

# Magnetostratigraphy of lower Cambrian strata from the Siberian Platform: a palaeomagnetic pole and a preliminary polarity time-scale

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**Abstract** – Four sedimentary sections seen in continuous exposures along the Lena River on the Siberian Platform in Yakutia contain a record of the geomagnetic field during the Tommotian and Atdabanian stages of Early Cambrian time. The direction of the stable remanent magnetization indicates that the Siberian platform was located on the equator, and the corresponding palaeomagnetic pole provides a well-dated extension of the Siberian apparent polar wander path. A belt of archaeocyathid bioherms which separates two major facies zones in the lower Cambrian was positioned on and aligned more or less parallel with the palaeoequator. The geographical position of this belt appears to have tracked the southward motion of the Siberian platform during post-Tommotian time. These palaeomagnetic results combined with the extensive biostratigraphy of the Siberian Platform provide a provisional geomagnetic polarity time scale for this part of Early Cambrian time. Comparison of these results with data of similar age from Central Australia suggests that strata of Tommotian and lower Atdabanian age are not present in the Amadeus Basin of Australia.

## 1. Introduction

During the past twenty years, many unmetamorphosed sedimentary sequences of late Proterozoic and Early Cambrian age have been reported from several continents, and the fauna described from them provide the earliest record of Phanerozoic life. Despite the large diversity of these various assemblages, the forms are provincial and it has proved difficult to correlate strata from one geographical area to another using only biostratigraphy. Because of these problems in correlation, the International Union of Geological Sciences (I.U.G.S.) and the International Geological Correlation Programme (I.G.C.P.) formed a joint working group (Project 29) to coordinate and promote further interdisciplinary study of these Precambrian–Cambrian sedimentary sequences. The ultimate goal for Project 29 is the selection of an international boundary stratotype for the base of the Cambrian system. Palaeomagnetic and magnetostratigraphic work reported here was initiated at the request of this group (Cowie, 1978).

Reliable biostratigraphic correlation from one palaeogeographical province to another in the Early Cambrian is at present limited to the stage level at best. Magnetic polarity stratigraphy could, in theory, yield a much finer stratigraphic correlation if the magnetization is closely related in time to deposition. A major problem with the attempt to use magnetic polarity stratigraphy in the Cambrian, however, is that the pattern of geomagnetic reversals is not yet known.

Although marine magnetic lineations provide this information for most of the Mesozoic and Tertiary (see Harland *et al.* 1982), there is as yet no known oceanic crust of Palaeozoic age which might provide the polarity history of the Palaeozoic. It is therefore necessary to piece together the magnetic polarity time scale from numerous, overlapping stratigraphic sequences that have been firmly correlated using a regionally established biostratigraphy. As is discussed below, the best stratigraphic sections for this purpose crop out over a wide area on the eastern half of the Siberian Platform in the Soviet Far East (Yakutia), and are particularly well exposed along the Lena and Aldan rivers. We report here the first palaeomagnetic results from four continuous, partially overlapping stratigraphic sections from the Lena River, ranging in age from the lowest zone of the Tommotian Stage to the top of the Atdabanian. Work on similar rocks from the Aldan River is currently in progress.

In addition to providing the first tentative polarity time scale for the lower Cambrian, the palaeomagnetic results reported here provide constraints on the palaeolatitude and palaeoposition of the Siberian Platform. They also help to calibrate an apparent polar wander (APW) curve for the interval studied, and have allowed several magnetic polarity chrons to be identified within the sections studied. These polarity chrons form the basis of a preliminary magnetic polarity time scale for the Early Cambrian that must now be tested and checked elsewhere. When compared

