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Palaeomagnetic study of Vendian and Early Cambrian rocks of South Siberia and Central Mongolia: was the Siberian platform assembled at this time?

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Abstract

A palaeomagnetic study of Vendian and Early Cambrian sediments from the Angara block of the Siberian platform: Shaman (52.08°N, 108.83°E) and Minya (58.0°N, 110.0°E) Formations, and the Tuva-Mongolian block: Tsagan-Olom and Bayan-Gol Formations (46.76°N, 96.37°E) isolated three different components of magnetization through thermal demagnetization. The stable high-temperature characteristic remanence directions show both normal and reverse polarities. The mean palaeopoles computed after these high-temperature components are: 32.0°S/71.1°E (dp/dm = 6.9°/13.8°) for the Vendian Shaman Formation (10 sites, 80 samples), 33.7°S/37.2°E (dp/dm = 8.6°/14.7°) for the Vendian Minya Formation (12 samples), 22.8°S/28.4°E (dp/dm = 10.8°/21.6°) for the Vendian Tsagan-Olom Formation (4 sites, 25 samples) and 21.4°S/167.1°E (dp/dm = 9.6°/19.1°) for the Early Cambrian Bayan-Gol Formation (6 sites, 49 samples). From a compilation of Vendian and Early Cambrian palaeopoles from the Anabar, Angara and Aldan blocks of the Siberian platform and Tuva-Mongolia block, we propose a model where these blocks were situated in an equatorial to low south palaeolatitude position, with their present-day southern boundaries facing the north pole. From the analysis of the scatter of these poles, we conclude that the Siberian platform might not have fully amalgamated by this time, and that significant rotations occurred after the Early Cambrian. Our new palaeopoles for the Tuva-Mongolia block, together with previously published ones, show that this block was already adjacent to Siberia by the Vendian and Early Cambrian. We propose that the large counterclockwise rotation of the Tuva-Mongolia block with respect to Angara block could mark the end of the closure of the part of the Palaeo-Asian ocean separating these two blocks, and could account for the occurrence of Vendian-Early Cambrian ophiolites in the region.

Keywords: Early Cambrian; Mongolia; Palaeomagnetism; Palaeoreconstructions; Siberian platform; Vendian

1. Introduction

Terrigeneous sediments of palaeontologically-based Vendian–Early Cambrian age are widely

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spread over the south of East Siberia (for Vendian System, see Sokolov and Ivanovsky, 1985). The lithological composition clearly indicates a transgressive character of these formations surrounding the lithospheric blocks and covering more ancient metamorphic complexes. Intense folding of Precambrian and Phanerozoic sediments in suture zones, nappes, thrusts, metamorphism and magmatism are interpreted by Belichenko et al. (1994) to suggest a number of accretion episodes of Late Precambrian, Early to mid-Palaeozoic and Mesozoic age in the region. Knowledge of the magnitude of pre- and post-Vendian–Early Cambrian movements is necessary for reconstruction of the palaeogeography. In turn this information is very important for regional geological mapping and estimation of oil and natural gas reserves, found in traps of Vendian–Early Cambrian age in the Siberian platform.

Vendian and Early Cambrian rocks have been the topic of active palaeomagnetic research since the late 1950s (Khamrov, 1958). However most of the palaeomagnetic poles have been obtained from fold zones around the Siberian platform (Fig. 1). The main purpose of this study was to establish magnetostratigraphic correlations of sediments at long distances in different folded zones. However, because they were obtained in deformed zones, the use of these data for palaeoreconstuctions of the Siberian platform is not appropriate and could lead to problems. Moreover, some of the measurements do not meet current requirements of reliability, and the corresponding palaeomagnetic poles are scattered by about 180° along a great circle (Kravchinsky and Konstantinov, 1997). Thus, obtaining palaeomagnetic poles from the Siberian platform is an important task.

An apparent polar wander path (APWP) for the Siberian platform from Present time to the Late Cambrian has been proposed by Khamrov (1991). The Neoproterozoic and Palaeozoic parts of this APWP were revised by Smethurst et al. (1998). However, the position of Siberian platform for Vendian and Early Cambrian times is significantly different according to different authors (Kravchinsky, 1979; Gurevich, 1981, 1984; Osipova, 1981; Kirschvink and Rozanov, 1984; Rodionov and Shemyakin, 1988; Pechersky and Didenko, 1995; Kirschvink et al., 1997; Pisarevsky et al., 1997). Thus, Smethurst et al. (1998), following Gurevich (1984) and Pavlov and Petrov (1996) suggested dividing the Siberian platform into two parts with different pre-Devonian tectonic histories.

In contrast, Zonenshain et al. (1990) and Rosen et al. (1994), suggested that Siberia formed by the amalgamation of a number of blocks in the following way: at 2200 Ma, these authors distinguish at least five blocks, the Aldan Precambrian shield, the Anabar (or Olenek) Precambrian shield, and the Tungus, Stanovoy and Angara blocks. They proposed that the system is composed of only two major blocks at 1700 Ma, a large Aldan block formed by amalgamation of the Aldan shield and the Stanovoy block, and a large Angara block comprising the Anabar shield, and the Tungus and Angara blocks (including the Sayan fold belt, the Yenisei Range and the Baikal region). The final amalgamation of these blocks to form the Siberian platform would have taken place before 1000 Ma (Zonenshain et al., 1990). However, to account for the results of the present study, we prefer to separate the Anabar Precambrian shield from the Angara block, and discuss the results in the frame of three major blocks: the Aldan, Angara and Anabar blocks (Fig. 1). The Anabar and Aldan blocks are separated by the Viluy graben, and the Aldan and Angara blocks by the Zhuya fault. The Zhuya fault, which is well exposed in the Baikal fold area, can be traced under the sedimentary cover of the Siberian platform by deep geophysical methods (Pismenniy et al., 1984; Kozlovsky, 1988), and is considered as the continuation of the Viluy graben. Finally, the boundary between the Anabar and Angara blocks is still problematic because deep geophysical methods suggest a few different faults under the sedimentary cover in the deep Precambrian basement of the platform.

Until recently, a series of ancient blocks in the south of the Siberian platform (Tuva-Mongolian, Khamar-Daban, Barguzin) were regarded as a part of the Siberian platform. However, at present, a number of Upper Riphean–Lower Cambrian ophiolitic zones to the south of the platform are well described (Sklyarov et al., 1994;

Gusev and Khain, 1995). These zones define the Palaeoasian Ocean (Zonenshain et al., 1976) separating the Siberian platform and Gondwanaland. The Tuva-Mongolian, Khamar-Daban and Central-Mongolian blocks were situated between these two major platforms. The boundary between the Barguzin block to the south, and the Angara and Aldan blocks to the north comprises Late Precambrian to Early Palaeozoic deformed areas, known as the Baikal-Patom fold belt (Fig. 1). The palaeomagnetic studies of this belt (Kravchinsky et al., 1990; Kravchinsky and Konstantinov, 1997; Konstantinov, 1998) have shown that its curved shape has been produced by an oroclinal bending mechanism. The origin of this oroclinal bending will be discussed later in this paper. The relative palaeoposition of Siberia to these blocks, and the time of accretion with the Siberian platform remain a subject of debate among geologists. Indeed, palaeomagnetism could bring valuable constraints to this history.

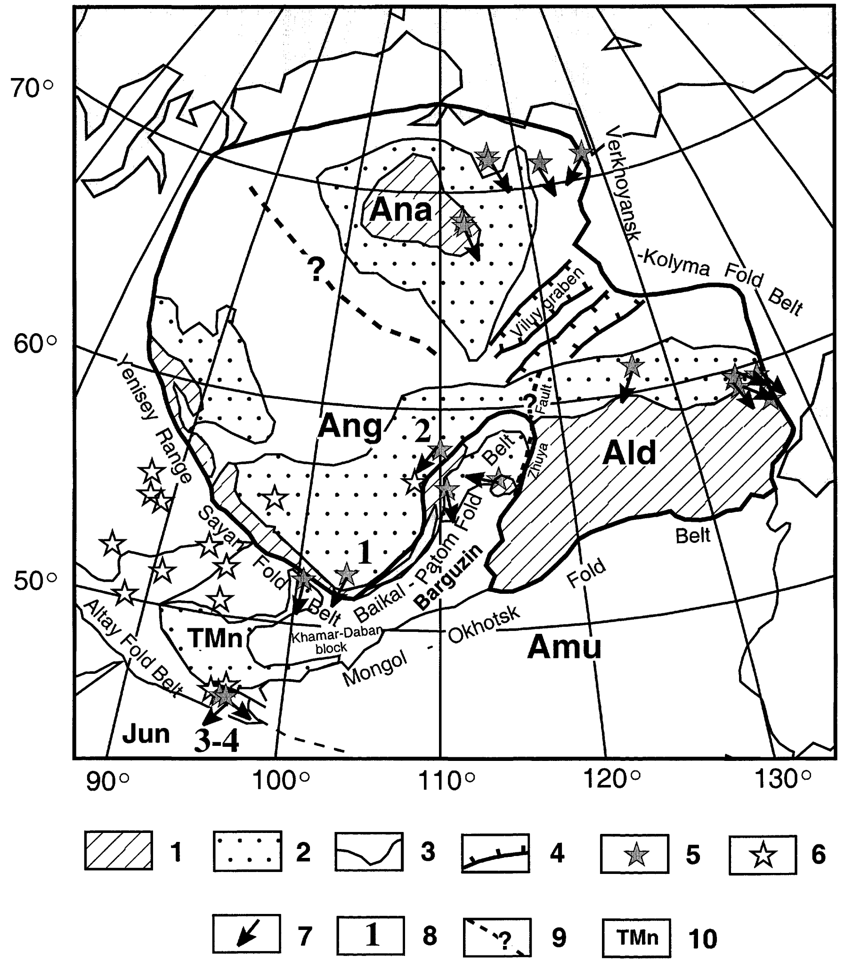

Fig. 1. Tectonic scheme of Siberia (simplified after Zonenshain et al. 1990). 1 — Precambrian shields; 2 — Riphean and Palaeozoic sediments; 3 — borders of geological structures; 4 — Viluy graben; 5 —l ocalities of palaeomagnetic investigations listed in Table 5 and used for palaeoreconstructions; 6 — localities of palaeomagnetic investigations listed in Table 5, but not used for palaeoreconstructions; 7 — palaeomagnetic declinations from selected palaeomagnetic poles of Table 5 (see text) used for further palaeoreconstructions; 8 — sampling sites: (1) Shaman Formation (Vendian), (2) Minya Formation (Vendian), (3) Tsagan-Olom Formation (Vendian), (4) Bayan-Gol Formation (Early Cambrian); 9 — possible block limits; 10 — names of blocks: Ang — Angara, Ald — Aldan, Ana — Anbar, TMn — Tuva-Mongolian, Barguzin — Barguzin, Amu — Amuria, Jun — Jungar.

The available reconstructions of the region in terms of the general tectonic evolution of the Central Asian fold belt (Kravchinsky, 1979; Zonenshain et al., 1990; Kravchinsky et al., 1990; Belichenko et al., 1994; Berzin et al., 1994; Pechersky and Didenko, 1995; Kuzmin and Kravchinsky, 1996) are open to criticism because of the lack of reliable palaeomagnetic data. In order to constrain the Late Precambrian–Early Palaeozoic tectonic history of the blocks composing and surrounding Siberia better, we present new palaeomagnetic results from Vendian formations from the southern border of the Siberian platform (Shaman and Minya Formations) and Tuva-Mongolian block (Tsagan-Olom Formation), and from an Early Cambrian Formation of the Tuva-Mongolian block (Bayan-Gol Formation).

2. Geology and sampling

We sampled four stratotype sections of Vendian and Early Cambrian age in the southern Siberian platform and Central Mongolia (Fig. 1). These sections comprise several formations and lie disconformably on Riphean rocks.

The first unit is the Yudomian (Vendian) Shaman formation (Khomentovsky et al., 1972; Khomentovsky, 1990), in the so-called Angara block (locality 1 in Fig. 1). Based on microphytolites and microfossils of the Ediacarian fauna (Khomentovsky, 1976), the Yudomian complex all over Siberia is estimated as beginning at 650–670 Ma, and finishing with the accumulation of the *Al. sunnaginicus* Zone, at 580–570 Ma (Khomentovsky, 1990). The Shaman Formation is overlain by the Irkut Formation which marks the end of the Yudomian complex (Khomentovsky, 1990). This means that the Shaman Formation could characterize the early part, and the Irkut Formation the late part of the Vendian epoch. Without any stronger argument, the age window for the Shaman Formation could span the interval from 650–600 Ma to the 600–545 Ma age of the Ediacarian epoch. We sampled 13 sites (98 samples) of fine-grained red sandstones of this formation, at Shaman Rock, near Shamanka village, on the Irkut River (52.08°N, 103.83°E). The Shaman Formation is composed of red sandstones of various grain size, with sandy limestones in its upper part, and is not metamorphosed in the Shamanka region. At this locality, the outcrops are about 70 m above the river level. However, due to access difficulties, only the lower 25 m have been sampled. The bedding is subhorizontal with little fluctuation (up to 5–10° dip, and 330–350° azimuth of dip).

The second unit, the Minya Formation from the Baikal region (locality 2 in Fig. 1), was sampled from the Chaya River outcrop, 1.5 km downstream from the Franksk waterfall (58° N, 110° E). This formation begins the Yudomian sedimentation on the east boundary of Angara block and is considered by Khomentovsky (1990) as the lateral equivalent of the Shaman Formation. The Minya Formation could represent the early part of the Vendian, because the overlying Usatov formation is also of Vendian age. Light-green, light-red and wine-red fine-grained sandstones and argillites of Yudomian age (Vendian) were sampled from the river bank outcrops. This formation is folded, but not metamorphosed. Sixteen oriented blocks were taken from a 120 m long section, where bedding planes dip monoclinally, at 30–60° towards 245–275°.

The Tsagan-Olom and Bayan-Gol Formations have been sampled in their stratotypes in the Zavkhan fold zone in the Gobi-Altay region of the central-western region of Mongolia. The tectonic position of this area is very important because it is situated between the Siberian platform to the north and Jungar, Tarim and North China blocks to the south. The formations are part of the Tuva-Mongolian block or microcontinent block (TMn in Fig. 1), which is bounded by the Altay mountain range to the west, the Sayan and Dzida fold zones to the north and the Central Mongolian (Amur) block to the south (Zonenshain, 1973). The Tuva-Mongolian block extends about 500 km E–W, and about 1000 km N–S.

