Late Devonian palaeomagnetism of the North Tien Shan, Kyrgyzstan: can secular variation vary on a short timescale?

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SUMMARY
We studied more than 80 lava flows from a ∼600-m-thick pile of Upper Devonian (Frasnian) basalts and andesites of the Aral Formation in the North Tien Shan (Kyrgyzstan, Central Asia). With the aid of stepwise thermal demagnetization, a high-temperature, dual-polarity component was reliably isolated from most flows. The primary origin of the high-temperature component is demonstrated by positive reversal, conglomerate and fold tests. The most prominent and intriguing feature of this Late Devonian data set involves a clear distinction in angular dispersion between the lower and upper parts of the studied section. A rather low concentration parameter (k = 13) and several directional anomalies characterize the lower section; in contrast, a much better grouping (k = 46) and a lack of directional outliers is observed for the dual-polarity vectors from the upper flow sequence of the formation. We analysed different mechanisms to account for this directional pattern and found that it is possible in just two ways. One is to assume that secular variation (SV) in the upper sequence is strongly under-represented, and it is a coincidence that the mean directions of both polarities are statistically antipodal, and the corresponding concentration parameters are statistically equal. The other explanation is to hypothesize that the magnitude of SV can vary several-fold at the same palaeolatitude and over time intervals estimated as 10^5–10^6 yr. This is in sharp contrast with other models of SV, where this magnitude has been assumed to be rather time-independent (for a given latitude). Our hypothesis accounts for the observed irregularities in palaeomagnetic data, but makes attempts to establish a correlation between SV and other parameters (geographic latitude, reversal frequency, age, etc.) more difficult. We are aware, however, that more data are needed to refute or confirm it.

Key words: Geomagnetic excursions; Palaeomagnetic secular variation; Asia.

INTRODUCTION
It is a widespread view that the most reliable information on many, albeit not all, characteristics of the past geomagnetic field comes from palaeomagnetic studies of thick lava series. That is why such data sets have acquired the special name of palaeo-secular variation of lavas, PSVL, and have been assigned their own special database. It has been proposed (Tauxe et al. 2003; Johnson et al. 2008) that a PSVL datum can only be regarded as reliable if it satisfies the following list of conditions:

(1) All samples from all sites are subjected to detailed demagnetization and principal component analysis;
(2) All site-mean directions (or virtual geomagnetic poles, VGPs) are based on at least three independently oriented samples per site;
(3) All sites come from a limited area, where relative tectonic rotations are improbable;
(4) A PSVL datum must be based on at least 20–25 sites to obtain a valid mean direction, whereas much larger data sets are required for an accurate evaluation of angular dispersion, elongation, etc.

To date, the overwhelming majority of PSVL data exist for the last 5 Ma, some 20 more are from the remaining part of the Cenozoic, and about 10 are of Mesozoic age. For several years, the oldest PSVL was from the ∼250 Ma old Siberian traps (Heunemann et al. 2004), but quite recently, the first analyses of mid-Proterozoic (∼1.1 Ga; Swanson-Hysell et al. 2009; Tauxe & Kodama 2009) and late Archean (2.8–2.45 Ga; Biggin et al. 2008a) results have appeared. Of special relevance to this paper is the complete lack of Palaeozoic PSVL data.

Acquiring just one PSVL datum entails discovering a suitable object, sampling of up to a hundred sites and extracting useful information from all of them, if possible. It is, therefore, an expensive
and labour-intensive venture, which is much easier to do for the late Cenozoic than for pre-Cretaceous times.

Be that as it may, in the course of our palaeomagnetic investigations involving tectonic analyses of a strongly curved mountain belts in Central Asia (Abrajevitch et al. 2008; Levashova et al. 2009), we have encountered several extensive lava series of Palaeozoic age. Palaeomagnetic stability tests from these volcanics indicated that magnetizations were likely primary, that is, acquired upon extrusion (Levashova et al. 2003, 2007, 2009; Abrajevitch et al. 2007, and references therein). However, these studies were in pursuit of tectonic purposes, so they did not need to be based on elaborate statistics and maximum-attainable numbers of cooling units. Although it is commonly thought that the last few million years adequately represent many parameters (e.g. angular dispersion) of the geomagnetic field for much of geological time, recent studies of late Archean to early Proterozoic secular variation (SV; Smirnov & Tarduno 2004; Biggin et al. 2008a) have alerted us to the possibility that there may be a trend due to, for instance, growth of the inner core. This would manifest itself in a tendency to have a more stable geomagnetic configuration, which is possibly less susceptible to reversals (Biggin et al. 2008a). Our motivation for this study, therefore, is to begin to alleviate the extreme scarcity of pre-Mesozoic PSVL data to see whether there is support for long-term evolution of the field idea from magnetic field records from the 300–540 Ma interval.

Our first choice for a Palaeozoic PSVL investigation was the Upper Devonian lava pile in Kyrgyzstan, where a presumably primary remanence had successfully been isolated from 15 flows in the lower 280 m of the section (Levashova et al. 2007). We significantly expanded the collection in 2009 and totalled with 82 flows from a much thicker stratigraphic interval (~650 m). Preliminary information on this collection that included a brief presentation of the data and their hypothetical interpretation was published in a Russian journal (Bazhenov & Levashova 2011). Here, we give a more complete data presentation of our field and in-door studies and would like to discuss in detail contentious interpretations that are provoked by this study.

GEOLoGICAL SETTING AND SAMPLING

The North Tien Shan tectonic zone occupies the southern part of the Ural–Mongol mobile belt, known otherwise as the Central Asia orogenic belt or the Altaids (Fig. 1a). The zone comprises isolated blocks with Precambrian basement rocks, disrupted slices of Cambrian and Early Ordovician island arc and shelf complexes, and Middle-Late Ordovician island-arc volcanics and sediments that were deformed and welded together by the Ordovician–Silurian boundary (Mikolaichuk et al. 1997). The Devonian subaerial volcanics reside on older rocks with a major unconformity in several isolated localities. The volcanics are covered nearly conformably by Upper Devonian–Lower Carboniferous sediments, mostly redbeds, which, in turn, are unconformably overlain by Upper Carboniferous volcanics. The entire zone was folded in the Late Permian,
Devonian palaeomagnetism of North Tien Shan

and its present-day structure was finally sculpted by late Cenozoic tectonism.

A thick pile of Middle-Upper Devonian sediments and volcanics in the Kyrgyz Range of the Tien Shan (Figs 1b, 2a and b) consists of more than 1000-m-thick volcanics of the Aral Fm., which rest conformably on arkosic sandstones, siltstones and a few metres thick basal conglomerate, dated as late Middle Devonian (Givetian) by microfossils and pollen (Malygina & Dodonova 1972). To the east, the Aral Fm. is conformably covered by Upper Devonian acid volcanics. The entire Devonian sequence is folded into a very gentle nearly isometric syncline (Fig. 1b); the age of folding is unconstrained and may be as young as late Cenozoic.

