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Upper Cambrian to Middle Ordovician magnetostratigraphy from the Kulumbe river section (northwestern Siberia)

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Abstract

We present the magnetostratigraphy of an Upper Cambrian to Middle Ordovician sedimentary section sampled along the Kulumbe river in northwestern Siberia. Thermal demagnetization yields the determination of two magnetic components. A component of steep inclination is interpreted as a remagnetization acquired during the emplacement of the Siberian traps at the Permian–Triassic boundary. Another component with a moderate inclination, essentially carried by hematite and sometimes by magnetite, likely represents a syndepositional or nearly syndepositional magnetization of the studied deposits. A sequence of 17 magnetic intervals is observed between the upper part of the Upper Cambrian and the Tremadoc, three of them being poorly defined by single samples. We also find that the Llanvirn magnetostratigraphic sequence contains only one reversed polarity interval. Together with magnetostratigraphic results previously obtained from the Moyero river section from Siberia, our data suggest the occurrence of a 25–30 Myr-long period during the Lower and the Middle Ordovician characterized by a very low magnetic reversal frequency (possibly containing a superchron), and dominated by reversed polarity. This geomagnetic feature would be compatible with a time constant of about 150 Myr in the reversal process through the whole Phanerozoic. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: Upper Cambrian; Middle Ordovician; Magnetostratigraphy; Kulumbe river

1. Introduction

Long periods without magnetic polarity reversals (also called superchrons) have been linked to major, in particular volcanic, events through the history of the Earth (e.g., Loper and McCartney, 1986; Courtillot and Besse, 1987; Larson and Olson, 1991; Gallet and Hulot, 1997). Two superchons are presently well known, one during the Upper Cretaceous, with a normal magnetic polarity and a duration of 35 Myr (e.g., Cande and Kent, 1995), and the second of reversed polarity between the Upper Carboniferous and the Upper Permian with a duration of about 60 Myr (the Kiaman superchon; e.g., Harland et al., 1989). The geomagnetic polarity sequence between these exceptional magnetic intervals suggests a long time constant of 150–200 Myr in changes in magnetic reversal frequency (McFadden and Merrill, 1984; Courtillot and Besse, 1987; Gallet et al., 1992). The rare magnetostratigraphic data obtained

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from biostratigraphically well-dated Paleozoic sections (e.g., Torsvik and Trench, 1991a; Kirschvink and Rozanov, 1984; Ripperdam and Kirschvink, 1992; Ripperdam et al., 1993; Torsvik et al., 1995a) presently do not allow the opportunity to clearly test if this long time constant in the geomagnetic field holds for older periods, and in particular to test if a third superchon occurred during the early Paleozoic (see Eide and Torsvik, 1996). However, two recent studies carried out from large compilations of paleomagnetic data suggest that a strong reversed polarity bias existed during the first half of the Ordovician which could indeed correspond to the presence of a superchron (Johnson et al., 1995; Algeo, 1996). Note that the Kiaman superchron was also recognized from similar first-order estimates from a more limited paleomagnetic database (McElhinny, 1971; Irving and Pullaiah, 1976). In order to establish a magnetic polarity sequence during the early Paleozoic, we investigated in a previous study the magnetostratigraphy of a sedimentary section along the Moyero river in the northwestern part of the Siberian Platform, which contains Upper Cambrian to Ordovician deposits (Gallet and Pavlov, 1996). That study indicates that the Arenig (Lower Ordovician) is characterized by a reversed magnetic polarity with no evidence for any reversal. The same characteristic could be also considered for the Llanvirn (older part of the Middle Ordovician), but the sampling density in this part of the sequence, of approximately 40 samples, prevents a firm conclusion. In contrast, a few reversals were detected during the middle part of the Llandeilo (Middle Ordovician). We present here a magnetostratigraphic study of another sedimentary section from Siberia, along the Kulumbe river, which provides new constraints on the reversal behaviour during the early Paleozoic.

2. Description of the Kulumbe section

The Kulumbe section is located in the northwestern part of the Siberian platform, approximately 150 km east of the Yenisey river (Fig. 1; Latitude: 68.0°N, Longitude: 88.8°E). This section outcrops along the Kulumbe river, where sediments with an age ranging from the Vendian (Uppermost Precambrian) to the Ordovician are exposed over a distance of about 10 km. These deposits are tilted 15° to 20° towards the east. Mikutskiy and Petrakov (1961) and Kravtsov (1967) believe that folding of the beds occurred in the Carboniferous, while Groisman (1970) and Malich (1975) consider that the folding may have continued until the Triassic. As in Moyero, the Kulumbe river section is locally intruded by dikes and sills which are associated with the Siberian traps. Samples were collected from these latter rocks to compare their paleomagnetic directions with those obtained from sediments.

During the summer of 1995, about 1200 m of stratigraphic sequence were sampled throughout 4 formations from the Upper Cambrian to the Lower Ordovician (Kulumbinskaya, Uigurskaja and Iltykskaya formations) and the Llanvirn (Middle Ordovician; Guragirskaya formation). These formations are dated by conodonts and endemic benthic faunas (trilobites, brachiopods and ostracods) which yield a regional stage zonation (Fig. 2; Datsenko et al., 1968; Rozova, 1968; Sokolov, 1982; Kanygin et al., 1987; Astahkin et al., 1991; Rozanov et al., 1992). The precise correlation between this local reference zonation, valid only for the northern part of Siberia, and the standard geologic time scale based on graptolite biostratigraphy from British sections is difficult. Brachiopods (e.g., *Angarella jaworowski* Asatk., *Leontiella gloriosa* Yadr.) and conodonts (e.g., *Coleodus* sp., *Erismodus asymmetricus*, *Necoleodus breviconus*) are strictly found in the upper part of the Guragirskaya formation and correlate to the Vikhorevian and Muktian horizons. These two horizons are conventionally assigned to the Llanvirn (e.g., Kanygin et al., 1987). This is also supported by the biostratigraphic data available from the Volgian horizon (Angir formation) and from the Kimaian horizon (Iltykskaya formation), which over- and under-lies the Guragirskaya formation, respectively (Rozova, 1968; Kanygin et al., 1987). In the Volgian horizon, *Phragmodus flexuosus* is the dominant conodont species, also known from North America where it is considered a part of the Llandeilo (5 and 6 Fauna of the Chazyan; Sweet et al., 1971; Sweet and Bergstrom, 1976). Most of the brachiopods and ostracods are also common in the Lachug horizon from northeastern Eurasia, where