The Tsagan-Olom and Bayan-Gol Formations are well exposed along the Zavkhan-Gol River (46.75° N, 96.37° E). The strata dip 10–30° toward the SSW and are disrupted by numerous thrust faults. Some localities in the Zavkhan tectonic zone are slightly metamorphosed (Khomentovsky and Gibsher, 1996), but our samples were taken from non-metamorphosed sediments along the Bayan-Gol ravine. Sampling was carried out by A. Kravchinsky during the international geological expedition in Mongolia organized by the Siberian Branch of the Russian Academy of Science in 1990. Mongolian ophiolites from the region have been studied by Pechersky and Didenko (1995); however, in such formations, bedding attitude is difficult to determine. To determine the palaeoposition of the Tuva-Mongolian block, we preferred to sample sediments with clear bedding orientation.

Thirty oriented blocks (about 60 samples) from 4 sites in the Tsagan-Olom Formation and 50 oriented blocks (80 samples) from 6 sites in the Bayan-Gol Formation were taken from an outcrop of the Bayan-Gol section (see Khomentovsky and Gibsher 1996), on the right bank of Zavkhan-Gol River near the village of Tayshir, about 4 km from the Bayan-Gol ravine. The 1750-m-thick Tsagan-Olom Formation, which disconformably overlies Neoproterozoic volcanic rocks of Dzabkhan Formation, consists of grey and black, commonly oolitic and in places sandy, limestones, containing water-plants. Palaeomagnetic samples were taken in the sandy limestones. This formation is dated palaeontologically as Vendian (600–545 Ma) by onkolites, stromatolites, and water-plants (Zonenshain, 1973; Khomentovsky and Gibsher, 1996). We sampled the first site of the Tsagan-Olom Formation a few metres above the contact with Dzabkhan Formation. The other samples were taken in the middle and upper parts of the formation. The Bayan-Gol Formation conformably overlies the Tsagan-Olom Formation in our sampling region. It has a thickness of about 1700 m and consists of sandstones and clay-rich limestones. Brachiopods, gastropods and chiolites suggest an Early Cambrian age (545–518 Ma). We sampled this formation in its lower part. The bedding along the sampled section is monoclinal, and for both formations, the direction of bedding dip varies from 165 to 200° with a dip angle from 25 to 35° for the Bayan-Gol, and 10 to 30° for the Tsagan-Olom Formation.

Another section of the Bayan-Gol Formation, the Saalany-Gol section, has already been studied for palaeomagnetism (Evans et al., 1996). Their results were obtained from the uppermost unit of the formation, above the levels we sampled, and the results of that study will be discussed below.

3. Laboratory experiments

The oriented blocks were subsampled by extracting two to three oriented 8 cm^3 cubes (referred to as samples, in the following). In total, about 240 samples from 24 sites were studied. Stepwise thermal demagnetizations and magnetic measurements of the samples were carried out in the Irkutsk Palaeomagnetic Laboratory (160 samples) and in the Institut de Physique du Globe de Paris (IPGP; 80 samples). Tables in this paper include only the samples with directions used for statistics.

The samples were demagnetized thermally in Irkutsk using ovens housed in three concentric μ-metal shields. The residual field is about 8 nT in the centre of the ovens. The samples were demagnetized using 12–50°C steps until around 690°C, and the remanent magnetization was measured with a JR-4 spinner magnetometer. Magnetic susceptibility was measured with a Kappa-bridge KLY-2 (Irkutsk) and a Molspin susceptibility-metre (Paris). In Paris, we used a custom-built oven (the residual field is about 4–6 nT), alternating field demagnetizer, a JR-5 spinner magnetometer and a three axis CTF cryogenic magnetometer. Data were processed using OPAL programs written by Vinarsky et al. (1987), the palaeomagnetic data treatment programs written by R. Enkin and the application PalaeoMac written by J.-P. Cogné at IPGP. In all cases, Zijderveld (1967) diagrams were constructed for each sample, results were analysed using principal component analysis (Kirschvink, 1980), and site-mean directions were calculated using Fisher (1953) statistics. For mixed populations of directions and remagnetization great circles, the combined analysis technique of McFadden and McElhinny (1988) was used.

4. Palaeomagnetic results

4.1. Shaman Formation, south of the Siberian platform

The Natural Remanent Magnetization (NRM) intensity of the redbed samples from this formation averages around 1.4×10^{-3} A/m, with an average magnetic susceptibility of $\kappa = 11.9 \times 10^{-5}$ SI units. The stepwise thermal demagnetization (Fig. 2 and Fig. 3) allowed us to isolate three different magnetization components in most of the 80 samples studied. An example of rock magnetic experiments is shown on Fig. 4.

A low temperature component (A; Fig. 5, Table 1) is defined between NRM and 250–300 °C steps. It has northerly declination and steep downward inclination in in-situ coordinates, and displays only one polarity. The average direction of component A is: $D = 356.2°$, $I = 82.0°$, $\alpha_{95} = 4.4°$, $N = 13$ sites. This is undistinguishable from the expected present geomagnetic field direction in the region: $D = 355.1°$, $I = 70.8°$. We thus conclude that the A component is a recent overprint.

After demagnetization of component A, an intermediate temperature component (B) is isolated between 300–350 °C and 580–600 °C (Fig. 2 and Fig. 3). In many cases, this component is very scattered, and could be identified in only 6 sites (from site 1-1 to 2-2, Table 1). For these sites it has northwest declinations with shallow positive or negative inclinations. Component B has a single polarity, and its average (Fig. 5, Table 1) is: $Dg = 312.9°$, $Ig = 3.3°$, $\alpha_{95} = 32.2°$, $n = 6$ for in-situ coordinates, and $Ds = 313.1°$, $Is = -5.8°$, $\alpha_{95} = 32.7°$, $n = 6$ after tilt-correction. The flat-lying beds ensure that both directions are very close to each other, and that no fold-test could be performed on these palaeomagnetic directions.

Although both Isothermal Remanent Magnetization (IRM) acquisition experiments and thermomagnetic curves [Curie point measurements, $Js(T)$] are dominated by hematite characteristics (Fig. 4), with a continuous increase of IRM intensity up to the maximum applied field of 1000 mT, and a Curie point at 675 °C, we can observe a small inflexion in the thermomagnetic curve (Fig. 4, lower diagrams) at about 580 °C. Therefore, component B could be carried by a small fraction of magnetite and/or large-grain hematite. We note finally that the thermomagnetic curve (Fig. 4, lower diagrams) is not reversible, and displays a sharp increase in magnetization intensity on cooling down. This is typical of redbeds, where heating may produce magnetite by mineralogical changes at high temperatures (Dunlop and Ozdemir, 1997).

The high-temperature, component (C) was isolated in the highest temperature range between 500 and 680 °C (Fig. 2 and Fig. 3). The maximum unblocking temperature of this component (680 °C), together with thermomagnetic curves (Fig. 4, lower diagrams), which display a Curie point at 675 °C, indicates that both magnetite and hematite might carry the C component. Although this component can be well defined in some samples (Figs. 2 and 3) about 40% of the samples (30 out of the 80 samples) show only great circle trends towards the location of C component. When it can be defined on demagnetization diagrams, the C component displays two polarities with shallow directions to either the southwest or northeast (Fig. 5c,d). Both polarities could be observed in two out of the ten sampled sites (Table 1). Reversal tests at the sample level give positive results at 95% probability (McFadden and Lowes, 1981) in tilt-corrected coordinates with critical $\gamma = 24.1°$ (Fig. 5d). The magnetostratigraphic column (Fig. 6) illustrates the distribution of normal and reverse polarities with time along the 25 m of the sampled section. The average direction of this component, calculated in the southwest polarity (Table 1 and Fig. 5c) is: $Dg = 206.8°$, $Ig = -3.5°$, $k = 10.7$, $\alpha_{95} = 15.5°$ in-situ coordinates; and $Ds = 207.3°$, $Is = 2.3°$, $k = 13.3$, $\alpha_{95} = 13.8°$ in tilt-corrected coordinates, $n = 10$ sites. Again, because of the flat-lying attitudes of sedimentary beds, no fold test could be done on these populations. The positive reversal test, together with the consistency of the magnetostratigraphic distribution, suggest that component C could be of primary origin. In that case, the great scatter of this component might be a result of incomplete separation of components B and C.

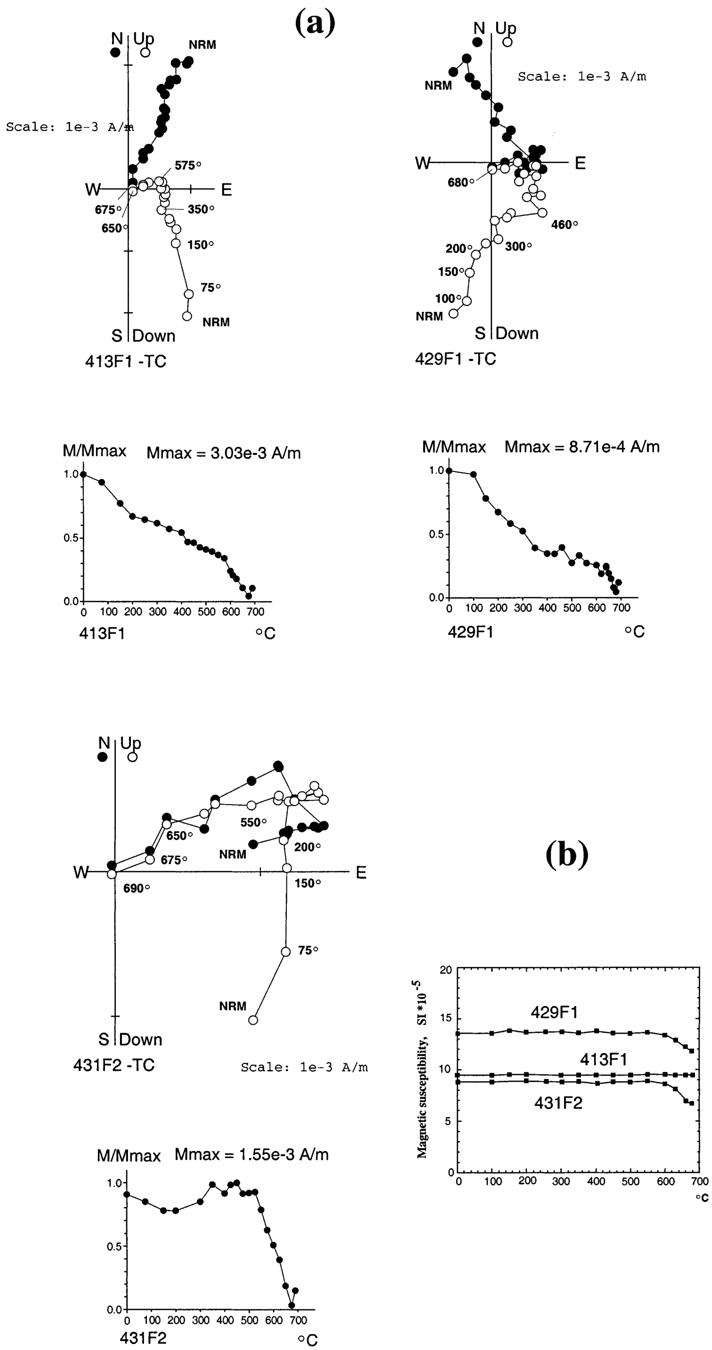

Fig. 2. Results of thermal demagnetization of Shaman Formation (Vendian, Siberia) samples. (a) Typical thermal demagnetization orthogonal vector plots (Zijderveld, 1967) in tilt-corrected coordinates, and magnetic intensity decay curves for samples which show northeast declinations. Closed (open) symbols in orthogonal plots: projections onto the horizontal (vertical) plane; temperature steps are indicated in °C. (b) Magnetic susceptibility (in SI units) changes during thermal demagnetizations.

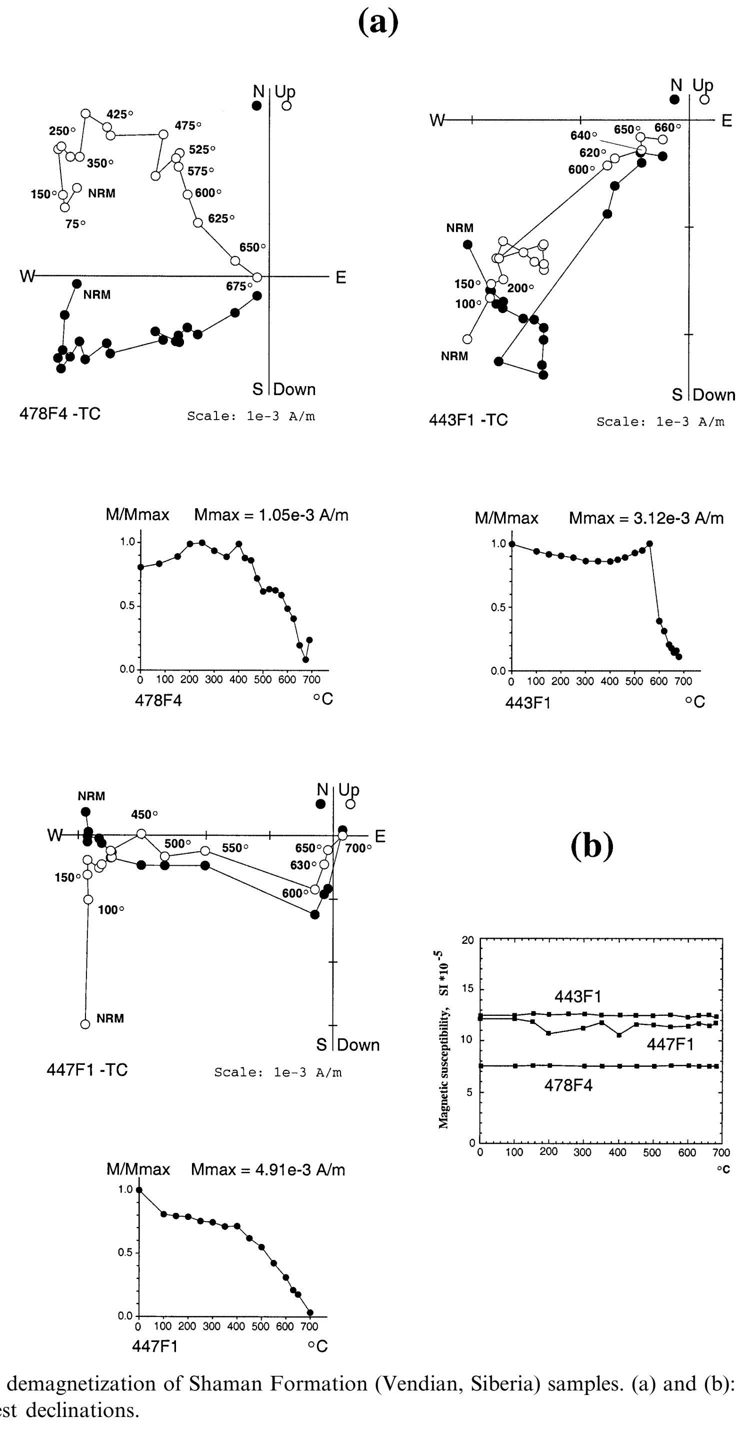

Fig. 3. Results of thermal demagnetization of Shaman Formation (Vendian, Siberia) samples. (a) and (b): same as in Fig. 2, but for samples showing southwest declinations.