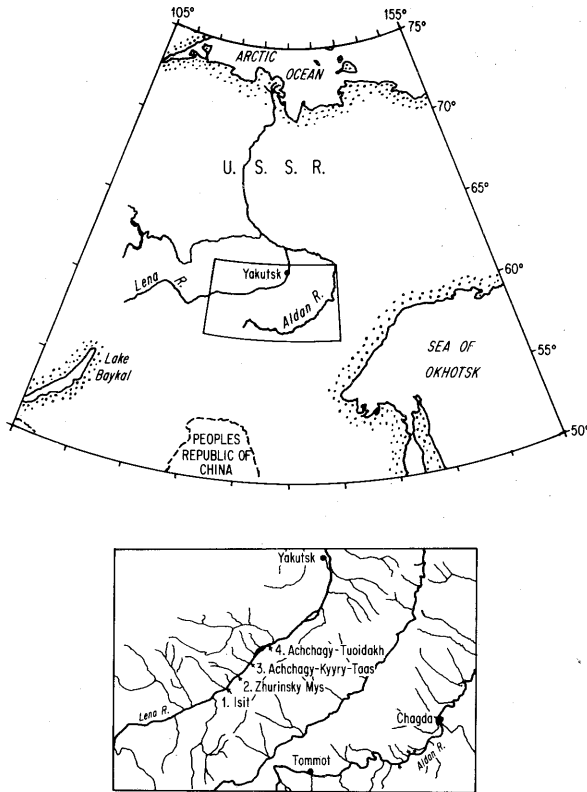


Figure 1. Locations of stratigraphic sections along the Lena River which were sampled for magnetostratigraphy in this study.

with palaeomagnetic results of similar age from other continents, these data should provide constraints for a tentative palaeogeographical reconstruction for the Tommotian Stage of the lower Cambrian.

## 2. Geology

### 2.a. Geologic setting

Samples for the palaeomagnetic analyses reported in this study were collected from exposures along the middle course of the Lena River (Fig. 1). This area of the Siberian Platform occupies the northern portion of the ancient Aldan shield, as defined by the extent of the underlying heavily metamorphosed Archaean basement. Between 20 and 500 metres of pale-yellow late Precambrian dolomite and limestone of the Yudoma Formation were deposited upon this basement, followed conformably in some areas by about 100 metres of reddish, sometimes silty carbonate of the lowest Cambrian Pestrotsvet Formation (Fig. 2). The Yudoma Formation is not seen in surface exposures along the Lena River, but where the equivalent strata have been located in subsurface boreholes it is here called the Tolba Formation. Carbonate sedimentation continued throughout the Middle and into the Late Cambrian, when the sequence was interrupted by a hiatus in deposition. The interval represented by this depositional gap is least in the northern part of the

