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Late Paleozoic geomagnetic-field estimates from studies of Permian lavas in northeastern Kazakhstan

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Abstract

Paleomagnetic studies of thick lava series are one of the most reliable sources of data on the ancient geomagnetic field. However, most of such data are younger than 5 Ma, with much fewer results on the rest of the Cenozoic and the Mesozoic. Two wholesome results are available for the Precambrian but none for the Paleozoic. Late Permian basalts and rhyolites from northeastern Kazakhstan were studied to obtain first estimates of the geomagnetic-field characteristics during that period. We present preliminary results on part of the collection (66 flows (sites)) from a section ~1600 m thick. The characteristic component of reversed polarity was isolated by stepwise demagnetization at all the sites with a slight error. This component is of prefolding age and, most likely, primary. No abnormal magnetization direction is observed in the data, and the average directions of the characteristic component at the sites are tightly clustered (D = 243.3°; I = –57.0°; k = 79.1; α_{95} = 2.0°; 65 sites). As compared with the published data on Cenozoic and Mesozoic thick lava series, secular variation was much weaker in the Late Permian than in the Mesozoic or Cenozoic, and the geomagnetic field was less disturbed. Secular-variation models based on the Late Cenozoic data show even more dramatic differences.

Keywords: geomagnetism; paleomagnetism; Paleozoic; thick lava series; geomagnetic-field characteristics

Introduction

Except the last 10–20 kyr, almost all the information about the geomagnetic field was obtained from paleomagnetic studies of natural objects. The key problem is how to distinguish between the geomagnetic signal and noise. Shortly after the start of paleomagnetic studies, it became clear that there are two types of "recorders": sedimentary and volcanic rocks. The undoubted advantage of the former is the possibility of obtaining long records of cross-sections without any clear signs of gaps. It appears that lavas are much inferior to sediments, because the discontinuity of effusions or intrusions of dikes is obvious and there were serious problems with dating the objects.

The situation turned out to be more complicated. Mechanisms distorting the geomagnetic record in sediments (first and foremost, inclination underestimation) were found. Also, it was found that the final fixation of the geomagnetic field takes place at a depth of up to 20 cm from the sediment surface rather than on this surface and this depth can vary with time, sediment composition, etc. Besides, the hypothesis of the continuity of even the most complete sedimentary sections turned out to be exaggerated, but this is worthy of a separate discussion.

On the other hand, it is obvious that the record of any lava unit or dike swarm is discontinuous. No universal causes why this record is distorted have been found yet, whereas the dating of volcanics has become dramatically more accurate with the development of isotope methods. Over the last two decades, there has been a boost in the quantity and quality of data on volcanics used to study the geomagnetic-field characteristics, as is not the case with publications on sediments. The most reliable information about many characteristics of the ancient magnetic field can be obtained from thick lava series (Merrill et al., 1996). Such data, called "paleosecular variation for lava" (PSVL) (Johnson et al., 2008; Merrill et al., 1996), make up a separate base. There are some requirements to the quality of PSVL results (Johnson et al., 2008): (1) all the samples should undergo complete stepwise demagnetization and component analysis; (2) the average directions (or virtual geomag-

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netic poles) for the flows should be calculated from no less than three independently selected samples; (3) all the flows and/or dikes should be localized in a small area in which tectonic movements are hardly possible; (4) to make conclusions about the characteristics of the ancient magnetic field, each PSVL result should be obtained for no less than 25–30 lava flows and/or dikes (sites), but the solution of many problems requires the study of three or four times more sites.

Now the vast majority of PSVL data yield ages younger than 5 Ma; fewer than 20 results have been obtained for the rest of the Cenozoic (5–65 Ma); and about ten results belong to the Mesozoic. For a long time, the oldest one was the result on Siberian traps (~250 Ma (Heunemann et al., 2004)), but results on Late Archean (2.8–2.45 Ga) (Biggin et al., 2008a) and Middle Proterozoic (1.1 Ga) rocks (Swanson-Hysell et al., 2009; Tauxe and Kodama, 2009) have been recently published. Besides, the first Paleozoic (Late Devonian) PSVL result has been obtained, but there has been no definitive assessment of the field characteristics (Bazhenov and Levashova, 2011). Three results for almost 3 Gyr are certainly not enough for the solution of most geomagnetic problems.

Such a situation is due to the small number of possible objects and to the complicated character of studies. For example, the Paleozoic volcanic sections of the Central Asian Fold Belt (Eurasia) often turn out to be completely remagnetized, or the primary magnetization is detected only in few flows. Since one reliable PSVL result requires data on many tens of flows, it is unreasonable to begin such work haphazardly. Therefore, the study has to be conducted in two stages. During the first stage, a large number of objects are studied for the solution of other problems (e.g., tectonic ones) and only the most promising objects are selected for more detailed sampling. The first preliminary PSVL result for Permian rocks is presented in this paper.

Geological description and sampling of the object

The Central Asian Fold Belt (CAFB) occupies enormous areas in central Eurasia. Numerous tectonic elements, which contain abundant Paleozoic volcanics, are distinguished within the belt. This might be the world's largest area of Paleozoic volcanics.

Volcanics aged from early Cambrian to early Permian are observed in the western CAFB, in Kazakhstan. Their formation is related to that of ancient ocean floors and suprasubduction structures and, to a small extent, to intraplate phenomena. By the late Early Permian, the last ocean basins had closed and suprasubduction volcanism had ended everywhere (Dobretsov, 2011; Khain, 1979; Korobkin and Buslov, 2011; Levashova et al., 2012). In the Late Permian, several isolated volcanic areas developed in Kazakhstan. They were shaped like irregular rounded basins from several tens to more than 100 km in size, unconformably superposed onto older structures (Fig. 1*b*). The volcanic units in the basins are usually slightly inclined or make up gentle folds, and stronger deformations are observed only near the faults. The lavas are dominated by basalts and basaltic andesites, but felsic volcanics are also present in considerable amounts. Volcanism in the basins is of the subalkalic type, and it is attributed to extension which followed collision and subduction in the CAFB (Peive and Mossakovskii, 1982; Tevelev, 2003). However, the above scheme of the Late Paleozoic tectonic evolution of Central and Eastern Kazakhstan is almost completely based on rare floral finds and further correlation of distant continental volcanic sections, which casts doubt on its accuracy (Lyapichev et al., 1993). Note the lack of isotopic ages for the volcanic units in this region.