4.2. Minya Formation, North Baikal region

Only one sample could be taken from each oriented block. Therefore, the following analysis is based on only 16 samples from the same monoclinal structure. Stepwise thermal demagnetization (Fig. 7) produces three different components. The low temperature component A is defined in the temperature range NRM 150° C. It could be defined in 10 out of the 16 samples, and its average direction is in in-situ coordinates (Table 2 and Fig. 8a): $Dg = 344.3°$, $Ig = 80.7°$, $\alpha_{95} = 10.1°$, $n = 10$ samples. We note that the precision parameter k increases upon untilting from $kg = 23.7$ to $ks = 55.8$, and this increase is significant at the 95% confidence level ($ks/kg = 2.35$, F critical value = 2.22 for $n = 10$ at the 95% probability level). However, because the in-situ average direction is very close to the expected present geomagnetic field direction in the region ($D = 354.0°$, $I = 75.6°$), and the unblocking temperature of this component is very low, suggesting that it is carried by hydroxides (goethite?) of weathering origin, we assume that the A-component is a recent geomagnetic field overprint.

The intermediate B component is defined between 150 and 580°C (Fig. 7). As for the Shaman Formation samples, the thermomagnetic curve (Fig. 4) displays a small inflexion, which suggests a small amount of magnetite with a Curie point below 600°C. This component which has a single polarity and northeast declination with intermediate inclination in tilt-corrected coordinates (Fig. 8b) could be defined in seven out of the 16 samples. Its precision parameter k increases upon untilting from $kg = 7.5$ to $ks = 13.1$. However this increase is not significant at the 95% probability level ($ks/kg = 1.75$, F critical value = 2.69 for $n =$

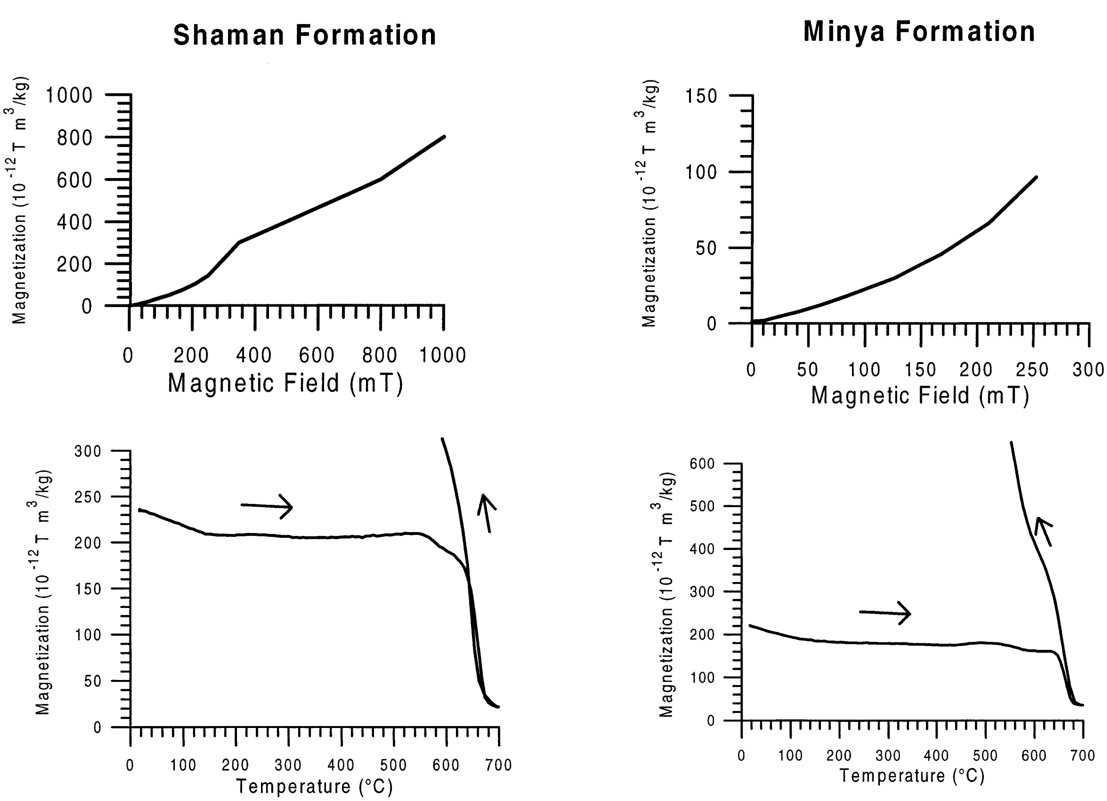

Fig. 4. Results of rock magnetic experiments for Shaman and Minya Formations (Vendian, Siberia) samples. Normalized isothermal remanent magnetization (IRM) acquisition curves (up) and Curie point thermomagnetic curves $Js(T)$ (down) for Shaman Formation sample 434 and Minya Formation sample 682.

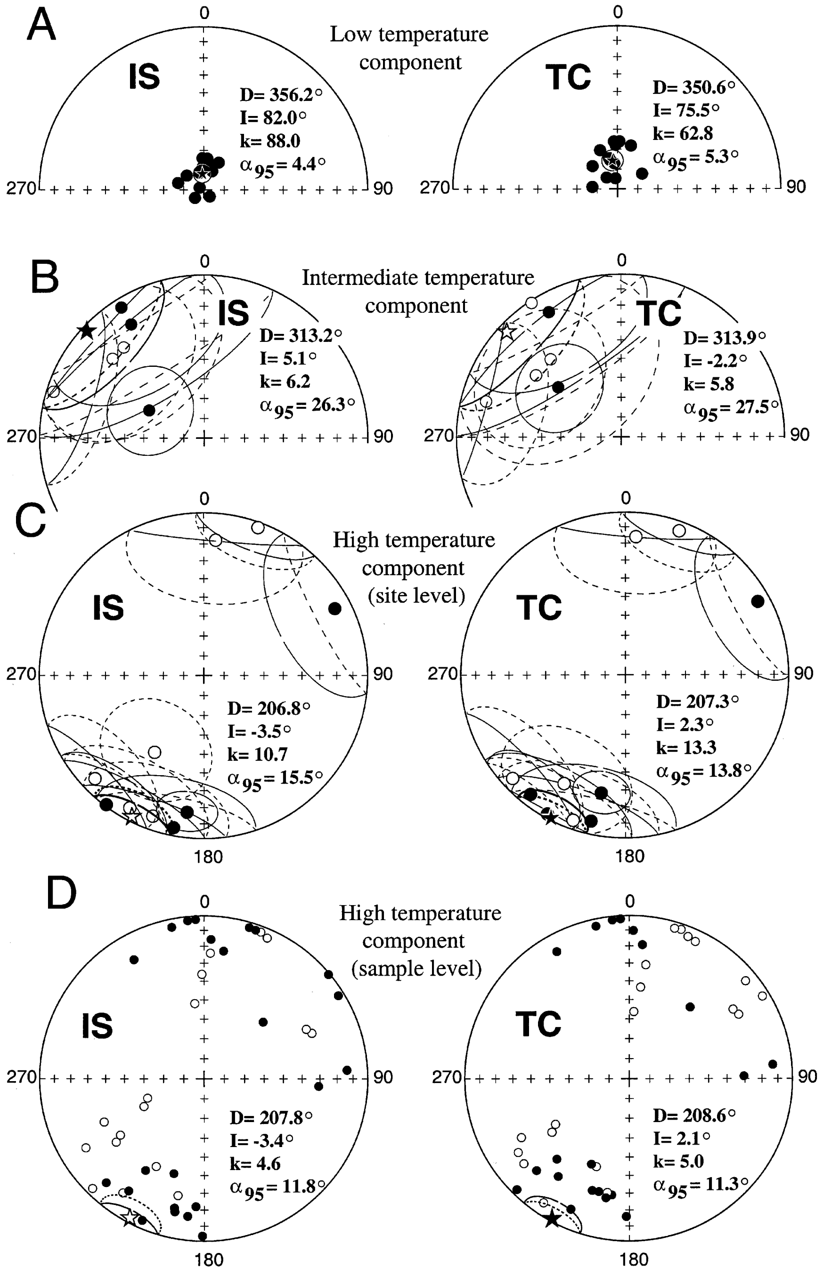

Fig. 5. Equal-area projections of Shaman Formation (Vendian, Siberia) site-mean directions of low (a), middle (b), and high (c) temperature components, calculated at the site level, with their α_{95} circles of confidence, shown in in-situ (left) and tilt-corrected (right) coordinates. (d): High temperature component calculated on samples level (without remagnetization great-circles). Closed (open) symbols: downward (upward) inclinations. Stars: formation mean direction. On stereonet (c), all the site-mean directions are shown in a single polarity, although for some sites both polarities can be observed at the sample level (see Table 1).

Table 1
Site-Mean palaeomagnetic directions for the low (A), intermediate (B) and high (C) temperature components of magnetization of the Shaman Formation (52.08° N, 103.83° E)

Site	*n*	*Dg*	*Ig*	*Ds*	*Is*	*k*	α_{95}	N/R
Component A								
1-1	9d	226.6	84.2	–	–	16.7	13.0	
		–	–	224.7	77.7	16.1	13.2	
1-2A	10d	24.8	79.7	–	–	17.0	12.1	
		–	–	345.4	74.0	18.1	11.7	
1-2B	9d	346.6	81.2	–	–	13.9	14.3	
		–	–	346.3	75.1	8.2	19.1	
1-3	14d	311.0	79.1	–	–	25.3	8.1	
		–	–	313.3	73.3	17.6	9.7	
1-4	14d	358.4	74.1	–	–	17.1	9.4	
		–	–	353.3	77.1	18.9	15.9	
1-5	8d	11.5	77.4	–	–	8.3	20.5	
		–	–	358.0	67.9	9.7	18.8	
1-6	13d	15.5	77.3	–	–	13.7	11.6	
		–	–	2.6	66.1	12.9	12.0	
2-2	9d	28.9	74.4	–	–	10.6	16.6	
		–	–	17.4	67.2	10.0	17.1	
2-3	7d	7.0	74.2	–	–	20.4	13.7	
		–	–	356.2	66.1	12.6	17.7	
3-1	7d	300.3	87.8	–	–	8.6	21.8	
		–	–	317.5	82.3	6.9	24.8	
3-2	7d	285.4	77.0	–	–	6.6	25.3	
		–	–	336.5	68.8	6.8	24.9	
3-3	7d	359.1	78.2	58.2	75.6	10.7	19.4	
3–4	4d	137.5	85.5	–	–	31.5	16.6	
		–	–	350.3	84.6	47.3	13.5	
Overall	13	356.2	82.0	–	–	88.0	4.4	only
Mean		–	–	350.6	75.5	62.8	5.3	normal polarity
Component B								
1-1[a]	2d	11.2	−74.7	–	–	10.3	88.3	
		–	–	51.5	−78.2	8.5	101.1	
1-2A	6d	328.0	6.1	–	–	2.3	57.3	
		–	–	326.7	−1.6	2.4	56.2	
1-2B	5d	287.3	−4.7	–	–	5.9	34.4	
		–	–	285.0	−16.3	6.2	33.4	
1-3	5d	327.7	18.5	330.4	12.7	4.8	39.0	
1-4[a]	6d	315.0	14.0	–	–	1.5	91.8	
		–	–	318.2	16.1	1.6	80.9	
1-5	4d	311.2	−27.1	–	–	6.7	38.3	
		–	–	306.3	−36.2	8.4	33.6	
1-6	9d	297.0	59.3	308.8	49.6	6.5	21.9	
2-2	6d	318.8	−26.9	–	–	3.3	43.9	
		–	–	318.2	−36.2	2.8	49.8	
Overall	6	312.9	3.3	–	–	5.3	32.2	only
Mean		–	–	313.1	−5.8	5.1	32.7	normal polarity
Component C								
1-1	4d+3cc	191.2	5.5	–	–	5.1	30.2	3/4
		–	–	193.1	8.8	4.7	31.9	
1-2A	6d+4cc	20.0	−3.7	-	–	5.5	22.8	4/6

Table 1 (*Continued*)

Site	*n*	*Dg*	*Ig*	*Ds*	*Is*	*k*	α_{95}	N/R
		–	–	20.4	−6.4	5.7	22.4	
1-2B[a]	4d+1cc	221.7	−12.6	–	–	2.5	61.6	5/–
		–	–	225.2	−0.7	2.2	68.8	($\alpha_{95}>30°$)
1-3	5d+1cc	62.8	11.0	–	–	4.6	35.1	–/6
		–	–	61.0	8.1	5.7	30.9	
1-4	6d+2cc	5.0	−17.6	–	–	3.3	35.8	–/8
		–	–	4.4	−16.0	3.9	32.4	
1-5	4d+1cc	216.8	1.2	–	–	12.1	23.5	5/–
		–	–	218.1	7.5	15.9	20.4	
1-6	5d+3cc	209.0	−7.9	208.1	2.3	4.3	30.4	8/–
2-3[a]	6d+2cc	334.2	9.7	–	–	2.0	52.0	–/8
		–	–	331.1	1.5	2.1	49.9	($\alpha_{95}>30°$)
3-1	4d+2cc	199.8	−9.2	–	–	6.6	28.9	–/6
		–	–	199.6	−6.0	5.6	31.7	
3-2	3d+4cc	212.4	−43.4	–	–	6.6	26.6	7/–
		–	–	209.1	−24.5	5.6	27.3	
3-3	1d+3cc	226.2	−9.2	–	–	21.9	27.3	4/–
		–	–	227.1	−7.3	18.1	30.1	
3-4	2d+1cc	187.0	16.6	191.4	26.8	141.7	12.2	3/–
Overall	10	206.8	−3.5	–	–	10.7	15.5	sites
Mean	sites	–	–	207.3	2.3	13.3	13.8	level
Overall	40	207.8	−3.4	–	–	4.6	11.8	samples
Mean	samples	–	–	208.6	2.1	5.0	11.3	level (only directions)

n: number of samples [directions (d) and great circles (cc)] accepted for computation of the site means; *Dg*, *Ig* (*Ds*, *Is*): Declination, Inclination of the site-mean direction in geographic (stratigraphic) coordinates; *k*, α_{95}: precision parameter and half-angle radius of the 95% probability confidence cone; N/R: number of normal (N) and reverse (R) directions.

[a] Site means not used for calculation of overall mean because of very high α_{95}.

7). Therefore, the pre- or post-folding origin of this component cannot be ascertained.