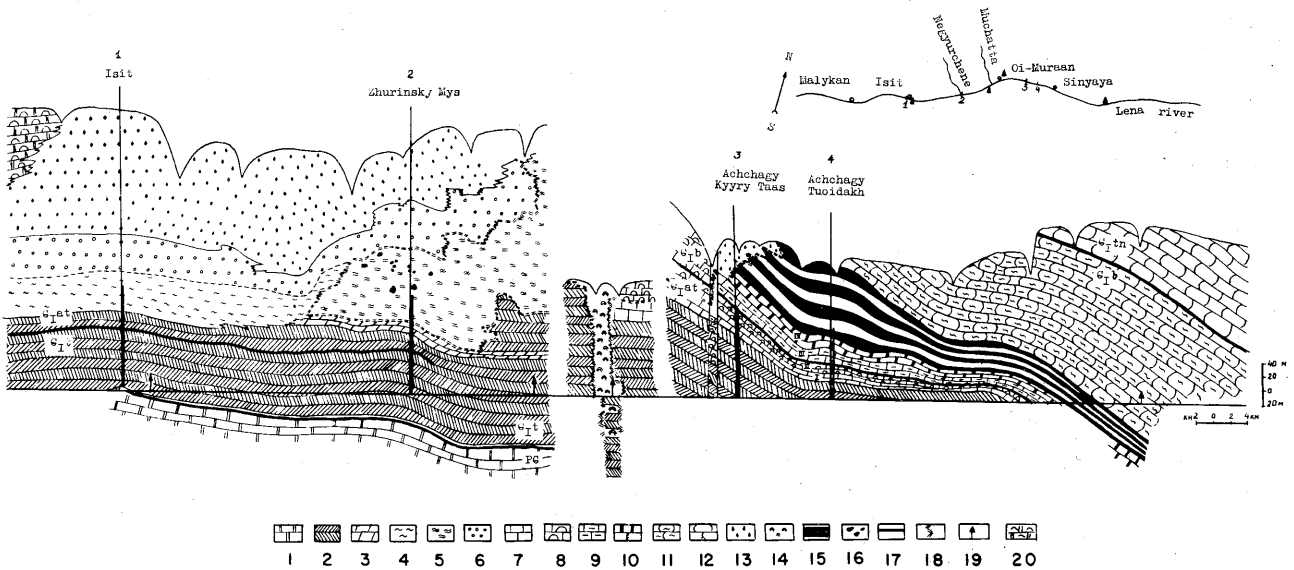


Figure 2. Stratigraphic sequence along the Lena River. The four localities sampled are as indicated. Strata examined from bore cores are shown below the river level indicated by the basal horizontal line. Strata drawn above this indicate cliff exposures. Stratigraphic and lithologic symbols are: (1) Tolba Formation: grey spotted, bedded dolomites. (2, 3) Pestrotsvet Formation: 2, red silt limestone and grey parallel-bedded limestone; 3, silt wave-bedded and nodular dolomites. (4, 5) Nochozoian Member: 4, grey wave-bedded limestones and silty dolomites; 5, yellow-grey wave-bedded dolomites. (6) Chuzan Member: oolite dolomites. (7-10) Perekhod Formation: 7, member I, green-grey and red silty limestones; 8, member II, white bedded limestones with biostromes; 9, member III, green-grey and red silty limestones; 10, member IV, dark grey and black thin bedded limestone. (11) Kutozgin Formation: grey-brown stinky limestone and dolomite. (12) Kelema Formation: white wave-bedded limestone. (13) Muchatta Formation: yellow coarse-grained dolomite. (14) Oi-muran biogenic massive archaeocyathid-algal bioherms. (15) Sinskian Formation: black thin-bedded stinky limestone. (16) Archaeocyathid-algal bioherms. (17) Stage boundaries. (18) Boundary of the zone of widespread organic build-ups. (19) Borehole locations. (20) Tolbochan Formation: intercalation of stromatiform massive dolomites and thin-bedded silty dolomites.

platform, where the Cambrian rocks are covered by upper Palaeozoic strata. The magnitude of this hiatus gradually increases to the southwest, where Cambrian rocks underlie those of Mesozoic age.

Strata in the study area are essentially flat-lying. Rare folds produce at most tilts of one or two degrees. Scattered feeder dikes, apparently related to the formation of Mesozoic flood basalts in some areas, cut through the sequence, but none has been located within several kilometres of the localities sampled in this study. Although kimberlite pipes have been discovered on the Siberian Platform, these and the flood basalts are located mainly in the northern and central part of the platform. The burial depth of these strata is not known, but the small, phosphate-bearing shelly fossils, including a protoconodont *Protohertzina*, are white in colour. The conodont alteration index of Epstein, Epstein & Harris (1977), if applicable to these early fossils, would suggest that the maximum burial temperature was never significantly above about 100 °C. It is unlikely, therefore, that these sediments possess secondary magnetic overprints of thermal origin. During the Tertiary, regional uplift occurred on the Siberian Platform as the major rivers carved wide valleys with steep walls. As a result, all samples examined in this study were subjected to varying degrees of surface weathering and generally possess a strong chemical remanent component (CRM) of more-or-less recent age.

### 2.b. Regional facies zonation

Lower Cambrian sediments on the Siberian Platform are grouped into three regional zones, termed here the southwest facies, transitional facies, and northeast facies (Fig. 3a). The southwestern zone consists of evaporites (dolomites, gypsum, salt) and rarely limestone. As one proceeds northeasterly towards the transitional zone, the evaporites diminish in abundance and are replaced by limestone. Entering the transitional zone from the southwest towards the northeast one first encounters oolitic dolomite, followed by dolomite and limestone containing archaeocyathid bioherms. These bioherms become more abundant towards the northeastern side of the transitional zone but do not extend appreciably into the northeastern facies zone. Noteworthy is the observation that these bioherms are found within the middle region of the Siberian continental area, as were many of the Niagaran reefs of the Great Lakes area within the continental area of the U.S.A. and Canada (Lowenstam, 1950). Rocks of Tommotian and Atdabanian age in the northeastern facies zone contain shallow-water, red and white limestone with variable concentrations of clastic material. In contrast, the overlying sediments of Botomian and Tojonian (Elankian) age are bituminous, black carbonaceous shales that presumably accumulated in deep water.

The three facies zones suggest the existence of a reef-like environment across part of the Siberian Platform during Early Cambrian time. The presence of channelled bioherms associated with ripple-marked red limestone and dolomite, some glauconite, and abundant small fossils with phosphatic shells, all imply shallow warm water conditions, presumably in low latitudes. A major finding of the palaeomagnetic work is that the reef-bearing transitional zone was more or less parallel to and nearly upon the equator when it formed, with the northeastern zone facing to the north. As schematically shown in Figure 3b, the geographical position of the transitional zone remained stable during Tommotian time, but following this it gradually moved towards the northeast (or palaeo-North) during Atdabanian and Botomian times. As discussed later, this positional change may have been the result of post-Tommotian plate motion of the Siberian Platform.