The Aral Fm. predominately consists of 1- to 10-m-thick flows of grey to black basalt, andesite-basalt and trachyandesite with several beds and lenses of conglomerate and carbonaceous sandstone. The volcanics are mostly massive, with decimetre-thick vesiculated margins, but entirely amygdaloidal flows occur as well. Separate thicker flows and series of thinner ones can be traced laterally for a few hundred metres, but both wedge out at a larger distance. Rather frequent sedimentary interbeds provide enough opportunities to measure bedding attitudes; additional measurements can be derived from best-defined flow surfaces. The flows often form staircase exposures and/or clearly visible flow surfaces, thus facilitating the recognition of cooling units. The foraminifera Bisphaera malevkensis Bis., Cribrosphaeroides cf. simplex Reitl., and Parathurammina cf. Paulis Byk., collected from calcareous sandstones, indicate that these rocks are Late Devonian, likely Frasnian, in age (A. V. Dzhenchuraeva personal Communication, 2005).

Levashova et al. (2007) studied the lower part of the Aral Fm. along two sections (Figs 2a and b). Nine flows were sampled in an ~100-m-thick section (L1) upward from the contact of the volcanics with underlying sediments. Section L2 is about 1 km to the south in a gorge, where the contact is not exposed. Here, 14 flows were collected from an ~150 m interval. The top of section L1 is likely to roughly correspond to the base of section L2, with the total sampled interval of about ~250 m. Six hand samples, oriented with a magnetic compass, were taken from each flow (hierarchically treated as a site). It should be noted that the clasts in the conglomerate beds represent sediments, granites and silicic lava, whereas no debris of mafic volcanics from the host Aral rocks was found (Malygina & Dodonova 1972). During the first sampling, Levashova et al. (2007) additionally searched for basalt and andesite cobbles but to no avail. Consequently, 16 clasts could only be sampled from silicic volcanics at sections L1 and L2.
from the two intraformational conglomerate horizons (black bars in Fig. 2b).

At the beginning of the second field season in 2009, our intention was to start at the top of section L1 and to continue sampling eastwards, that is, up-section, along the brook, but we found a zone of hydrothermal alteration (Figs 2a and c), where originally black and grey volcanic rocks have been transformed into a light-brown rock, often with a fine-grained sulphide mineral. As a result, we first sampled northwards and uphill (21 sites in section A). A hydrothermal layer of less than 10 m in thickness was found in the lower third of section A; one site, N4857, was taken from altered rocks to determine secondary components, whereas some 20-m-thick intervals below and above this altered layer were skipped as the safety margins. Then, we ‘jumped’ over the main alteration zone (cross-hatched spot in Figs 2a and c) and resumed sampling further eastward in section B (Figs 2a–c). Structural relationships show that the gap between the top of section A and the base of section B is about 50 m. Note that the study area is dissected by several faults (Fig. 2a), which might have distorted this estimate. We did not find, however, any indication of fault-conjugated displacements in the continuous cliffs along the southern side of the brook valley. Moreover, an easily recognizable andesite flow with large plagioclase phenocrysts over lain by an ~2-m-thick conglomerate was found at the base of B section (at ~420 m in Fig. 2b), and the same units are displaced on the other wall of the fault by less than 5 m. We estimate that approximately 300 m of the upper part of the total visible section (i.e. above section B) remain unsampled because of very steep cliffs (grey shading in Fig. 2a) and an increasing probability of lightning-induced remagnetization closer to the ridge crest (dot-dashed line in Fig. 2a).

In sum, 21 lava flows were sampled from an ~250-m-thick interval at section A. Its base is about 15 m (2–3 flows) above the top of section L1; thus sections A and L2 overlap (Fig. 2b). As most cooling units wedge out over several hundred metres, it does not seem likely that the same flow could be studied twice in sections A and L2; hence each site-mean can be treated as an independent spot-reading of the ambient field. After an ~50 m gap, the sampling was resumed in section B, and 23 more flows were sampled in an ~250 m interval. When the 24 flows from the earlier studied sections L1 and L2 are added (Figs 2a and b), we arrive at a total of 68 sampled flows from an ~600-m-thick interval. At all outcrops in sections L1, L2, A and B, the Aral rocks dip 10° to 15° to the southeast, according to multiple measurements carried out on several sedimentary layers.

The third new section (C) is located on the southeastern limb of the syncline (Fig. 1b), where a limited part of the formation is exposed. No sediments were found, so that bedding attitudes had to be measured on flow boundaries. The C section cannot be matched precisely with the others, but it is positively either roughly coeval with, or younger than, section B. 14 sites were sampled from section C over an ~100 m interval.

In 2009, seven to eight hand samples were oriented with the aid of a magnetic compass, collecting from different levels of a given flow. Samples were laterally spread in a given site over a distance of up to 15 m, which is larger than the typical flow thickness. This was done to minimize the chance that all samples from a site were collected from a tilted or displaced lava block. We estimate that, as a whole, every alternating flow has been sampled: thicker (>5 m) adjacent flows could be studied in some cases, whereas up to 30-m-thick intervals had to be skipped because of fracturing, strong weathering or poor quality of exposure in other situations.

**PALAEO MAGNETIC ANALYSIS**

**Methods and the comparison with preliminary studies**

Cubic specimens of 8 cm³ volume were sawed from oriented hand blocks. In the palaeomagnetic laboratory of the Geological Institute of the Russian Academy of Science in Moscow, one specimen from each hand sample was stepwise demagnetized 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 m Am⁻¹; the magnetometer was placed inside large Helmholz coils to reduce the ambient field. 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 with anchoring of the final linear segments to the origin of the vector diagrams, when appropriate. 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 ChRM was determined with anchoring of the final linear segments to the origin of the vector diagrams, when appropriate. All component analyses and calculations were carried out with the Paleomac software (Cogne 2003). As has already been noted, a brief presentation of the data and a hypothesis that the variable scatter of palaeomagnetic directions in the Aral volcanics is related to the SV magnitude were published in a Russian journal (Bazhenov & Levashova 2011).

For this paper, sister specimens from nearly all samples that were taken in 2009 (i.e. more than 350 specimens) were stepwise demagnetized in the palaeomagnetic laboratory of the University of Michigan in Ann Arbor utilizing an Analytical Services TD-48 thermal demagnetizer with internal residual fields of <10 nT, or in treatments up to 200 mT with a Sapphire Instruments SI-4 AF demagnetizer. Measurements were carried out with a 2G Enterprises cryogenic magnetometer in a magnetically shielded room with a rest field typically less than 200 nT. Exactly the same methods of analysis were used in both laboratories.