The high-temperature C component demagnetizes in the highest temperature range, between 350 and 690 °C. In tilt-corrected coordinates, it has either southwest declination and upwards inclination (Fig. 7, sample M679T1), or a northeast downwards direction (Fig. 7, sample M680T1). In that case, it is very close to the B component, though still easily distinguishable at sample level. This component could be isolated in six samples (Table 2) from which only the sample M679T1 shows a southwest direction, the other five having the northeast direction. However, in six other samples, the demagnetization path trends towards the C component along a great-circle, defining a clear remagnetization plane between B and C (e.g. see sample M677T1, Fig. 7). Because of the high unblocking temperature (Fig. 7), high IRM coercivity and high Curie point (at about 680 °C) of the samples (Fig. 4), the C component is likely to be carried by hematite.

The tilt correction induces an increase in the precision parameter *k* of the average direction from $kg=6.7$ to $ks=13.1$ ($n=12$, Fig. 8c and Table 2). Although the tilt-corrected *ks* parameter is about twice as large as the in-situ one, this increase is not significant at the 95% probability level. However, because of the presence of both polarities, we assume that the C component is the primary magnetization of the Minya Formation. The average tilt-corrected C component, in the southwest quarter of stereonet (Table 2, Fig. 8c) is: $Ds=237.7°$, $Is=-35.9°$, $k=13.1$, $\alpha_{95}=12.7°$, $n=12$ samples.

4.3. Tsagan-Olom and Bayan-Gol formations, Central Mongolia

Because of similar behaviour in demagnetizations for low and middle temperature components

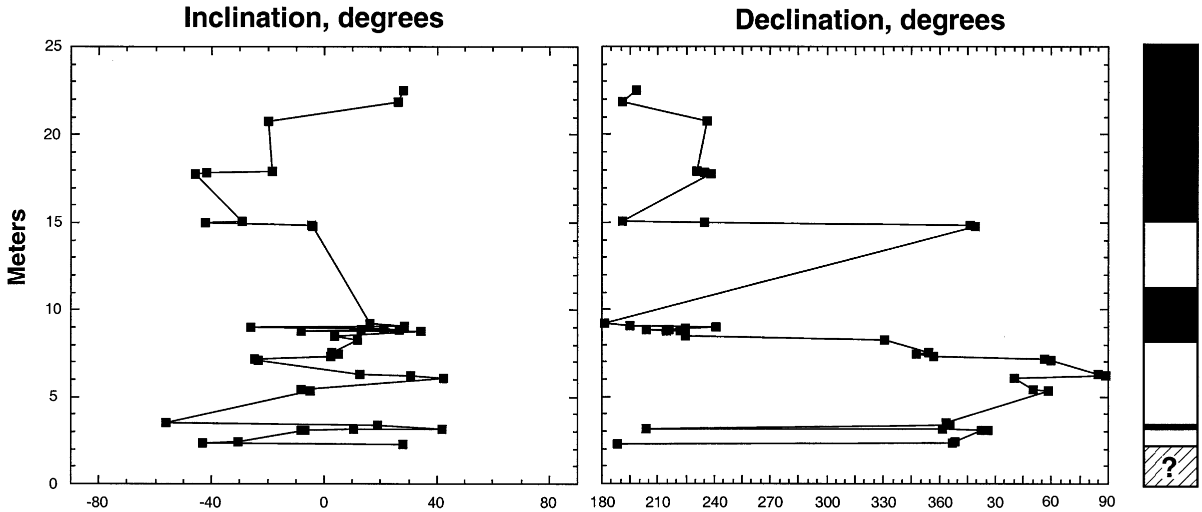

Fig. 6. Magnetostratigraphic profile for Vendian Shaman Formation (Siberia). Although large scatter of inclinations from −40 to 40° can be seen, the two polarities can be distinguished well from the declination profile. Black (white) area: normal (reverse) polarity.

of the Vendian Tsagan-Olom and Early Cambrian Bayan-Gol Formations, results of demagnetization experiments are presented and discussed together. As in the two previous cases, stepwise thermal demagnetizations (Fig. 9 and Fig. 10) allowed us to isolate three magnetization components. Examples of rock-magnetic experiments are shown in Fig. 11.

The low temperature A component demagnetizes between NRM and 200–250°C, in some cases up to 330°C. It has a steep northerly inclination in in-situ coordinates, with a single polarity, and has been recovered in the majority of the samples from these sedimentary beds. Its average in-situ direction ($Dg = 4.1°$, $Ig = 70.9°$, $\alpha_{95} = 6.3°$, $n = 10$) is not significantly different from the present-day magnetic field direction ($D = 360.8°$, $I = 66.5°$). Although the precision parameter k increases from 59.7 (in-situ) to 96.8 after tilt correction (Table 3, Fig. 12a), the difference is not significant at the 95% level. Therefore, accounting for its low unblocking temperature, we assume that the A component is likely to be a recent overprint of weathering origin.

The intermediate temperature B component is very well resolved between 200 and 525–580°C (Fig. 9 and Fig. 10). It has a very steep upward inclination, with a single polarity. Its unblocking temperature range, together with the results of thermomagnetic experiments (Fig. 12) which display a clear Curie point at about 560–575°C, suggests that the B component is carried by magnetite. Its average direction (Table 3 and Fig. 12b) is: $Dg = 203.9°$, $Ig = -66.3°$, $k = 28.5$, $\alpha_{95} = 9.2°$ in in-situ coordinates, and $Ds = 285.9°$, $Is = -82.1°$, $k = 59.7$, $\alpha_{95} = 6.3°$ after tilt-correction for $n = 10$ sites. Owing to very slight variations in bedding attitude, the fold test is inconclusive at the 95% level ($ks/kg = 2.09$, F critical value $= 2.22$). However, if we exclude the mean direction of site 4 where α_{95} is larger than 25°, the formation mean direction becomes: $Dg = 209.2°$, $Ig = -66.0°$, $k = 31.3$, $\alpha_{95} = 9.3°$ in in-situ coordinates, and $Ds = 284.3°$, $Is = -79.7°$, $k = 117.6$, $\alpha_{95} = 4.8°$ after tilt-correction for $n = 9$ sites. In this case, the precision parameters ratio ($ks/kg = 3.76$) is higher than the 99% F critical value (3.37) and the fold test is positive. We therefore assume that this component could be a pre-folding overprinting and the palaeopole deduced from the B component is discussed below in tilt-corrected coordinates.

Component C has the highest unblocking temperature range of 425–500 to 600–690°C. Owing to its weak intensity, this component could be

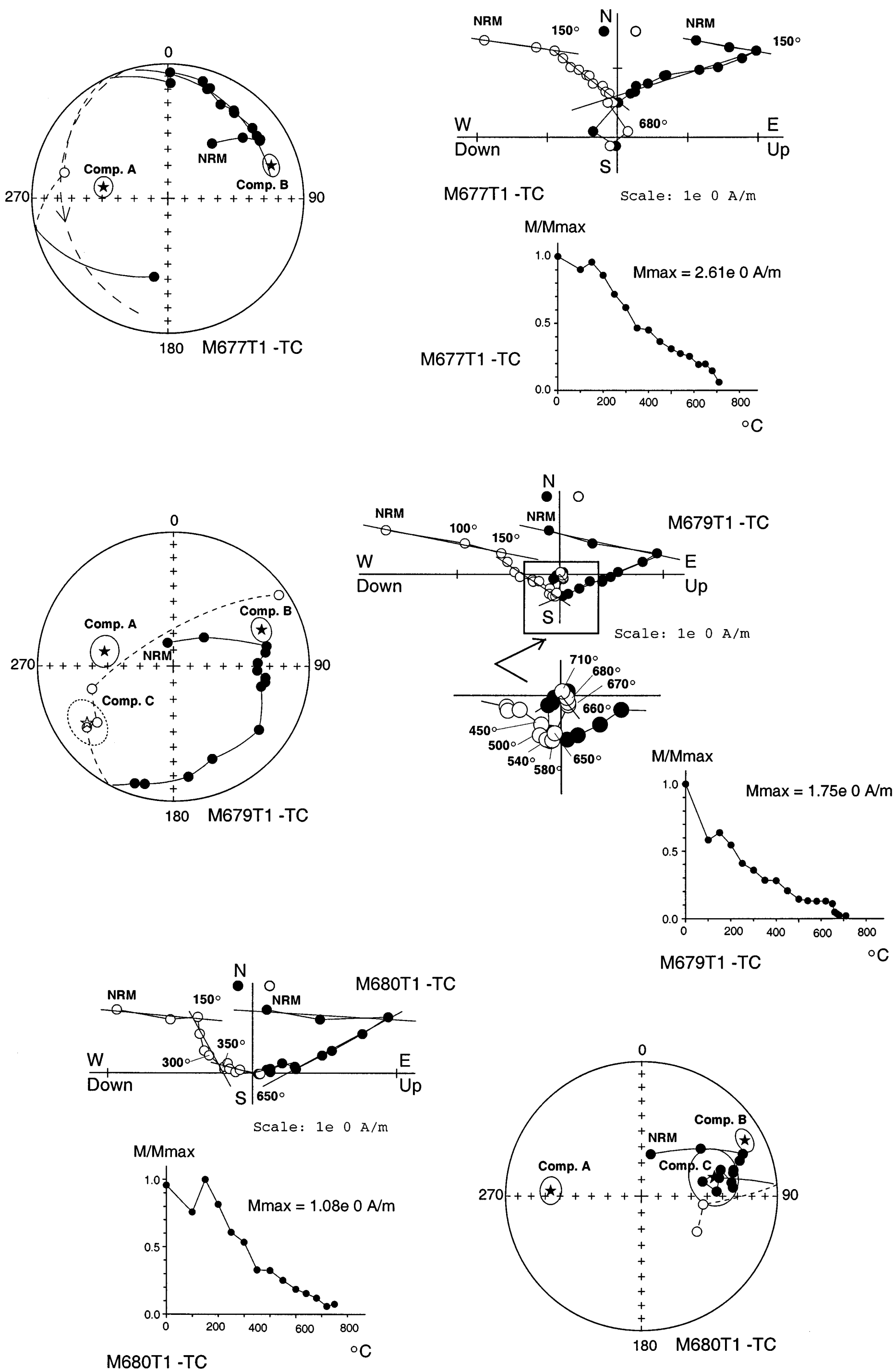

Fig. 7. Results of thermal demagnetization of Minya Formation (Vendian, Siberia) samples. Equal-area projections illustrating demagnetization path during experiments. Stars: directions of magnetization components with α_{95} circles of confidence determined on the orthogonal plots (a: low, b: middle, and c: high temperature components). Orthogonal vector plots (Zijderveld, 1967) in tilt-corrected coordinates; same conventions as in Fig. 2. Magnetic intensity decay curves.

Table 2
Formation-mean directions of low (A), intermediate (B) and high (C) components of magnetization computed at the sample level for the Minya Formation at the Chaya River locality (58.0° N, 110.0° E)

Component	*n*	*Dg*	*Ig*	*Ds*	*Is*	*k*	α_{95}	N/R
A	10	344.3	80.7	–	–	23.7	10.1	10/–
		–	–	272.6	44.5	55.8	6.5	
B	7	54.0	−1.4	–	–	7.5	23.6	7/–
		–	–	48.1	32.6	13.1	17.3	
C	6d+6cc	62.2	−4.4	–	–	6.7	18.3	5/7
		–	–	237.7	−35.9	13.1	12.7	

n: number of samples [directions (d) and great circles (cc)] accepted for computation of the formation mean; *Dg*, *Ig* (*Ds*, *Is*): Declination, Inclination of the site-mean direction in geographic (stratigraphic) coordinates; *k*, α_{95}: precision parameter and half-angle radius of the 95% probability confidence cone; N/R: number of normal (N) and reverse (R) directions.

resolved in only about 70% of the demagnetized samples. In the remaining 30%, however, the demagnetization path trends towards this component along great circles. The high unblocking temperature of this component (Fig. 9 and Fig. 10), together with the high Curie point in thermomagnetic experiments, and high IRM coercivities (Fig. 11) suggest that the C component could be carried by hematite, or both titanomagnetite and hematite. The C component shows two polarities for both the Tsagan-Olom and Bayan-Gol formations (Fig. 12c, d and Fig. 13).

For the Vendian Tsagan-Olom Formation, the C component has either northeast or southwest shallow to intermediate inclinations (Table 3; Fig. 12c and 13a). Both polarities could be observed in two out of the four sites. For the Early Cambrian Bayan-Gol Formation, the C component has either northwest or southeast shallow to intermediate inclinations (Table 3; Fig. 12d and Fig. 13b). Both polarities could be observed in 4 out of the 6 sites. Probably because of its low intensity, and overlapping temperature spectra of B and C, the scatter of the population of C components is quite high at both the sample (Fig. 13) and site levels (Table 3; Fig. 12c, d). Both reversal and fold tests are inconclusive. However, because of the presence of two polarities, we assume that the tilt-corrected mean direction of the C component could be the primary magnetization of Tsagan-Olom and Bayan-Gol Formations.

At site level for the Vendian Tsagan-Olom Formation, the mean direction in tilt-corrected coordinates is: $Ds = 58.8°$, $Is = 5.3°$, $k = 19.2$, $\alpha_{95} = 21.5°$, $n = 4$ site averages (Table 3; Fig. 12c). For the Early Cambrian Bayan-Gol Formation: $Ds = 118.3°$, $Is = -6.3°$, $k = 13.3$, $\alpha_{95} = 19.0°$, $n = 6$ site averages (Table 3; Fig. 12d). It is surprising that the B component passes a positive fold test, whereas the C component, which we interpret as primary, gives an inconclusive test. However, we note that the strike of the bedding planes is directed ESE, that is to say, very close to the average direction of C components for both the Bayan-Gol and Tsagan-Olom Formations. We therefore suggest that the failure of the fold test for the C component arises from the similar direction of C and the rotation axis of the tilt-correction.

5. Discussion

The four formations studied display a low temperature A component that is parallel or close to the present-day magnetic field direction. We interpret this as a recent overprint, and do not discuss the A components any further.

