Geophys. J. Int. (2003) **154,** 829–840

Magnetic reversal frequency and apparent polar wander of the Siberian platform in the earliest Palaeozoic, inferred from the Khorbusuonka river section (northeastern Siberia)

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Accepted 2003 March 31. Received 2003 March 29; in original form 2002 September 16

SUMMARY

Marly limestones that crop out along the Khorbusuonka river (northeastern Siberian platform) define a well-dated Lower and Middle Cambrian sequence which was sampled for magnetostratigraphy. In the upper part of the section, from the uppermost Lower Cambrian (Toyonian stage) to the Middle Cambrian (Amgan and Mayan stages), thermal demagnetization isolates two magnetic components carried either by magnetite, haematite or both. The first is parallel to the recent geomagnetic field at the site and is removed in the low to middle temperature range. The second component is isolated at higher temperatures and has dual magnetic polarities. This component yields a positive (but partial since we consider only two sites) fold test with other Middle Cambrian data previously obtained from the distant Kulumbe river section, and was probably acquired during sedimentation or at an early stage of diagenesis. It records a very high magnetic reversal frequency, of at least six to eight reversals per Myr, during the entire Middle Cambrian (assuming a ~10 Myr duration for this epoch). A much more complex palaeomagnetic behaviour is observed within the upper Tommotian–lower Atdabanian (Lower Cambrian) part of the Khorbusuonka section. Demagnetization diagrams show large overlaps between magnetic components, which prevents the isolation of a clear magnetic component at high temperatures. Analysis of these overlaps is, however, consistent with the existence of an ill-determined primary magnetic direction for the Lower Cambrian, which is very different from that isolated in the Middle Cambrian. Although still in need of further confirmation, the possibility that a large drift in Siberian apparent polar wander occurred over a rather short time during the Lower Cambrian appears to be supported by our data.

Key words: apparent polar wander (APW), early Palaeozoic, magnetic reversal frequency, magnetostratigraphy, Siberia.

1 INTRODUCTION

Several magnetostratigraphic studies have focused on establishing the geomagnetic polarity sequence during the Early Palaeozoic (Kirschvink & Rozanov 1984; Torsvik & Trench 1991; Trench *et al.* 1991; Ripperdam & Kirschvink 1992; Ripperdam *et al.* 1993; Gallet & Pavlov 1996; Pisarevsky *et al.* 1997; Pavlov & Gallet 1998, 2001). These works indicate that a ~25 Myr long interval characterized by a strong reversed polarity bias, hence possibly a superchron, occurred from the Lower Ordovician (Arenig) to the Middle Ordovician (Llanvirn and part of the Llandeilo; Algeo 1996; Gallet & Pavlov 1996; Pavlov & Gallet 1998). In contrast, the upper part of the Middle Cambrian is characterized by frequent magnetic polarity reversals (Pavlov & Gallet 2001). In order to refine knowledge of the reversal frequency for this part of the Palaeozoic, we investigated the magnetostratigraphy of a new Siberian section which extends our previous results back in the past to the entire Middle Cambrian (Amgan and Mayan stages) and to the uppermost Lower Cambrian (Toyonian stage).

The Khorbusuonka section also provides new palaeomagnetic data for the Tommotian and Atdabanian stages of the Lower Cambrian. This period is fascinating because of the 'explosion of life' which probably occurred at that time over an interval perhaps as short as ~10 to 20 Myr (e.g. Bengston 1994; Kirschvink *et al.* 1997). Several hypotheses have been suggested to explain what triggered this crucial event in the Earth's history, including major and rapid plate reorganization, changes in sea water chemistry, and/or drastic climate change (e.g. Hoffman *et al.* 1998). One of the most intriguing scenarios has been proposed by Kirschvink *et al.* (1997), who suggested a possible episode of inertial interchange true polar wander (IITPW). This would have consisted of a fast migration of the geographic reference frame relative to the spin axis by 90° resulting in a drift of ∼90° in the APWP of all continents.

The letter suggestion is still strongly debated (e.g. Torsvik *et al.* 1998; Meert 1999) because it relies on the interpretation of the very few palaeomagnetic data presently available for the earliest Palaeozoic. In support of their hypothesis, Kirschvink *et al.* (1997) used palaeomagnetic results obtained from the Siberian platform (Kirschvink & Rozanov 1984; Gallet & Pavlov 1996). In particular, they considered a Lower Cambrian pole that Kirschvink & Rozanov (1984) obtained from the Petrotsvet Formation, which outcrops along the Lena river. This pole is indeed very different from the Middle Cambrian pole, which we have determined from the Kulumbe river section (Pavlov & Gallet 2001). However, there are potential problems with the Kirschvink and Rozanov data (see also Meert 1999). First, Siberia may have consisted of two blocks, the Anabar-Angara and the Aldanian blocks, which may have rotated relative to each other by ∼20°during the Middle Palaeozoic opening of the Viluy rift system (e.g. Pavlov & Petrov 1997; Smethurst *et al.* 1998). When this rotation is corrected for, the angular distance between the Lower and Middle Cambrian poles decreases to ∼50°. Another problem arises from the fact that the Kirschvink and Rozanov pole has not been clearly supported by other palaeomagnetic studies of Siberian sections: most existing Lower Cambrian data are quite different (e.g. Khramov 1991; Pisarevsky *et al.* 1997, and references therein) and happen to be closer to our Middle Cambrian pole. A major objective of our continuous sampling of the Lower and Middle Cambrian deposits of the Khorbusuonka section was therefore to solve these apparent contradictions.

2 THE KHORBUSUONKA RIVER SECTION

The studied section is located along the Khorbusuonka river in the northeastern part of the Siberian platform (latitude = 71.5°N; longitude = 124.0°E; Fig. 1). The well-exposed Lower–Middle Cambrian sediments that crop out there contain numerous fossils (trilobites, brachiopods and small shelly fossils), making it one of the most complete geological records of that age (e.g. Kabankov 1959; Savitsky *et al.* 1972; Astahkin *et al.* 1991; Korovnikov 1998, 2002). The Cambrian part of the section is divided into five formations (from bottom to top): Kessyusa, Erkeket, Kuonamka (only ∼3 m thick), Yunkyulyabit–Yuryakh and Tyuessala (e.g. Kabankov 1959; Savitsky *et al.* 1972; Astahkin *et al.* 1991). In this paper, we will present a magnetostratigraphic sequence isolated for ∼120 m of the section, ranging from the upper part of the Erkeket Formation to the Yunkyulyabit–Yuryakh Formation, the ages of which encompass the Toyonian, the Amgan and the Lower Mayan stages. In contrast, we will see below that the palaeomagnetic data obtained from the lower part of the section, within the Kessyuasa and the lower part of the Erkeket Formations (Tommotian–Atdabanian age), cannot be placed in a magnetostratigraphic context.

The rocks mainly consist of alternations of centimetre-thick marly reddish and greenish coloured limestones that were deposited in a shallow water environment (Fig. 2). They lie nearly horizontal, show no trace of alteration, and are not intruded by the Siberian traps, which are absent in the vicinity of the study area.