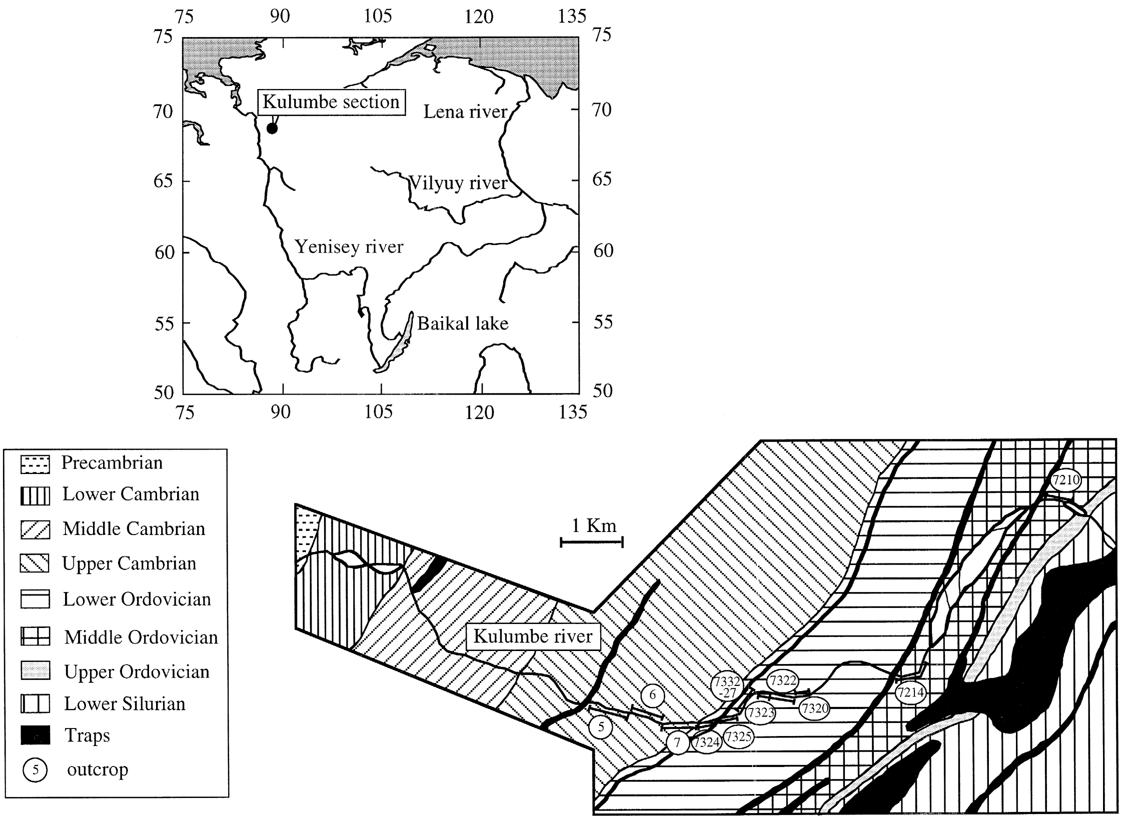

Fig. 1. Locality and simplified geological maps of the Kulumbe river section (after Vysotsky and Andreeva, 1969).

they are associated with the graptolite Glyptograptus teretiusculus zone, implying a Lower Llandeilo age (Kanygin et al., 1987; Harland et al., 1989). The Kulumbe section contains the stratotype of the Kimaian horizon, rich in conodonts, brachiopods and ostracods. The conodont assemblage found in the Kimaian horizon is similar to the one characterizing the D fauna from North America which is correlated to the Upper Arenig (Ross et al., 1982). Altogether the biostratigraphic data therefore indicate a Llanvirn age for the Guragirskaya formation. Moreover, there is no evidence for significant sedimentary hiatuses in this part of the Kulumbe section (in contrast to other sections along the Lena river; Sokolov, 1982).

The reference section of Batyrbay from southern Kazakhstan also provides constraints on the correlation of the Uigurskaya and a part of the Iltykskaya formations with the Tremadoc (Rozova, 1986; Dubinina, 1990; [1] Rozanov et al., 1992). But we recall that the definition of the Cambrian/Ordovician boundary is still matter of debate and a global stratotype section has not yet been chosen (e.g., Ripperdam and Kirschvink, 1992). For Siberian sections, this lack of agreement yields two possibilities. The first, proposed by the Russian Interdepartmental Stratigraphic Committee (1983), is to locate the Cambrian/Ordovician boundary at the base of the Mansian stage, which is well-defined in Siberia from brachiopods and trilobites (Fig. 2; Yadrenkina, 1974; Ogienko, 1977). The second, suggested by the Cambrian/Ordovician boundary International Working

[1] Dubinina, S.V., 1990. The conodont stratigraphy of Cambrian–Ordovician deposits from Kazakhstan. Unpublished Thesis, Moscow.