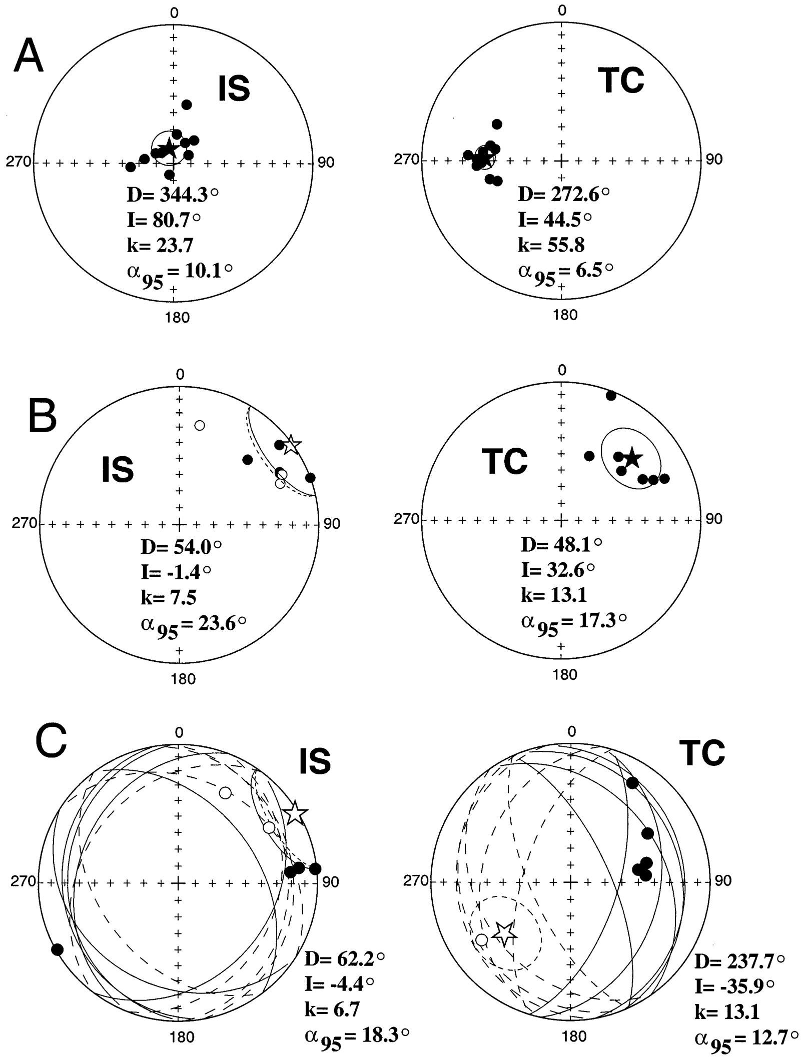

Fig. 8. Equal-area projections of Minya Formation (Vendian, Siberia) palaeomagnetic directions, at the sample level, of low (a), middle (b), and high (c) temperature components with their α_{95} circles of confidence shown in in-situ (left) and tilt-corrected (right) coordinates. Same conventions as in Fig. 5. Stereonet c illustrates the combined analysis of directions and great circles (McFadden and McElhinny, 1988) used to determine this component.

The palaeopoles corresponding to the B (intermediate temperature) and C (high temperature) components have been computed for the Shaman, Minya, Tsagan-Olom and Bayan-Gol Formations (Table 4; Fig. 14 and Fig. 15). These palaeopoles are discussed in comparison with a composite reference Apparent Polar Wander Path (APWP) for Siberia, which is composed of the Eurasian APWP of Besse and Courtillot (1991) and Van der Voo (1993) from Present to 220 Ma, and the Siberia APWP of Smethurst et al. (1998) for the Palaeozoic (248–538 Ma).

5.1. B-component palaeopoles

The lack of any fold test for this component for the Shaman and Minya Formations, ensures that discussion on these palaeopoles remains tentative. As noted above, the mean direction of the B component from the Shaman Formation is almost

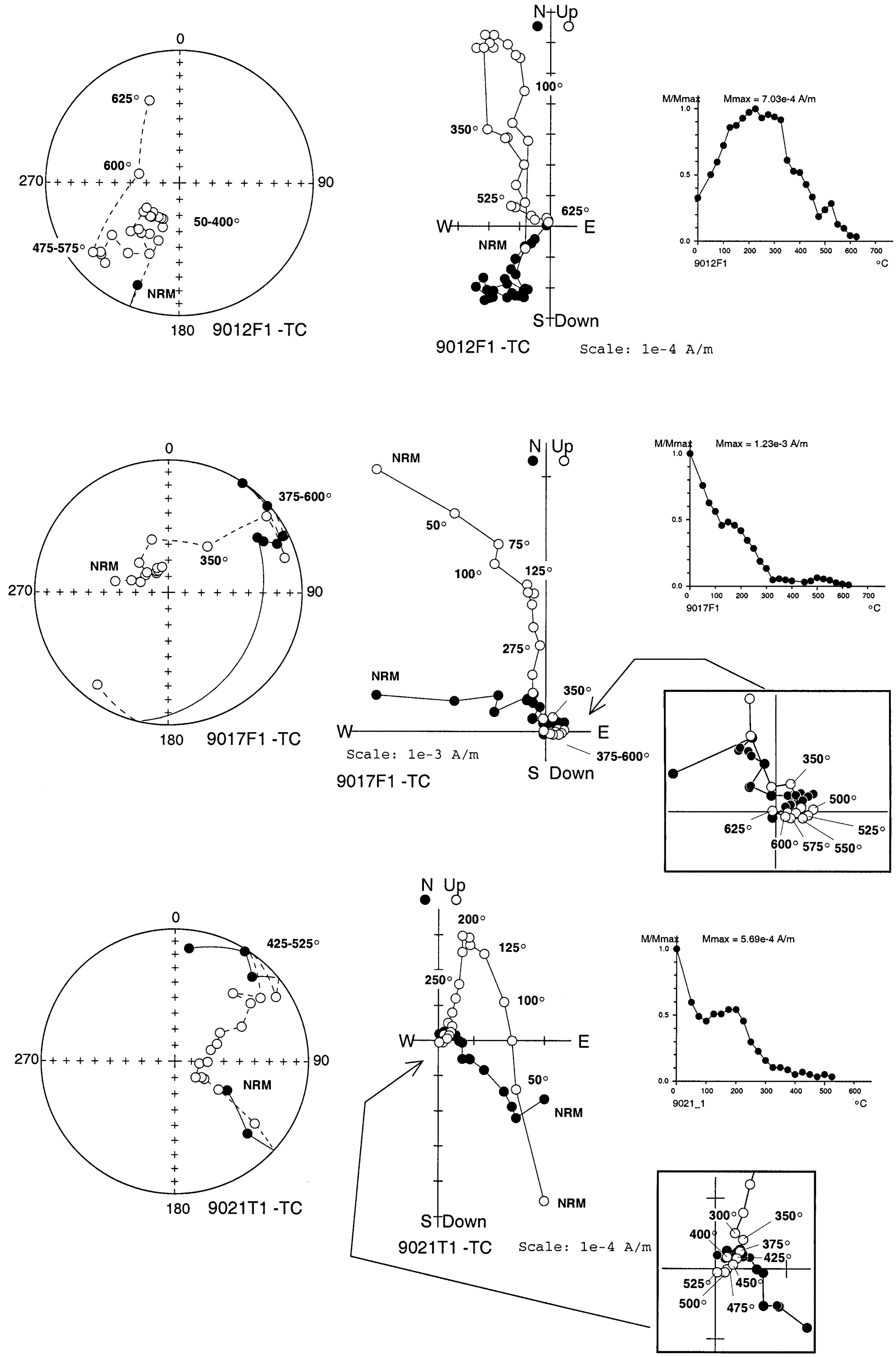

Fig. 9. Results of rock magnetic experiments for Tsagan-Olom Formation (Vendian, Mongolia) samples. Left: equal-area projections illustrating demagnetization path during experiments. Middle: orthogonal vector plots (Zijderveld, 1967) in tilt-corrected coordinates and magnetization changes during thermal demagnetizations. Same conventions as in Fig. 2.

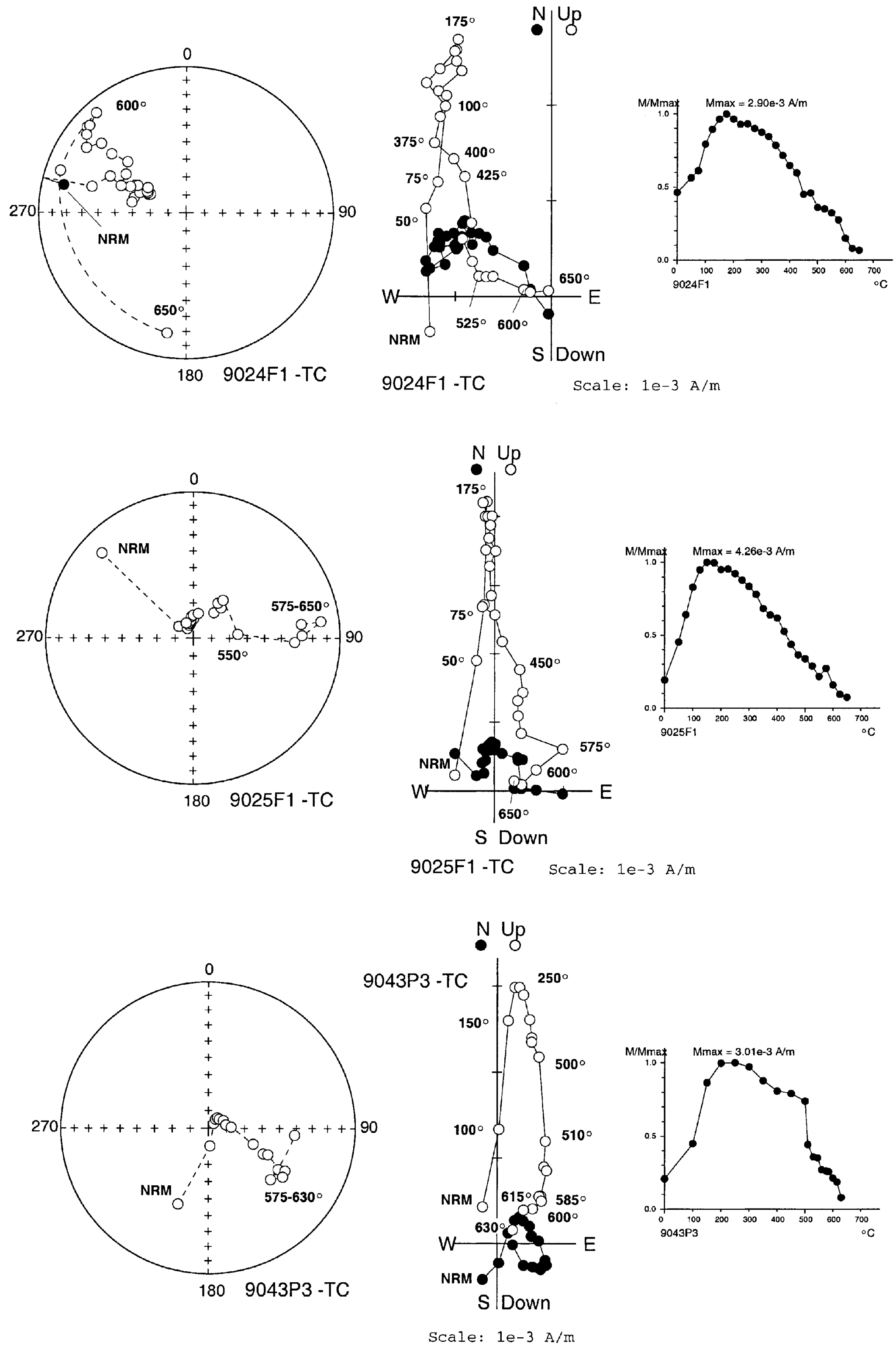

Fig. 10. Results of rock magnetic experiments for Bayan-Gol Formation (Early Cambrian, Mongolia) samples. Left: equal-area projections illustrating demagnetization path during experiments. Middle: orthogonal vector plots (Zijderveld, 1967) in tilt-corrected coordinates. Right: Magnetic intensity decay curves. Same conventions as in Fig. 2.

identical in in-situ and tilt-corrected coordinates. We have computed the palaeopole from the tilt-corrected direction (Table 4). With a small counterclockwise rotation around a vertical axis at the sampling location, our Shaman B component pole compares well with the 456–500 Ma (Ordovician) pole of the reference APWP of Smethurst et al. (1998) (Fig. 14).

On the basis of intraplate magmatism, post-collision granite complexes described in the Gorniy Altay region (northern Tuva-Mongolian block in present-day coordinates) and subduction complexes (volcanic arc complexes, gabbro-tonalite-plagiogranite intrusives), Berzin et al. (1994) considered that collision between the Tuva-Mongolian block and Siberia may have begun during the Ordovician, and continued into the Silurian, in the West Sayan Mountains region. We therefore tentatively link the B remagnetization component of the Vendian Shaman Formation to the beginning of this collision.

The B component palaeopoles of the Minya Formation in either in-situ or tilt-corrected coordinates (Table 4) are a long way from the reference APWP, and are therefore difficult to interpret. Because these poles are only based on seven directions on the sample level, we do not try to explain completely the origin of this component at this early stage in the study of the Minya Formation.

The B component palaeopoles of the Tsagan-Olom and Bayan-Gol Formations have been computed for two cases, after in-situ (Bg in Table 4) and after tilt-corrected (Bs in Table 4) average directions. The in-situ Bg Mongolia pole compares well with the Early Cretaceous 140 Ma pole of the reference APWP. It could represent the later closure of the Mongol-Okhotsk ocean by the Late Jurassic–Early Cretaceous (e.g. see Kuzmin and Fillipova, 1979; Zonenshain et al., 1990; Kravchinsky, 1990, 1995; Enkin et al., 1992; Kuzmin and Kravchinsky, 1996; Halim et al., 1998), which is marked by the Mongol-Okhotsk fold zone south of the Tuva-Mongolian block (Fig. 1). Because of the positive fold test for B component, a second more likely case is that the tilt-corrected Bs palaeopole of Tsagan-Olom and Bayan-Gol formations lies along the small circle centered on the sampling locality. This small circle also encloses the 360 Ma (Early Carboniferous) or 220–190 Ma (Late Triassic–Early Jurassic) poles of the reference APWP (Fig. 15). In the first case, this palaeopole could tentatively be linked to a remagnetization of these formations at the end of the collision between the Tuva-Mongolian block and the Siberia block (Berzin et al., 1994), and, in the second case, to the beginning of closure of the Mongol-Okhotsk ocean in the region (Zonenshain et al., 1990).

Recently, Evans et al. (1996) obtained palaeomagnetic results from the same Bayan-Gol Formation but in a different place (pole 21, Table 5, Fig. 15). The authors interpreted their magnetization as either primary or secondary. The corresponding palaeopole is situated quite close to the great circle joining our Bayan-Gol C palaeopole and the Bs palaeopole. This suggests two conclusions: (1) the actual remagnetization direction in our Early Cambrian Bayan-Gol Formation is indeed correct in the tilt-corrected coordinates, and (2) the pole of Evans et al. (1996) could have resulted from an incomplete separation between a high-temperature primary component and the remagnetization intermediate temperature component.

5.2. C-component primary palaeopoles

Mainly because of the presence of both polarities, and although we have no fold test, we have interpreted the high unblocking temperature C-component as the primary magnetization in each of the four studied formations. In order to discuss the palaeopoles computed after these C-component magnetizations, we selected the Vendian–Early Cambrian poles that have a reliability code equal to one and higher from the palaeomagnetic databases of McElhinny and Lock (1996) and of Khamrov (1975–1989) for Siberia, Tuva, Mongolia and the Altay-Sayan Mountains, which separate the Tuva-Mongolian block from the Siberian platform (Table 5). These poles are shown in Fig.

