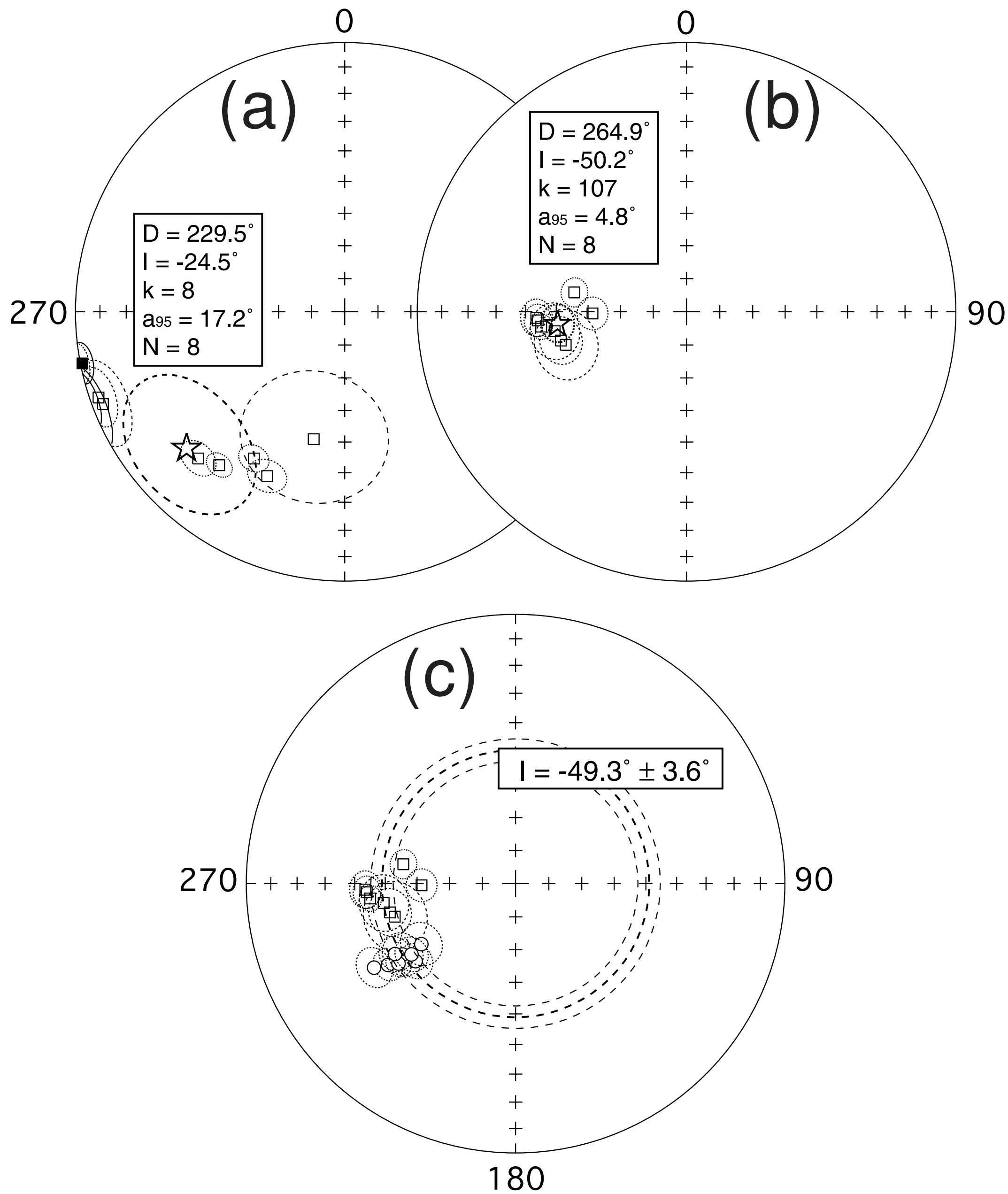

Figure 4. a–b. Stereoplots of site mean directions (squares) (thin lines) for locality A before (a) and after tilt-correction (b). Star and thick line are locality-mean direction with associated confidence circle. (c) Tilt-corrected site mean directions (thin lines) for localities A (squares) and B (circles) with associated confidence circles. Thick (thin) dashed line is the mean inclination (confidence limits) calculated with the aid of the inclination-only statistics (McFadden & Reid 1982).