The first brief version of this study (Bazhenov & Levashova 2011) raised objections from an editor and a reviewer (Gurary & Pechersky 2011), for the insufficient support with rock-magnetic data in particular. The results of the now-expanded study have been presented at scientific meetings where they raised some criticisms too. Finally, the first version of this paper elicited numerous reviewers’ comments when it was submitted to *Geophysics Journal International*. To properly respond to criticisms, more laboratory studies and analyses were carried out. In particular, a Magnetic Properties Measurement System (MPMS) and a Vibrating Sample Magnetometer (VSM) at the Institute for Rock Magnetism in Minneapolis have been employed to accumulate some data characterizing the magnetic carriers in the volcanics. As a result, this version is more cautious, with quite a number of alternative explanations and interpretations considered.

**Directional analysis**

The intensity of natural remanent magnetization (NRM) ranges from 0.01 to >10 A m⁻¹ in volcanic rocks of the Aral Fm. A low-temperature component (LTC) is usually removed below 300–350 °C, but in some cases, may persist up to 500 °C. LTC
directions are reasonably grouped at most sites, and its overall mean direction \((D = 351^\circ, I = 62.5^\circ, \alpha_95 = 5^\circ, N = 54\) sites) is close to the present-day dipole field \((D = 0^\circ, I = 62^\circ)\) in the area. This remanence is likely to be of very recent viscous origin, perhaps with some contributions from ‘weathering’ components.

After the removal of the LTC, a single high-temperature component (HTC), which shows a rectilinear decay to the origin, was isolated from most samples. HTC unblocking temperatures are about 580°–600° in some samples (Figs 3a–c), while most remanence is destroyed above 650° in the others. In the lower part of the volcanic pile (sections L1, L2 and A), demagnetizations indicate magnetite

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**Figure 3.** Representative thermal demagnetization plots of the Upper Devonian volcanic rocks in stratigraphic coordinates. Left and middle columns are for ‘standard’ and anomalous sites, respectively, from the lower part of the lava pile (sections L1, L2 and A); right column is for sites from the upper part (sections B and C). Full (open) dots represent vector endpoints projected onto the horizontal (vertical) plane. Temperature steps are in degrees Celsius. Magnetization intensities are in mA m\(^{-1}\). For clarity, NRM points are omitted from some plots, and coordinate axes vary from plot to plot.
as main remanence carrier, with some scarce haematite; however, many samples are fully demagnetized between 600° and 650° (compare upper and middle rows in Fig. 3). It is most probably because the remanence is carried by magnetite as well as partly oxidized magnetite. In contrast, some samples from sections B and C (Figs 3f and i) reveal unblocking temperatures well above 580 °C, indicating that magnetite may be absent in volcanics from the upper part.

The data on sister specimens that were independently treated at two palaeomagnetic laboratories proved to be very similar, and the directions on sister specimens were pooled by calculating sample means at the first level of statistical treatment. The site-means based on single-specimen data from Bazhenov & Levashova (2011) differ from the combined data (Tables S1 and S2) by less than 2°; on average. This observation indicates that palaeomagnetic noise on the within-sample and within-site levels are adequately averaged.

The new collection and that studied by Levashova et al. (2007) are from different parts of the same lava sequence and the samples show similar demagnetization characteristics; so the data from the entire Aral sequence were pooled. In 7 out of 82 sites investigated, no stable remanence could be isolated, or the HTC directions were very dispersed (\(\alpha_{95} > 25°\) and/or \(k < 10\)); in the dispersed sites, the remanence is strongly dominated by the component aligned along the present-day field, and isolation of weak HTC is not reliable. In particular, no stable remanence was identified at site N4857 from hydrothermally altered rocks. All isolated components at site M1450 form a strongly smeared distribution that stretches from the direction of the present-day field to the ‘typical’ Devonian vectors of normal polarity with a northwestern declination and moderately steep positive inclination; this datum has also been rejected. Although a great circle can be fitted to component directions, so that they then could be used as suggested by McFadden & McElhinny (1988), this datum would not be representative of SV. This leaves 74 site-means with acceptable precision, as listed in Tables S1 and S2. Of them, eight site-means are anomalous, as the corresponding VGPs are more than 45° away from the overall mean direction.

When lava flows are emplaced in rapid succession, their palaeomagnetic directions may form tight directional groups (DGs), and the common practice is to replace the multiple similar site-means with a DG-mean (e.g. Riisager et al. 2003; Chenet et al. 2008, 2009). We did this by comparing the first and second site-means in each stratigraphically ordered succession with the aid of statistical F-criteria, closely following the approach outlined in, for example, Riisager et al. (2003) and Chenet et al. (2008, 2009). If the difference was statistically significant, the first flow was considered as an independent spot-reading of the field, and the second and third flow was tested, etc. When the difference between a pair of site-mean directions was statistically insignificant, the next flow was added, until a site with significantly different direction was met. All sites with statistically identical directions were treated as a DG. Several DGs were recognized, which resulted in 55 unit directions, 47 site-means and 8 DG-means. Of them, 48 entries (42 sites, 6 DGs) form a rather well-defined cluster, whereas the remaining seven directions (6 sites and one DG of 2 sites) are anomalous and all belong to the lower sections (L1, L2 and A; Figs 4a and b). These anomalies were first identified visually; then, the site-means were converted to poles, and all ‘suspects’ proved to fall more than 45° away from the mean pole (Fig. 4b). It is worth noting that demagnetization characteristics of the ‘standard’ samples from the cluster (left column, Fig. 3) are similar to those with anomalous directions (middle column, Fig. 3). Note also the mean directions and statistical parameters of the data sets change just slightly whether they are calculated for original site-means only or for a mixture of site-means and DG means (Table 1).

Normal polarity is predominant in the Aral volcanics; reverse rocks are seen only in the lower parts of sections B and C plus a single reverse flow in section L2 (site M9024, Fig. 2b). Nonetheless, the number of reverse polarity vectors is sufficient for a reversal test. For the entire data set, two polarity-means differ by \(\gamma = 13.9°\), which is less than the critical value, \(\gamma_{95} = 14.5°\), although concentration parameters of 15.3 and 38.7 for normal and reverse data, respectively, are statistically different (McFadden & McElhinny 1990). Nevertheless, the reversal test can be considered positive (class C) for the whole data set.