### 2.c. Dolomitization

Most of the fine-grained dolomites in the southwestern and transitional facies belts have been interpreted as being of primary origin, mainly because these dolomites have similar porosities and petrologic textures as do the limestone units with which they are intercalated (Rozanov & Rozanov, 1973). Occasional beds in these sequences are composed of dolomite of probable secondary origin. These lithologically distinctive dolomitic beds extend continuously along river exposures for several tens of kilometres, and they can be identified over wide areas in boreholes. They are commonly poor in faunal content, and are distinguished by their low relative porosity.

Secondary dolomitization also exists in the region of the Lena River, but it is centred in the transitional zone on the archaeocyathid bioherms. Within the central part of these structures the recrystallization is at places extensive, and in some cases they contain dolomite crystals up to 1 cm. However, strata adjacent to these structures do not appear to have been significantly altered, and the areas of recrystallization were thus avoided during the collection of palaeomagnetic samples.

### 2.d. Biostratigraphy

Carbonates on the Siberian Platform contain some of the most diverse and widespread assemblages of lower Cambrian shelly fossils yet identified. Abundant archaeocyathids, and a variety of small shelly fossils (brachiopods, archaeogastropods, monoplacophorans, hyolithids, protoconodonts, etc.) are found well below the first trilobites (*Profallotaspis*). This assemblage of pre-trilobitic fossils was used to define the Tommotian Stage (Rozanov, 1966, 1967; Rozanov & Missarzhevsky, 1966), and the first

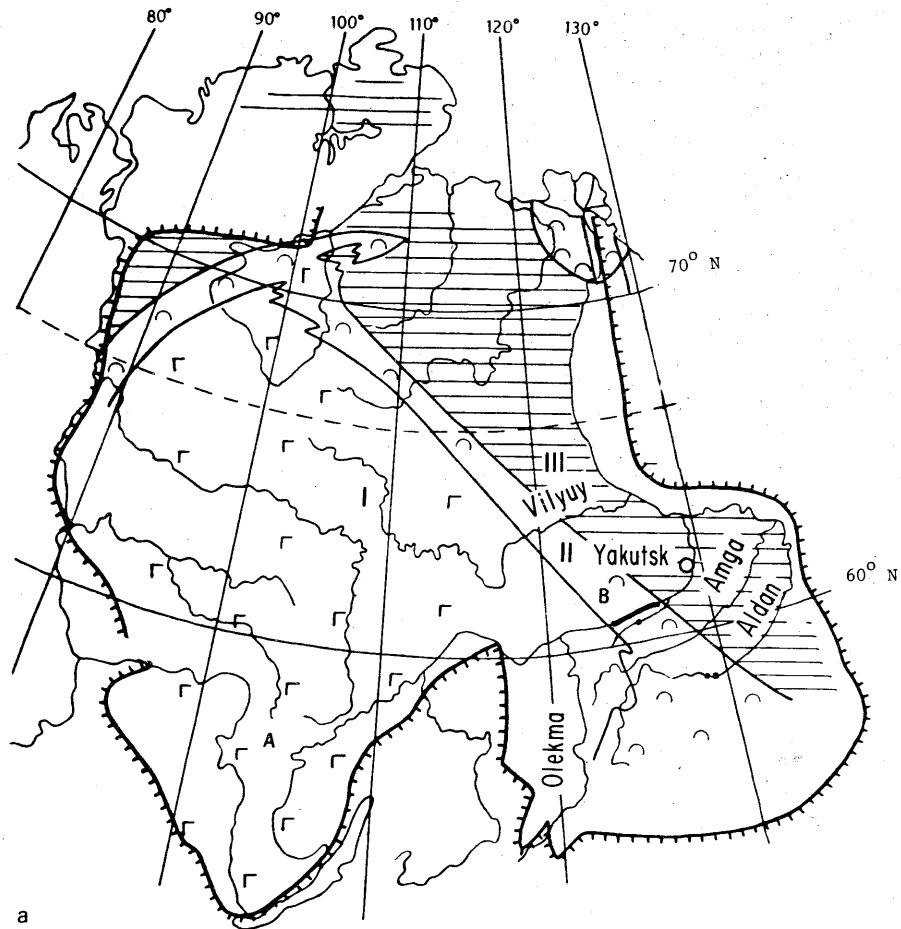
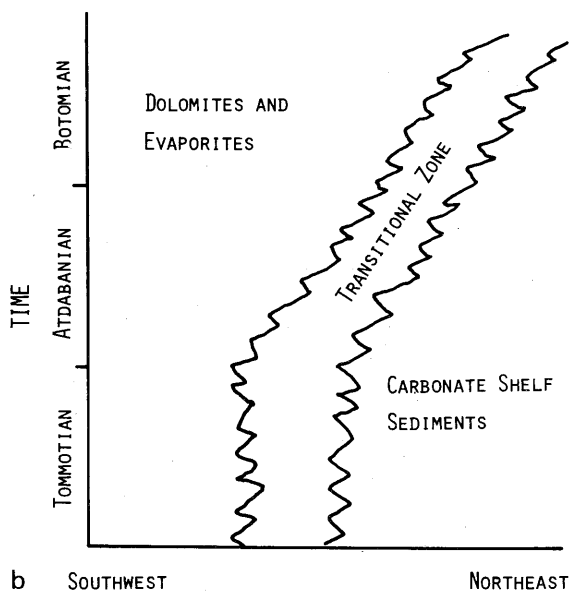