The Bakanas basin in northeastern Kazakhstan is the largest Permian superposed structure of this type (Fig. 1*a*). Late Carboniferous–Early Permian felsic volcanics are here overlain by the lava unit of the Bakaly Formation (600–2600 m thick), which consists of basalts and basaltic andesites with several thick sheets of felsic lavas; thin sediment interbeds of discontinuous extent occur rarely. Based on molluskan and floral finds, K.Z. Sal'menova and V.Ya. Koshkin (1990) assign the Bakaly Formation to the Late Permian. However, the age of 283.0 ± 2.4 Ma, determined by laser ablation for 21 grains of primary-magmatic zircon from the felsic lavas of one sheet, indicates that this unit is Early Permian. The deformations observed within the Bakanas basin (more often, gentle monoclines) are usually attributed to movements along large strike-slip faults in the late Triassic–early Jurassic (Samygin, 1974). However, the final folding in most of Kazakhstan is of disputable age (maybe, late Permian–early Triassic).

The sampled section in the east of the basin, more than 2000 m thick, contains hundreds of basalt and basaltic-andesite flows few meters thick (sometimes, up to 10 m thick) (Fig. 1*b*). They coexist with several felsic-lava flows, two of which are a few tens of meters thick and some others are several meters thick. Sedimentary interbeds are very rare, but the flow boundaries in some places are distinct enough for bedding measurement. Also, the flow boundaries are often marked off by oxidized red crusts, which are well-defined against the background of the gray-black lavas. Almost everywhere, the most stable flows make up a system of parallel ridges and cuestas, whose average strikes agree, according to direct measurements, with slight variations. As a result, the average value for several direct measurements of bedding (dip azimuth/dip angle 260/18) at most of the sites was used to correct paleomagnetic data for the bed inclinations, and only the easternmost sites are characterized by slightly steeper dips (260/25); this is also the case with felsic-tuff beds under the lowermost basalt flows.

This section was previously studied along a large profile (one sample from a flow) in search of zones of different polarities (Levashova et al., 2003). This work yielded the following main results:

(1) the only strong high-temperature component was distinguished reliably in the vast majority of the lava samples;

(2) this component always had reversed polarity with tightly clustered directions; no anomalous directions were observed;