The Aral rocks are gently folded, and the fold test (McElhinny 1964) is inconclusive for the combined data set, as well as for the lower part of the sequence (Table 1). In contrast, the grouping of B & C directions does improve upon tilt correction (Table 1). The increase is marginally below the 95 per cent critical value (McElhinny 1964), but becomes significant at a lower (90 per cent) level. The best data grouping is reached at 90 per cent unfolding, the maximum \(k\) value of 48.0 being just barely different from the \(\Delta\) value of 46.4 in stratigraphic coordinates. Moreover, another version of the fold test (McFadden 1990) is positive at 95 per cent confidence level. Hence we think that the HTC in the Aral volcanics is pre-folding. Unfortunately, the positive fold test does not impose strong constraints on the remanence age, as, because of the lack of overlying rocks, deformation could have taken place at any time from the Carboniferous to the Quaternary.

As noted, Levashova et al. (2007) had to sample the clasts of silicic volcanics from two conglomerate beds, as the host basalt and andesite are absent in these beds altogether. They isolated a single component that shows rectilinear decay to the origin from the clasts; the conglomerate test for this component is positive. As demagnetization characteristics of the clasts and host rocks are very similar, Levashova et al. (2007) concluded that these data taken together point to the absence of remagnetization also in the host rocks. The reversal and fold tests for the Aral volcanics are also positive. Taken together, these lines of evidence strongly favour the primary origin of the HTC in these rocks.

Scatter, outliers and dispersion

As noted, slight differences in demagnetization characteristics exist between the upper (section B and C) and lower (sections L1, L2 and A) parts of the sequence. Much more pronounced, however, are the differences in directional data, as can be seen when comparing Figs 4(a) and (c). Although clustering of non-anomalous vectors is undisputable in the lower part of the sequence, their rather high scatter is further underlined by five anomalies in the L1 and A sections (Table S1, grey-shaded rows; see also Figs 4a and b). Moreover, two anomalous directions from adjacent flows are significantly different (sites M1265 and N4822, Figs 4a and b), and most likely belong to different geomagnetic events. Other two anomalies are found in section L2, for which precise correlation with the other two sections is difficult. Note that only one anomalous site (n3761, Table S1) falls between normally and reversely magnetized rocks, whereas all other anomalies are intercalated inside sequences of normal polarity data; these then have to be regarded as geomagnetic excursions. Thus, the palaeomagnetic record from the lower part of the Aral Fm. implies the existence of a strongly disturbed geomagnetic field. In general, this pattern resembles that of late Cenozoic data from the
Erebus Volcano in Antarctica, where numerous anomalies surround a rather diffuse core (Lawrence et al. 2009).

A markedly different pattern is revealed by the upper part of the formation, where, irrespective of polarity, unit vectors are much better clustered (Tables 1 and S2), and where anomalous directions are absent altogether (Fig. 4c). In particular, no transitional directions were found between the adjacent sites of opposite polarity. The reversal test for the combined sections B and C is positive ($\gamma = 7.4^\circ$, $\gamma_{\text{crit}} = 10.1^\circ$, class C), and concentration parameters for normal and reverse directions are statistically identical (Table 1), as required by an ‘ideal’ reversal test (McFadden & McElhinny 1990). In both sections B and C, a larger upper part is normal and a narrower lower interval is reverse. Hence these two sections, which are from the opposite limbs of the broad syncline (Figs 1b and 2a), are either nearly coeval, or section C is younger. An answer to this question depends on the location of the syncline axis, but, unfortunately, no bedding measurements are available between the B and C sections (Fig. 1b); this is the reason for the portrayal of two different placements of the section (as C1 and C2) in Fig. 2b.

It should be emphasized that, even after the omission of anomalous directions, the scatter (as measured by the concentration parameter, $k$) in its upper part is nearly four times less than in the lower part (Table 1), which is statistically significant. This difference retains irrespective of whether original site-means only or DG-means and site-means were used. Note that some site-means, from the lower horizons in particular, are not very precise, and incompletely averaged within-site dispersion may have contributed to a higher scatter of the data from the L1, L2 and A sections. As the angular dispersion, $s$, and concentration parameter, $k$, are related by the equation $s^2 = \frac{s^2_{\text{total}} - s^2_{\text{site}}}{n}$, a possible distortion by within-site dispersion due to orientation or measurement error was evaluated with the aid of the following equation:

$$s^2_{\text{field}} = s^2_{\text{total}} - \frac{s^2_{\text{site}}}{n},$$

which relates the SV-related angular dispersion $s^2_{\text{field}}$ to the observed angular dispersion $s^2_{\text{total}}$ minus within-site angular dispersion $s^2_{\text{site}}$ divided by $n$. In this equation, the bar-$s$ and bar-$n$ parameters are the average values of the within-site concentration parameter and the number of samples in each lava flow or sites in each DG, respectively (Merrill et al. 1996). The corrected $k$ values for the lower and upper data sets are very similar to the non-corrected ones (see entries 6 and 9 in Table 1); hence, the contribution of the within-site
scatter to the total dispersion is negligible. A still simpler test is to exclude all poorly defined data with, say, $\alpha_{95} > 10^a$ and recalculate concentration parameters; this test accomplishes no noteworthy change (entries 7 and 12 in Table 1). We therefore conclude that the statistically significant difference in dispersion between two parts of the Aral Formation is a real and robust phenomenon. As many scientists prefer to work in pole space with standard angular deviation of the Aral volcanics. 

**Table 1.** Summary of HTC directions in the Aral volcanics.

<table>
<thead>
<tr>
<th>#</th>
<th>Sections</th>
<th>N</th>
<th>$D$ (°)</th>
<th>$I$ (°)</th>
<th>$k$</th>
<th>$\alpha_{95}$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>All (sites)</td>
<td>66</td>
<td>308.4</td>
<td>35.3</td>
<td>16.4</td>
<td>4.4</td>
</tr>
<tr>
<td>2</td>
<td>All (sites &amp; DG)</td>
<td>48</td>
<td>306.0</td>
<td>36.5</td>
<td>308.7</td>
<td>42.7</td>
</tr>
<tr>
<td>3</td>
<td>All normal</td>
<td>41</td>
<td>303.0</td>
<td>44.3</td>
<td>15.2</td>
<td>5.5</td>
</tr>
<tr>
<td>4</td>
<td>All reverse</td>
<td>7</td>
<td>142.5</td>
<td>$-47.2$</td>
<td>38.7</td>
<td>9.8</td>
</tr>
<tr>
<td>5</td>
<td>A+L1+L2 (sites)</td>
<td>30</td>
<td>297.2</td>
<td>29.3</td>
<td>294.8</td>
<td>41.1</td>
</tr>
<tr>
<td>6</td>
<td>A+L1+L2 (sites &amp; DG)</td>
<td>25</td>
<td>295.5</td>
<td>32.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>A+L1+L2 ($\alpha_{95} &lt; 10^a$)</td>
<td>15</td>
<td>300.5</td>
<td>28.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>B+C (sites)</td>
<td>36</td>
<td>318.5</td>
<td>39.2</td>
<td>298.8</td>
<td>40.3</td>
</tr>
<tr>
<td>9</td>
<td>B+C (sites &amp; DG)</td>
<td>23</td>
<td>317.8</td>
<td>39.5</td>
<td>319.9</td>
<td>42.7</td>
</tr>
<tr>
<td>10</td>
<td>B+C normal</td>
<td>17</td>
<td>317.3</td>
<td>42.7</td>
<td>319.2</td>
<td>44.0</td>
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<td>11</td>
<td>B+C reverse</td>
<td>6</td>
<td>145.3</td>
<td>$-47.5$</td>
<td>317.3</td>
<td>42.7</td>
</tr>
<tr>
<td>12</td>
<td>B+C ($\alpha_{95} &lt; 10^a$)</td>
<td>21</td>
<td>317.8</td>
<td>38.7</td>
<td>319.9</td>
<td>44.5</td>
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</tbody>
</table>