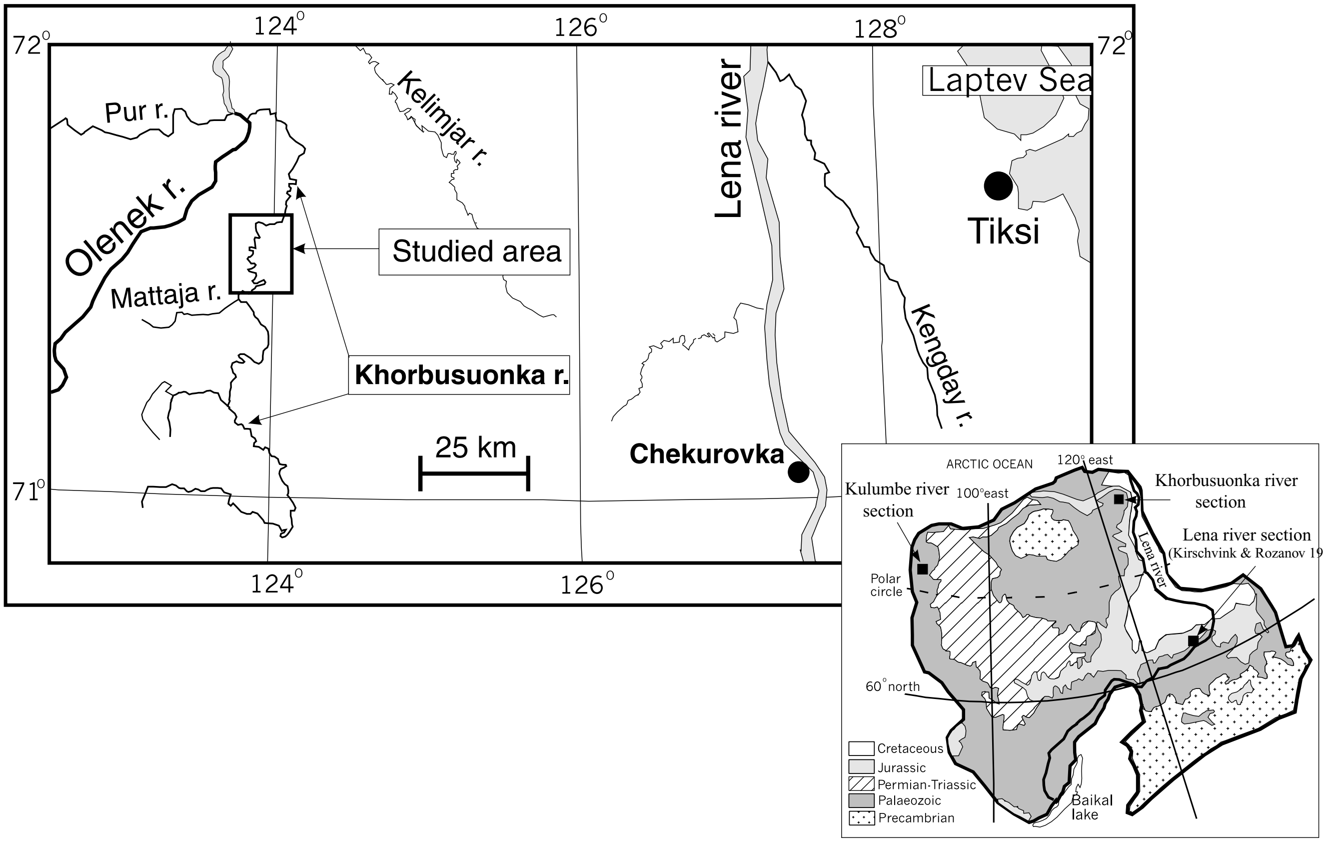

Figure 1. Location of the Khorbusuonka river section and simplified geological map of the Siberian platform.

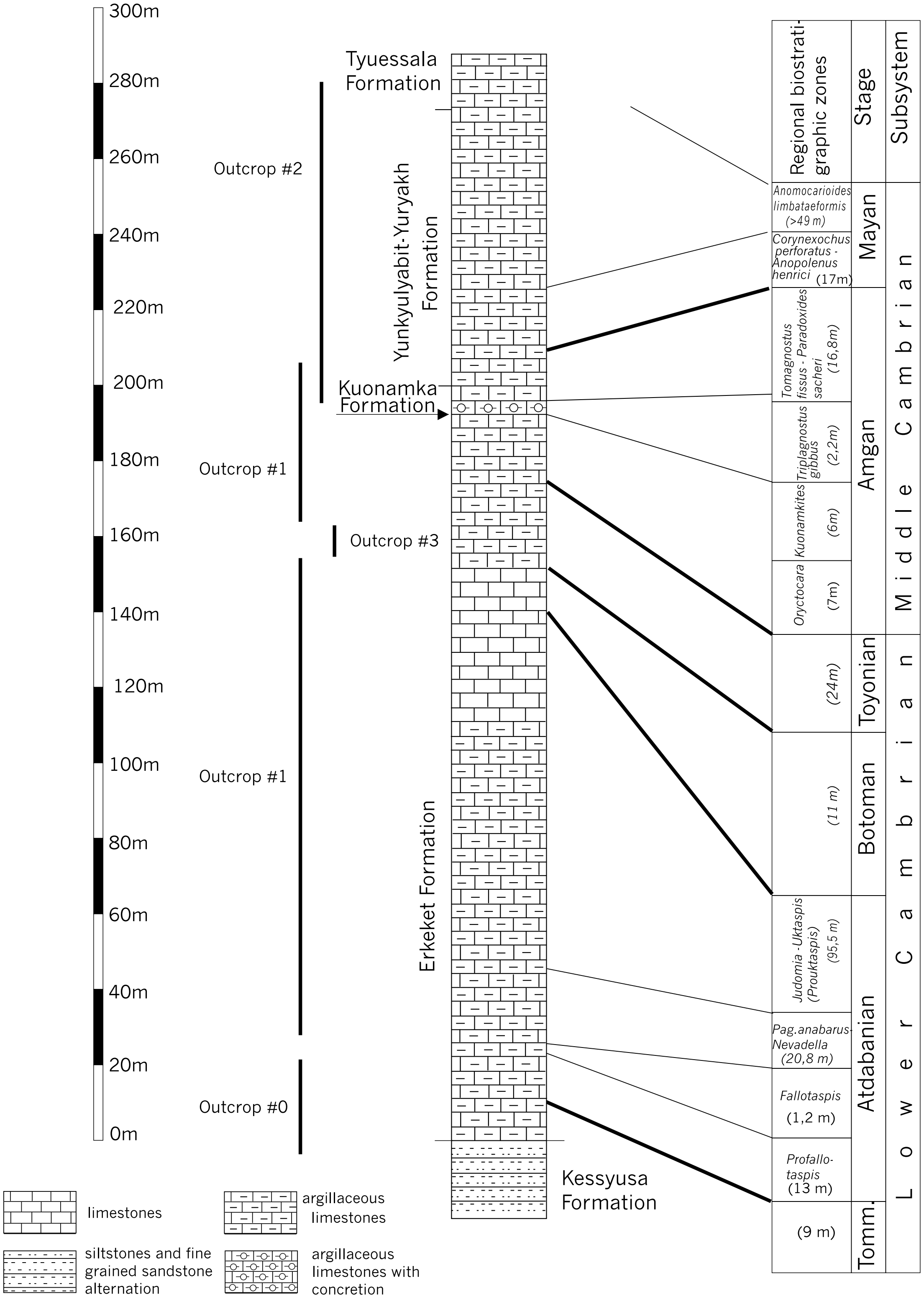

Figure 2. Simplified lithostratigraphy and biozonation of the Lower to Middle Cambrian sediments outcropping along the Khorbusuonka river (after Korovnikov 2002).