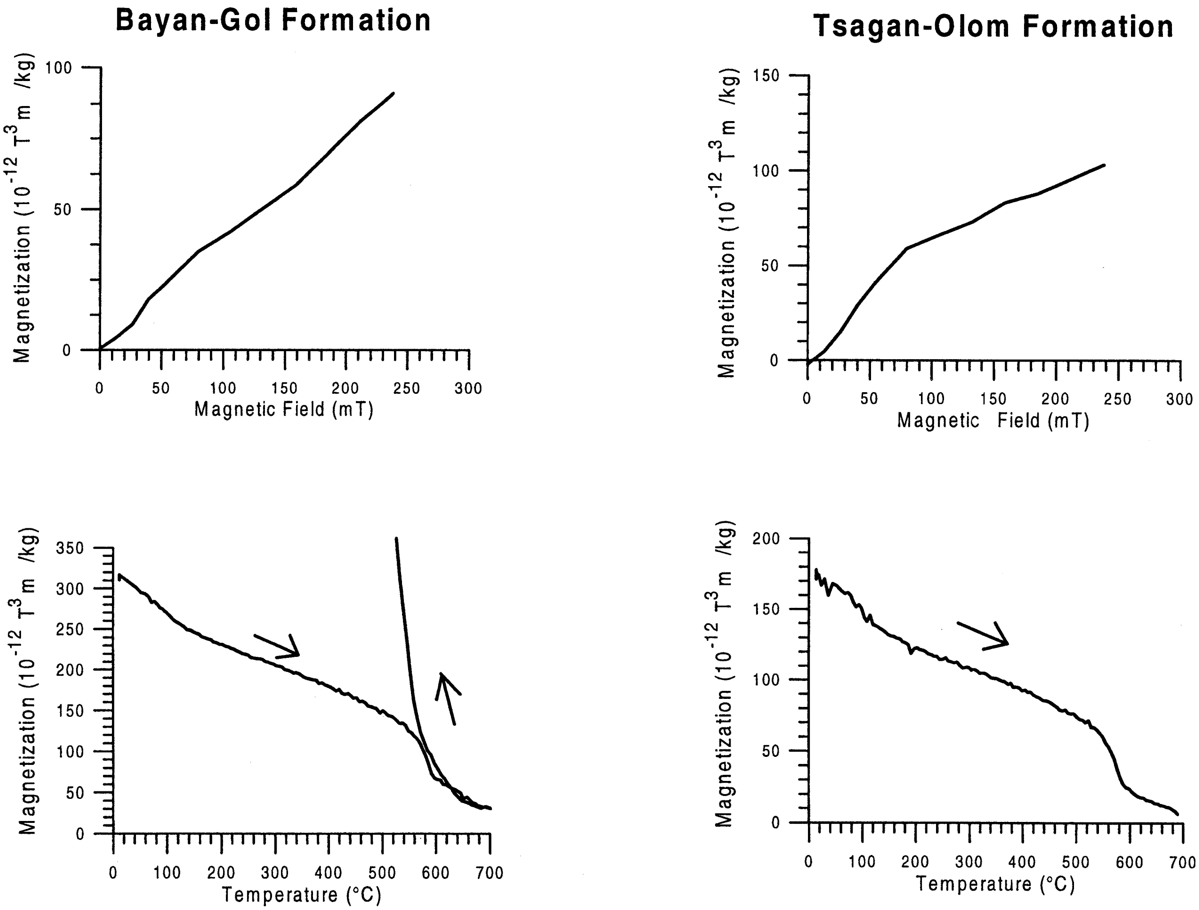

Fig. 11. Results of rock magnetic experiments for Tsagan-Olom (Vendian) and Bayan Gol (Early Cambrian) Formations. Normalized isothermal remanent magnetization (IRM) acquisition curves (up) and thermomagnetic curves (down) for Bayan-Gol Formation sample 9033 and Tsagan-Olom Formation sample 9049.

14 for Siberia and Fig. 15 for Mongolia and Tuva along with the reference APWP for Siberia (Smethurst et al., 1998).

5.2.1. Shaman and Minya formations — Siberia block

According to our proposed separation of Siberia into three blocks (Angara, Anabar and Aldan), we have separated the list of Siberian poles into three subsets (Table 5, Fig. 14): poles Nos. 1–5 from the Aldan block (grey symbols in Fig. 14), poles Nos. 6–8 from the Angara block (open symbols), and poles Nos. 9–14 from the Anabar block (closed symbols). Although a majority of palaeopoles lies near the Early Palaeozoic part of the APWP (Fig. 14), some of them show a significant departure from this curve. We note, however, that the population of poles falls into two groups that roughly align on a small circle centred on the Siberian craton. At a first level of analysis, we therefore assume that this distribution may result from rotations around vertical axes located at the sampling sites.

We have computed the palaeopoles for the Shaman and Minya Formations (Nos. 7 and 8 in Table 5 and Fig. 14) by assuming that the south-directed C component palaeomagnetic directions are the normal polarity direction. This implies that the studied areas were situated near the palaeo-equator ($1.2 \pm 6.9°$ for the Shaman For-

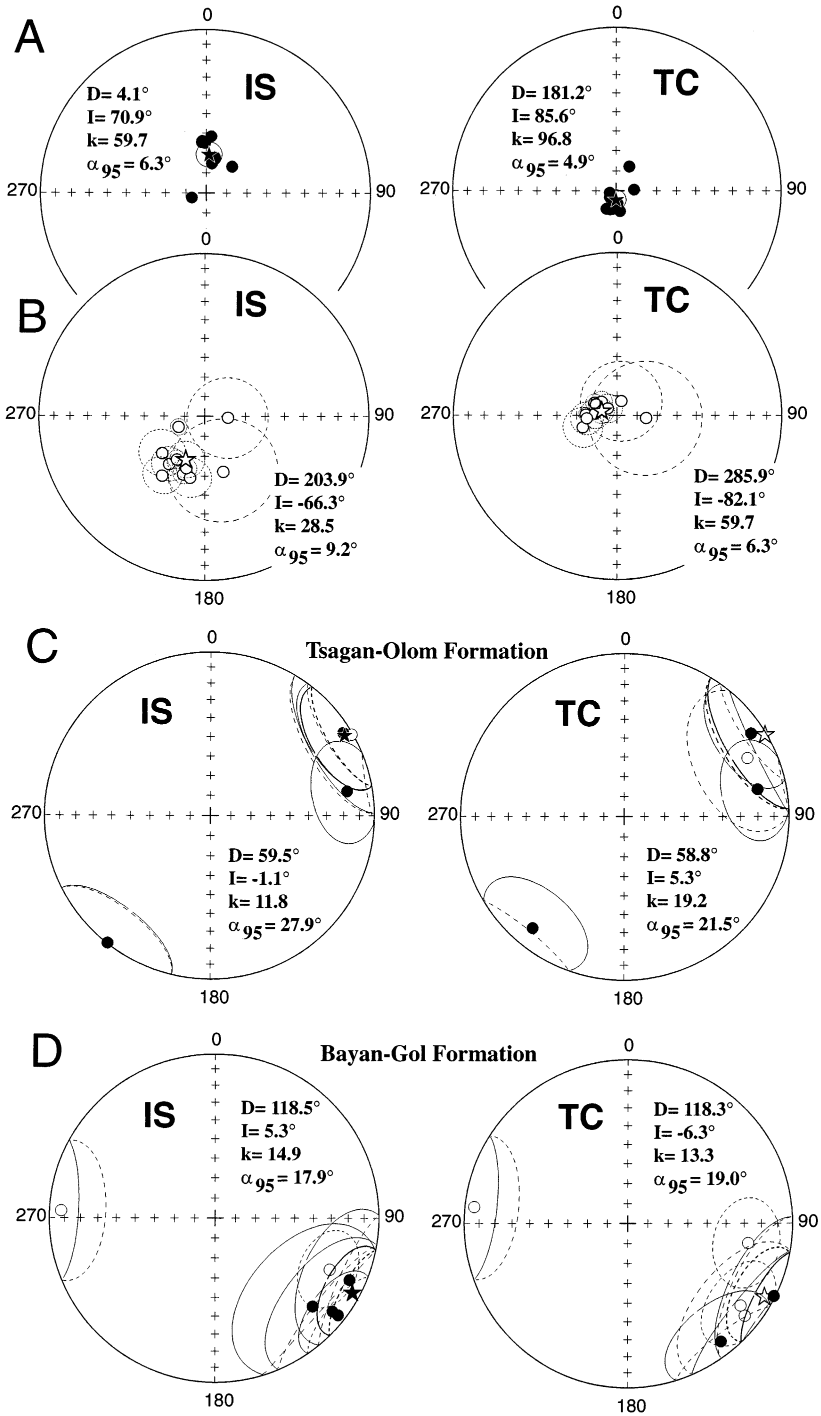

Fig. 12. Equal-area projections of Tsagan-Olom (Vendian) and Bayan-Gol (Early Cambrian) Formations (Mongolia) site-mean directions of low (a), middle (b), and high (c and d) temperature components with their α_{95} circles of confidence shown in in-situ (left) and tilt-corrected (right) coordinates. Stars: mean direction for all sites. Same conventions as in Fig. 4.

Table 3
Site-mean palaeomagnetic directions for the low (A), intermediate (B) and high (C) temperature components of magnetization of the Bayan-Gol and Tsagan-Olom Formations, Central Mongolia (46.75° N, 96.37° E)

Site	*n*	*Dg*	*Ig*	*Ds*	*Is*	*k*	α_{95}	N/R
Component A								
Tsagan-Olom Formation								
2	10d	13.0	71.8	–	–	95.2	5.0	
		–	–	28.1	76.3	58.7	6.4	
3	6d	44.1	71.8	–	–	7.2	26.8	
		–	–	85.2	81.2	5.9	30.2	
4	4d	10.4	75.1	–	–	115.2	8.6	
		–	–	198.5	80.2	74.6	10.7	
5	5d	252.2	82.5	169.7	79.7	10.1	25.3	
Bayan–Gol Formation								
6-1	10d	14.4	72.5	–	–	41.2	7.6	
		–	–	174.5	83.8	19.0	11.4	
6-2	10d	4.9	61.6	–	–	79.1	5.5	
		–	–	255.0	86.7	71.5	5.8	
6-3	10d	358.4	65.1	–	–	129.1	4.3	
		–	–	224.4	85.5	195.9	3.5	
6-4	10d	358.5	65.1	194.2	81.5	117.4	4.5	
6-5	12d	355.5	64.0	–	–	101.3	4.3	
		–	–	193.1	80.6	130.7	3.8	
6-6	7d	355.0	64.7	–	–	116.5	5.6	
		–	–	208.3	79.8	155.3	4.9	
Overall	10 sites	4.1	70.9	–	–	59.7	6.3	only
Mean		–	–	181.2	85.6	96.8	4.9	normal polarity
Component B								
Tsagan-Olom Formation								
2	10d	247.8	−75.9	–	–	141.7	4.1	
		–	–	271.1	−74.5	183.1	3.6	
3	6d	228.9	−61.8	–	–	34.1	11.6	
		–	–	250.1	−72.0	46.4	9.9	
4	4d	162.1	−60.8	–	–	13.0	26.5	$\alpha_{95} > 25°$
		–	–	95.5	−75.5	11.3	28.6	
5	6d	93.2	−78.8	16.5	−82.5	11.9	20.2	
Bayan-Gol Formation								
6-1	9d	216.6	−60.1	–	–	36.4	8.6	
		–	–	274.2	−79.2	47.5	7.5	
6-2	10d	215.6	−53.1	–	–	27.9	9.3	
		–	–	264.0	−75.0	35.8	8.2	
6-3	11d	212.7	−64.3	–	–	94.2	4.7	
		–	–	299.6	−77.2	108.7	4.4	
6-4	10d	199.7	−62.4	–	–	94.0	5.0	
		–	–	311.9	−79.8	84.2	5.3	
6-5	12d	200.6	−58.8	–	–	83.4	4.8	
		–	–	297.9	−78.3	124.0	3.9	
6-6	7d	193.7	−58.2	–	–	36.2	10.2	
		–	–	307.0	−84.3	70.0	7.3	
Overall	10 sites	203.9	−66.3	–	–	28.5	9.2	only
Mean		–	–	285.9	−82.1	59.7	6.3	reverse polarity
Overall	9 sites	209.2	−66.0	–	–	31.3	9.3	only
Mean	(without site 4)	–	–	284.3	−79.7	117.6	4.8	reverse polarity

Table 3 (*Continued*)

Site	*n*	*Dg*	*Ig*	*Ds*	*Is*	*k*	α_{95}	N/R
Component C								
Tsagan-Olom Formation								
2	5d+2cc	78.4	18.5	79.9	16.6	9.8	20.7	6/1
3	6d	219.3	13.1	–	–	9.0	23.6	6/–
		–	–	218.5	0.5	8.2	25.0	
4	5d+1cc	64.3	−18.2	–	–	5.9	30.4	1/5
		–	–	59.9	−0.9	6.3	29.2	
5	5d+1cc	56.4	8.5	57.8	5.2	10.2	22.4	–/6
Overall	4	59.5	−1.1	–	–	11.8	27.9	
Mean		–	–	58.8	5.3	19.2	21.5	
Bayan-Gol Formation								
6-1	7d+2cc	114.8	10.7	–	–	3.9	27.9	5/4
		–	–	116.1	1.0	3.7	28.8	
6-2	4d+3cc	114.4	−24.4	–	–	14.8	16.9	8/–
		–	–	99.4	−26.8	11.5	19.3	
6-3	5d+3cc	272.8	−7.8	–	–	5.4	26.5	4/4
		–	–	276.2	−6.3	5.3	27.0	
6-4	5d+1cc	128.5	9.5	128.3	−10.3	6.0	30.3	4/2
6-5	8d+4cc	128.3	5.1	–	–	6.8	18.0	
		–	–	126.1	−16.3	6.3	18.8	12/–
6-6	4d+3cc	132.2	21.0	–	–	3.7	36.5	6/2
		–	–	141.7	9.3	8.2	23.1	
Overall	6	118.5	5.3	–	–	14.9	17.9	
Mean		–	–	118.3	−6.3	13.3	19.0	

n: number of samples [directions (d) and great circles (cc)] accepted for computation of the site means; *Dg*, *Ig* (*Ds*, *Is*): Declination, Inclination of the site-mean direction in geographic (stratigraphic) coordinates; *k*, α_{95}: precision parameter and half-angle radius of the 95% probability confidence cone; N/R: number of normal (N) and reverse (R) directions.

mation), or at low south palaeolatitudes ($-19.9 \pm 8.6°$ for the Minya Formation; Table 5), and that the present-day southern margin of the Siberia platform was facing the north pole in Vendian times. This is in agreement with the palaeoposition of Siberia in the Palaeozoic, as proposed by Kravchinsky (1979), Khamrov (1982) and Smethurst et al. (1998).