Notes: Studied sections are labelled as in the text and Figs 1(b) and 2(a). #1–4, means for all sections: #1, overall mean for all sites; #2, mean for directional groups (DGs) and remaining sites (see text for detail); #3 (4) same as #2 for data of normal (reverse) polarity. #5–7, means for sections A+L1+L2 (Lower Aral): #5, mean for all sites; #6, mean for DG’s and remaining sites; #7, same as #6 for all data with $\alpha_{95} < 10^a$. #8–12, mean for sections B and C (Upper Aral): #8, mean for all sites; #9, mean for DG’s and remaining sites; # 9 (10) same as #9 for data of normal (reverse) polarity; same as #9 for all data with $\alpha_{95} < 10^a$. Anomalous sites are excluded everywhere. N, number of sites and sites and DGs; D, declination; I, inclination; k, concentration parameter; $\alpha_{95}$, radius of confidence circle (Fisher 1953). For # 6 and 9, observed values of concentration parameter (those corrected for residual within-site scatter) are presented (see text for detail).
which is the lower limit for SV averaging (Merrill et al. 1996). All in all, there are all reasons to believe that the SV is well represented in this data set.

Formally, the presence of both polarities in a data set is often considered as a strong indication of a long time interval being spanned and SV being averaged; this reasoning is further enforced if the data ‘pass a reversal test which suggests adequate representation of the SV’ (Biggin et al. 2008b). This is what we found in the B&C data set. Moreover, the concentration parameters for reverse and normal subsets are statistically identical; in other words, the reversal test is double positive (Table 1), which further strengthens the conclusion that that the SV are adequately represented in B&C data set.

Carriers of the remanence and rock magnetic experiments

Demagnetization data (Fig. 3) seem to indicate the presence of magnetite and haematite in varying proportions as the principal remanence carriers in the Aral volcanics. In principle, a pattern similar to that depicted in Fig. 3(c) or (f) may be due to haematite alone, its coarser and finer grains carrying ‘haematite’ and ‘magnetite’ components, respectively. To evaluate this possibility, we compared alternating field and thermal demagnetization data for sister specimens (Fig. 5). As expected, the samples that are completely demagnetized by 600°, show magnetite-like alternating field demagnetization plots (Fig. 5a), while the samples with the remanence that is entirely unblocked above 600° reveal the typical

Figure 5. Analysis of magnetite and haematite components for those sites where both remanences are isolated from more than two samples. (a–d) Plots of magnetization intensity versus alternating field (solid line & blue dots) and temperature (dashed line & red dots) on the left and right in each box, respectively. Initial parts of all plots (<5 mT and <200°) corresponding to removal of the low-temperature component are omitted from the plots. (e) Exsolution structure pointing to magnetite existence in a sample where the main part of the NRM resides in haematite. (f) For each site, the magnetite direction is rotated to the projection centre, and the haematite direction is shown as a filled circle. For clarity, confidence circles (thin lines) are shown only for a few haematite data. Star and thick red line, overall haematite mean and its 95 per cent confidence circle. The grey dot is the only deviating haematite site-mean based on three samples, and has been excluded from computation of the haematite mean. The 5° circle around the projection centre is shown as a thick dashed line (in green) for reference.
‘haematite’ behaviour (Fig. 5b). In ‘mixed’ samples, both magnetite and haematite patterns are observed in lower and higher fields, respectively (Figs 5c and d). Exsolution structures, which are typical for high-temperature oxidation, also point to existence of magnetite even in haematite-rich samples (Fig. 5e). Thus we conclude that the mixture of magnetite and haematite is, in fact, present in these rocks.

Close agreement of magnetite and haematite directions, such as observed in the Aral Fm. (Fig. 2), is common in lava series and is often attributed to high-temperature oxidation of magnetite during, or immediately after, lava emplacement (e.g. Levashova et al. 2009; Swanson-Hysell et al. 2009). Usually, this agreement is estimated qualitatively or by comparing the overall mean directions of the different components (Tauxe & Kodama 2009). Here, we have quantified the relationship between magnetite (with unblocking temperatures <580 °C) and haematite components (>600 °C) by separately isolating them and calculating the corresponding site-means for those sites where both components are found in three or more samples. This proved to be possible for 29 sites. Subsequently, each pair of site-means is transferred to the centre of a stereonet in such a way that the magnetite component mean is placed at the projection pole.

If the acquisition of these components were separated by a substantial time interval, the transferred haematite directions would be dispersed and systematically displaced from the projection pole. We do not observe this (Fig. 5f): 28 haematite site-means are tightly, and nearly symmetrically distributed around the projection pole, deviating typically by less than 5°. The overall average angle between the magnetite and haematite direction is 3°. Only one mean, based on only three samples, deviates by more than 10° (grey circle in Fig. 5f) and has been discarded from further consideration. At none of the 28 retained sites, the angular difference between two components is statistically significant.

Thus, haematite vectors are nearly symmetrically distributed around the projection pole (i.e. the magnetite mean in Fig. 5e), and the overall haematite mean differs from it by less than 2°. Haematite and magnetite directions are in tight accord and indicate that the acquisition of the two components was nearly contemporaneous. If historical archeomagnetic data (e.g. Gallet et al. 2002) would be taken as a yardstick, such an angular difference would represent a delay of a few centuries, at most.