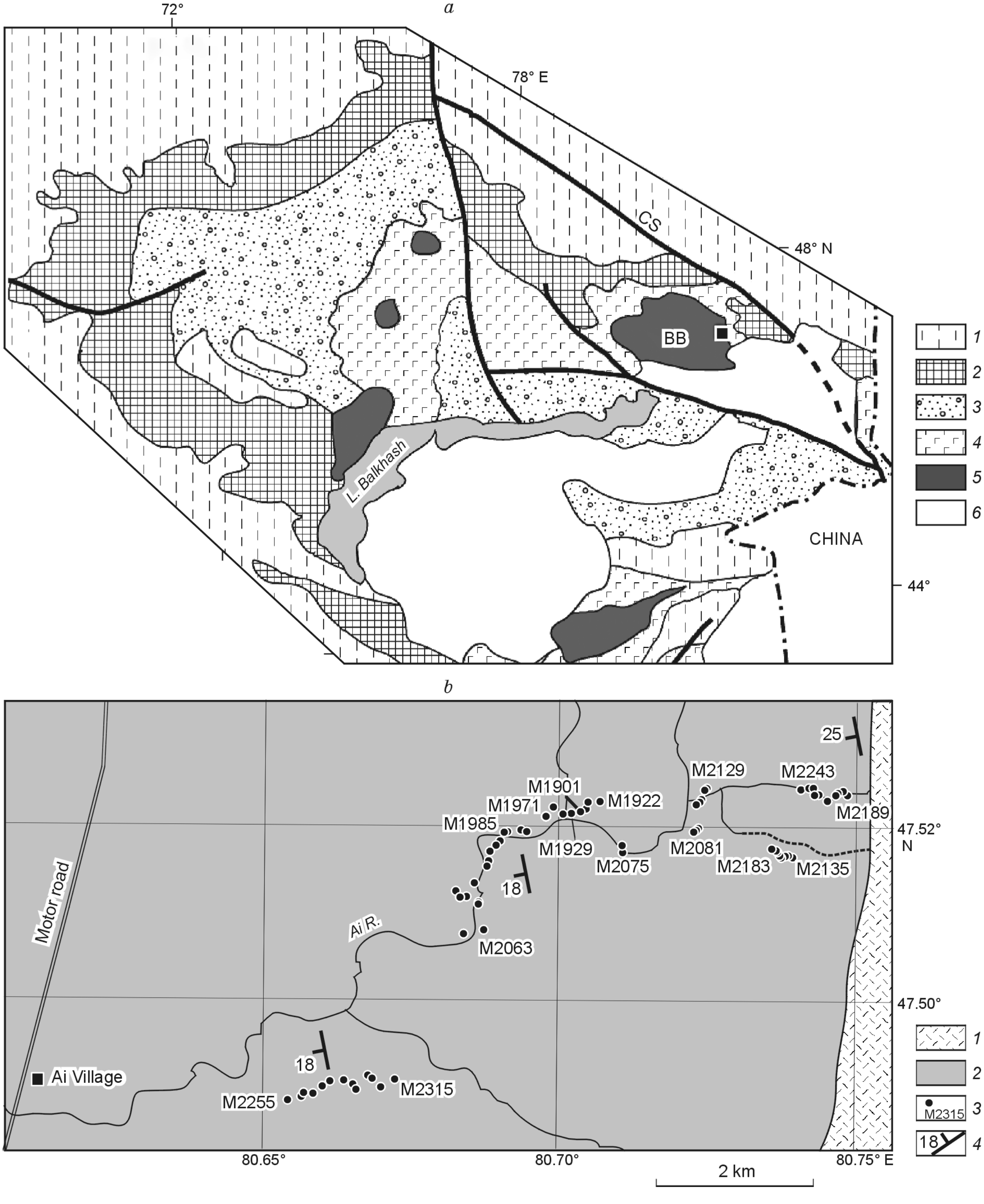

Fig. 1. Tectonic sketch map of Kazakhstan (*a*) and a scheme for the sampling of the Late Permian rocks in the eastern side of the Bakanas basin (*b*). *a*: *1*, Undivided Precambrian and Early Paleozoic; *2*, Silurian–Middle Devonian suprasubduction volcanics; *3*, Middle Paleozoic accretionary complexes and flysch; *4*, Middle Carboniferous–Early Permian volcanics of the Balkhash–Ili belt; *5*, Late Permian volcanics of superposed basins (BB, Bakanas basin); *6*, Meso-Cenozoic sediments. The main faults are shown by heavy lines; CS, Chingiz strike-slip fault (Samygin, 1974). Black square, Fig. 1*b*. *b*: *1*, Late Permian felsic tuffs; *2*, Late Permian basalts with individual rhyolite flows; *3*, sampling areas (sites) with numbers; *4*, dips and strikes.

(3) this component was a prefolding one, as demonstrated by comparison with data on sections from the Bakanas basin;

(4) the paleomagnetic pole for one of the studied sections agrees with the Late Permian pole of stable Europe, and the other is rotated with respect to this pole.

Such obvious positive paleomagnetic data, great thickness, large number of flows, and good exposure made this section suitable for the study of the characteristics of the Permian geomagnetic field. In 2011, 66 flows were considered within one monocline, starting from the basalt contact with the underlying felsic tuffs: 64 of basalts and two of felsic lavas. In total, an interval of 1600–1700 m was sampled (Fig. 1*b*). Note that neighboring flows were almost never selected owing to the exposure conditions and the aim of studying the maximum interval of the section. According to a rough estimate, the number of separate flows in the studied interval was three to four times that of the studied flows. The interval studied in 2011 was approximately twice the size of that which had been sampled before (Levashova et al., 2003). Despite the thorough search, no "cool" conglomerate mentioned by other authors (Sal'menova and Koshkin, 1990) was found. A few lava-breccia beds were observed, but they were unsuitable for a paleomagnetic test of pebbles.

Six or seven samples, oriented with a magnetic compass, were taken from one flow (site). Not a single case was observed when the rocks influenced the compass readings. As an additional precaution, the author tried to select samples with very different orientations at each site. In that case, the rocks did influence the compass readings, the magnetization directions would be very widely scattered within the site. The samples within the site were distributed along the flow over a distance no smaller than the flow thickness to reduce the possible effect of the movements of separate blocks during the cooling of lava. The coordinates of each site were measured, making it possible to order them in stratigraphic succession (Fig. 1*b*).

Methods and results of laboratory studies

In the Paleomagnetic Laboratory of the Geological Institute (Moscow), one cubic sample from each hand specimen was subjected to stepwise (up to 20 steps) temperature demagnetization to 700 °C in a hand-made furnace with a two-layered permalloy shield (remanent field ~10 nT). Magnetization was measured with JR-4 and JR-6 spin magnetometers (noise 0.05 mA/m), placed in Helmholtz coils to compensate for the external magnetic field. The heating results were shown by orthogonal diagrams (Zijderveld, 1967), and linear path segments including no less than three dimensions were used to distinguish the magnetization components (Kirschvink, 1980). Data on samples from one flow were averaged (Fisher, 1953), and the average site vectors were used for the analysis. All the types of analysis and calculations were performed using the PaleoMac software (Cogné, 2003).

On heating to 200 °C (rarely, to 300 °C), the unstable component in the samples, whose amplitude varies greatly, is destroyed (Fig. 2). For 42 sites in which this component is