Palaeomagnetic samples were collected in four different localities, 1.5 km upstream (outcrop no 0) and some 8 (outcrop no 1), 25 (outcrops nos 2 and 3) and 27 (outcrop no 4) kilometres, respectively, downstream from the mouth of the Mattaia river (Fig. 1). In general, sampling was performed with a stratigraphic interval of ∼0.3–1.5 m and was conducted along with biostratigraphic investigations (Korovnikov 1998, 2002, Fig. 2).

3 PALAEOMAGNETIC RESULTS

3.1 Uppermost Lower Cambrian (Toyonian)–Middle Cambrian

Magnetization measurements were carried out using a 2 G three-axis cryogenic magnetometer in the magnetically shielded laboratory at the Institut de Physique du Globe de Paris. Samples were thermally demagnetized in 10–15 steps. All measurements were processed using the PaleoMac software (Cogné 2003). They revealed the presence of two magnetic components (Fig. 3). A low-temperature component (LTC) is isolated up to ∼300 °C. It is composed of only normal polarity directions parallel to the present Earth's magnetic field at the site (Fig. 4a; Table 1). A high-temperature component (HTC) is observed above ∼400–450 °C up to ∼540–580 °C or 640–680 °C depending on samples (Fig. 3). The HTC component has dual

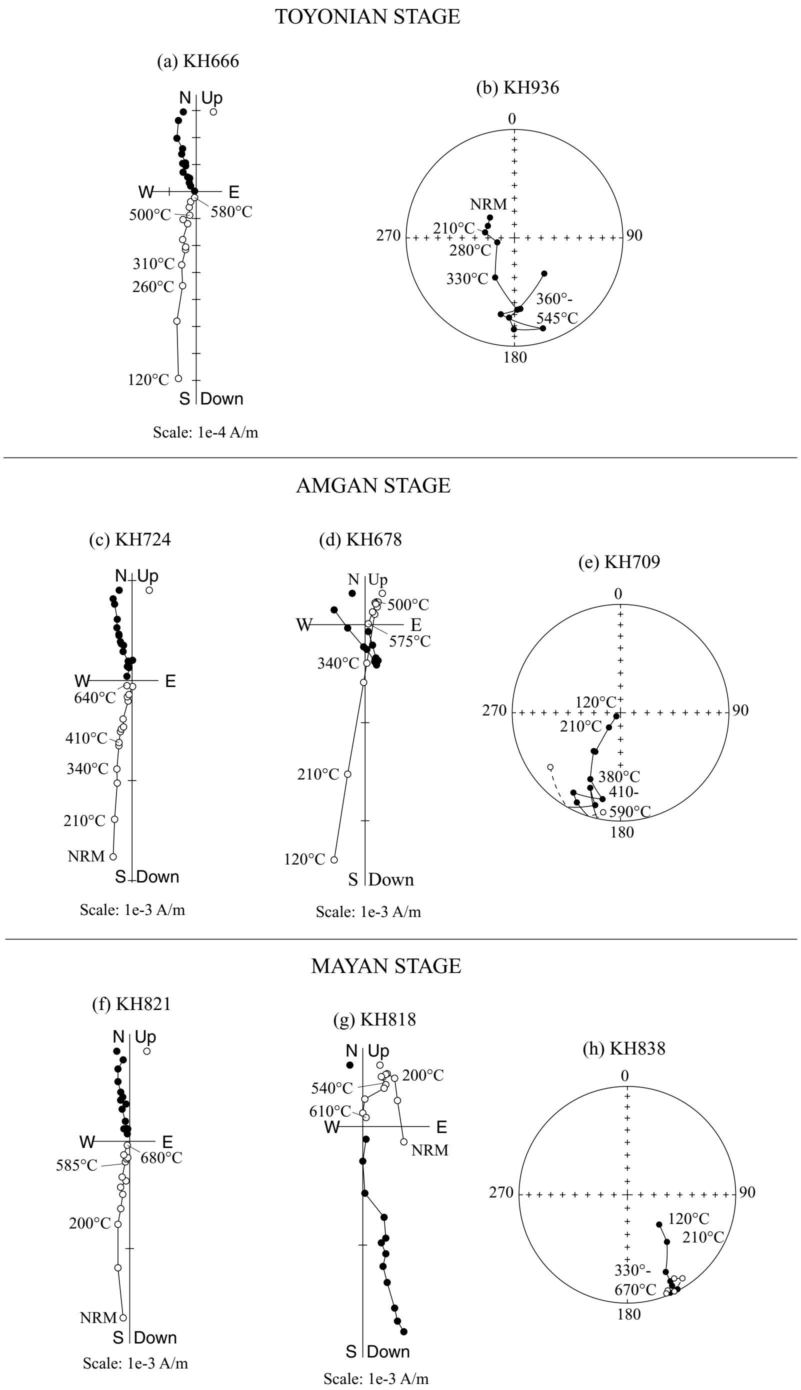

Figure 3. Thermal demagnetization of samples from the upper (uppermost Lower Cambrian–Middle Cambrian) part of the Khorbusuonka river section. (a), (c), (d), (f) and (g) examples of orthogonal vector diagrams. The closed (open) symbols refer to the horizontal (vertical) plane. Note that the strata are not tilted. (b), (e) and (h) examples of equal-area projection of directions obtained during thermal demagnetization. The closed (open) symbols refer to directions in the lower (upper) hemisphere.

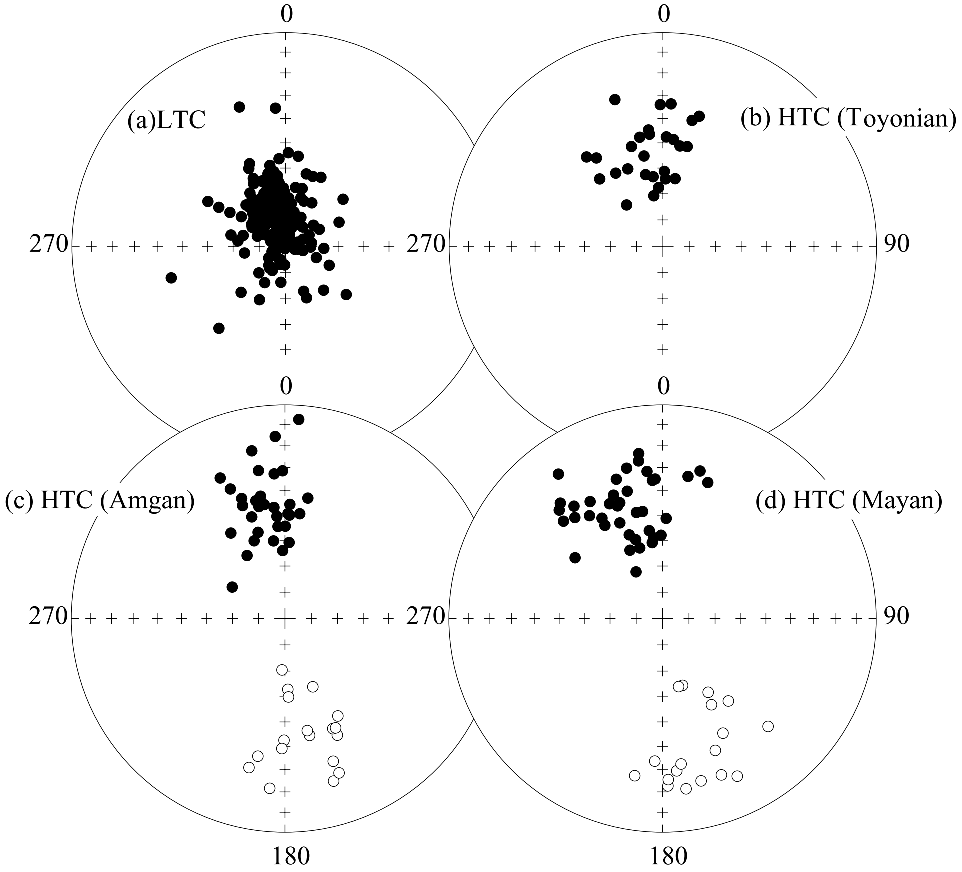

Figure 4. Equal-area projection of directions obtained for the Toyonian (uppermost Lower Cambrian), Amgan (Lower part of the Middle Cambrian) and Mayan (upper part of the Middle Cambrian) stages. Same conventions as in Fig. 3. Only HTC directions unbiased (or less contaminated) by the LTC component are reported in these figures (i.e. the great circles are not shown).