The Vendian of the Angara block is characterized by pole No. 6 (Gurevich, 1982), and the poles we obtained in the Shaman (7) and Minya (8) Formations. However, pole No. 6 (Gurevich, 1982) cannot be used for further reconstructions, because redbed samples were demagnetized only by AF demagnetization. We therefore discard it from further discussion. Because the Shaman and Minya poles were obtained from palaeomagnetic directions with both polarities, in only slightly deformed areas in the Angara block, and from localities situated about 800 km apart, we consider that these poles characterize the Angara block in Vendian time. Obviously, there is some angular discrepancy between these two poles, which could be due to tectonic reasons (Minya Formation has monoclinal bedding on the border of the Siberian platform), or to differences in the age of these two formations within the Vendian system. We note, however, that the Minya pole should be considered as preliminary because it is based on only 12 samples, whereas the Shaman pole is based on 10 sites; and only further palaeomagnetic investigations can help to resolve this discrepancy.

If these Shaman and Minya poles are characteristic of the Angara block, they may provide evidence for a large (about 40°) clockwise rotation of this block with respect to the Anabar block. In effect, we can consider two hypotheses: (1) either pole No.14, which is consistent with Early Cambrian poles and the reference APWP, is indeed characteristic of the Anabar block, and in this case the pole No. 13 has been rotated, or (2) pole No.13 which is close to our Angara poles reflects a consistency in the palaeoposition of Angara and Anabar, and the pole No. 14 has been rotated. If the latter were true, the reference APWP does not reflect the actual palaeoposition of these blocks. In the present state of palaeomagnetic investigations, we cannot choose between these two hypotheses.

If we turn to the comparison between the Angara (Shaman and Minya) and Aldan blocks, their relationships remain unclear. In effect, although there are two Vendian poles Nos. 4 and 5 (Pavlov, 1993) for the Aldan block (Table 5), they are significantly rotated from poles from the Angara and Anabar blocks. Moreover, we note that these two poles have an age from 660 to 640 Ma, and do not therefore reflect Vendian age.

The majority of the Early Cambrian poles are clustered around southeast coast of Australia (Fig. 14). Three poles may characterize the Aldan block: these are poles No. 1 (Osipova, 1975), 2 (Kirschvink and Rozanov, 1984), and 3 (Osipova, 1986). Pole No. 3 has a very low demagnetization code according to the scale of McElhinny and Lock (1996). For this reason, we consider only poles 1 (Osipova, 1975) and 2 (Kirschvink and Rozanov, 1984) as being characteristic of the Early Cambrian period for this block. Unfortunately, these two poles are widely separated along a small-circle centred on the sites, which denotes a large relative rotation between these two areas. This is surprising as both poles are from the consolidated Aldan block. Although we cannot reject the possibility that both poles 1 and 2 are characteristic of the

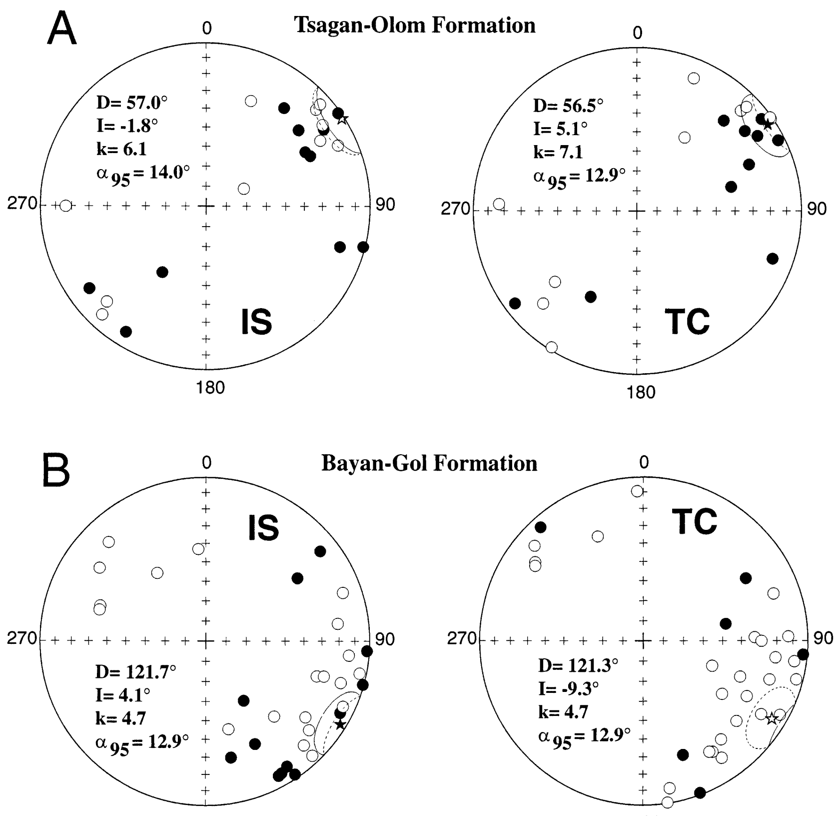

Fig. 13. Equal-area projections of Tsagan-Olom (Vendian) and Bayan-Gol (Early Cambrian) Formations (Mongolia) site-mean directions of high-temperature components on a single sample level (without the remagnetization great-circles) shown in in-situ (left) and tilt-corrected (right) coordinates. Stars: mean direction for all sites. Same conventions as in Fig. 4.

Table 4
Palaeomagnetic poles from the Siberian platform (Shaman and Minya) and Mongolia (Tsagan-Olom and Bayan-Gol) obtained in this study from characteristic components

Component	Locality latitude	Locality longitude	Pole latitude	Pole longitude	dp/dm	*N*
Shaman Formation (Vendian)						
Bs	52.08	103.83	−22.3	155.8	16.5/32.8	6 S
C	52.08	103.83	−32.0	71.1	6.9/13.8	10 S
Minya Formation (Vendian)						
Bg	58.0	110.0	−17.5	52.0	11.8/23.6	7 s
Bs	58.0	110.0	−36.5	48.1	11.1/19.6	7 s
Cs	58.0	110.0	−33.7	37.2	8.6/14.7	12 s
Tsagan-Olom (Vendian) and Bayan-Gol (Early Cambrian) Formations						
Bg	46.75	96.37	70.3	171.0	12.4/15.2	9 S
Bs	46.75	96.37	38.8	121.5	8.8/9.2	9 S
Tsagan-Olom Formation (Vendian)						
Cs	46.75	96.37	−22.8	28.4	10.8/21.6	4 S
Bayan-Gol Formation (Early Cambrian)						
Cs	46.75	96.37	−21.4	167.1	9.6/19.1	6 S

Pole latitude, Pole longitude: latitude, longitude of palaeomagnetic poles computed after intermediate (B) and high (C) temperature components of magnetization; dp/dm: semi-axes of the confidence ellipse of palaeomagnetic pole. *N*: number of sites (S) or samples (s) used to determine pole.

Aldan block, with some unknown mechanism for their difference, we can analyse the Aldan block palaeoposition in two ways, where the Early Cambrian palaeoposition of Aldan block is characterized by either pole No. 1, or pole No. 2.

If pole No. 1 of Table 5 (Osipova, 1975) represents the palaeoposition of the Aldan block, this would imply a similar palaeolatitudinal position of the Aldan and Anabar blocks (poles 9–12) inside a coherent Siberian platform (Fig. 14). In that case, pole No. 2 (Kirschvink and Rozanov, 1984) would reflect a local rotation of the sampling area relative to the Anabar block, which is not supported by geological data.

On the other hand, if pole No. 2 is characteristic of the Aldan block, we note that it is consistent with our Vendian poles from the Angara block (Fig. 14), with maybe a slight difference in relative palaeolatitudinal positions. No rotation of the Siberian platform would have taken place during the Vendian and Early Cambrian, and both the Angara and Aldan blocks would have experienced the same amount of relative rotation with respect to the Anabar block (Fig. 16). In that case, the oroclinal bending of the Baikal-Patom folded arc (e.g. see Fig. 1) between Angara and Aldan blocks would not have been produced by a relative movement between the Angara and Aldan (Kravchinsky et al., 1990; Konstantinov, 1998), but could be the result of later Barguzin block collision, as suggested by Zonenshain et al. (1990). In effect, these authors proposed that the Barguzin micro-block accreted to Siberia between the Cambrian and Devonian, which could have been responsible for the deformation of the arc.

To conclude, we note that only new palaeomagnetic investigations in the interior of the Angara and Aldan blocks can help solve these questions. However, an important point arising from this discussion is the possibility of large post-Early Cambrian rotations between the blocks forming the Siberian platform, and we therefore propose an alternative model where the amalgamation of Anabar, Aldan and Angara was not fully achieved by the Vendian–Early Cambrian.

5.2.2. Tsagan-Olom and Bayan-Gol Formations — the Tuva-Mongolian block

Our new Vendian Tsagan-Olom Formation pole obtained for the Tuva-Mongolian block

Table 5
Selected Vendian–Early Cambrian palaeomagnetic poles from Siberian platform, Mongolia, Tuva and Altay-Sayan folded zone

No	Age	PLAT	PLONG	DP	DM	SLAT	SLONG	Palaeolat	TESTS	*B*	*N*	TREAT	CODE	PLACE	STRAGE	Authors, Year
Aldan block of Siberia platform																
1	525–545	−46	181	5.7	9.5	59.5	135.0	−22	M	12	19	T	2	Aldan Region, Russia	CBL	Osipova, 1975
2	525–545	−16.6	65	3.1	6.2	61.0	126.8	−1.7	Ro		50	ATH	4	Yakutsk, Lena River, Siberia	CBL	Kirschvink and Rozanov, 1984
3	518–545	46	342	2.5	4.5	59	135	−17.3	N	2	18	TAV	1	Inican River, Aldan Region, Russia	CBL	Osipova, 1986
4	640–660	−19	175	4.7	9.2	58.1	137.1	6.8	N	1	21	T	2	Kavalkhan, Utchur-Maya Region, Aldan	PT3-V	Pavlov, 1993
5	640–660	−20	180	4.5	9	59.3	136.8	3.2	N	1	24	T	2	Kyry-Ytygha, Utchur-Maya Region, Aldan	PT3-V	Pavlov, 1993
Angara block of Siberia platform																
6	545–650	−56	110	2	4	55.3	97.5	−38.6	N	1	66	A	2	Tagul River, red beds Russia	V	Gurevich, 1982
7	545–650	−32.0	71.1	6.9	13.8	52.08	103.83	1.2	M, Ro	13	71	T		Shaman Formation	V	This study, 2001
8	545–650	−33.7	37.2	8.6	14.7	58.0	110.0	−19.9	M, Ro		12	T		Minya Formation	V	This study, 2001
Anabar block of Siberia patform																
9	518–545	−32	137	4.2	7.7	71.5	116	−14.6	N	40	40	TV	2	Udzha River, Russia	CBL	Rodionov, 1984
10	525–545	−39	153	6.5	11	68.5	112.5	−21.7	Ro, M	4	20	T	2	Olenek River, Northen Siberia	CBL	Osipova, 1975
11	518–535	−44.8	158.7	5.7	8.8	70.9	122.6	−28.6	Ro, M	8	23	T	4	Erkeket Formation, Olenek River, Northen Siberia	CBL	Pisarevsky et al., 1997
12	535–545	−37.6	165.0	9.3	15.4	70.9	122.6	−22.7	Ro, M	4	12	T	4	Kessuysa Formation, Olenek River, Northern Siberia	CBL	Pisarevsky et al., 1997
13	545–650	7.2	228.2	5.6	11	71	128	3.5	F+, R−, M	1	21	T	2	Lena River Basin, Russia	V	Komissarova, 1989
14	545–650	−26	127	4.7	9.2	71.5	116	−7.8	N	8	8	T	2	Tomtor River, Russia	V	Rodionov, 1984
Mongolia																
15	518–545	−14.7	48.6	7.5	14	46.3	96.1	15.5	F+		15	T	3	Khan-Tayshir mountains, Western Mongolia	CBL	Pechersky and Didenko, 1995
16	518–545	−24.1	103.3	3.3	5.8	46.3	96.1	19.3	Ro	6	51	T	3	Khan-Tayshir mountains, Western Mongolia	CBL	Pechersky and Didenko, 1995
17	548–590	−35.5	37.6	3.5	6.7	46.5	95.5	−18.6	Ro	6	33	T	3	Udzeltu-Gol River, Western Mongolia	V	Pechersky and Didenko, 1995
18	518–650	−27.9	48,2	6,5	13	46,4	96	4	N	3	63	T	3	Urigal-Gol, Udzeltu-Gol Rivers, Western Mongolia	V-CBL	Pechersky and Didenko, 1995
19	518–650	−22.6	105.6	4.1	7	46.3	96.5	20.6	N	10	41	T	3	Urigal-Gol River, Naran Massif, Western Mongolia	V-CBL	Pechersky and Didenko, 1995
20	518–650	−17.6	129.7	3,6	6.2	46.3	96.1	19.3	N	3	18	T	3	Khan-Tayshir Mountains, Western Mongolia	V-CBL	Pechersky and Didenko, 1995
21	518–545	4.0	115.0	4.6	4.6	46.50	95.45	44.2	Ro, M		193	T	4	Bayan Gol Formation	CBL	Evans et al., 1996
22	545–650	−22.8	28.4	10.8	21.6	46.76	96.37	−2.7	Ro, M	4	25	T		Tsagan-Olom Formation	V	This study, 2001
23	518–545	−21.4	167.1	9.6	19.1	46.76	96.37	−3.2	Ro, M	6	49	T		Bayan-Gol Formation	CBL	This study, 2001
Tuva																
24	518–545	−30	153	5.1	10	50.5	95	−5.4	M, Ro	6	48	T	4	South Tuva, Russia	CBL	Pechersky and Shelestun, 1989
25	518–545	37	326			52	95	9.5	Fo	8	72	T	2	South Tuva, Russia	CBL	Grishin et al., 1991
26	518–545	42	325	7.6	14	52	95	13.5	Fo	3	26	T	2	South Tuva, Russia	CBL	Grishin et al., 1991
27	518–545	33	328	5.7	11	52	95	6.8	N	5	46	T	2	South Tuva, Russia	CBL	Grishin et al., 1991
28	518–650	−40	140	4.4	8.4	51.3	90.7	−10.9	Go		21	T	3	Shatsk Ophiolite Massif, Western Tuva	V-CBL	Pechersky and Didenko, 1995