Now we need to examine whether the dispersion differences between the lower and upper parts of the Aral Formation may be attributed to different rock magnetic properties (e.g. grain size or domain state). To this end, two instruments at the Institute for Rock Magnetism in Minneapolis have been employed: an MPMS and a VSM. The VSM has yielded hysteresis parameters and First-Order Reversal Curves (FORC diagrams). These measurements indicate that the grain size distribution ranges from single-domain (SD) to multidomain (MD) for the upper part of the Formation, with most of the data in the pseudo-single domain (PSD) field (Fig. 6). The values from the upper part (red squares in Fig. 6) overlap those of the lower part, but the latter are entirely in the PSD field, having a smaller range than those of the upper part.

Using the MPMS, remanence as a function of low temperature (20–300 K) is measured, and acquired in a small field (5 mT) either during cooling from room temperature (FC), or acquired at 20 K, after cooling in zero field (ZFC) and then letting it warm up while measuring the magnetic moment. Low-temperature cycling (300 → 20 → 300 K) involves a room-temperature saturation isothermal remanence (SIRM) acquisition and measurement as a function of temperature (Fig. 7). In samples from the upper, as well as the lower, part of the Aral Formation, the remanence is much diminished in a transition at about 120 K (Bowles et al. 2009), and this is observed both upon warming and upon cooling (Fig. 7). This Verwey transition is diagnostic of PSD and MD magnetite (Jackson et al. 2011). Haematite also undergoes a transition (‘Morin’), but our samples did not reveal this, other than as a very broad convex upward part of the RT curves; however, haematite is unquestionably present and a remanence carrier, uniquely identified by its unblocking temperatures above 600 °C.

WHAT COULD CREATE THE OBSERVED PATTERN?

We successfully isolated a dual-polarity characteristic remanence from more than 70 lava flows and presented strong evidence that
Figure 7. Remanence as a function of low-temperature, obtained by a Magnetic Properties Measurement System (MPMS) at the Institute of Rock Magnetism (IRM) at the University of Minnesota, which shows the similarities between a sample from the lower part of the Aral Formation (m1322) and a sample from the upper part (m1391), and clear indications of the Verwey transition at about 120 K; this transition is diagnostic of magnetite (likely in PSD or MD state, see Fig. 6). The remanence is acquired in a low (5 mT) field either during cooling (FC) from room temperature, or acquired at 20 K, after cooling in zero field (ZFC) and then letting it warm up while measuring the magnetic moment. Low-temperature recycling (300 → 20 → 300 K) involves a room-temperature saturation isothermal remanence (SIRM) acquisition and measurement as a function of temperature (RT).

this remanence is primary and was acquired either during cooling or very soon after that as a result of oxidation. We think that the main finding of our study is the difference between the distributions of palaeomagnetic directions in the lower and upper parts of the geologically uniform volcanic pile. Typical concentration parameter values in most SV models are below 40. For instance, they range from 15 to about 30, depending upon the latitude, in the model of Tauxe & Kent (2004). The overall mean inclination for the Aral Fm. (Table 1) corresponds to a palaeolatitude of about 26°; thus, the model by Tauxe & Kent (2004) predicts \( k = \sim 16 \) for an area at this latitude. It is clear that the predicted value agrees well with that for the lower Aral Fm. \( (k = \sim 13) \), but is significantly less than the value for the upper Aral Fm. \( (k = \sim 50) \). At the same time, \( k \) values of about 50 are not unheard of among PSVL results, as exemplified by late Cenozoic data from British Columbia (Mejia et al. 2002) or Cretaceous data from Arctic Canada (Tarduno et al. 2002). Thus, with respect to our data, we may look for an explanation of either severely scattered directions in the lower part of the section or outright ones in the upper part.

There is a possibility that the lower section may be affected by hydrothermal activity (Fig. 2a), disturbing the magnetizations, thus accounting for its increased scatter, whereas the upper section might not. However, the available data (Figs 5 and 6) do not reveal large differences in rock magnetic parameters through the lava pile. Through the entire pile, there are no veins, changes of colour or other features related to such hydrothermal alteration (of course, except for the well-localized altered zones themselves). Note also that section L1 in the ‘dispersed’ data set is the remotest from the alteration zone (Fig. 2a). Finally, the complete lack of secondary components in these volcanics, except for the present-day overprint, also testifies against this assumption.

On the other hand, the SV might have been strongly reduced in sections B&C by long-term remagnetization. In our case, judging by orthogonal plots (Fig. 3), one must assume that the rocks are completely overprinted, which is apparently compatible with the presence of oxidized magnetic minerals. We cannot explain, however, why the conglomerate and double reversal tests are positive in this case. Moreover, the widely disparate dispersions in the lower part of the section are difficult to connect with remagnetization; hence this process would have had to completely reset the remanence in the upper part of the formation, but leave it unaffected in the lower part. Lastly, it is very difficult to explain why the haematite and magnetite components are so similar at the within-site level, but reveal much larger scatter at the between-site level. Therefore, if the observed pattern was indeed created by a remagnetization process, it must have been a strange and extremely selective one. Thus, we conclude that the rock-magnetic explanations cannot account for the observed pattern.

Since magnetic compasses were used for sampling, strongly magnetized basalts might have affected their readings and create an artificial scatter in the lower part of the section. This ‘threat’ was foreseen in advance and countered in two ways. First, we routinely checked whether the rocks affected compass readings and did not find a single case of such an influence. Second, we chose the samples with as many different orientations as possible at each site. In reality, it is very unlikely that the compass readings were distorted, but component directions remained clustered at the within-site level. It is worth adding that the NRM intensities and susceptibilities were broadly similar throughout the volcanic pile. In sum, it seems impossible to invoke orientation errors and/or local magnetic anomalies as the source of higher scatter in the lower part of this pile.

The entire pile in the western part of the area crops out as a nearly perfect homocline (sections L1, L2, A and B, Fig. 2c); no local deformations or detached blocks within the flows were found throughout the entire pile. Hence it is unlikely that the higher scatter in the lower part of the pile is due to unaccounted-for tectonic motions.

It is known that a correct description of the geomagnetic field requires space–time averaging (Merrill et al. 1996, and references therein), and the data from a limited area may produce false minima of SV magnitude, as is well known from the example of the Pacific Dipole Window (Doell & Cox 1972). Thus, the Aral data set may...
also be attributed to regional lows of SV. The life span of such lows, however, is thought to be not more than a few thousand years (Merrill et al. 1996), whereas the above-presented arguments, especially the presence of both polarities, point to intervals that are 100 times longer.

The conventional wisdom regards the presence of two polarity groups as strong evidence that sampling encompasses a long enough time interval of more than $10^2$–$10^3$ yr, so that adequate averaging of the SV is likely to have been achieved. This opinion is further substantiated if the reversal test is ‘double positive’, meaning that polarity-means are statistically antipodal, and that the corresponding concentration parameters are statistically equal, which is, in fact, observed for the upper Aral result (Fig. 4c and Table 1).