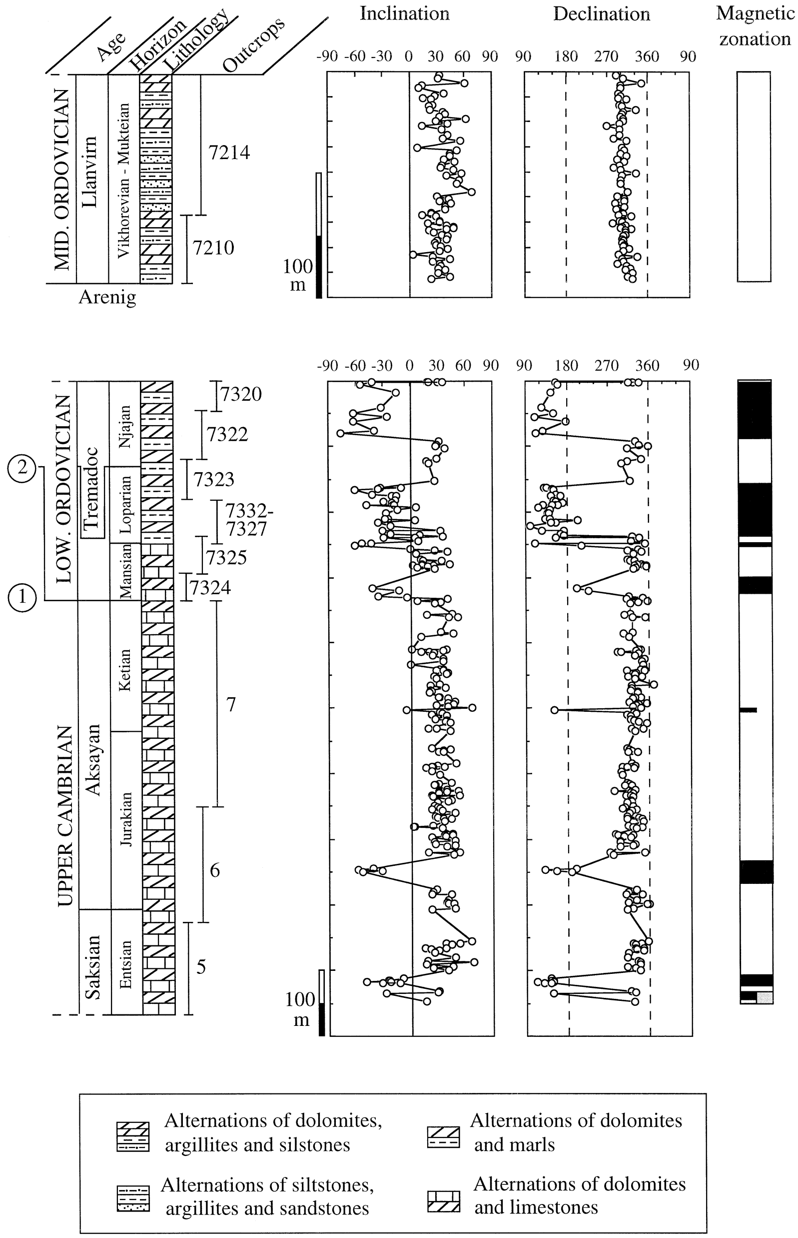

Fig. 2. Magnetostratigraphy of the Kulumbe river section. Magnetic intervals defined by only one sample are indicated by half bars. The lithology is after Rozova (1968), Sokolov (1982); and Rozanov et al. (1992). The numbers 1 and 2 indicate two possibilities for the location of the Cambrian/Ordovician boundary.

Group (1986), would be to define this boundary on the basis of assemblages of conodonts, by the first appearance of either the conodont species *Cordylodus lindstromi* or of *Cordylodus proavus*. Considering the preliminary correlation of the biostratigraphic data obtained from Siberia with those obtained from the Batyrbay section, the choice of *C. proavus* would locate the Cambrian/Ordovician boundary during the uppermost part of the Loparian or at the base of the Njajan stage (Fig. 2; Dubinina, 1990; Rozanov et al., 1992).

The lithology of the Kulumbe deposits is described in several studies (Rozova, 1968; Sokolov, 1982; Rozanov et al., 1992). It corresponds to a shallow water marine environment of sediment deposition. The Kulumbinskaya formation consists of about 650 m of Upper Cambrian limestones and dolomites with varying grey to black, greenish and reddish colours. The Uigurskaya formation is thinner (165 m) and mostly comprises alternating deposits of limestones and dolomites in its lower part (during the Mansian stage, Fig. 2) and of reddish marls and dolomites in its upper part (during the Loparian). Only the lower part of the Iltyksaya formation, corresponding to the Njajan stage, was sampled through a thickness of approximately 130 m (Fig. 2). The lithology of this formation essentially consists of alternating greyish marls and dolomites. Finally the Llanvirn is represented by the Guragirskaya formation, which consists of a 170 m section of limestones, marls, dolomites, locally interbedded with fine-grained sandstones.

3. Paleomagnetic results

Paleomagnetic analyses were carried out in a magnetically shielded laboratory at the Institut de Physique du Globe de Paris. Magnetization was measured with a 3 axis CTF cryogenic magnetometer. Thermal demagnetization was performed using a laboratory-built oven, employing about 20 demagnetization steps per sample.

Examples of orthogonal demagnetization diagrams are shown in Fig. 3. Two different demagnetization styles are observed. The first is common to red and green samples, for which the magnetization is very stable (Fig. 3a–f). In these samples, one or two components of magnetization are observed. One has a steep inclination (in-situ coordinates), and is observed as a secondary component in the low to medium-high ($< 580°$) temperature range (Fig. 3a,c). The other component has a moderate inclination, and is either isolated as a single magnetization (Fig. 3d) or in the high temperature range after elimination of the steep-inclination component (Fig. 3a,c). When the component of moderate inclination is isolated as a single magnetization, alternating field (AF) demagnetizations are unable to remove a part of the magnetization (Fig. 3e). When samples with two component are AF demagnetized, at least half of the NRM is eliminated which yields a direction which is indistinguishable from the one obtained in the low to medium-high unblocking temperature range (Fig. 3a,b). Taken together, these demagnetization experiments suggest that the steep-inclination component is carried by magnetite, whereas the moderate-inclination component is carried by hematite. The second demagnetization style concerns the black and grey samples (Fig. 3g), for which the magnetization often becomes unstable at high temperatures ($> 450°C$). The alteration of the magnetic mineralogy during the thermal process is probably due to the presence of iron sulfides. The maximum unblocking temperatures observed for these samples are close to 600°C and magnetite is the principal carrier of the characteristic magnetic remanence. Although the demagnetization paths are sometimes very scattered at high temperatures for these samples, two magnetic components are again observed, one with a steep inclination and the second with a shallower inclination. However, most of the grey samples show only the component of steep inclination.