still not well known when the Kiaman superchron of reversed polarity ended. Some authors place the end of the Kiaman in the Tatarian (<253 Ma), while others shift it to the boundary between the Kungurian and Kazanian stages (i.e. approximately 258 Ma; Opdyke & Channell 1996, and references therein). Our study shows that the ChRM directions are of uniformly reversed polarity in the Bakalin Formation. Thick stratigraphic intervals are studied at both localities, in particular at locality B where the section includes tens of lava flows of various compositions. It is difficult to imagine that this entire section accumulated during a short epoch of reversed polarity after the Kiaman superchron. It seems to us much more likely that the studied section accumulated during this superchron at or before approximately 260 Ma. If this is true, the palaeontological age is somewhat on the young side, and the Bakalin Formation could be of earliest Late Permian or latest Early Permian age.

INTERPRETATION

Kazakhstan is bordered by Baltica in the west, Siberia in the north-east and the Tarim block in the south, which is separated from Kazakhstan by the Tien Shan fold belt. To define the position of Kazakhstan with respect to these major continental blocks and to correctly evaluate its internal deformation one should compare palaeomagnetic results from Kazakhstan with the corresponding reference data. There are many palaeopoles from well-dated Permian rocks from the European platform and Western Europe (Torsvik

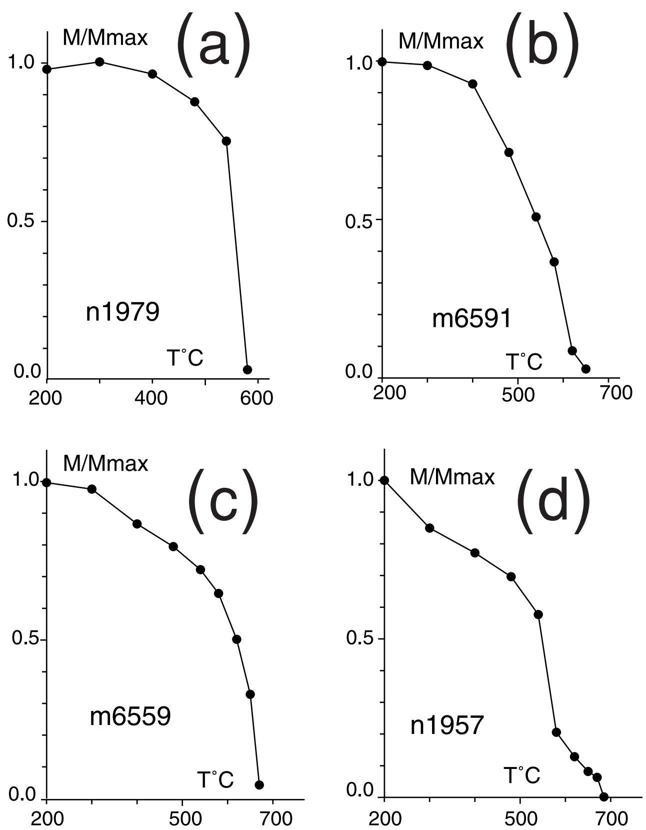

Figure 5. Change of NRM intensity during thermal demagnetization of the samples represented in Fig. 3.

et al. 2001), and this segment of the European APWP is rather precise. We divided the Permian, which is approximately 45 Ma long, into three 15 Ma long intervals. We grouped European palaeopoles from the database (Torsvik *et al.* 2001) accordingly, followed by the calculation of mean poles for each 15 Ma window (Fig. 6; Table 2). These three mean poles are then compared with our results from Kazakhstan. After this comparison, both in terms of declination differences (rotations) and palaeolatitudes, we will then compare our results with Siberian reference poles.