However, it is important to ask: how likely is it that the double-positive reversal test is a coincidence, and, in fact, the SV is strongly underrepresented in sections B&C? Let’s assume that the dispersed lower data set (L1&L2&A) covers the entire range of SV and provides a correct estimate of the angular dispersion, and that we are trying to estimate the probability of randomly getting a B&C result from the diffuse ‘true population’. The probability of this joint event is equal to the product of several ‘unit’ probabilities: of the B&C normal data having lower-than-expected scatter, of the B&C reverse data being overtight too, of the corresponding means being antipodal, and of concentration parameters being statistically identical. We cannot accurately evaluate the probability of each unit event but are sure that each unit probability cannot exceed 0.5; it is, perhaps, more likely that each is much less. Therefore, the probability of the joint event is less than 0.1 even for the very conservative estimates we adopted; in other words, the probability of randomly getting the observed pattern is low to very low, but, of course, it is not zero. Unfortunately, we cannot prove that section C is younger than section B (C2 in Fig. 2b); had it been an established observation, the total chain of ‘coincidences’ would have to be applied to four successive polarity zones, which would border the ridiculous.

We then looked for an alternative explanation of the situation when two parts of a geologically uniform sequence display disparate patterns of angular dispersions, both patterns being produced by a primary remanence acquired in thick sections of presumably longer duration than thought to be the minimum for SV to be averaged. This aspect is puzzling because it is commonly assumed that the SV magnitude stays approximately constant at a given palaeolatitude and does not vary with time spans on the order of a mere million years. This basic assumption is actually a deep-rooted belief, as it is not difficult to find data sets with the overall scatter being larger than the commonly adopted level, say, with $k < 10$. What is difficult indeed is to prove that this high dispersion is fully due to SV. To date, several attempts to deal with highly dispersed data, for example, for the Southwestern USA (Tauxe et al. 2003), were not overly successful.

A search in the opposite direction, that is, among overtight data sets, appears to be more promising. Because this can be a complicated matter, several conditions must be met. For instance, it is very desirable to have time-series, and not randomly sampled outcrops. In our Aral case, little could have been suspected, had the sites been taken randomly from the lava pile. Another very important pre-requisite is the presence of two polarities, which gives firmer grounds to suggest that a sufficiently long time interval was covered.

Our search produced quite a few cases that can be considered as compatible with the VSV hypothesis (Table 2). All results in this table are based on lava flows, detailed stepwise demagnetization and principal component analysis. All results, except the Cretaceous Cis-Baikal one, are on stratigraphically ordered collections. Normal or reverse polarity was found in three or more sites for each. The reversal test is not positive in all cases, but the angular difference between polarity-means is more than 170° everywhere. Concentration parameter values are large to very large, although the statistical equality condition is not always satisfied for both polarities. The weakest spot of these results is that the number of sites is moderate to small, and that there are less than 10 sites for at least one of the two polarities (Table 2). Despite these self-evident shortcomings, two important points emerge. First, the ages of these ‘overtights’ range from the Devonian to Pliocene; hence VSV is not tied to a unique interval. Second, the $k$ values in Table 2 appear to indicate that the degree of SV attenuation may vary over a much wider range than is indicated by the Aral data.

### Table 2. Overtight palaeomagnetic data on volcanics.

<table>
<thead>
<tr>
<th>Locality</th>
<th>Age</th>
<th>N</th>
<th>N/R</th>
<th>$D(\circ)$</th>
<th>$I(\circ)$</th>
<th>k</th>
<th>$\alpha_95(\circ)$</th>
<th>$k_a/k_b$</th>
<th>$\gamma(\circ)$</th>
<th>$\gamma_{crit}(\circ)$</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>S Georgia</td>
<td>~4</td>
<td>25</td>
<td>17/8</td>
<td>356.8</td>
<td>55.9</td>
<td>159</td>
<td>2.3</td>
<td>226/154</td>
<td>5.8</td>
<td>4.6</td>
<td>(1)</td>
</tr>
<tr>
<td>NE China</td>
<td>6–10</td>
<td>18</td>
<td>11/7</td>
<td>354.3</td>
<td>56.7</td>
<td>184</td>
<td>2.6</td>
<td>181/405</td>
<td>5.9</td>
<td>4.7</td>
<td>(2)</td>
</tr>
<tr>
<td>Mongolia</td>
<td>28–32</td>
<td>26</td>
<td>8/18</td>
<td>1.0</td>
<td>56.8</td>
<td>75</td>
<td>3.3</td>
<td>257/76</td>
<td>9.9</td>
<td>6.3</td>
<td>(3)</td>
</tr>
<tr>
<td>Cis-Baikal</td>
<td>~118</td>
<td>12</td>
<td>6/6</td>
<td>30.8</td>
<td>66.8</td>
<td>56</td>
<td>5.8</td>
<td>48/56</td>
<td>2.2</td>
<td>12.3</td>
<td>(4)</td>
</tr>
<tr>
<td>N Kazakhstan</td>
<td>Tm−1</td>
<td>7</td>
<td>3/4</td>
<td>55.9</td>
<td>69.1</td>
<td>208</td>
<td>4.2</td>
<td>300/293</td>
<td>6.8</td>
<td>7.3</td>
<td>(5)</td>
</tr>
<tr>
<td>Kyrgyzstan²</td>
<td>D1</td>
<td>23</td>
<td>17/6</td>
<td>317.8</td>
<td>44.0</td>
<td>46</td>
<td>4.5</td>
<td>52/38</td>
<td>7.4</td>
<td>10.1</td>
<td>(6)</td>
</tr>
</tbody>
</table>

Notes: Age in Ma or as geological divisions: Tm−1, Middle-Late Triassic, D1, Late Devonian. All data are in stratigraphic coordinates. N/R, number of normal/reverse unit vectors. $k_a/k_b$, concentration parameters for normal/reverse data (shaded, if these values differ insignificantly). $\gamma, \gamma_{crit}$, observed angular difference between two polarity-means and 95 per cent critical angle, respectively (McFadden & McElhinny 1990); shaded, if $\gamma < \gamma_{crit}$. Ref.: (1)—Gogutichaichvili et al. 1997; (2)—Zheng et al. 2002; (3)—Hankard et al. 2007; (4)—Metelkin et al. 2010; (5)—Bazhenov et al. 2008; (6)—this paper. Other notation as in Table 1.