We show in Fig. 4 the magnetic directions isolated by least-square analysis (Kirschvink, 1980). We have first grouped together the directions of steep inclination (Fig. 4a). These directions, which have a reversed polarity, are very similar to those obtained from the volcanic intrusions sampled within the Kulumbe section (Table 1). As in Moyero, this component likely results from in situ growth of diagenetic magnetite triggered by fluid flow during the emplacement of the Siberian traps at the Permian/Triassic boundary (Jackson et al., 1988; Gallet and Pavlov, 1996). In Fig. 4b,c,d, we present the directions of moderate inclination, respectively obtained for the Llanvirn, the Tremadoc and the Upper Cambrian. The mean directions estimated for these three periods of time are given in Table 1. In all cases, the directions are well clustered. The Llanvirn exhibits only a reversed magnetic polarity, whereas the Tremadoc and the Upper Cambrian have directions of mixed normal and reversed polarities, with a

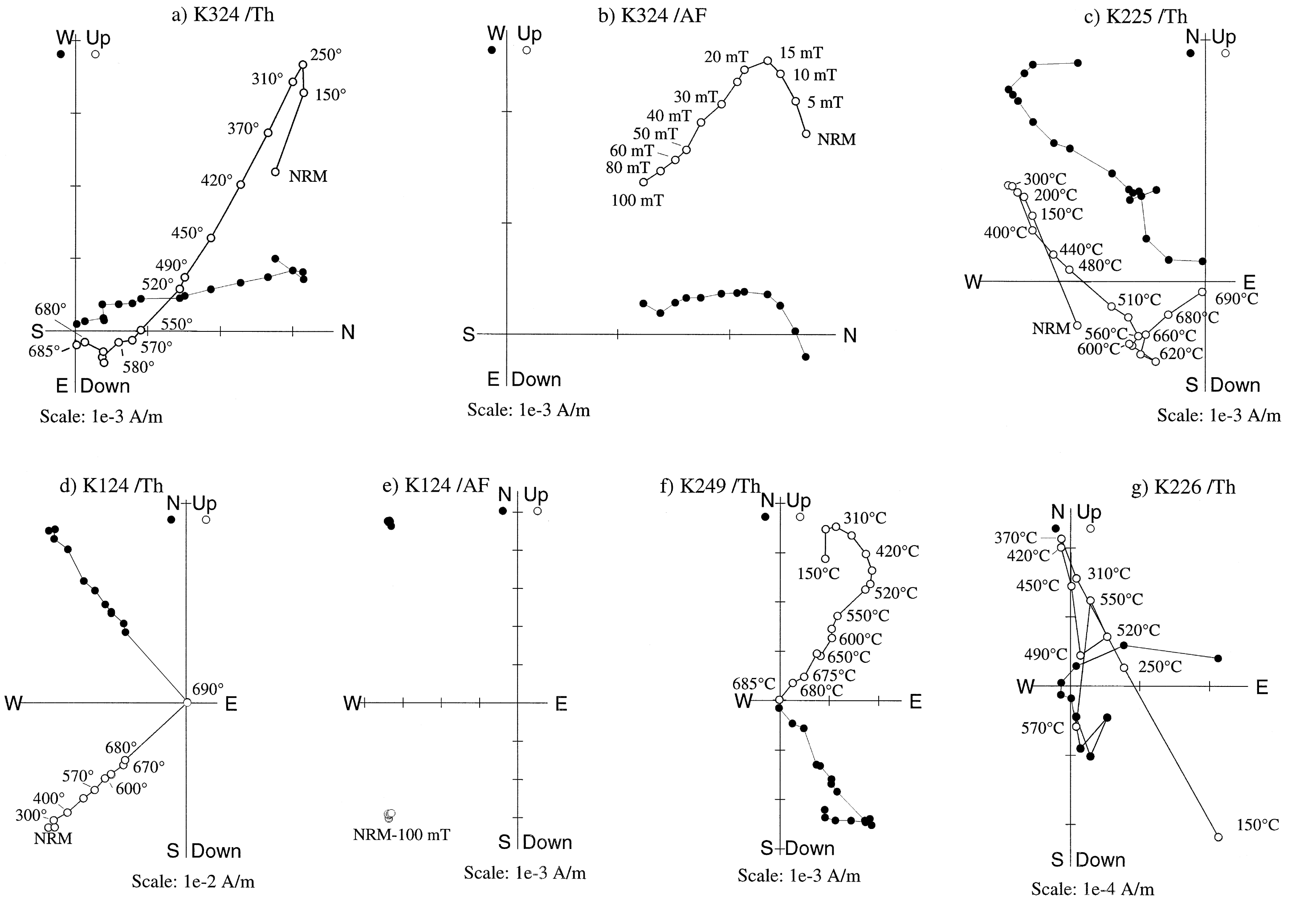

Fig. 3. Examples of thermal demagnetization of samples from the Kulumbe river section. Solid symbols are in the horizontal plane, and open symbols in the vertical plane. All diagrams are in stratigraphic coordinates.