Declination differences and rotations

Our pole for locality B (PLat = 42.8°; PLong = 172.4°; A95 = 3.6°) falls close to the European APWP, whereas the pole for locality A (PLat = 25.5°; PLong = 151.7°; A95 = 5.3°) is far from the European poles (Fig. 6). The locality-mean inclinations are statistically identical, while the mean declinations of A and B differ by approximately 30°. The reference declinations for all three time windows and the mean declination for locality B are found to agree within the error limits (Table 2). Given this general agreement of the B pole with the European poles, there is no indication that locality B underwent rotations with respect to Europe. However, it seems clear that locality A is rotated clockwise. Whether the deviating declination at locality A is due only to a local deformation or whether one should envision a more regional pattern of rotations cannot be determined from the results for two localities alone.

The study area lies on the northwestern continuation of a Late Permian to Early Triassic sinistral wrench zone where strike-slip motion of considerable magnitude has been hypothesized (Allen *et al.* 1995). Moreover, the emplacement of alkali volcanics of the Bakalin Formation and its counterparts are thought to be related to the wrench-conjugated extension (Allen *et al.* 1995). However, counter-clockwise rotations are expected to occur in a left-lateral wrench zone, whereas our B result does not show any rotation with respect to northern Eurasia (i.e. Eurasia and Siberia), and the A result is rotated clockwise not counter-clockwise. Instead, the inferred rotation of the A result is compatible with Early to Middle Jurassic dextral strike-slip motion along the Chingiz Fault, which has been inferred from geological data (Samygin 1974). There are, however, no structural data to either further confirm or rule out this hypothesis.

Inclination and palaeolatitude differences

When the European mean poles of Table 2 are used to calculate expected palaeomagnetic inclinations for the study area (47.5°N, 80.5°E), the reference values for 275–245 Ma differ significantly from our observed overall mean inclination of 49.3° ± 3.6°. The largest difference (ΔI in Table 2) of 9.7° ± 4.2° occurs for the 245–260 Ma window, which is thought to be the age of the rocks according to palaeontological dating. We examine three possible reasons for this discrepancy: (1) a different (older) age for the rocks, (2) relative north–south movements and (3) a departure from the geocentric axial dipole (GAD) model for Permian times. The differences between our B pole and the reference poles can also be seen in Fig. 6 where it is recognized that the B pole is far-sided with respect to all three European mean poles.

Although a slightly older age than that indicated by geological data has already been mentioned as a possibility, the difference of 4.4° ± 4.2° (Table 2) for the 261–275 Myr window is still statistically significant, albeit not very large. The B pole falls well within the distribution of contemporaneous European reference poles, and the co-latitude small circle corresponding to the overall mean inclination overlaps with approximately half of them. Thus we conclude that a slightly older age is a distinct possibility.

If we assume that the age of magnetization of the B pole is Late Permian, the ΔI value of 9.7° ± 4.2° would imply a post-Permian northeastward (poleward) movement of the study area with respect to Europe. Assuming that Siberia and Europe were already welded together, this would imply convergence between Kazakhstan and Siberia of approximately 1000 ± 500 km. However, good agreement of Permian palaeolatitudes from regions south of Kazakhstan with the European reference values allows no such movement of our study area with respect to Siberian and European palaeopoles (Bazhenov *et al.* 1999).

The third explanation we wish to examine involves the GAD hypothesis, which is fundamental to palaeomagnetism. However, recently it has been suggested that long-term non-dipole (notably octopole) fields can be recognized in the European–North American database (Van der Voo & Torsvik 2001). The effects of an octopole field in southern Europe and the southwestern states of the USA (where most of the results come from) are small, as these areas are located near the equator where zonal octopole fields are near-zero. Thus, correction for a 10 per cent octopole contribution, which is the magnitude suggested by Van der Voo and Torsvik, displaces the reference poles by only a few degrees. In contrast, the Permian mid-latitude location of Kazakhstan would see errors of some 5° introduced in its palaeopole location. Recalculation of the B mean direction, while incorporating a 10 per cent octopole field, yields a value of −53.7° for the inclination and a palaeopole at approximately