Figure 3.a. Regional facies map of the lower Cambrian sediments on the Siberian Platform. I. Southwestern zone: a saliferous basin with lagoonal conditions of sedimentation (also called the western, the Olekma facial region). II. Transitional zone: carbonate bank deposits with oolitic dolomites and archaeocyathid bioherms (also called the Sinyaya–Botoma facial region). III. Northeastern zone: shelf of an open sea with reddish carbonates and black shales (also called the eastern and Yudomian–Oleneck facial regions). The equatorial position and orientation of the transitional zone is also shown on the Tommotian reconstruction of Figure 12.



b. Schematic diagram showing the northeastward migration of the transitional facies over the open shelf sediments during the Atdabanian and Botomian stages. This shift may be due to the southwards drift of the Siberian Platform between Early and Middle Cambrian time.

occurrence of this rich assemblage of faunas has been selected as the guiding principle for the selection of global Precambrian–Cambrian boundary stratotype (Cowie, 1978).

The archaeocyathid and trilobite assemblages in Siberia are used to divide the lower Cambrian into four stages, named in order the Tommotian, Atdabanian, Botomian (or Lenian), and Tojonian (or Elankian). Each stage is in turn divisible into numerous zones (Fig. 4). At present, the Early Cambrian of this area is subdivided into more correlatable zones than are contemporaneous deposits of any other region. The zonal boundaries can be correlated over wide areas on the Siberian Platform, and into southwest Mongolia (Drozdova *et al.* 1981). Moreover, the stage levels are identified tentatively on the East-European Platform (Keller & Rozanov, 1979), Karatau (Missarzhevsky & Mambetov, 1981), Australia (Rozanov & Debrenne, 1974), Morocco (Debrenne & Debrenne, 1978), Nova Scotia and Newfoundland (Landing, Nowland & Fletcher, 1980), North America (Palmer & Rozanov, 1976; Mount, Gevirtz & Signor, 1983; McMenemy, Awramik & Stewart, 1983), and China (Luo *et al.* 1982). The biostratigraphic framework of this region