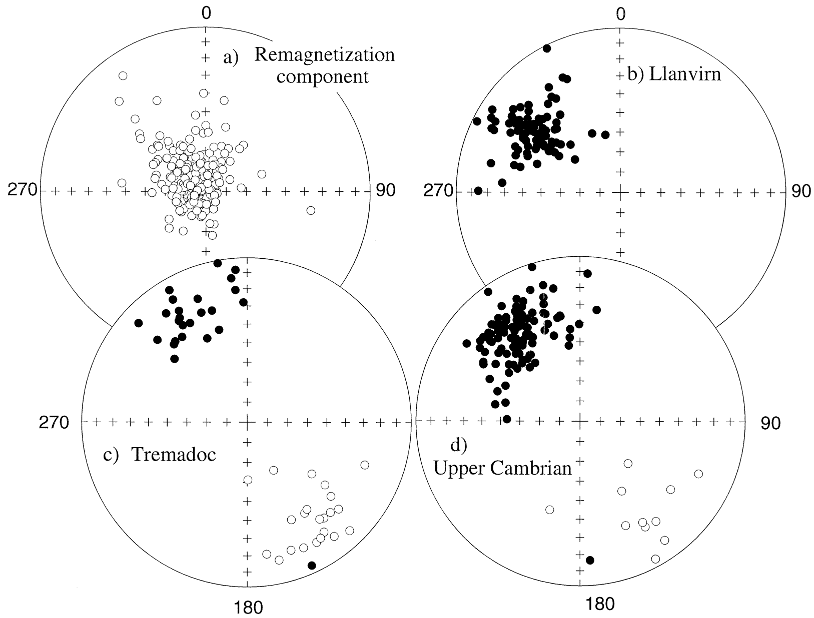

Fig. 4. Equal area projections of the directions isolated through the Kulumbe river section. The closed (open) symbols indicate directions of positive (negative) inclination. (a) Directions before bedding correction obtained for a high-inclination component of reversed polarity. The directions of moderate inclination are separated following their age between the Llanvirn, the Tremadoc and the Upper Cambrian (b,c,d, respectively). These latter directions are in stratigraphic coordinates.

positive reversal test (Tremadoc: $\gamma = 2.3°$, $\gamma c = 10.1°$; Upper Cambrian: $\gamma = 3.3°$, $\gamma c = 10.8°$; McFadden and McElhinny, 1990).

Previous studies (e.g., Khramov, 1991; Van der Voo, 1993; Torsvik et al., 1995b; Gallet and Pavlov, 1996) clearly indicate a southern hemisphere location for the Siberian Platform until the Middle Ordovician. Siberia probably crossed the equator during

Table 1
Mean paleomagnetic directions and related VGP obtained from the Kulumbe river section for the Llanvirn, the Tremadoc and the Upper Cambrian.

	N	Dg	Ig	Ds	Is	a_{95}	K
Remagnetization	211	317.5°	−80.1°	304.6°	−58.5°	2.0	24.8
Traps (Pavlov et al., in prep.)	3 sites	322.4°	−81.6°	314.8°	−63.1°	6.7°	339.9
Llanvirm	87	303.6°	16.7°	305.1°	35.4°	3.2°	23.2
Tremadoc							
Normal	25	145.0°	−13.2°	149.2°	−30.8°	7.6°	15.4
Reverse	20	322.9°	11.2	326.6°	31.1°	6.4°	26.9
Total (R)	45	323.8°	13.0°	327.9°	31.7°	4.9°	20.6
Upper Cambrian							
Normal	13	144.3°	−8.4°	147.7°	−31.8°	13.0°	11.2
Reverse	142	320.9°	11.5°	325.1°	34.3°	3.1°	16.0°
Total (R)	155	321.2°	11.3°	325.3°	34.1°	3.0°	15.6

We also estimate a mean direction for a remagnetization component which is similar to the mean paleomagnetic direction obtained from volcanic intrusions (Pavlov et al., in prep.).