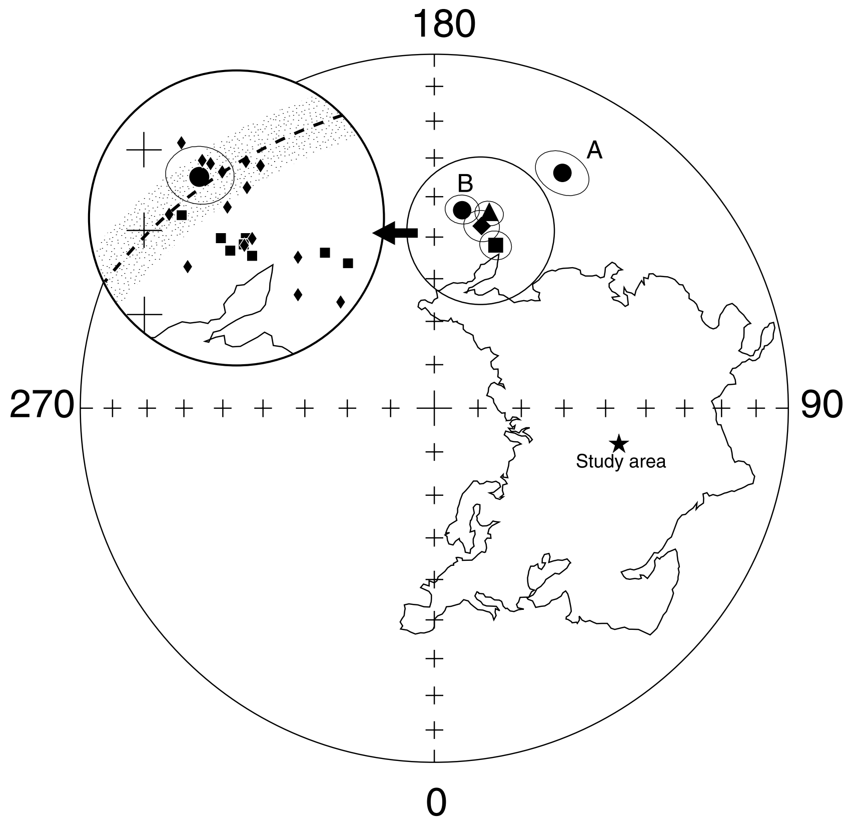

Figure 6. The mean European poles for 245–260 Ma (square), 261–275 Ma (diamond) and 276–290 Ma (triangle) time windows (see text) and the mean pole for localities A and B (circles) together with associated confidence circles. The zoomed circle (inset) shows the distribution of European unit poles for 245–260 Ma (squares) and 261–275 Ma (diamonds) and the pole for locality B. Thick dashed line, co-latitude small circle centred on the sampling area with its confidence limits (shaded band).

Table 2. Comparison of the reference and observed palaeomagnetic directions.

Pole	N	PLat	Plong	A95	ΔD[1]	ΔI[2]
(245–260)	8	49.4	159.8	3.5	0.5 ± 7.4	9.7 ± 4.2
(261–275)	15	45.9	165.9	3.8	0.4 ± 7.2	4.4 ± 4.2
(276–290)	15	42.4	164.7	3.0	-4.4 ± 6.3	3.0 ± 3.6

[1] With respect to the mean declination for locality B.
[2] With respect to the overall mean inclination.
Comments. Pole, time window for which the mean pole is calculated (see the text for details); N, the number of unit poles used; PLat, PLong, latitude and longitude of the mean pole (in °N and °E, respectively); A95, radius of confidence circle; ΔD, ΔI, the difference between the reference and observed declinations and inclinations, respectively. Error limits for ΔD and ΔI are calculated as suggested by Demarest (1983).

46°N, 167°E, which is very close to the 261–275 Ma reference pole of Table 2.

It is not possible at this point to make a choice between these three explanations. What we can conclude is that, with the discrepancy not being very large, it appears that the sampling area was very close to northern Eurasia, if not already welded on to it.