²For sections B and C only.
The characteristic duration of time intervals with strongly subdued SV magnitudes cannot have much exceeded 1 Myr; had it been otherwise, such intervals would have been already found, in particular, among the sufficiently numerous Cenozoic PSVL results. On the other hand, the existence of (nearly) antipodal directions with a similar dispersion in adjacent polarity zones indicates that the intervals with decreased SV magnitude are likely to be much longer than the duration of transitional zones (≈5 ky) or the longest periods in the SV spectrum (≈10 ky) (Merrill et al. 1996). Therefore, the probable length of such intervals may fall between 10^5 and 10^6 yr. Of course, these are very rough estimates; moreover, the intervals with different SV magnitudes are unlikely to have sharp boundaries.

To verify or falsify the VSV hypothesis, one must demonstrate whether very different SV magnitudes are observed simultaneously in distant parts of the globe. For instance, a recent study of minor andesite intrusions of Late Triassic age (40Ar–39Ar age of ≈210 Ma) from the southeastern Ukrainian Shield (Yuan et al. 2011) revealed dual-polarity data (k = 96, N = 12 sites from seven intrusions) that form two very tight polarity groups and pass the reversal test (γ = 2.1°, χ = 8.9°, class B). A similarly tight grouping is found in Middle-Late Triassic lava flows from Kazakhstan (Table 2; Bazhenov et al. 2008). This case, however, is not compelling, as the Ukrainian datum is not from lava flows, but from intrusions, where partial SV attenuation could have taken place. Besides, the age of the Kazakhstan result is inferred, rather than proven, thus further underlining the validity of the case. And, to make matters worse, both results are based on very limited statistics.

It is worth stressing once more that the presence of at least two polarity zones is crucial simply because a single-polarity data set will almost inevitably remain under suspicion of the SV being underestimated. It may be that the real number of the overtights is actually much larger, but they remain unsuspected if one polarity only is present in a data set. Thus, all depends upon finding two or more exactly coeval dual-polarity PSVL results from different areas. This task cannot be accomplished for old rocks simply because the accuracy of age determinations is comparable to, or larger than, the length of the proposed characteristic times of 10^6–10^7 yr for SV changes. In other words, it is not very likely to find a lava series that is exactly coeval to the Aral Flm., but if one did, it would be nearly impossible to prove that it is so. Examining Table 2, only the Pliocene result from Southern Georgia (Gogitshaichvili et al. 1997) may have a suitable counterpart from a distant part of the Earth somewhere as a feasible target.

Being sufficiently cautious with introducing the VSV hypothesis apparently justifies some words about its consequences. For instance, the recent compilation within the framework of the Time-Averaged Field Initiative (Johnson et al. 2008) did not reveal a clear dependence of SV magnitude upon latitude, despite the greatly enlarged data set. The VSV hypothesis can easily account for this unpleasant surprise; the apparently irregular dispersion observed by Johnson and colleagues (2008) may well be the result of an SV magnitude that is dependent upon latitude as well as time. A study of PSV during the Jurassic, when reversals were frequent, also did not reveal a linear pattern, whereas results from the Cretaceous Normal Superchron conformed more to the expected latitudinal dependence (Biggin et al. 2008b).

The observed difference in concentration parameters between the Lower and Upper Aral data sets (Fig. 4 and Table 1) corresponds to values of standard angular deviation, s, of 22.4° and 11.9°, respectively. In other words, the relative intensity (ratio) of the long-term average axial dipole and the fluctuating non-axial and higher-order fields changes just about two-fold, but results in a very different appearance for two the data sets. A natural question is what will happen if this ratio changes about twofold in the opposite direction. The corresponding value of k will be between 40° and 45°, and the k value will be just about 4, thereby immediately rendering the correct polarity determination of many unit vectors a rather perilous matter. Moreover, the very distinction between steady-state and anomalous directions becomes dubious, at best. It is not a purely hypothetical case either: Devonian volcanics are known from different parts of the Siberian craton and its periphery but, despite numerous exposures and the lack of strong alteration, multiple attempts to obtain a reliable palaeomagnetic pole from these rocks have failed thus far because of extremely high between-site scatter of palaeomagnetic directions (Kazansky et al. 2007; A.V. Shatsillo, personal communication, 2010), whereas the wider known result (Kravchinsky et al. 2002) is just a limited subset of what is available. Within the VSV hypothesis, these failures can be explained by a very low ratio of the axial dipole (held constant) and fluctuating components.

Among other consequences of the VSV hypothesis, it is worth noting that the very concept of the time-averaged field is to be revised so that the accurate determination of a mean field direction appears to require appreciably shorter time intervals (10^5–10^6 yr) than the duration from which one can estimate the angular dispersion of field directions (10^6–10^7 yr or more). In turn, this implies that much more information may be needed to establish with some confidence the relationship between SV magnitude and (1) palaeolatitude (Johnson et al. 2008), (2) reversal frequency (Tarduno et al. 2002) and (3) core growth or the Earth evolution in general (Biggin et al. 2008a). Even formerly straightforward palaeopole determinations may be affected as it becomes questionable whether SV is adequately averaged. Of course, mean directions or poles can be based on the same statistics as before, but how to assess the associated confidence intervals is not clear.

As discussed earlier, we could not find a ‘local’ (i.e. involving present-day magnetic anomalies) alteration and remagnetization explanation for the observed pattern in the Upper Devonian Aral lava series of the North Tien Shan. If we refer to geomagnetic origin of this pattern, we have to choose between a coincidence and VSV hypothesis. Naturally, this hypothesis calls for more tests on thick lava piles, consisting of many tens or even a hundred flows. And the psychologically most difficult part of future studies is the unpredictability, as we see no way to forecast the concentration parameter value.

CONCLUSIONS

We studied 80+ flows of Upper Devonian basalts and andesites in the North Tien Shan and successfully isolated a dual-polarity, HTC for ~90 per cent of them. A primary origin of this component is supported by positive conglomerate, reversal and fold tests. The most intriguing feature of this Devonian data set is that we have obtained very different directional patterns in the lower and upper halves of the studied >600-m-thick lava sequence: palaeomagnetic directions are rather dispersed in the lower one (k ~13), about 25 per cent of them being anomalous, whereas the vectors are about four times more tightly grouped (k ~46), and without any anomalies altogether, in the upper half. We have exhaustively analysed several non-geomagnetic and geomagnetic explanations for such data, but none can be considered realistic and probable. Hence we propose a hypothesis that the SV magnitude may vary several-fold over time intervals of ~10^5–10^6 yr to account for the observed pattern. This concept, however, is in discord with other SV models, where
the SV magnitude is assumed to be constant. Several supportive palaeomagnetic results with unusually high clustering are found in the literature, although not yet numerous and reliable enough to dispel all possible doubts and objections. Moreover, a recently published paper (Smith-Boughner et al. 2011) cautiously points to the possibility that basic characteristics of geomagnetic field may vary on intervals of few million years. Therefore, we suggest that many more studies are needed to check the validity of this hypothesis.

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