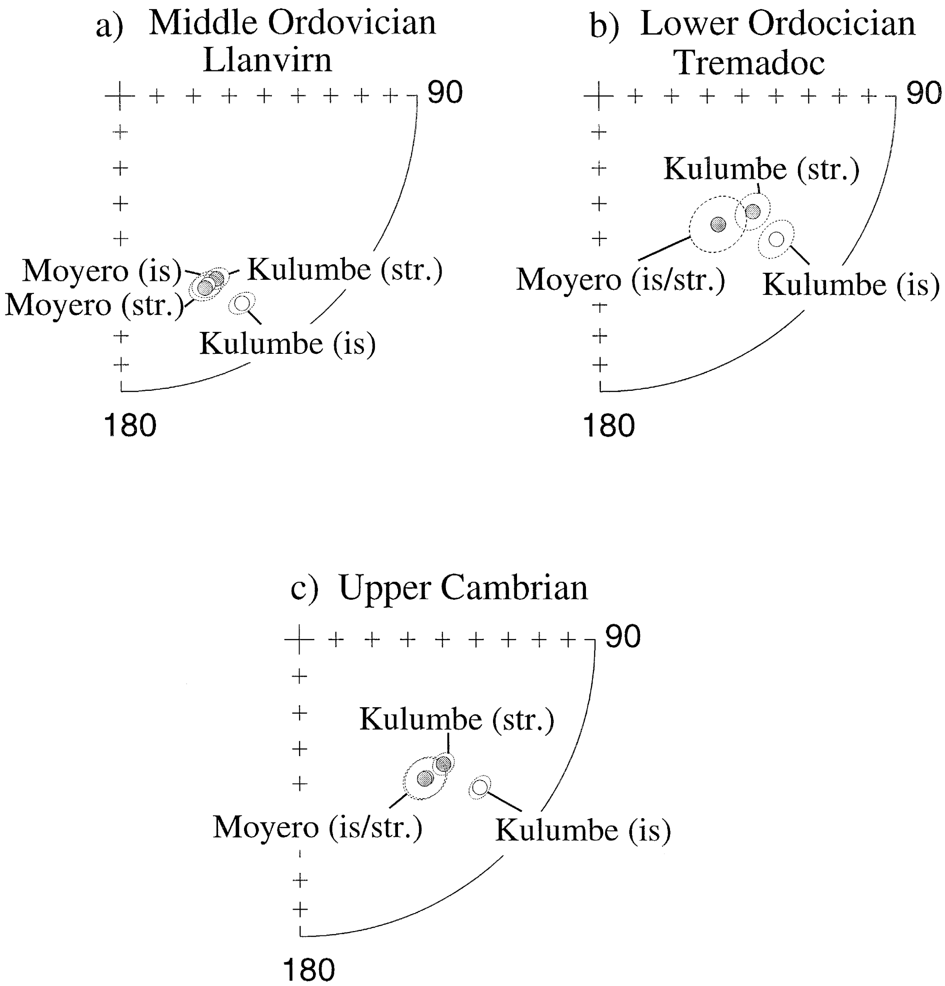

Fig. 5. Comparison of the VGP obtained in this study with those previously obtained from the Moyero river section (Gallet and Pavlov, 1996). The open symbols indicate data before tilt correction (is), whereas tilt-corrected data (str.) are shown with closed symbols.

the Caradoc (upper part of the Middle Ordovician; Torsvik et al., 1995b; Gallet and Pavlov, 1996). This location is of course essential to attribute a magnetic polarity to the observed directions. Our data confirm the nearly 180°-rotation experienced by Siberia since the early Paleozoic (e.g., Khramov, 1991; Van der Voo, 1993; Torsvik et al., 1995b; Gallet and Pavlov, 1996). Fig. 5 shows a comparison of the virtual geomagnetic poles (VGP) obtained from the Moyero and Kulumbe sections (Gallet and Pavlov, 1996). Although data from only two sections are considered (no statistics can thus be computed), we clearly obtain a better cluster after bedding correction for the three periods, which indicates a (partial) positive fold test. We therefore observe the same apparent polar wander path (APWP) from both sections. Together with the antipodal normal and reversed mean directions observed for the Tremadoc and the Upper Cambrian, these two characteristics indicate that the component of moderate inclination observed from the Kulumbe section was likely acquired during the sediment deposition or soon after. A comparison between the APWP from the Moyero river section and the ones previously proposed for Siberia (Khramov, 1991 and Van der Voo, 1993) can be found in Gallet and Pavlov (1996).

4. Discussion

The results obtained from the Kulumbe river section provide a magnetostratigraphic sequence from the upper part of the Upper Cambrian to the Lower Ordovician (whatever the definition of the Cambrian/Ordovician boundary). A sequence of 17 magnetic intervals is observed, but three of them are only defined by one sample (half bars in Fig. 2). The data also obtained for the Llanvirn show only a reversed polarity as in Moyero (Gallet and Pavlov, 1996). Together the results from Kulumbe and Moyero suggest the occurrence of a long reversed magnetic polarity interval, with no evidence for reversals, encompassing the Arenig and the Llanvirn. The magnetostratigraphic sequence from Moyero shows that this interval ends during the Middle Llandeilo (Middle Ordovician). The Kulumbe sequence further indicates that the onset of this interval occurs at the end of the Tremadoc (Lower Ordovician), during the uppermost part of the Njajan stage. The duration of this reversed polarity interval is difficult to estimate. Odin and Odin (1990) suggest a duration of about 15 Myr for the Arenig, while the duration of the Llanvirn is shorter (15 Myr including the Llandeilo). It seems therefore reasonable to propose a duration of about 25 to 30 Myr for this interval, which would thus correspond to a superchron. This is remarkable in that our results are in very good agreement with the conclusion reached by Johnson et al. (1995) and Algeo (1996), although a completely different approach was used. However, the possibility of missing short magnetic intervals in our sections cannot be excluded because the magnetization through the Arenig and the Llanvirn is essentially carried by hematite. The precise duration for magnetization acquisition in these samples is therefore difficult to estimate and a few magnetic short polarity intervals may have been lost during the magnetization lock-in process. At present, only a very low magnetic reversal frequency, with a strong reversed polarity bias, is quite certain. In particular, neither the Kulumbe nor the Moyero section confirm the presence of three short normal polarity intervals during the uppermost Arenig and the Llanvirn as proposed by Torsvik et al. (1995a) from the Swedish Gullhögen Quarry section (see also Torsvik and Trench, 1991b). But Torsvik et al. (1995a) show a strong asymmetry

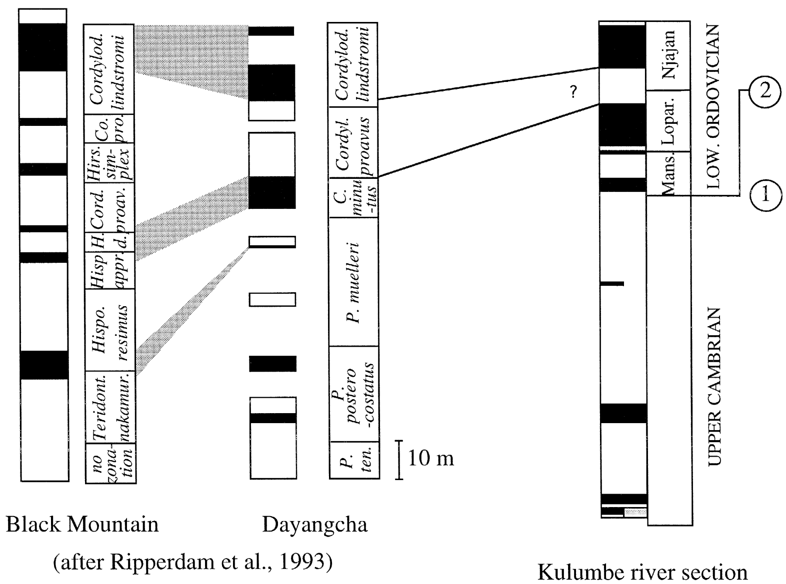

Fig. 6. Comparison of the Upper Cambrian to Lower Ordovician magnetostratigraphic sequence obtained from the Kulumbe river section with previous sequences from Australia (Black Mountain section; Ripperdam and Kirschvink, 1992) and China (Dayangcha section; Ripperdam et al., 1993).Shaded zones correspond to the correlations proposed by Ripperdam et al. (1993). The two possibilities for the location of the Cambrian/Ordovician boundary from Siberian sections are indicated by the numbers 1 and 2 (see the text).