Comparisons with Siberian and Tarim reference poles

Unfortunately, many Permian and Triassic poles for Siberia are of low reliability. The situation is further aggravated by the fact that many Permian poles listed in catalogues are obtained from trap-related intrusions and volcanic formations, which are likely to have formed during a 1–2 Myr long interval encompassing the Permian–Triassic boundary (Renne & Basu 1991). Nevertheless, the overall agreement of the European and Siberian APWPs is rather good (Fig. 7), and the Triassic poles of these blocks coincide. The Siberian Late Palaeozoic poles are slightly, by 7°–10°, far-sided with respect to the European ones, but these differences are within the error limits, first of all because of the low accuracy of the Siberian data and secondly these poles are also possibly affected by octopole fields. Thus, large movements between the European and Siberian blocks appear to be unlikely.

Permian palaeomagnetic directions from Tarim and the Tien Shan are rotated counter-clockwise through various angles with respect to the European and Siberian reference declinations; at the same time, Late Permian palaeolatitudes agree well with the European grid (Bazhenov *et al.* 1999). Tarim and the Tien Shan bound Kazakhstan to the south and southeast. Therefore, no direction from which Kazakhstan could arrive is realized, and a large-scale convergence with Eurasia can be ruled out.

We conclude that the study area was already attached to the European, Siberian and Tarim blocks in the Late Permian. This indicates that models that assume a large-scale displacement between the European and Siberian cratons at the final stage of the evolution of the Ural–Mongol fold belt (Altaids) (Sengör *et al.* 1993; Sengör & Natal'in 1996) should assign the timing of such displacements, if any, to before the Late Permian. These models have assumed that the Siberian block and adjacent parts of the Altaids were displaced westward or northwestward (in present-day coordinates) by approximately 1500 km in the Late Permian. A westward

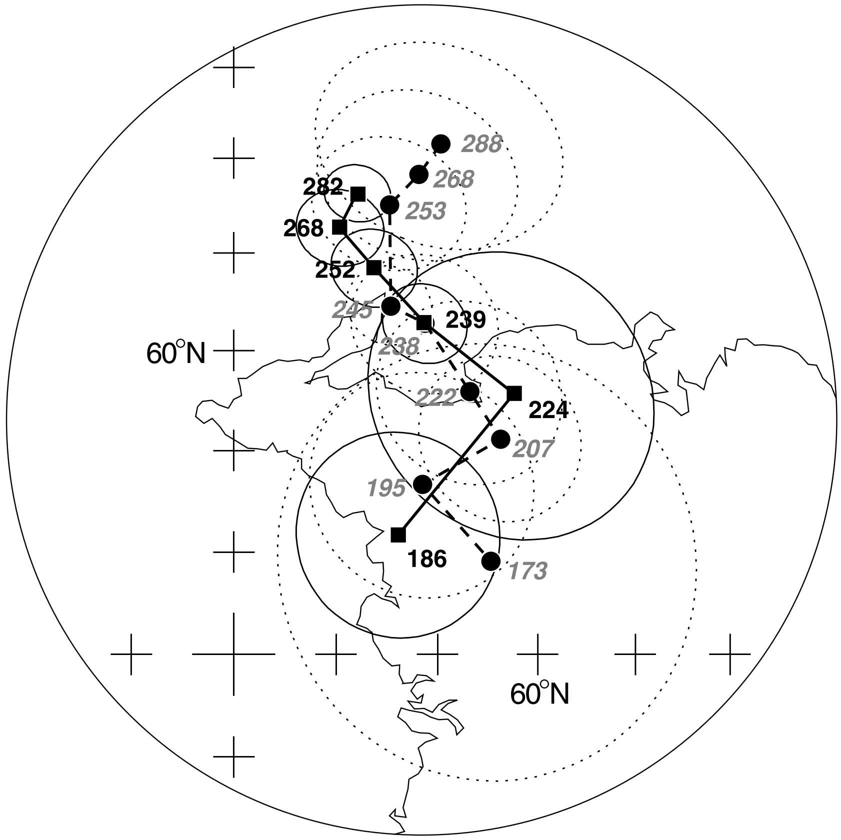

Figure 7. Permian–Early Mesozoic segments of the European (squares and solid lines) and Siberian (filled circles and dotted lines) APWPs with associated confidence circles; solid straight and grey italicized numbers are the ages in Ma of the mean poles of the European and Siberian platforms, respectively. The European Permian poles (252–282 Ma) are calculated as described in the text; other poles are from Van der Voo (1993).