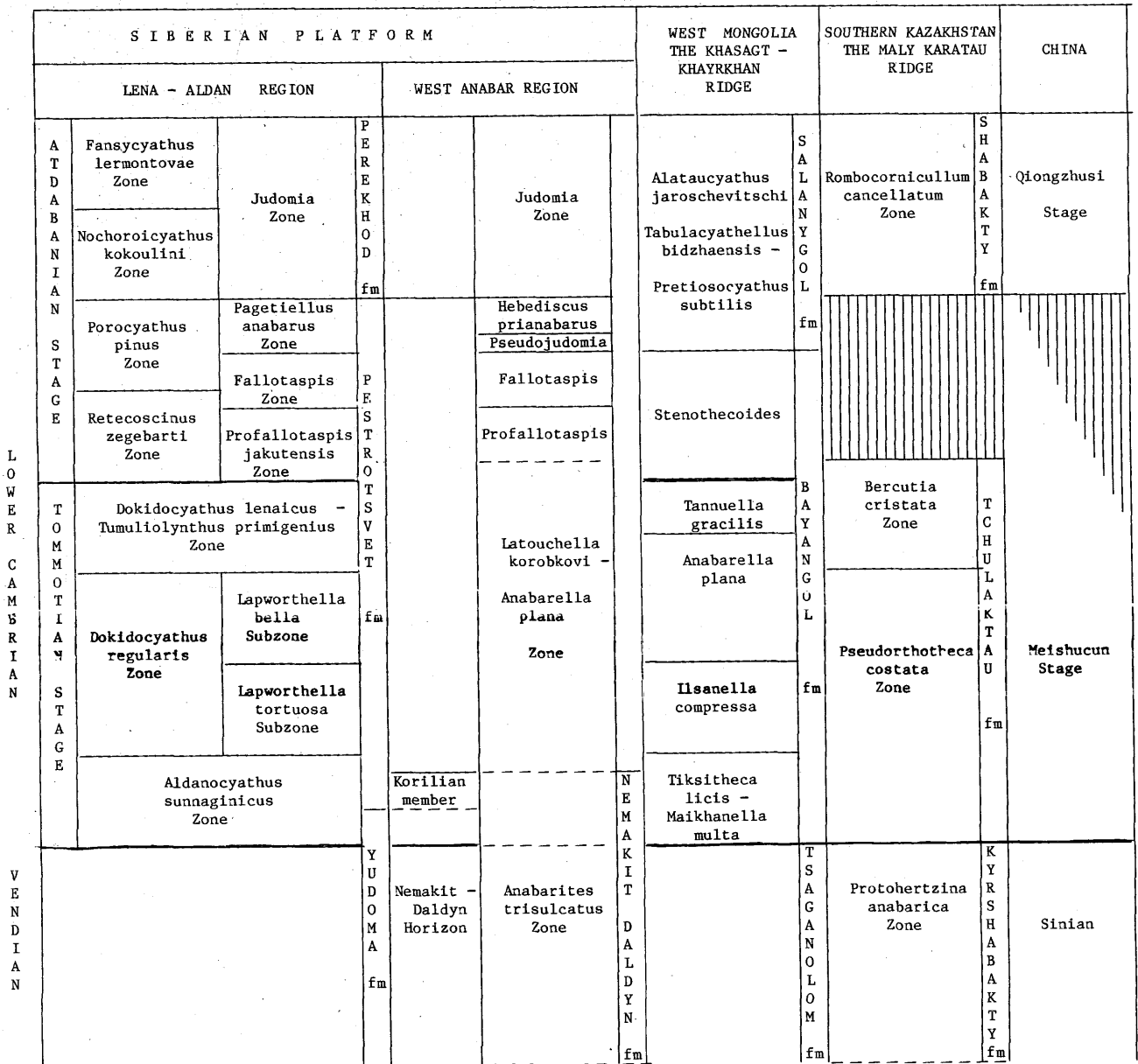


Figure 4. Biostratigraphic correlation for the Tommotian and Atdabanian stages of the Siberian Platform and approximate regional correlation with other areas.

therefore holds the most promise for the construction and calibration of a polarity time scale for the Early Cambrian. Figure 5 shows the biostratigraphic correlation for the Tommotian, Atdabanian and Botomian strata at the four localities sampled for magnetostratigraphy along the Lena River.

### 3. Palaeomagnetic analysis

#### 3.a. Methods and techniques

A total of 440 oriented samples were collected for palaeomagnetic analysis from the four localities shown on Figure 1. Average sampling density ranged between one and three samples per metre and one sample per horizon. Samples were either oriented as blocks or were cut in the field with a portable diamond-tipped

drill. Discrete stratigraphic horizons collected in this fashion for each sample are shown with respect to the biostratigraphic scale (Figs 10 and 11). From one to four cylindrical specimens, 2.5 cm in diameter, were cut from each oriented sample for palaeomagnetic analysis.

All measurements of magnetic remanence were made with a superconducting rock magnetometre housed in a mu-metal shielded room. This instrument is about two orders of magnitude more sensitive and much faster than conventional spinner magnetometres, and has a background noise level of about  $5 \times 10^{-12}$  Am<sup>-2</sup>. At least one specimen from each of the samples was subjected to from six to ten progressive thermal demagnetization steps, up to 600 °C for the pale sediments, and to 680 °C for the red-coloured limestone. A smaller set of specimens was progressively