between the normal and the reversed polarity directions that they interpret as resulting from non-dipole field disturbances rather than an artefact of remagnetization. This characteristic cannot be tested from our data. Note that the results obtained by Torsvik et al. (1995a) do not preclude the possibility of a reversed polarity superchron during most of the Arenig that is followed by a period characterized by a strong reversed polarity bias. We also briefly remind the discordant results obtained by Farr et al. (1993) from Arkansas, which shows 16 magnetic intervals from the Upper Arenig to the Llanvirn. But as previously discussed by Algeo (1996) (see also Gallet and Pavlov, 1996), this latter discrepancy may arise from a misinterpretation of the age of the magnetic component considered as primary by Farr et al. (1993). Moreover, the reversed polarity directions obtained by Torsvik et al. (1995a) from the Lanna limestones of Upper Arenig age do not show magnetic reversals during this period. We mention that the age of the magnetostratigraphic data obtained from the Moyero and Kulumbe sections does not allow the possibility to test another bias toward a normal magnetic polarity (a superchron?) during the Upper Ordovician as suggested by Algeo (1996).

The Uppermost Cambrian to Tremadoc magnetostratigraphic sequence from the Kulumbe section can be compared to data previously obtained from Australia (Black Mountain section; western Queensland; Ripperdam and Kirschvink, 1992) and northeastern China (Dayangcha section; Jilin province; Ripperdam et al., 1993). Unfortunately, correlations between these sections are very difficult, because the precise calibration between the Siberian stage zonation and the standard Geologic time scale is not yet available (Fig. 6). We can propose a possible correlation between the Dayangcha and the Kulumbe sequences, based on the reversed polarity interval observed within the *C. proavus* conodont zone and within the lower part of the Njajan stage (Fig. 6), two intervals which may have the same age (Rozova, 1968, 1986; Rozanov et al., 1992). However, the comparison with the Black Mountain section, which shows some additional short magnetic intervals not observed at Dayangcha, suggest hiatuses in the magnetostratigraphic record from the Chinese section (Ripperdam and Kirschvink, 1992; Ripperdam et al., 1993). Additional work is presently in progress in order to improve the Upper Cambrian magnetic polarity sequence from Siberian sections.

Acknowledgements

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References

Algeo, T.J., 1996. Geomagnetic polarity bias patterns through the Phanerozoic. J. Geophys. Res. 101, 2785–2814.

Astahkin, V., Pegel, T., Shabanov, Y., Sukhov, S., Sundukov, V., Repina, L., Rozanov, A., Zhuravlev, A., 1991. The Cambrian system on the Siberian Platform. Int. Union Geological Sci. 27, (in english).

Cande, S., Kent, D.V., 1995. Revised calibration of the geomagnetic polarity timescale for the late Cretaceous and Cenozoic. J. Geophys. Res. 100, 6093–6095.

Courtillot, V., Besse, J., 1987. Magnetic field reversals, polar wander, and Core–Mantle coupling. Science 237, 1140–1147.

Datsenko, V., Zhuravleva, I., Lazarenko, N., Popov, Y., Chernychova, N., 1968. Biostratigraphy and fauna of Cambrian deposits of the northwest of the Siberian Platform (in Russian). Nedra, Leningrad, 242 pp.

Eide, E., Torsvik, T., 1996. Paleozoic supercontinental assembly, mantle flushing, and genesis of the Kiaman superchron. Earth Planet. Sci. Lett. 144, 389–402.

Farr, R., Sprowl, D., Johnson, J., 1993. Identification and initial correlation of magnetic reversals in the lower to middle Ordovician of Northern Arkansas. In: Application of Paleomagnetism to sedimentary geology. SEPM Spec. Pub., vol. 49, p. 83–93

Gallet, Y., Besse, J., Krystyn, L., Marcoux, J., Théveniaut, H., 1992. Magnetostratigraphy of the Bolücektasi Tepe section (southwestern Turkey): Implications for changes in magnetic reversal frequency. Phys. Earth Planet. Interiors 73, 85–108.

Gallet, Y., Pavlov, V., 1996. Magnetostratigraphy of the Moyero river section (north-western Siberia): constraints on geomagnetic reversal frequency during the early Palaeozoic. Geophys. J. Int. 125, 95–105.

Gallet, Y., Hulot, G., 1997. Stationary and non-stationary behaviour within the geomagnetic time scale. Geophys. Res. Lett. 24, 1875–1878.

Groisman, Y., 1970. Tectonics of the Khantaya–Kureyka region (in Russian). In: Geology and mineral deposits of the northwestern part of the Siberian Platform, Trans. of Arctic Geology Institute. Nedra, Leningrad, Vol. 162, pp. 171–186.

Harland, W., Armstrong, R., Cox, A., Craig, L., Smith, A., Smith, D., 1989. A geologic time scale. Cambridge Univ. Press, 263 pp.

Irving, E., Pullaiah, G., 1976. Reversals of the geomagnetic field, magnetostratigraphy, and relative magnitude of paleosecular variation in the Phanerozoic. Earth Sci. Rev. 12, 35–64.

Jackson, M., McCabe, C., Ballard, M., Van der Voo, R., 1988. Magnetite authigenesis and diagenetic paleotemperatures across the northern Appalachian basin. Geology 16, 592–595.