displacement, however, would have resulted in the pre-deformation Siberian poles being near-sided with respect to the European ones, while they are actually far-sided (Fig. 7). The observed distribution of the European and Siberian poles may at best be accounted for by an eastward (and not a westward) displacement of north Siberia with respect to Europe, because of extension in the West Siberian Basin in the latest Permian–Early Triassic. Such models have already been proposed (Khramov *et al.* 1982; Bazhenov & Mossakovsky 1986), but the low quality and precision of the Siberian APWP still leave them speculative.

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REFERENCES

Allen, M.B., Sengör, A.M.C. & Natal'in, B.A., 1995. Junggar, Turfan and Alakol basins as Late Permian to? Early Triassic extensional structures in a sinistral shear zone in the Altaid orogenic collage, Central Asia, *J. geol. Soc., Lond.,* **152,** 327–338.

Bazhenov, M.L. & Mossakovsky, A.A., 1986. Horizontal movements of the Siberian Platform in the Triassic: paleomagnetic and geological evidence, *Geotektonika,* **1,** 59–69 (in Russian).

Bazhenov, M.L., Burtman, V.S. & Dvorova, A.V., 1999. Permian paleomagnetism of the Tien Shan fold belt, Central Asia: the succession and style of tectonic deformation, *Tectonophysics,* **312,** 303–329.

Bazhenov, M.L., Levashova, N.M., Collins, A.Q., Van der Voo, R. & Degtyarev, K.E., 2002. The Kazakhstan orocline (Central Asia). Part 1: Paleomagnetism and paleolatitudinal motion, GSA Abstracts with Programs, **34,** 490.

Cogné, J.P., Halim, N., Chen, Y. & Courtillot, V., 1999. Resolving the problem of shallow magnetizations of Tertiary age in Asia: insights from paleomagnetic data from the Qiangtang, Kunlun, and Qaidam blocks (Tibet, China), and a new hypothesis, *J. geophys. Res.,* **104,** 17 715–17 734.

Degtyarev, K.E. & Ryazantsev, A.V., 1993. Geology of the orogenic Silurian and continuous sections in the Caledonides of Kazakhstan, in *Geology and Metallogeny of Central Kazakhstan,* pp. 64–82, Moscow, Nauka.

Demarest, H.H. Jr., 1983. Error analysis for the determination of tectonic rotation from paleomagnetic data, *J. geophys. Res.,* **88,** 4321–4328.

Dunlop, D.J. & Ozdemir, O., 1997. *Rock Magnetism,* p. 573, Cambridge University Press, Cambridge.

Grishin, D.V., Pechersky, D.M. & Degtyarev, K.E., 1997. Paleomagnetism and reconstruction of Middle Paleozoic structure of Central Kazakhstan, *Geotectonics,* **31,** 71–81.

Khramov, A.N., Goncharov, G.I., Komissarova, R.A., Pisarevsky, S.A., Pogarskaya, I.A., Rzhevsky, Yu.S., Rodionov, V.P. & Slautsitais, I.P., 1982. *Paleomagnetology,* p. 312, Nedra, Leningrad (in Russian).

Kirschvink, J.L., 1980. The least-square line and plane and the analysis of palaeomagnetic data., *Geophys. J. R. astr. Soc.,* **62,** 699–718.

Koshkin, V.Y., 1969. The Central Kazakhstan strike-slip fault, *Geotektonika,* **1,** 52–67 (in Russian).

Kurchavov, A.M., 1994. The lateral variability and evolution of orogenic volcanism in the fold belts, *Geotectonics,* **2,** 3–18.

Kurchavov, A.M., Baskina, V.A., Bakhteev, M.K. & Mossakovsky, A.A., 1999. Geodynamic and paleotectonic interpretation of petrochemical zonation of volcanic belts, *Geotectonics,* **1,** 64–80.