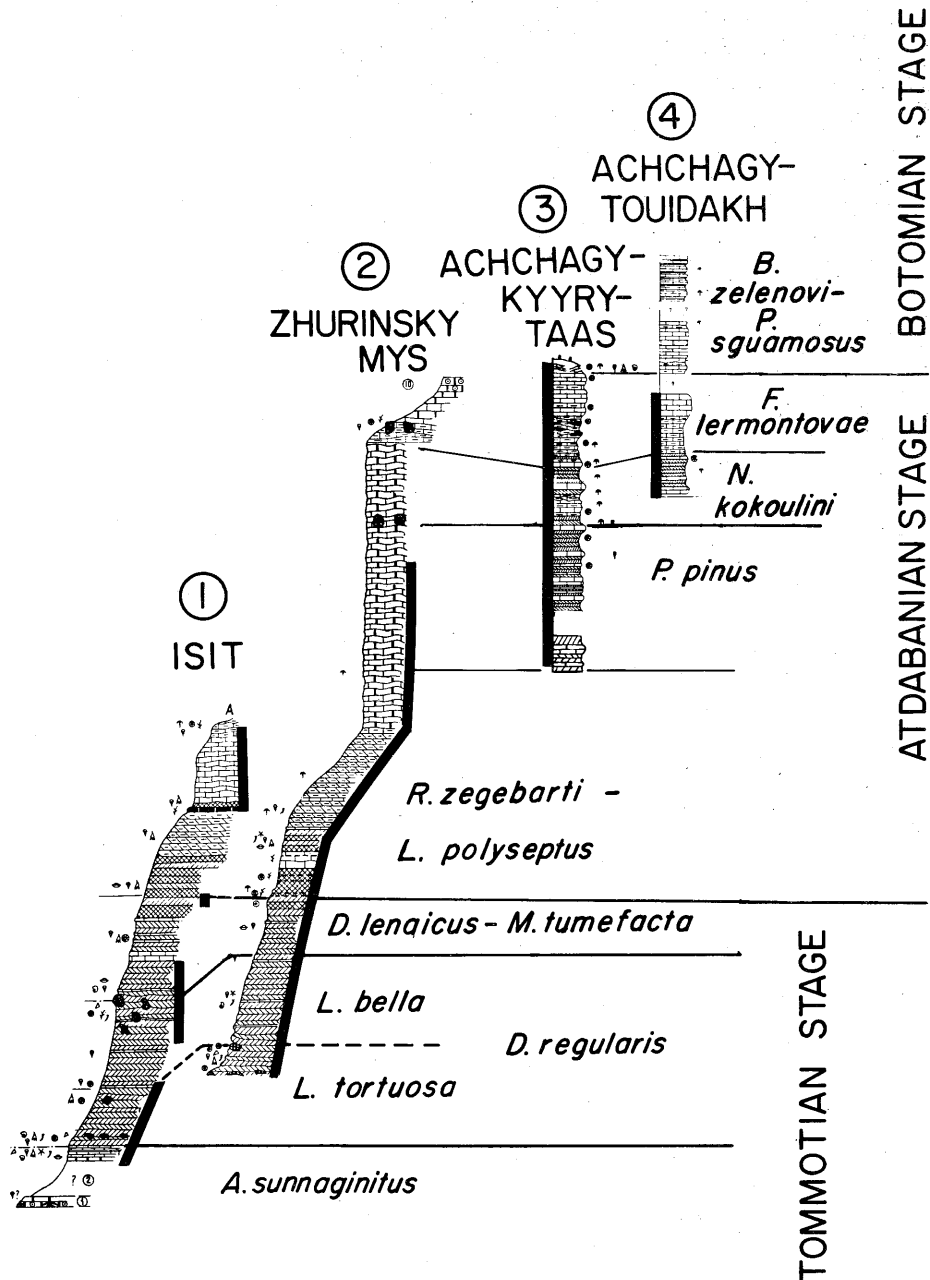


Figure 5. Biostratigraphic and lithostratigraphic correlations between the four localities sampled for magnetostratigraphy. Lithologic symbols are the same as those shown on Figure 2, and the thick vertical bars indicate the approximate horizons sampled for palaeomagnetic study.

demagnetized using alternating fields (Af) of up to 100 mT, and one group was chemically demagnetized by dissolving ferric iron oxides with a buffered sodium dithionite solution (Mehra & Jackson, 1958; Kirschvink, 1981). For each demagnetized specimen, groups of adjacent colinear and coplanar points on the vector demagnetization paths were determined using principal component analysis, and the directions of the corresponding lines and planes of best fit were found by the method of least-squares (Kirschvink, 1980).