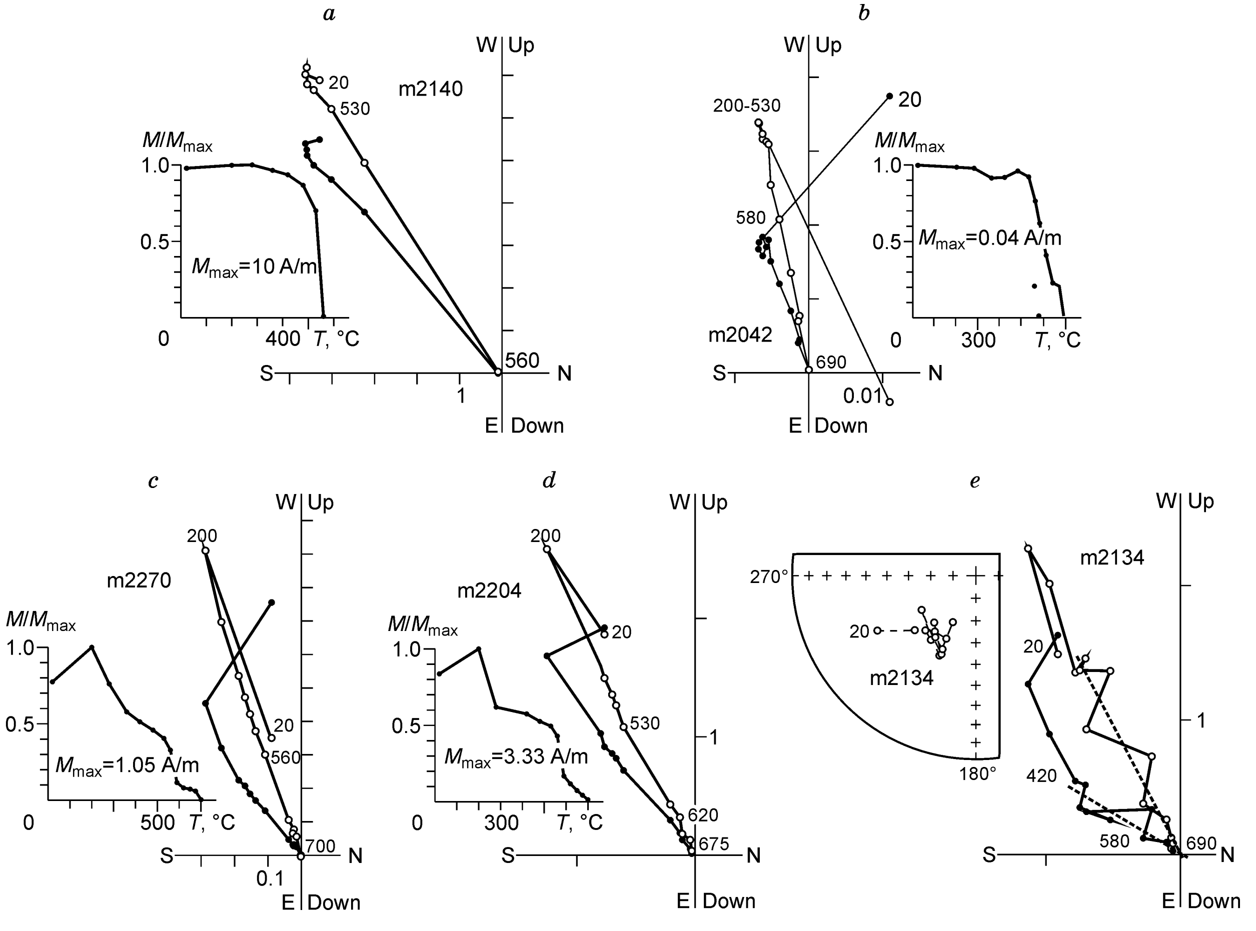

Fig. 2. Demagnetization of representative samples of Permian volcanics. Zijderveld diagrams are given in stratigraphic coordinates; filled (open) symbols are projections onto a horizontal (vertical) plane; dashed line on panel *e* shows the high-temperature component in the sample. Natural remanent magnetization curves are normalized to the initial value. All the symbols on the stereogram are projected onto the upper hemisphere.

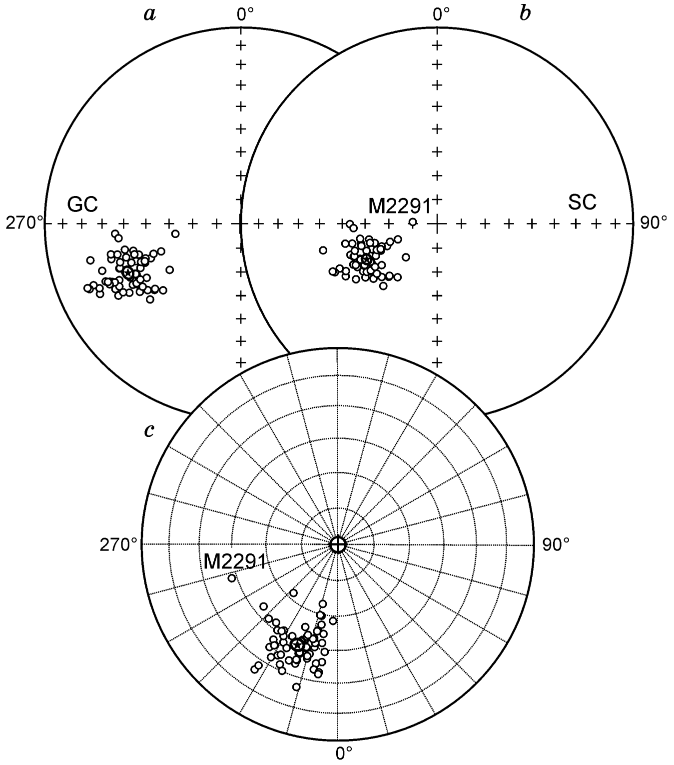

Fig. 3. Stereograms of the average directions of the high-temperature component for the sites (*a*, *b*) and corresponding virtual poles (*c*) in geographic (*a*) and stratigraphic (*b*, *c*) coordinates. Unit directions and poles are shown by circles; their confidence circles are not presented for better readability. The average directions for all the data are indicated by stars with a confidence circle (heavy line). All the symbols and lines are projected onto the upper hemisphere.

determined with satisfactory accuracy, its average direction (D = 6.5°; I = 66.1°; and α_{95} = 3.1°) differs insignificantly from the direction of the present-day dipole field (D = 0°; I = 65.4°). Apparently, this low-temperature component is characterized by viscous nature and young age.

As a rule, the subsequent heating of 90% of the samples reveals a distinct high-temperature component (HTC), which declines to zero on orthogonal diagrams and always has reversed polarity (Fig. 2*a*–*d*). The demagnetization data are noisier only in 10% of the collection, but the HTC in these samples is also easy to identify (Fig. 2*e*). Judging by the blocking temperatures, this component is observed in magnetite and hematite in different proportions; note that samples with different ferromagnetic materials might be present in one flow. When substantiated detection of the "magnetite" (less than 580 ºC) and "hematite" (more than 580 ºC) components (Fig. 2*c*) was possible, their directions coincided within few degrees, with accidental differences. Therefore, both components appeared within fields of approximately the same direction. This situation, often observed in lavas, is usually explained by high-temperature oxidation of magnetite during or shortly after the cooling of the flows (Levashova et al., 2009; Swanson-Hysell et al., 2009). The HTC directions are well-grouped within the flows: The concentration parameter within the sites varies from 30 to >500, averaging ~110. For a total of 66 sites, the radius of the confidence circle is more than 15° for only one site (M2225), and it is less than 10° for 52 sites[1]. Such data quality is considered good even for Late Cenozoic data if the number of samples from each site is larger (Johnson et al., 2008).