Table 1. Palaeomagnetic results obtained from the upper part of the Khorbusuonka river section.

	N	Geographical coordinates				Stratigraphic coordinates				Reversal test	
		D (deg)	*I* (deg)	*K*	α_{95} (deg)	*D* (deg)	*I* (deg)	*K*	α_{95} (deg)	γ (deg)	γ_c (deg)
LTC component											
General	210	342.1°	79.4°	35.6	1.7°	343.0°	78.9°	37.4	1.6°		
HTC component (Toyonian)											Normal polarity
Reversed polarity	28	350.8°	53.5°	25.9	5.5°	351.1°	53.4°	25.6	5.5°		
General	35	171.6°	−54.6°	24.3	5.0°	172.0°	−54.5°	24.0	5.1°	–	–
HTC component (Amgan)											
Normal polarity	30	169.2°	−45.1°	21.2	5.9°	169.9°	−44.8°	20.9	5.9°		
Reversed polarity	21	350.0°	47.4°	20.1	7.3°	350.4°	46.8°	19.8	7.3°		
General	51	169.5°	−46.5°	21.1	4.4°	170.1°	−46.0°	20.8	4.5°	2.0°	9.2°
HTC (Mayan)											
Normal polarity	57	167.1°	−42.1°	15.3	5.0°	167.0°	−41.8°	14.9	5.0°		
Reversed polarity	50	343.3°	43.1°	23.2	4.3°	343.3°	42.8°	23.9	4.2°		
General	107	165.2°	−43.3°	19.3	3.2°	165.1°	−43.0°	19.3	3.2°	2.9°	6.6°
HTC (Middle Cambrian: Amgan+Mayan)											
Normal polarity	87	168.0°	−43.1°	17.4	3.7°	168.2°	−42.7°	17.0	3.8°		
Reversed polarity	71	345.2°	44.4°	22.2	3.7°	345.3°	44.0°	22.2	3.7°		
General	158	166.6°	−44.3°	19.8	2.6°	166.8°	−44.0°	19.8	2.6°	2.5°	5.3°

N is number of samples or sites averaged; D and I are declination and inclination of mean paleomagnetic directions; K is concentration parameter (Fisher 1953); α_{95} is radius of 95 per cent confidence interval; γ and γ_c are angular distances (McFadden & McElhinny 1990).

polarity, southeast (respectively, northwest) and upward (respectively, downward) directions with moderate inclinations (Fig. 4). Thermal demagnetization characteristics seem to indicate that the magnetization is dominantly carried by magnetite in the Toyonian and the Amgan samples (e.g. Figs 3a and d) and both by haematite and magnetite in the Mayan samples (e.g. Figs 3f and g). The examples of demagnetization behaviour shown in Figs 5(a)–(d) further indicate that when magnetite and haematite appear to carry the

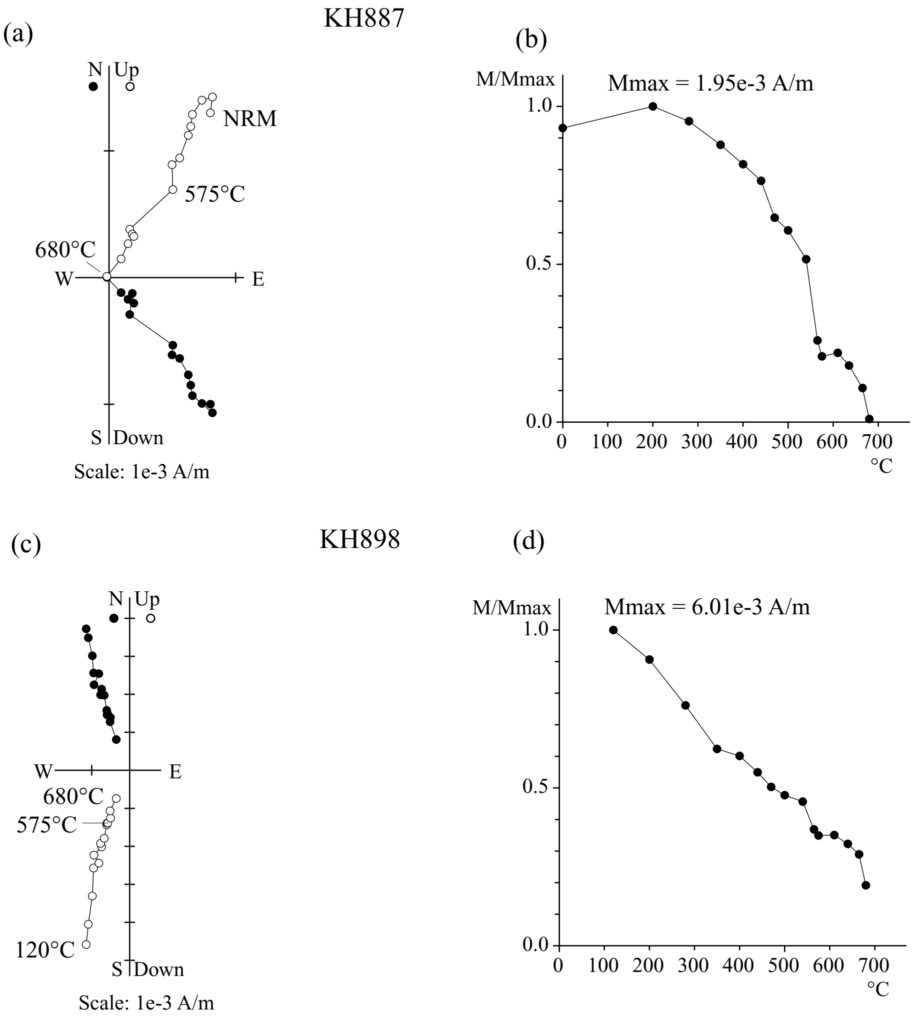

Figure 5. Thermal demagnetization diagrams for two samples from the Mayan stage and corresponding magnetization moment versus temperature evolutions showing clearly the presence of both magnetite and haematite.

magnetization together, the two minerals have clearly recorded the same palaeomagnetic component in the same polarity state.

A relatively large overlap between the LTC and HTC components often occurs in the moderate to high-temperature range. Consequently, the HTC directions are sometimes biased by the LTC component and cannot be determined by principal-component analysis (Figs 3b, e and h). Note that demagnetizations in alternating fields do not allow one to better isolate the final component. For these cases, we determined great circles, which were considered together with fitted lines for mean direction computations (McFadden & McElhinny 1988). This problem of overlap between components is particularly critical for the Toyonian stage for which no normal polarity directions can be obtained by principal-component analysis (Fig. 3b). The situation is much more favourable for samples of Amgan and Mayan age, which both provide a positive reversal test (McFadden & McElhinny 1990, Table 1). We recall that the polarity option chosen in Table 1 is guided by the fact that Siberia was located in the southern hemisphere during the earliest Palaeozoic (e.g. Khramov & Rodionov 1980; Van der Voo 1993; Gallet & Pavlov 1996).