Johnson, P., Van Patten, D., Tivey, M., Sager, W., 1995. Geomagnetic polarity rate for the Phanerozoic. Geophys. Res. Lett. 22, 231–234.

Kanygin, A., Moscalenko, T., Yadrenkina, A., 1987. Ordovician System of the Siberian Platform (in English). Nauka, Novosibirsk.

Khramov, A., 1991. Standard nets of paleomagnetic poles for plates of North Eurasia: the connection with the problem of geodynamics of the territory of USSR (in Russian). In: Paleomagnetism and paleogeodynamics of the territory of USSR. VNIGRI, Leningrad, pp. 154–176.

Kirschvink, 1980.

Kirschvink, J., Rozanov, A., 1984. Magnetostratigraphy of lower Cambrian strata from the Siberian Platform: a palaeomagnetic pole and a preliminary polarity time-scale. Geol. Mag. 121, 189–203.

Kravtsov, 1967. Tectonics of the Khantayka–Sigovaya region (in Russian). In: Geology of the Siberian Platform, Trans. of the Arctic Geology Institute, Vol. 133.

Larson, R., Olson, P., 1991. Mantle plumes control magnetic reversal frequency. Earth Planet. Sci. Lett. 107, 437–447.

Loper, D., McCartney, K., 1986. Mantles plumes and tyhe periodicity of magnetic field reversals. Geophys. Res. Lett. 13, 1525–1528.

Malich, N., 1975. Tectonic development of the sedimentary cover of the Siberian Platform (in Russian). Nedra, 216 pp.

McElhinny, M., 1971. Geomagnetic reversals during the Phanerozoic. Science 172, 157–159.

McFadden, P.L., McElhinny, M., 1990. Classification of reversal test in paleomagnetism. Geophys. J. Int. 103, 725–729.

Mikutskiy, S., Petrakov, V., 1961. Tectonics of Peri-Eniseyan part of North of the Siberian Platform. Trans. Siberian Inst. Geol. Min. Resour. 7, 46–57, (in Russian).

McFadden, P., Merrill, R., 1984. Lower mantle convection and geomagnetism. J. Geophys. Res. 89, 3354–3362.

Odin, S., Odin, C., 1990. Echelle numérique des temps géologiques. Géochroniques 35, 12–21.

Ogienko, L., 1977. The biostratigraphical division of Lower Ordovician in the southern part of the Siberian Platform (in Russian). In: Problems of Ordovician and Silurian Stratigraphy of Siberia. Novosibirsk, pp. 55–59.

Pavlov et al., in prep.

Ripperdam, R.L., Kirschvink, J., 1992. Paleomagnetic results from the Cambrian–Ordovician boundary section at Black Mountain, Georgina Basin, western Queensland, Australia. In: Webey, Laurie (Eds.), Global Perspectives on Ordovician Geology. Balkema, Rotterdam, pp. 93–103.

Ripperdam, R.L., Magaritz, M., Kirschvink, J., 1993. Carbon isotope and magnetic polarity evidence for non-depositional events within the Cambrian–Ordovician boundary section near Dayangcha Jilin Province, China. Geol. Mag. 130, 443–452.

Ross, R., Adler, F., Amsdan, G., Bergstrom, D., Bergstrom, S., 1982. Ordovician system in the United States of America. Correlation charts and explanatory notes. Int. Union Geol. Sci. 12, 1–73.

Rozanov, A., Repina, L., Apollonov, M., 1992. Cambrian of Siberia (in Russian). Trans. Geological Geophysical In-te, Vol. 1992. Nauka, Novosibirsk.

Rozova, A., 1968. Biostratigraphy and trilobites of Upper Cambrian and Lower Ordovician of northwest of the Siberian Platform (in Russian). Nauka, Moscow.

Rozova, A., 1986. Correlation of upper Cambrian sections of South Kazakstan and Siberian Platform (in russian). In: Biostratigraphy and Paleontology of Cambrian of Northern Asia. Moscow, pp. 25–39.

Sokolov, B., 1982. Ordovician of the Siberian Platform: key section on the Kulumbe River. Trans. of the Institute of Geology and Geophysics, Vol. 605. Nauka, Novosibirsk, 118 pp.

Sweet, W., Ethington, R., Barnes, C., 1971. North American Middle and Upper Ordovician conodont faunas. Geol. Soc. Am. Mem. 127, 163–193.

Sweet, W., Bergstrom, S., 1976. Conodont biostratigraphy of the Middle and Upper Ordovician of the United States Midcontinent. In: The Ordovician system. Cardiff, pp. 121–151.

Torsvik, T., Trench, A., 1991a. Ordovician magnetostratigraphy: Llanvirn–Caradoc limestones of the Baltic platform. Geophys. J. Int. 107, 171–184.

Torsvik, T., Trench, A., 1991b. The Lower–Middle Ordovician paleofield of Scandinavia: southern Sweden 'revisited'. Phys. Earth Planet. Interiors 65, 283–291.

Torsvik, T., Trench, A., Lohmann, K., Dunn, S., 1995a. Lower Ordovician reversal asymmetry: an artefact of remagnetization or non dipole field disturbances. J. Geophys. Res. 100, 17885–17898.

Torsvik, T., Tait, J., Moralev, V., McKerrow, W., Sturt, B., Roberts, D., 1995b. Ordovician palaeogeography of Siberia and adjacent continents. J. Geol. Soc. London 152, 279–287.

Van der Voo, R., 1993. Paleomagnetism of the Atlantic, Tethys and Iapetus Oceans. Cambridge Univ. Press, Cambridge.

Vysotsky, A., Andreeva, O., 1969. Ordovician Kulumbe river section. In: The Data on Geology and Mineral Deposits of Eastern Siberia, Vol. 112. Nedra, Leningrad, pp. 68–82.

Yadrenkina, A., 1974. The brachiopods of Upper Cambrian and Lower Ordovician of the northwest of the Siberian Platform (in Russian). Novosibirsk.