The paleomagnetic data are better grouped in stratigraphic coordinates than in geographic ones, but the difference is statistically insignificant (Fig. 3*a*, *b*, Table 1). Recall that the studied section coincides with one of the objects studied by N.M. Levashova et al. (2003). This paper presents results for two objects, for one of which the fold test is clearly positive, but the objects are rotated with respect to each other. Therefore, the fold test was used only for inclinations (McFadden and Reid, 1982) and turned out to be positive; the best inclination convergence is also observed in stratigraphic coordinates. Thus, the studied volcanics show obvious prefolding magnetization. As pointed out above, no object for the pebble test was found in this unit. Rather, the reversed polarity of all the studied flows in a section no less than 1600 m thick indicates that the rock magnetization appeared during the Kiama superchron, whose upper boundary is aged ~265 Ma (Opdyke and Channell, 1996). Finally, the pole obtained in this work agrees with the Early Permian (290–270 Ma) segment of the polar-wander path for stable Europe (Fig. 4) (Torsvik and Cocks, 2005), which is consistent with the zircon age 283.0 ± 2.4 Ma.

The average HTC directions for the sites show a compact distribution in stratigraphic coordinates (Fig. 3*b*), but additional selection based on the size of the confidence circle is usually made to assess the field characteristics; also, anomalously directed sites are discarded. As a rule, it is required that the confidence circle have a radius of less than 10° (sometimes, 15° is permitted) (Johnson et al., 2008). If the last criterion is accepted, we should discard only one site, M2225, with α_{95} = 15.9°. The abnormality criterion is often that the inclination of a single pole from the average pole of the data totality should be more than 45°. Only one site (M2291) might be abnormal, particularly if the pole distribution is considered (Fig. 3*b*, *c*). However, the angle for this result is also considerably smaller (36°), so that site M2291 is considered good. Finally, we can discard sites with α_{95} between 10° and 15° and calculate the average for the remaining 52 sites. As a result, four average directions and corresponding poles were calculated (Table 1): 1, all 66 sites; 2, without site M2225 (65 sites); 3, without sites M2225 and M2291 (64 sites); 4, only for sites with α_{95} < 10° (52 sites) and without site M2291. All four average vectors are mutually consistent within one degree; the concentration parameter varies somewhat more but also slightly. Since site M2225 has to be excluded, option 2 will be used in the subsequent analysis (Table 1).

If several flows erupt rapidly one by one (in the course of tens and few hundreds of years), the HTC directions therein are known to be very similar (Chenet et al., 2008; Riisager et al., 2003) and the paleomagnetic directions make up compact

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[1] The complete table of site averages is not given here for space considerations. It is available from the author: mibazh@mail.ru.

Table 1. Main paleomagnetic results for the Upper Permian lavas of northeastern Kazakhstan

Result	*n*	GC				SC				Note
		D°	*I*°	*k*	α_{95}°	*D*°	*I*°	*k*	α_{95}°	
Paleomagnetic directions										
Average 1	66	246.5	–37.3	57.4	2.3	243.3	–57.0	79.1	2.0	All the sites
Average 2	65	246.4	–37.4	57.0	2.4	243.1	–57.0	78.5	2.0	Without M2225
Average 3	64	246.3	–37.0	62.1	2.3	242.9	–56.6	87.4	1.9	Without M2225 or M2291
Average 4	52	246.0	–36.8	66.3	2.4	242.5	–56.5	94.0	2.0	Without M2291 or sites with $\alpha_{95} > 10°$
DG + sites	38	246.8	–37.3	52.4	3.2	243.7	–57.1	71.4	2.8	All the DG and sites
DG + sites	37	246.6	–36.4	51.8	3.3	243.4	–57.1	70.3	2.8	Without M2225
DG + sites	36	246.4	–36.8	59.5	3.1	243.1	–56.5	83.7	2.6	Without M2225 or M2291
Paleomagnetic poles										
Pole	*n*					Φ°	Λ°	*K*	A_{95}°	Note
1	66					158.1	44.1	49.0	2.5	All the sites
2	65					158.2	44.2	48.8	2.5	Without M2225
3	64					158.9	44.0	56.4	2.4	Without M2225 or M2291
4	52					159.3	44.3	61.1	2.5	Without M2291 or sites with $\alpha_{95} < 10°$

Note. The results are designated as in the text. GC and SC, Geographic and stratigraphic coordinates. *n*, Number of unit vectors (sites and DG) or corresponding poles. *D*, Declination; *I*, inclination; *k*, concentration parameter (Fisher, 1953). α_{95}, Confidence-circle radius; Φ, northern latitude of the pole; Λ, eastern longitude of the pole; *K*, concentration parameter; A_{95}, confidence-circle radius.

clusters (directional groups, DG). The group average is used in the interpretation instead of several tightly clustered site averages; the similarity is assessed using the statistical *F*-criterion or simply from the confidence-circle overlap. The requirement of this approach to place the data in stratigraphic succession is met in this case. Thirty-eight average vectors (15 DG and 23 sites) were obtained using this approach; note that most of the groups consist of two neighboring flows. Like for individual sites, several versions of calculating the grand average were tried, and all the grand average directions were similar regardless of the data used and the rejection of some results (Table 1).