The primary or near-primary origin of the HTC component isolated in the upper part of the section is constrained by several lines of evidence. Similar palaeomagnetic directions are obtained from samples having magnetite and/or haematite as predominant magnetic carriers. There is no relationship between the predominant magnetic carriers and the polarity state of samples. Most samples rejected because of scattered demagnetization behaviour are located close to or at the transition between intervals of opposite polarities. Positive reversal tests are obtained for the Amgan and Mayan stages (Table 1; McFadden & McElhinny 1990). The mean directions obtained for the Amgan and Mayan stages are identical at the 95 per cent confidence level ($\gamma = 4.7° < \gamma_c = 5.5°$; McFadden & McElhinny 1990). And the general Middle Cambrian direction estimated is very close to the Mayan direction previously obtained from the Kulumbe section (Pavlov & Gallet 2001), ~1400 km away from Khorbusuonka ($\gamma = 3.8° \sim \gamma_c = 3.5°$; after transferring the mean direction obtained from Kulumbe to Khorbusuonka based on virtual geomagnetic poles). This agreement between data from Khorbusuonka and Kulumbe is no longer valid when they are considered before tilt correction ($\gamma = 18.5° \gg \gamma_c = 3.7°$), which constitutes a partial, very large-scale fold test. Both the Khorbusuonka and the Kulumbe data show the occurrence of numerous polarity reversals. Moreover, the Upper Cambrian and Ordovician parts of the Kulumbe section, represented by the same lithology as that of the Middle Cambrian, exhibit a limited number of magnetic reversals (Pavlov & Gallet 1998).

Finally, the poles derived for the Middle Cambrian from Kulumbe and Khorbusuonka are different from all other younger poles known for the Siberian platform (e.g. Torsvik *et al.* 1995; Gallet & Pavlov 1996; Pavlov & Gallet 1998; Smethurst *et al.* 1998).

3.2 Tommotian–Atdabanian

The demagnetization diagrams obtained in the lower part of the Khorbusuonka section show a rather large variety of palaeomagnetic behaviour. In Fig. 6, we report the main types of demagnetization paths, including examples showing how the demagnetization paths may vary within the defined categories. The thermal demagnetizations first isolate a magnetic component up to 400–450 °C, which has roughly the same direction as the LTC component observed in the upper part of the section (Fig. 7a). After removal of this component, palaeomagnetic behaviour is in all cases rather complex because of strong overlaps between components and less stable magnetization, which prevents a robust determination of the HTC directions. A relatively simple behaviour is illustrated by samples KH760 and KH761 (Figs 6a and b), which may involve a single HTC component underlying the LTC component. These two samples may indicate the existence of a dual-polarity component with northeast (respectively, southwest) declinations and shallow inclinations (Fig. 6a, behaviour 'α', and b, behaviour '$-\alpha$', respectively). Samples KH773 and KH746 (Figs 6c and d) may correspond to the same behaviour, although the HTC is obscured because of larger overlaps with the LTC component. The demagnetization path of sample KH743 (Fig. 6e) also may indicate 'α' behaviour, as in KH760, although the final demagnetization steps above 580 °C might still indicate an underlying '$-\alpha$' component. This may reflect the lock-in of two magnetizations of opposite polarity during and/or soon after sediment deposition. This could be consistent with the observation that above 400 °C magnetization is mainly carried by haematite (although we failed in all cases to isolate a stable magnetic component above 600 °C) with a small fraction of magnetite as demonstrated by thermal demagnetization of three-axis differential isothermal remanent magnetization Lowrie 1990). This magnetic mineralogy is confirmed by alternating field demagnetizations, which are clearly unable to isolate the magnetic components. In the case of sample KH743 (Fig. 6e), and perhaps sample KH745A (Fig. 6f), which may be another noisy example of '$-\alpha$' behaviour, the haematite could have formed over a time interval including a polarity reversal.

We must mention two other, rather rare, types of behaviour, illustrated by samples KH486 and KH779 (Figs 6g and h). These are rather similar to the 'α' and '$-\alpha$' behaviours, except that the probable underlying HTC magnetization is directed in the NW ('β' behaviour), respectively SE ('$-\beta$' behaviour) quadrant. This behaviour may either reflect a true component, with a direction similar to the Middle Cambrian HTC direction (Fig. 4), or a fictitious component due to the overlap of two components including a predominant LTC and another (southwest-directed?) component. The first possibility has been considered by several authors when defining the Lower Cambrian pole of the Siberian platform (e.g. Pisarevsky *et al.* 1997, see below Section 4.2). Finally, sample KH782 (Fig. 6i) may either illustrate an example of 'α' behaviour, but with an HTC component directed to the E rather than to the ENE or NE, or yet another kind of '$-\beta$' behaviour.

To aid in the analysis of the possible underlying HTC components, we plotted the great circles from all those demagnetization diagrams for which such great circles can be safely determined (this was done for the topmost part of the Kessyusa Formation and the lowermost part of the Erkeket Formation; Fig. 7b). For comparison, we show in Fig. 7c the best defined great circles isolated within the upper part of the Khorbusuonka section, the latter being unambiguously due to overlaps between the LTC and the Middle Cambrian HTC components. It appears that a majority of the great circles have different orientations, respectively, in the lower and upper parts of the section, although a few great circles share the same orientation in both (the intersection of the great circles gives the LTC direction). Figs 7(d) and (e) show the directions of poles of the demagnetization planes isolated within the lower and upper parts of the section, respectively, and Figs 7(f) and (g) are the corresponding density diagrams. Figs 7(d) and (f) confirm a strong grouping of the great circle poles near azimuth/dip $= 140/20°$, hence a preferred mean great circle in the direction $\sim 50°$. It is worth pointing out that the mean great circle determined in the same way in the upper part of the section (Fig. 7g) contains the HTC normal and reversed mean directions independently obtained from principal-component analysis (Table 1). This supports the existence of an underlying primary HTC component in the lower part of the section with a generally shallow inclination and NE direction.

4 DISCUSSION

4.1 Magnetic reversal frequency during the Middle Cambrian

The Toyonian–Mayan palaeomagnetic data are reported as a function of their stratigraphic position in Fig. 8. For the demagnetization diagrams showing great circles, we reported biased estimates of the 'true' directions corresponding to the great circle segments defined by the ends of the demagnetization paths. The declinations of these directions (open dots in Fig. 8) yield a clear sequence of magnetic polarities. The magnetostratigraphy of the uppermost Lower and Middle Cambrian parts of the Khorbusuonka section shows the occurrence of numerous magnetic polarity intervals. Ten intervals are observed during the Toyonian, 24 during the Amgan (depending on the correlation between sections nos 1 and 2) and 30 during the Mayan stage. Many of them have a small stratigraphic thickness (less than 1 m) and are defined by only one sample. In addition to the constraints listed in section 3.3, the possibility that very local remagnetization of some samples may artificially have increased the number of magnetic zones seems unlikely because of the results obtained from a detailed magnetostratigraphy (~80 samples) carried out on another ~5 m thick Lower Mayan outcrop (section 4 in Fig. 8; INTAS project, Pavlov *et al.* in preparation). In this sequence, thin magnetic intervals of ~20–30 cm are observed, defined by several samples, which gives us confidence in their geomagnetic significance. As the sampling density in our sections is notably smaller, the number of magnetic intervals we obtain is probably a minimum estimate.