Table 5 (*Continued*)

No	Age	PLAT	PLONG	DP	DM	SLAT	SLONG	Palaeolat	TESTS	*B*	*N*	TREAT	CODE	PLACE	STRAGE	Authors, Year
Altay Sayan fold zone																
29	518–650	−44	135	9	17	50	88.6	−12.3	G+, Fo, Ro	7	36	T	3	Kurai Range, Gorny Altai, Russia	V-CBL	Pechersky and Didenko, 1995
30	518–545	−25	82	2	4	54.3	89.3	10.5	M	1	49	T	2	Kuznetsk Alatau, Russia	CBL	Zyatev and Merkulov, 1982
31	518–545	−42	118	4.4	8.5	54.5	88.4	−9.8	N	3	11	T	3	Medvezhiya Mountain, Kuznetsk Alatau	CBL	Pechersky and Didenko, 1995
32	518–545	−44	140	1.9	3.4	55.5	97.5	−15.8	M	58	87	TAV	1	Sayan Region, Russia	CBL	Davydov and Kravchinsky, 1971
33	518–545	−42	97.6	6.7	13	52	86.8	−4.5	F*o, Ro	2	8	T	3	Katun and Biya Rivers, Gorny Altai, Russia	CBL	Pechersky and Didenko, 1995
34	518–545	−31	64	2	4	55.5	88	1.1	M	1	21	TA	2	Kuznetsk Alatau, Russia	CBL	Zotkevich and Ponomarev, 1973
35	518–545	−45	53	6	11	55.5	88	−14.8	M, Ro	7	150	TA	1	Kuznetsk Alatau, Russia	CBL	Zotkevich and Ponomarev, 1973
36	545–650	46.2	269	3.8	7,3	52	100.5	8.7	Fo	2	22	T	3	Khoito-Boxon River, Eastern Sayan, Russia	V-CBL	Kravchinsky, 1995
37	545–650	26.6	310	4	8	52.8	93.5	−4.5	N		10	T	3	Kurtushibinsky Range, Western Sayan, Russia	V-CBL	Pechersky and Didenko, 1995

Notes: No.: number of pole, corresponding to Figs. 11–14; Age: age of rocks from database of McElhinny and Lock (1996); PLAT, PLONG: latitude, longitude of the palaeomagnetic pole; DP/DM: semi-axes of the 95% confidence ellipse of palaeomagnetic pole; SLAT, SLONG: latitude, longitude of the sampling locality; Palaeolat: palaeolatitude, TEST: stability tests after McElhinny and Lock (1996) (N: no tests, M: magnetic mineralogy experiments, Ro: reversal test, F: fold test); *B*: number of samples in the study; *N*: number of sites in the study; TREAT: laboratory treatment (T: thermal, A: alternating field, V: viscous demagnetizations); CODE: laboratory analytical procedures code from database of McElhinny and Lock (1996); STRAGE: stratigraphic age (CBL: Lower Cambrian, V: Vendian, PT3: Upper Proterozoic)

(Table 5, Fig. 15) is situated near southern Africa, and is highly discordant with our new Early Cambrian Bayan-Gol Formation pole which is situated around southeastern Australia near the group of poles from Tuva (poles 24–28, Table 5, Fig. 15). As for the Siberia poles just discussed, all the poles for Tuva-Mongolia are widely scattered, but lie along a small circle which also contains our new poles (Nos. 22 and 23). This denotes the importance of tectonic rotations within the Tuva-Mongolia block. From our new poles, this rotation can be estimated at $120.5 \pm 15.0°$ between our Vendian Tsagan-Olom locality and the Early Cambrian Bayan-Gol locality. Our pole provides a palaeolatitude of $-2.7 \pm 10.8°$ for the studied area in the Vendian (Tsagan-Olom Formation) and $-3.2 \pm 9.6°$ for the Early Cambrian (Bayan-Gol Formation), consistent with previous estimates (Table 5).

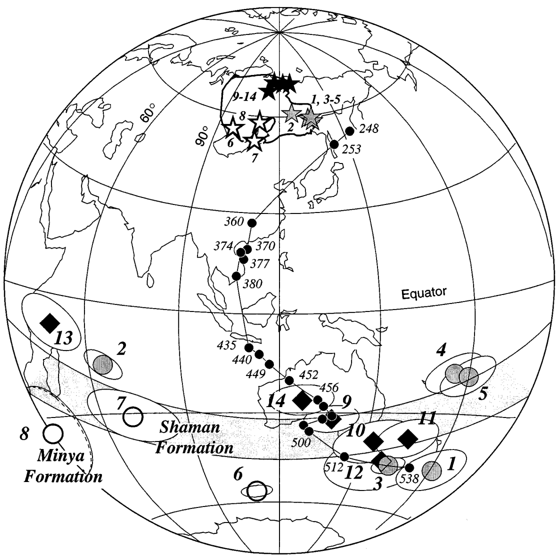

Fig. 14. Equal-area projections of Vendian and Early Cambrian palaeomagnetic poles from Siberia, with their 95% ellipses of confidence, numbered according to Table 5. Small dots are the Siberia platform APWP (Smethurst et al., 1998), with the age indicated in Ma. Closed diamonds and stars: palaeopoles and sites from the Anabar block; Shaded symbols and stars: palaeopoles and sites from the Aldan block; Open symbols and stars: palaeopoles and sites from the Angara block. The poles from the C components of the present study are the pole No.7 (Shaman Formation) and 8 (Minya Formation). The best-fit small-circle through the data and centred on the average sites location is drawn.

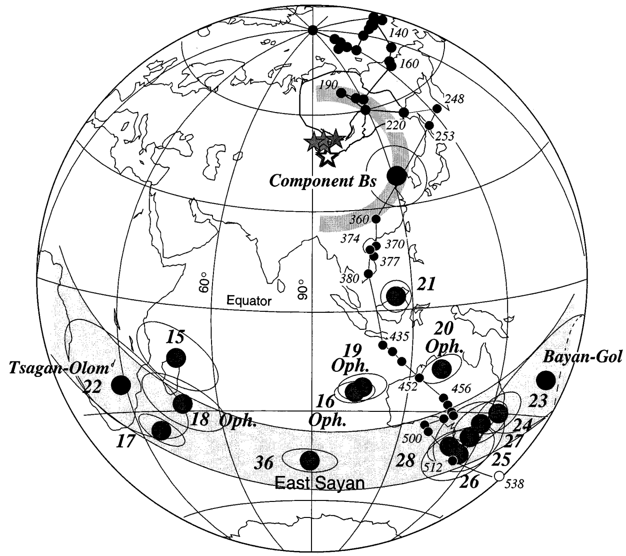

Fig. 15. Equal-area projections of Vendian and Early Cambrian palaeomagnetic poles, with their 95% ellipses of confidence, from the Tuva-Mongolian block, numbered according to Table 5. Small dots are the Siberia platform APWP (Besse and Courtillot, 1991; Van der Voo, 1993 from Present to 220 Ma, and Smethurst et al., 1998 for the Palaeozoic, 248–538 Ma) with the age indicated in Ma. Stars: sampling sites. The poles computed after the C component of Tsagan-Olom and Bayan-Gol Formations (this study) are the poles Nos. 22 and 23. The small-circle passing through our new Early Cambrian Bayan-Gol Formation pole, and centred on the site location (white star) is drawn. Oph.: palaeopoles obtained in ophiolites. The small-circle passing through our component Bs (middle temperature component) palaeopole for Tuva-Mongolia block (Mongolia Bs, see text) shows possible rotation.

We further note that the small circle containing the Tuva-Mongolian poles is very similar to the one containing palaeopoles from Siberia, and also contains the Vendian palaeopole of the East Sayan fold area (pole No. 36; Kravchinsky, 1995), which separates the Siberian platform and Mongolia. Altogether, this leads us to conclude that there has not been any significant palaeolatitudinal change between the Siberian and the Tuva-Mongolia blocks since the Vendian–Early Cambrian. This is shown on the schematic reconstructions of Fig. 16, where the Tuva-Mongolia block is placed adjacent to the Angara block.

This position of the Tuva-Mongolia block, adjacent (if not fully accreted) to Siberia in Vendian–Early Cambrian times, is consistent with the conclusions of Sengör et al. (1993). This, however, contradicts some of the observations and interpretations of Zonenshain et al. (1990). In effect, based on sedimentological and palaeontological evidence, and also on the presence of Cambrian ophiolites between Mongolia and Siberia, Zonenshain et al. (1990) assumed that the Tuva-Mongolia block was isolated within the Palaeoasian Ocean which separates Gondwanaland and Siberia, and that it was still separated from Siberia by the Early Cambrian. Evans et al. (1996) followed this idea, and interpreted the position of their pole (pole No. 21, Fig. 15) as arising from a significant north-south convergence after the Early Cambrian. However, the authors discussed the possibility that their Bayan-Gol Formation palaeomagnetic directions could be remagnetizations, and, from our discussion of the B component palaeopoles (see above), we suggest that it could arise from a bad separation of magnetic components. In any case, we suggest that this pole cannot be used for reconstruction of Mongolia in the Vendian–Early Cambrian.

In order to explain the occurrence of Vendian–Early Cambrian ophiolites between Tuva-Mongolia and Siberia, without any palaeolatitudinal changes between these two blocks since the Vendian–Early Cambrian, we propose the following hypothesis. Although the palaeopoles of Tuva-Mongolia are scattered along a small-circle, one can observe a cluster of some of them, including our new Bayan-Gol pole (poles 23–28). We tentatively assume that this cluster represents the position of the Early Cambrian palaeopole, whereas the remaining poles have been rotated later. The palaeopole computed from poles 23–28 lies at lat. = $-34.2°$, long. = $150.4°$, $A_{95} = 9.2°$, $n = 6$ poles. This palaeopole, which lies on the Early Cambrian part of the Siberian APWP, may characterize the Early Cambrian of the Tuva-Mongolian block. It shows a large clockwise rotation with respect to the Vendian palaeopoles we obtained in the Tsagan-Olom Formation and in the Shaman and Minya Formations from the Angara block. Because the palaeolatitudes are consistent, this could denote a post-Early Cambrian scissors-like closure of any ocean remaining between Tuva-Mongolia and Siberia (Fig. 16). This closure could also be responsible for the development of the East

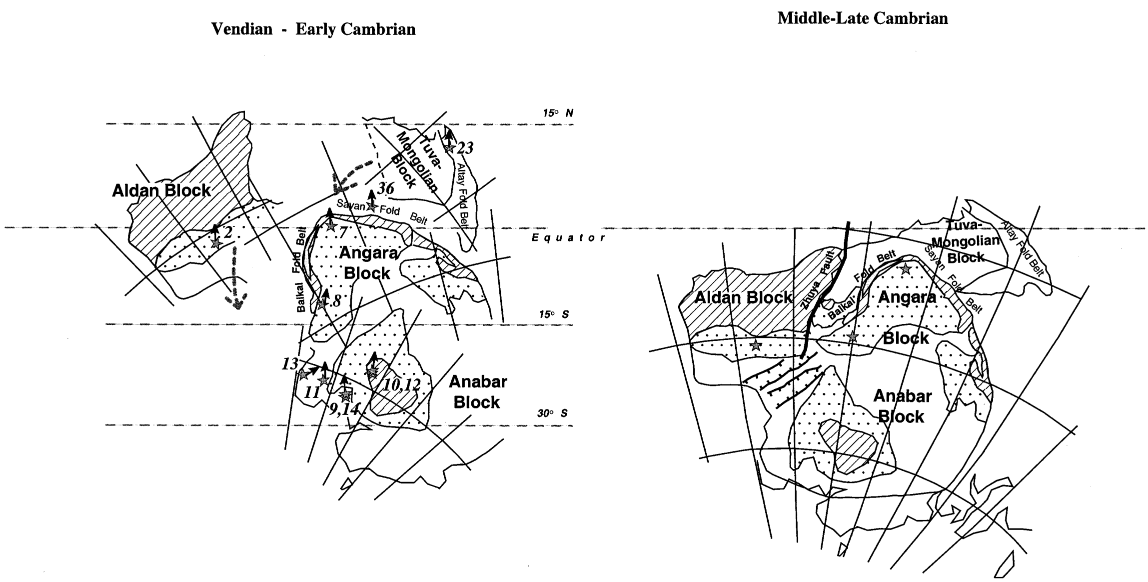

Fig. 16. Tentative palaeogeographic reconstructions of the Aldan, Angara, Anabar and Tuva-Mongolia blocks during Vendian–Early Cambrian (left), and Middle–Late Cambrian (right; after Smethurst et al., 1998) times. To the left, we use the second hypothesis of palaeoposition of the Aldan block following pole No.2 of Kirschvink and Rozanov (1984); see text). Block limits and legend are drawn according to Fig. 1.

Sayan fold zone, which was deformed in Pre-Ordovician times (Zonenshain, 1973; Belichenko et al., 1994). This reconciles the lack of palaeolatitudinal change between Tuva-Mongolia and Siberia and the evidence of oceanic crust between these two blocks.

6. Conclusions

The palaeomagnetic study of three Vendian and one Early Cambrian sedimentary successions from the Angara block of Siberia (Shaman and Minya Formations) and the Tuva-Mongolia block (Tsagan-Olom and Bayan-Gol Formations) allowed us to characterize a high-temperature magnetization component, showing both normal and reverse directions, in each succession. Although no fold test could be performed on these palaeomagnetic directions, we interpret these components as the primary magnetization of the series. A comparison of the new palaeopoles we computed with a compilation of previously published data from Siberia, Tuva-Mongolia and Altay-Sayan fold zone allows us to draw the following conclusions.

We separate the Siberia platform into three main blocks (Anabar, Angara and Aldan) for the purpose of analysing the different palaeomagnetic data sets. Significant discrepancies between the palaeopoles derived show that the Siberia platform might not have been fully consolidated by the Vendian and Early Cambrian. Some significant rotations between the Anabar and Angara, and maybe the Aldan, blocks, and possibly some slight latitudinal relative movements between the Aldan and Angara blocks, took place after this period. The Cambrian to Devonian development of the Baikal-Patom fold arc (Kravchinsky et al., 1990; Zonenshain et al., 1990; Konstantinov, 1998) could have partly resulted from these movements. In this case, complete amalgamation of Siberian blocks could have been achieved only by Early to mid-Palaeozoic times.

Our new palaeopoles for the Tuva-Mongolia block confirm previously published poles, and show that this block was already adjacent to Siberia by the Vendian and Early Cambrian. Thus, no significant amount of oceanic crust existed between the Tuva-Mongolia and Siberian blocks at that time. However, there could have been some relative rotations between these two blocks during the Vendian and Cambrian, which could be related to the final stages of an ocean closure, which could explain the presence of ophiolites in this zone. Finally, only new palaeomagnetic investigations can help to constrain the Precambrian and Palaeozoic history of these blocks better.

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