Note that the existing methods for distinguishing DG are good for scattered distributions with a concentration of less than 40. In our case, the concentration parameter is at least twice as high; therefore, the angular distances between the HTC directions in the neighboring flows are very likely to be shorter than the critical value quite by chance, particularly if the average site vector has $\alpha_{95} \approx 10°$. The predominant DGs of two sites are especially suspicious. This problem can be solved only by doubling or even tripling the number of samples in a flow, but this is impossible owing to many causes; note that the collection already contains more than 400 samples. Considering the uncertainties in the DG determination and the very close similarity between the results, we selected the result averaged for 65 sites in the subsequent analysis (option 2, Table 1).

Interpretation and discussion of the results

To determine the characteristics of the ancient geomagnetic field, it is very important to know the concentration parameter of the field directions and to estimate the statistical validity of this parameter. As stated above, the dips and strikes determined for the easternmost sites were slightly different from the bedding of most of the collection. Certainly, this is a simplification, and the bedding in the section must show some variation. With purely prefolding magnetization (as is the case with the HTC in the Bakaly lavas), the neglect of

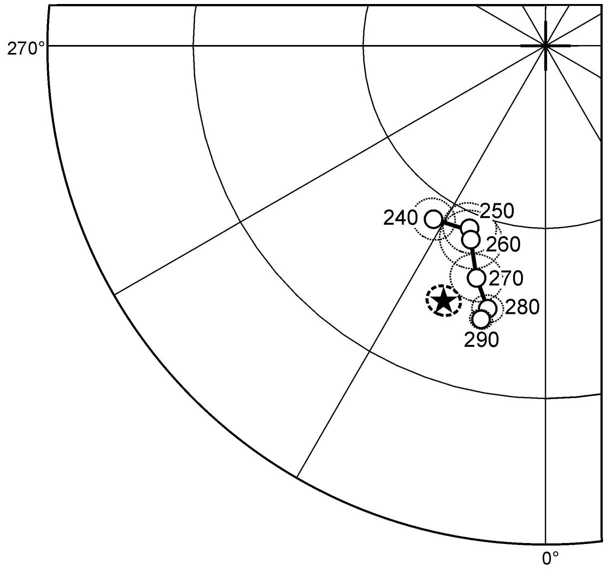

Fig. 4. Comparison of the paleomagnetic pole for the lavas of the Bakaly Formation (star with a confidence circle, shown by a heavy dashed line) with the wander path of the South Pole of stable Europe (Torsvik and Cocks, 2005). Standard poles are shown by small circles with confidence circles (fine dashed lines) and ages (Ma), connected by a heavy solid line. All the symbols and lines are projected onto the Southern hemisphere.

Table 2. Main characteristics of the studied thick lava series older than 10 Ma and their paleomagnetic results

No.	Object	AGE	φ°	λ°	*N*	*I*°	α_{95}°	pLAT°	ΔP°	*k*	*E*	References
1	US, Steens Mountain	17	43	242	50/48	60.4	3.8	41.3	4.4	29.8	1.64	[1]
2	North China	20	41	112	40/34	58.9	3.4	39.6	3.8	52.2	1.49	[2]
3	Kerguelen Island	27	–49	69	98/92	–68.7	2.4	–52.0	3.4	40.3	1.42	[3]
4	Yemen, traps	30	16	44	69/64	0.8	4.4	0.4	2.2	17.3	3.20	[4]
5	Faroe Islands	58	62	353	44/44	61.2	4.5	42.3	5.3	24.0	1.34	[5]
6	India, Deccan Plateau[1]	65	19	73	91/89	49.2	5.0	30.1	4.4	10.0	2.75	[6]
7	Arctic Canada	95	79	267	37/37	80.1	3.6	70.8	6.6	56.4	1.52	[7]
8	Mongolia[2]	120	44	102	143/132	66.1	1.9	48.4	2.5	42.1	1.48	[8]
9	Northern Argentina, traps	130	–32	296	59/52	–48.9	3.0	–29.8	2.6	44.3	1.33	[9]
10	Parana River, traps[3]	130	–22	312	68/63	–34.0	3.1	–18.6	2.0	34.6	1.96	[10]
11	Lesotho, traps	180	–30	29	47/47	–53.7	3.2	–34.2	3.1	42.0	4.50	[11]
12	Siberia, traps	250	70	90	44/42	75.4	2.7	62.5	4.5	68.1	1.39	[12]
13	Northeastern Kazakhstan	280	49	81	66/65	57.0	2.0	37.6	2.1	79.1	1.62	[13]
14	Lake Superior, traps	1100	47	269	77/70	44.1	2.4	25.8	1.9	49.3	1.49	[14]

Note. AGE, Round age, Ma. φ, Object latitude (negative for the Southern hemisphere). λ, Eastern longitude of the object. *N*, Number of unit vectors (sites and DG): published/used. pLAT, Object paleolatitude, calculated from a dipole formula. ΔP, Symmetrical confidence interval for the paleolatitude. *E*, Elongation of the unit-vector distribution (Tauxe and Kent, 2004). References: [1], Jarboe et al., 2008; [2], Pan et al., 2005; [3], Plenier et al., 2002; [4], Riisager et al., 2005; [5], Riisager et al., 2002; [6], Chenet et al., 2008; [7], Tarduno et al., 2002; [8], van Hinsbergen et al., 2008; [9], Geuna and Vizán, 1998; [10], Ernesto et al., 1999; [11], Kosterov and Perrin, 1996; [12], Heunemann et al., 2004; [13], present paper; [14], Tauxe and Kodama, 2009. The rest of the legend is as in Table 1.

[1] The analysis was carried out for all the results (sites and DG distinguished by the authors) with $\alpha_{95} < 15°$, which were recalculated for the common point with the coordinates specified in the table.

[2] The entire data set was used.

[3] The data were recalculated for the common point with the coordinates shown in the table.

dips and strikes must reduce the true scatter; i.e., the calculated concentration parameter must be lower than the true value. Consequently, the obtained concentration (Table 1) is the lower limit of the true value of this parameter.