The large number of polarity intervals observed during the upper part of the Amgan stage and the dependence of the recovered magnetic signature upon sample distribution prevent the determination of a definite correlation between section nos 1–3 and section no 2 (Fig. 8). Moreover, the time resolution provided by biostratigraphy does not appear to be sufficient to reliably constrain the correlation. The same problems are encountered in the correlation between the Khorbusuonka and Kulumbe sections. The upper part of section no 2 in Khorbusuonka corresponds to sediments deposited during the lower and possibly during the middle part of the *A. limbataeformis* zone, while the lower part of the Kulumbe section is dated from the upper and possibly middle part of the same trilobite zone. There is no

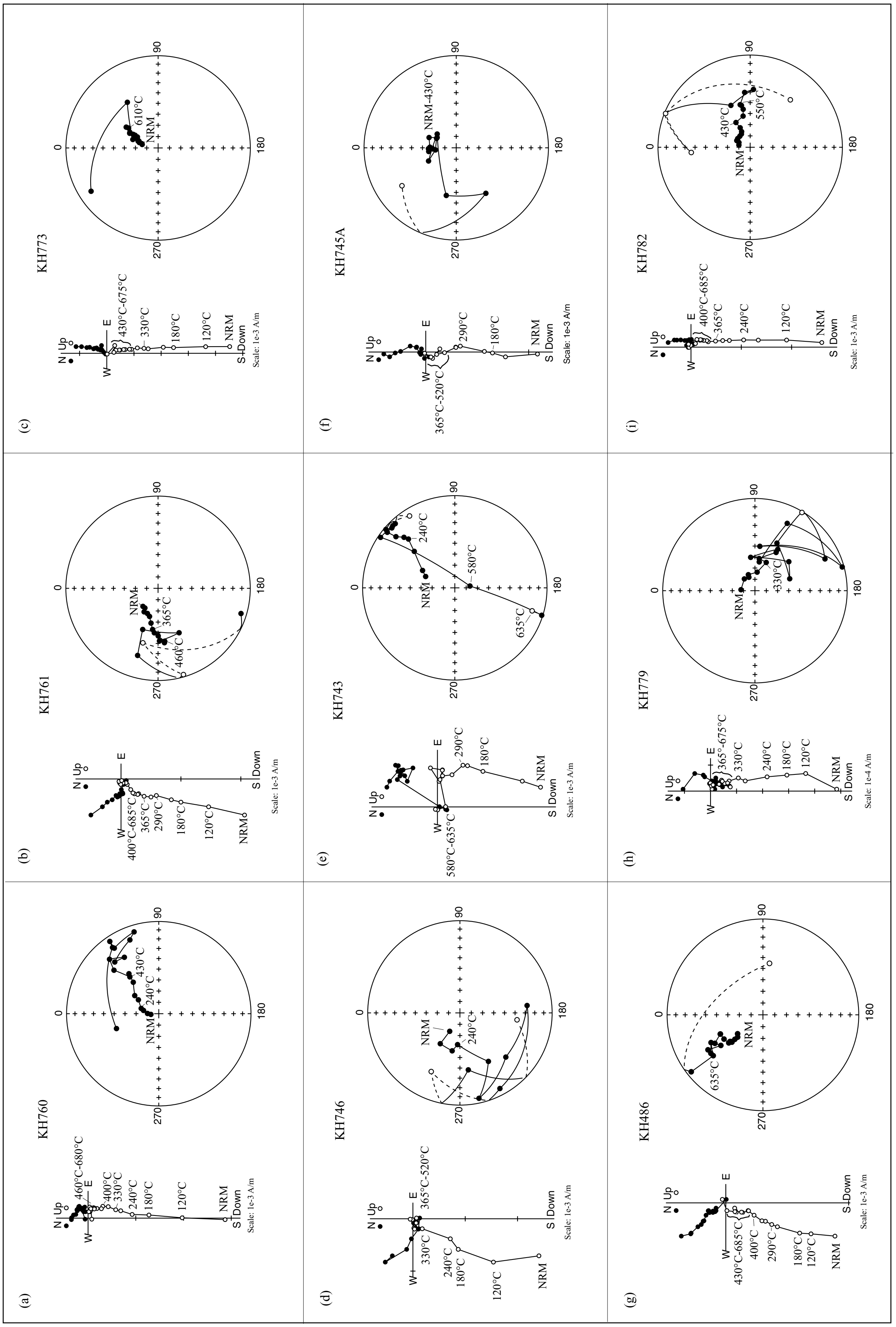

Figure 6. Thermal demagnetization of samples from the lower (Tommotian–Atdabanian) part of the Khorbusuonka river section. Same conventions as in Fig. 3.

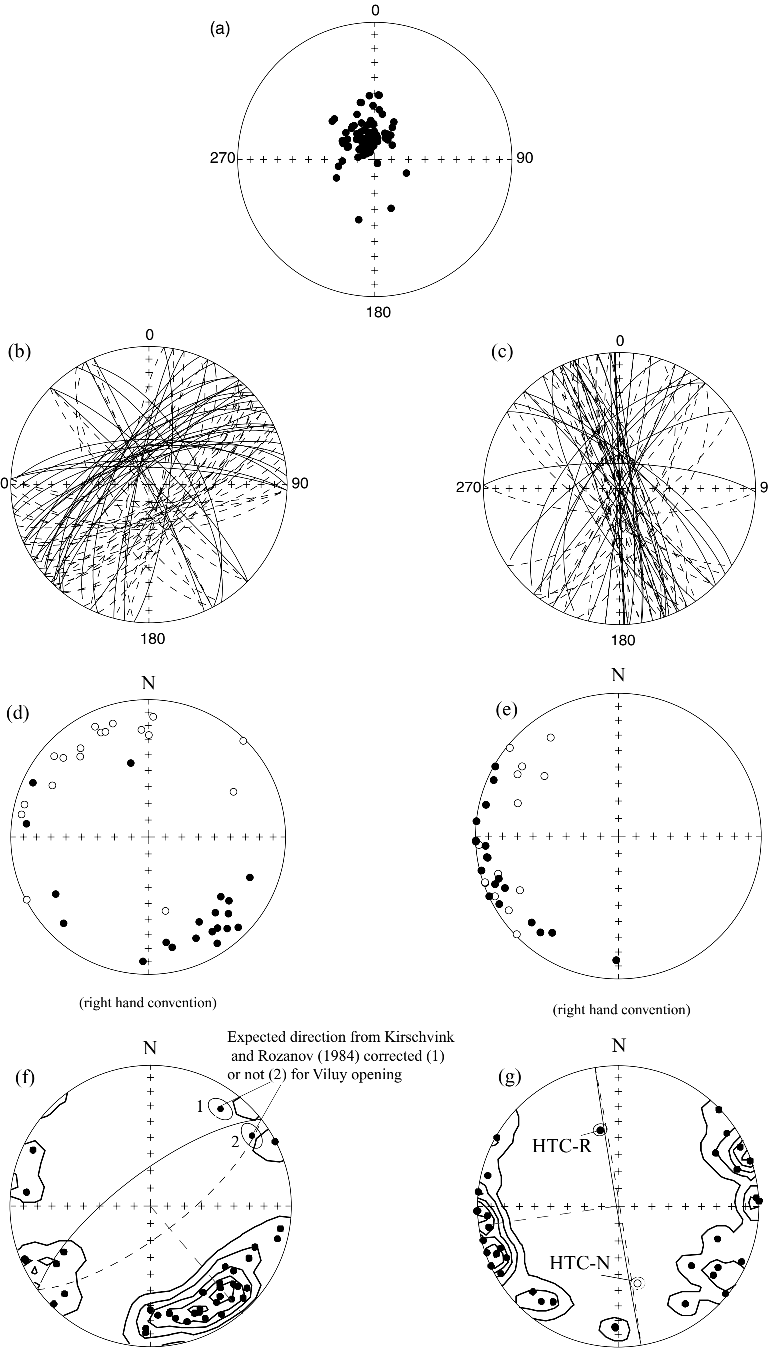

Figure 7. Equal-area projection of directions isolated in the low to middle temperature range in samples from the lower part of the Khorbusuonka section (a). (b) and (c) great circles determined from samples from the lower (b) and upper (c) parts of the section. (d) and (e) directions of the normals to the demagnetization planes isolated within the lower (d) and upper (e) parts of the section, and corresponding density diagrams (f and g, respectively). Same conventions as in Fig. 3.