Lyons, J.J., Coe, R.S., Zhao, X., Renne, P.R., Kazansky, A.Y., Izokh, A.E., Kungurtsev, L.V. & Mitrokhin, D.V., 2002. Paleomagnetism of the early Triassic Semeitau igneous series, eastern Kazakhstan, *J. geophys. Res.,* **107,** B7, 10.1029/2001JB000521.

McFadden, P.L. & Jones, D.L., 1981. The fold test in palaeomagnetism, *Geophys. J. R. astr. Soc.,* **67,** 53–58.

McFadden, P.L. & McElhinny, M.W., 1988. The combined analysis of remagnetization circles and direct observations in palaeomagnetism, *Earth planet. Sci. Lett.,* **87,** 161–172.

McFadden, P.L. & Reid, A.B., 1982. Analysis of palaeomagnetic inclination data, *Geophys. J. R. astr. Soc.,* **69,** 307–319.

Mossakovsky, A.A., Ruzhentsev, S.V., Samygin, S.G. & Kheraskova, T.N., 1993. Central Asian fold belt: geodynamic evolution and formation, *Geotectonics,* **6,** 3–32.

Opdyke, N.D. & Channell, J.E.T., 1996. *Magnetic stratigraphy, International Geophysics Series,* Vol. 64, p. 346, Academic Press, London.

Pechersky D.M. & Didenko, A.N., 1995. *The Paleoasian Ocean,* p. 296, OIFZ, Moscow (in Russian).

Renne, P.R. & Basu, A.R., 1991. Rapid eruption of the Siberian traps flood basalts at the Permo-Triassic boundary, *Science,* **253,** 176–179.

Sal'menova, K.Z. & Koshkin, V.Y., 1990. *Stratigraphy and Flora of the Late Paleozoic in the North Balkhash Area,* p. 160, Almaty, Navka.

Samygin, S.G., 1974. *The Chingiz Strike-slip Fault and its Position in the Structure of Central Kazakhstan,* p. 208, Moscow, Nauka.

Sengör, A.M.C. & Natal'in, B.A., 1996. Paleotectonics of Asia: fragments of a synthesis, in *The tectonic Evolution of Asia,* pp. 486–640, eds Yin A. & Harrison M., Cambridge, Cambridge University Press.

Sengör, A.M.C., Natal'in, B.A. & Burtman, V.S., 1993. Evolution of the Altaid tectonic collage and Palaeozoic crustal growth in Eurasia, *Nature,* **364,** 299–307.

Stewart, S.A., 1995. Palaeomagnetic analysis of plunging fold structures: Errors and a simple fold test, *Earth planet. Sci. Lett.,* **130,** 57–67.

Tectonics of Kazakhstan, 1982. *Explanatory Notes to Tectonic Map of East Kazakhstan, 1:2 500 000,* p. 139, Moscow, Nauka.

Torsvik, T.H., Van der Voo, R., Meert, J.G., Mosar J. & Walderhaug, H.J., 2001. Reconstructions of the continents around the North Atlantic at about the 60th parallel, *Earth planet. Sci. Lett.,* **187,** 55–69.

Van der Voo, R., 1993. *Paleomagnetism of the Atlantic, Tethys and Iapetus Oceans,* p. 411, Cambridge University Press, Cambridge.

Van der Voo, R. & Torsvik T.H., 2001. Evidence for late Paleozoic and Mesozoic non-dipole fields provides an explanation for the Pangea reconstruction problems, *Earth planet. Sci. Lett.,* **187,** 71–81.

Van der Voo, R., Degtyarev, K.E., Collins, A.Q., Levashova, N.M. & Bazhenov, M.L., 2002. The Kazakhstan orocline (Central Asia). Part 2: Evidence for relative rotations, *GSA Abstracts with Programs,* **34,** 490–491.

Zaytsev, Y.A., 1984. *Evolution of Geosynclines: an Oval Co-centric Zonal Type,* p. 208, Moscow, Nedra.

Zijderveld, J.D.A., 1967. AC demagnetization of rocks: analysis of results, in *Methods in Palaeomagnetism,* pp. 254–286, ed. Collinson, D.W., Creer, K.M. & Runcorn, S.K., Elsevier, Amsterdam.