To study the field structure, it is vital to know the quality of the averaging of the secular variation in the collection; an interval of ~100 kyr is considered enough (Merrill et al., 1996). There is no direct evidence proving the duration of this interval, be it a series of ages from different parts of the section or the presence of zones of different polarities. On the other hand, sections more than a kilometer thick in which hundreds of flows accumulated much faster than for 100 kyr are not recorded even in the most active and “regular” recent volcanoes. For example, rapidly accumulated intervals are several times thinner on the Hawaiian Islands, with their extremely stable volcanism (Laj et al., 1999). Even for traps, the estimated duration of the formation of units of similar thickness is usually about a million years (Chenet et al., 2008). The long accumulation period of the Bakaly Formation is also evidenced by numerous oxidized crusts of the flows, which indicate pauses in effusion. Thus, the secular variation in the collection must be well-averaged.

So, the concentration parameter for the collection is about 80. Is this value high or low? The answer can be obtained by comparing this result with data on other thick lava units or with theoretical models. The first approach required analyzing available data on lava units, except the data on the interval 0–5 Ma (which is a subject for a separate study). The following criteria were used for the selection:

(1) the result was obtained within a small area, in which tectonic movements were hardly possible and structural data were noncontradictory;

(2) the result was obtained for no fewer than 25 lava flows; a small number of dikes were allowed, but data on dike swarms were excluded, because there are usually no criteria to determine the degree of the secular-variation averaging for them;

(3) at least five independently selected samples were studied from each igneous body (flow or dike);

(4) the paleomagnetic data on all the samples were obtained by detailed stepwise demagnetization and component analysis of the demagnetization results (Kirschvink, 1980);

(5) the site averages were determined from at least four samples with an error less than 15°;

(6) anomalous sites were excluded using the method described above; if such selection had been made by the authors of the publication, their estimate was accepted;

(7) the directions show a single distribution after the selection.

We emphasize that extremely few data on any age do meet all the criteria (Table 2). For example, there are abundant data on the Emeishan (Permian) lavas of China, but mutual rotations of some sections are well-defined (Liu and Zhu, 2009, and references therein). The number of the studied flows is usually much smaller than the permissible minimum. Finally, some results are absolutely extraordinary. For example, most of the unit vectors for West Greenland make up two very tight clusters several tens of degrees from each other.

A very important parameter of secular-variation models is the dependence of the secular-variation amplitude on latitude or, more generally, paleolatitude. It would be better to study it for a moderately long but limited time interval (e.g., several Myr). This is now possible only for the last 5 Myr, and older data are too few to be further divided by age. Therefore, a single concentration (k) vs. paleolatitude (φ) plot had to be constructed for all the available data; the paleolatitude was calculated from a dipole formula ($\tan I = 2 \tan \varphi$) using the average inclination I of an individual result. A wide scatter of the data is very conspicuous (Fig. 5*a*). Theoretically, the concentration parameter might increase poleward, but this is not very likely. Also, the data on low (less than 20°) and high (more than 60°) paleolatitudes are certainly very scarce. The second feature is explained by the small size of the high-latitude areas. However, the obvious scarcity of low-latitude data is confusing, because results with very different ages were used. However, the scatter appears too wide even for the well-studied middle latitudes to fit into a single regularity. It may be argued that the minimum size of the collection (30 measurements) accepted during the selection is still too small for reliable determination of the concentration parameter, by analogy with ordinary dispersion of 1D data. However, about half the results used were obtained from 50 or more sites (Fig. 5*a*, large symbols), but their scatter is not at all narrower.

Heavy dashed line in this figure shows a concentration–latitude dependence, according to the secular-variation model of Tauxe and Kent (2004). This model was developed for describing data aged 0–5 Ma, but it is often used for any age. The theory predicts a poleward increase in the concentration parameter (i.e., a decrease in the dispersion) of paleomagnetic directions, but otherwise it shows poor agreement with the experiment.

Also, it was predicted that the secular-variation amplitude (the concentration parameter can be used to estimate this amplitude) must be considerably different for single-polarity superchrons and for epochs with frequent polarity reversals (McFadden et al., 1988), which might have been confirmed by the data available at that moment. It appears that a new test performed recently for a much larger array of more reliable data has confirmed the prediction, but, compared to the previous analysis (McFadden et al., 1988), it has revealed much smaller differences, close to data with statistical errors (Biggin et al., 2008b). Three of the results shown in Fig. 5*a* were obtained for superchrons: no. 7, for the Cretaceous basalts of the Canadian Arctic Archipelago (Tarduno et al., 2002); no. 8, for the Cretaceous basalts of Mongolia (van Hinsbergen et al., 2008); and no. 13, for the lavas of northeastern Kazakhstan (present paper). Results no. 7 and 13 do show high concentration; the Permian result is higher than the others, whereas no. 8 is low. However, three results, with none of them for the tropics, are too few.