clear resemblance between the two magnetic signatures that might favour a time-shift between the two studied sections, but again we cannot exclude discrepancies due to sampling effects. Hence, the data presently available from Kulumbe and Khorbusuonka do not allow us to establish an accurate geomagnetic polarity timescale during the Middle Cambrian. However, both give strong evidence for high magnetic reversal frequency during this epoch.

Our new results indicate that the Middle Cambrian is characterized by at least 54 magnetic intervals (combining the Amgan and Mayan data). Furthermore, considering the magnetostratigraphic sequence previously obtained from Kulumbe, this number may increase up to ∼70–80 intervals, depending on the correlation between the Kulumbe and Khorbusuonka sections. The computation of a reversal frequency estimate strongly relies on the duration of the Middle Cambrian, which is still not unambiguously determined (see, for example, short discussion in Meert 1999 or in Pavlov & Gallet 2001). Pavlov & Gallet (2001) considered a maximum duration of ∼13 Myr, but a duration of ∼10 Myr is assumed in most recent Cambrian timescales (Davidek *et al.* 1998; Landing *et al.* 1998;

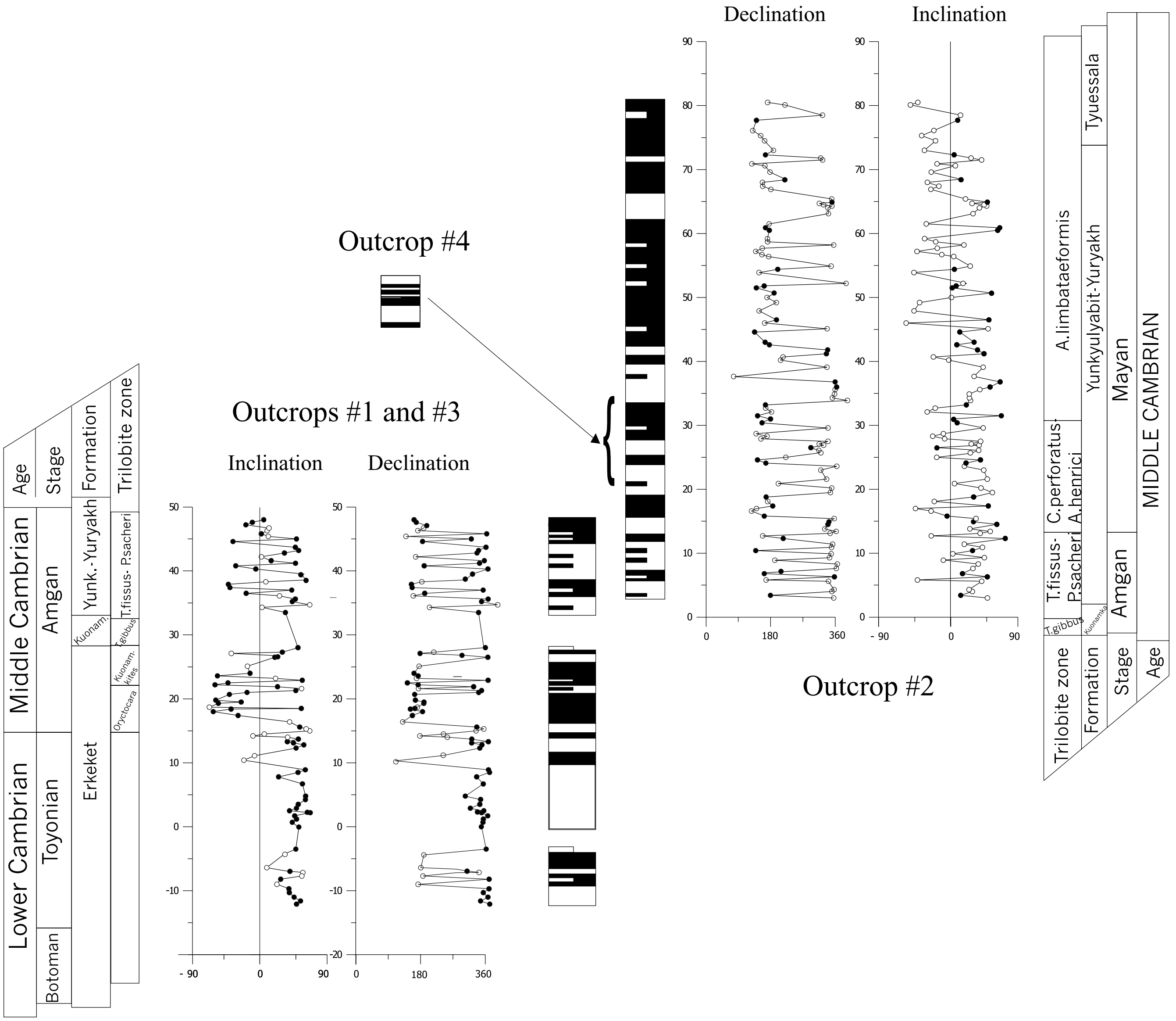

Figure 8. Toyonian to Mayan magnetostratigraphy from the Khorbusuonka section. Section no 4 corresponds to a small magnetostratigraphy sequence carried out to constrain the geomagnetic origin of the magnetic polarity intervals of small thickness (see the text). The open dots refer to biased directions not considered for mean computations but which provide an information on magnetic polarity.

Encarnaçion *et al.* 1999). These would imply a magnetic reversal frequency of no less than ∼six to eight reversals per Myr during the Middle Cambrian. This very high value may be comparable to the reversal frequency observed during the Middle Jurassic, for instance during the Bajocian stage as documented by the magnetostratigraphy of the Carcabuey section (Steiner *et al.* 1987). This may also be the case during the time (probably Oxfordian–Callovian) of the oldest (pre-M29) oceanic magnetic anomalies (Handschumacher *et al.* 1988; Sager *et al.* 1998). In more recent times, high reversal frequencies occurred during the Miocene but with a mean value of only ∼4 Myr^{-1}. The reversal frequency that we propose during the Middle Cambrian may therefore not be unusual, if we assume that only few short magnetic intervals were missed because of the sampling process or if the duration of the Middle Cambrian was not shorter than 10 Myr (which cannot be excluded from the available radiometric data).