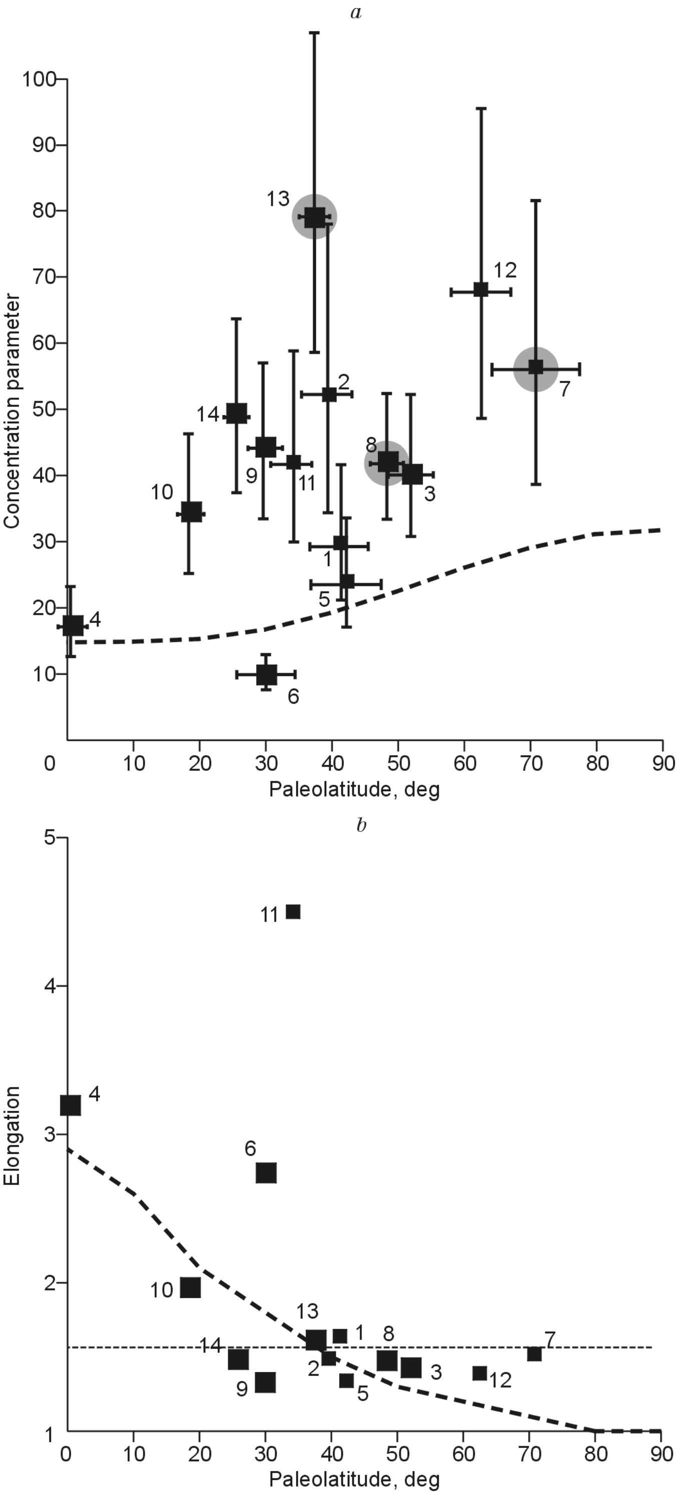

Fig. 5. Dependence of the concentration parameter of paleomagnetic unit directions (*a*) and the elongation of the distribution of these directions (*b*) on paleolatitude. Data on the Southern and Northern hemispheres are combined and numbered as in Table 2. Results based on more than 50 unit directions are indicated by large symbols. Heavy dotted lines are predictions of the secular-variation model (Tauxe and Kent, 2004), constructed from data on the last 5 Ma. Errors in the determination of paleolatitude (concentration parameter) on plot *a* are shown by horizontal (vertical) lines (the errors in the paleolatitude determination for some results are close to the sizes of the symbols). Two results for the Cretaceous superchron (no. 7) and the Kiama superchron (no. 13) are marked off by gray circles. Fine dashed line on panel (*b*) is the minimum elongation which can be found with statistical condidence for a collection of 50 unit directions.

The secular-variation model (Tauxe and Kent, 2004) introduced the "elongation" parameter (*E*), which describes the elongation of the direction distribution. According to this model, the maximum elongation (about 3) should be on the Equator, and it gently decreases poleward to 1 (Fig. 5*b*, heavy dotted line); the elongation should be along the meridian. The experimental data appear to satisfy the theory (except site no. 11). However, any distribution of several tens of paleomagnetic directions will always have an elongation more than unity owing to selective fluctuations, even in the case of selection directly at the pole. The elongation should be statistically significant. Fine dashed line (Fig. 5*b*) shows 95% critical elongation for a collection of 50 unit vectors. A vast majority of the sites plot below this line (the elongation is insignificant) or slightly above it (the elongation is marginally significant). In fact, this parameter is reliably estimated only for collections of >100 unit directions (Tauxe and Kent, 2004). However, such collections almost do not exist and will hardly be abundant in future, simply because of the small amount of such thick lavas. Therefore, it is surprising how freely this parameter is used to determine the inclination underestimation, even for collections of few tens of unit directions.

So, the situation with the elongation seems clear. Yet, what causes such a wide scatter of the concentration parameter? According to the statistical convention, a reliable concentration (dispersion) estimate requires about 50 unit directions. In this case, we are faced with high uncertainty. First, even vast collections from a thick unit are often not enough for the good averaging of secular variation. However, the presence of zones of different polarities in most of the collections (Table 2) suggests that the studied intervals lasted for several Myr. Since most of the results are bipolar, the scatter is largely due to them. Let us see what additional reliability criteria could be introduced for the subsequent data selection.

Let us assume that all the results (Table 2, Fig. 5*a*) are free of gross errors and, therefore, realistic. Recall that secular-variation models are explicitly or implicitly based on two assumptions. First, the variation has a globally ordered structure, which is one of the causes of the variation amplitude–latitude dependence. Second, the main characteristics of the secular variation remain approximately the same for the entire time interval. It may be argued that the first assumption is not fulfilled, but this is inconsistent with data on the Late Cenozoic field (Johnson et al., 2008; Merrill et al., 1996). Theoretically, this assumption also appears unrealistic (Merrill et al., 1996). Let us turn to the second assumption. It was assumed that the variation amplitude depends on the reversal frequency (Biggin et al., 2008b; Tarduno et al., 2002), as mentioned above. Although some researchers state that the Archean variations were weaker (Biggin et al., 2008a; Smirnov et al., 2011), the second assumption was considered true. However, it has been recently hypothesized that the secular-variation amplitude can vary by several times within short (few Myr) time intervals (Bazhenov and Levashova, 2011). If so, the observed data scatter (Fig. 5*a*) is easily explained by the fact that data on intervals with initially different variation are summarized on one plot. Nevertheless, this is also a hypothesis, whose confirmation requires a large body of new data.

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