4.2 A fast drift in the APWP of Siberia during the Lower Cambrian?

We tentatively propose that the complex palaeomagnetic behaviour observed in the lower part of the Khorbusuonka section is mainly due to the lock-in time of magnetization, linked to delayed growth of haematite, which would on average have lasted longer than the average duration of magnetic polarity intervals during the earliest Palaeozoic, and perhaps longer than the lock-in time of magnetization in the upper part of the Khorbusuonka section. The lock-in of magnetic components with opposite directions and strong overlaps, together with a large remagnetization in more recent times, may indeed explain most of the demagnetization paths we observe. This possibility seems reasonable and would avoid the uncomfortable need to explain why remagnetization would have affected the Lower Cambrian strata but not the Middle Cambrian ones, when no significant lithological change occurs between the two parts of

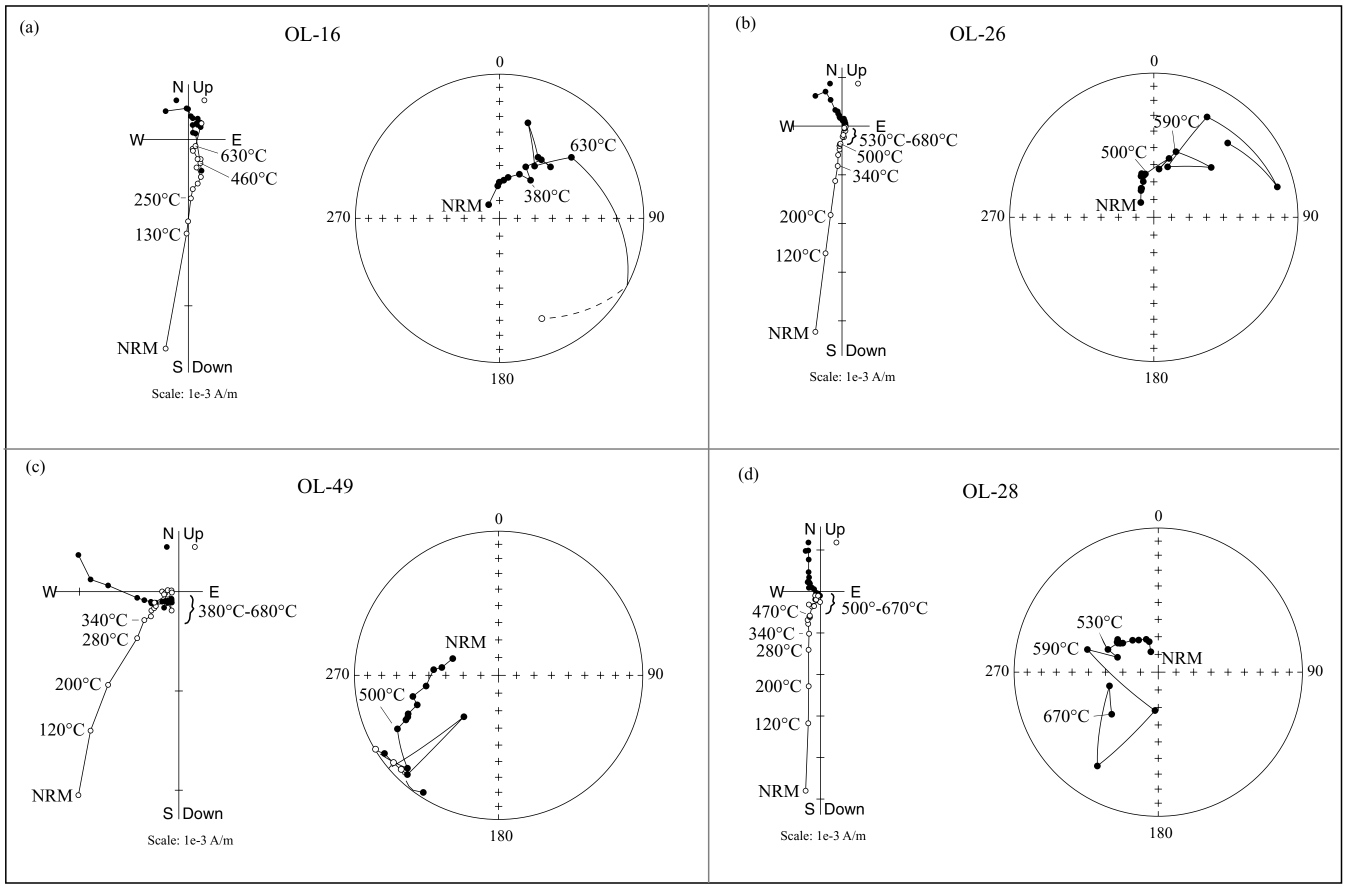

Figure 9. Demagnetization diagrams obtained from samples taken in the Erkeket Formation from the Olenek section. These samples exhibit the 'α' (a and b) and '$-\alpha$' (c and d) behaviours previously defined based on results from the Khorbusuonka section.

the section. Considering our discussion in Section 4.1, this could imply either that the specific palaeomagnetic behaviour observed within the lower part of the section results from a magnetic reversal frequency during the Tommotian and the Atdabanian even higher than during the Middle Cambrian, or that magnetic mineralogy changed slightly, resulting in different recording properties. Clearly, this interpretation is not unique and any definite description of geomagnetic field behaviour during the earliest Palaeozoic will require additional results.

If we assume that the northeast (southwest) HTC component, which is revealed by the great circles for our Tommotian–Atdabanian samples (Figs 7d and e), was acquired soon after sedimentation, then there would be a very large difference between this lowermost Cambrian palaeomagnetic direction and that obtained for the Uppermost Lower Cambrian (Toyonian)–Middle Cambrian. This directional shift would have occurred during the Late Atdabanian, the Botoman and the Early Toyonian, an interval of at most ~10 Myr for which we could not obtain palaeomagnetic data (samples being too weakly magnetized above ~400 °C). The distribution of the demagnetization planes indicates a shift in direction of ~60°, but even larger shifts are possible (Fig. 7f). The distribution of poles of circles observed in Fig. 7(b) is very similar to that obtained by Kirschvink & Rozanov (1984) from the Lena section (see fig. 6c in their paper) and our mean great circle lies close to the mean Lower Cambrian direction proposed by these authors (Fig. 7f).

Our interpretation would seem to be contradicted by the data of the same age with a NW mean palaeomagnetic direction reported by Pisarevsky *et al.* (1997) from the Olenek river, only ~80 km away from Khorbusuonka. We also collected some samples along the Olenek river, both in the Kessyusa and Erkeket Formations, for direct comparison with our results from Khorbusuonka. The palaeomagnetic behaviour observed in these samples is very similar to that from Khorbusuonka, showing complex demagnetization paths at high temperatures, with in most cases the 'α' and '$-\alpha$' behaviours we previously defined (Fig. 9). The discrepancy between the interpretation of Pisarevsky *et al.* (1997) and ours could thus be due to a different interpretation of the overlaps between the HTC and LTC components.

As a general matter, we believe that the ambiguity presently existing on the position of Siberia during the Lower Cambrian essentially arises from complex palaeomagnetic behaviour in the samples studied so far, which casts doubt on the reliability of ancient data obtained from Siberia using incomplete demagnetization procedures. Our study should therefore motivate further palaeomagnetic investigations of Lower Cambrian Siberian sections. Until better quality data become available, the view that a large drift in Siberian apparent polar wander occurred over a rather short time during the Lower Cambrian finds some support in our complex data.

ACKNOWLEDGMENTS

We thank Stuart Gilder for helpful comments on the manuscript. We are also grateful to Cor Langereis who gave very detailed and useful comments. VP was supported by the Russian Foundation for Basic

Researches (RFBR, grant no 01-05-64819), by INTAS (grant no 99-01273) and by the University of Paris 7. This is IPGP contribution no 1905 and INSU CNRS no 341.

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