### 3.b. Results

Samples of reddish-weathering carbonate from the Pestrotsvet Formation have moments of natural remanent magnetization (NRM) typically ranging between  $10^{-8}$  and  $10^{-9}$  Am<sup>-2</sup>, and intensities in the range from  $10^{-3}$  and  $10^{-4}$  Am<sup>-1</sup>, whereas the pale-weathering carbonates have somewhat weaker moments ranging between  $10^{-9}$  and  $10^{-10}$  Am<sup>-2</sup>. The NRM vectors for most specimens were clustered strongly about the direction of true present axial field (Fig. 6A, B), suggesting that the strongest component of NRM reflects surface weathering during Late Quaternary time.

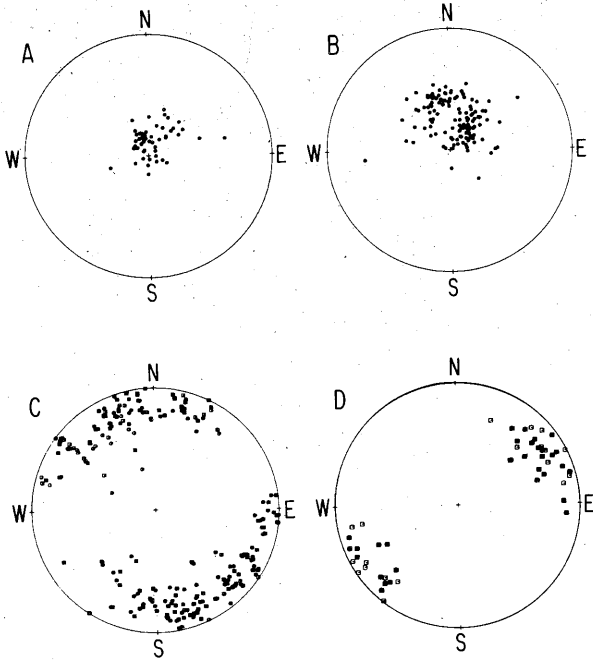


Figure 6. NRM directions from pale carbonates at Achchagy-Kyyry-Taas (A) and reddish carbonates at Zhurinsky Mys (B), showing a dominating present field component on the samples. (C) Directions of normal vectors to demagnetization planes from Zhurinsky Mys. These directions fall into two elongate, anti-parallel clusters representing migrations of the remanence vector to the northeast or southwest. These groups indicate normal and reversed polarities of the Early Cambrian geomagnetic field, and are the basis for the worst-estimate directions given in Table 1. (D) Stable Cambrian directions from samples which clean up during progressive thermal demagnetization. All figures are equal-area projections with open symbols for upper hemisphere directions.

Progressive thermal demagnetization in most samples yields systematic angular shifts from the initial steeply dipping northerly direction towards two groups (northeast and southwest) with shallow inclinations. From the specimen demagnetization diagrams (Fig. 7), this procedure is seen to remove a strong magnetic component that is centred around the present axial field. The small shifts in direction towards the northeast and southwest are, similarly, the result of a much weaker two-polarity component having an apparently slightly higher blocking temperature spectrum. Despite the reddish colour of many of the limestone samples, very few remain stably magnetized above the Curie temperature of magnetite (580 °C), suggesting that fine-grained magnetite rather than haematite, goethite, or maghaemite is responsible for the high blocking temperature component (Fig. 7A is one such example). In a few samples, however, haematite apparently provides a component of the remanence, and stable directions are recovered above 600 °C (Figs 7B, C). On the other hand, the pale-weathering carbonates lose a sizeable fraction of their remanence at relatively low temperatures, and most became too weak to measure above about 400 °C (Figs 7D, E). Of the 440 specimens that were subjected to progressive thermal demagnetization, 50 responded well to the thermal cleaning, yielding two groups of shallow-inclination, stable magnetic directions (northeast and southwest). Magnetic directions from this group of specimens were found by the principal component method (Fig. 6D; average directions are given in Table 1). Only specimens with angular errors of less than 10° have been used in this statistical analysis.

Table 1. Summary of palaeomagnetic directions from the lower Cambrian sediments on the Lena River (61° N, 126.8° E)

Group	Number of samples and total	Mean direction		Bingham statistics					Eigenvalues			Fisher stats	
		Dec.	Inc.	$\kappa^1$	$\kappa^2$	$\alpha_{\min}$	$\alpha_{\max}$	ov. az.	$\lambda^1$	$\lambda^2$	$\lambda^3$	$\kappa$	$\alpha_{95}$
Cambrian primary direction	50	58.9 (58.1)	3.4 3.9	-9.8 -10.6	-5.4 -5.5	5.1 4.8	7.1 6.9	8.8 10.8	41.8 42.2	5.4 5.3	2.8 2.5	11.1 11.7	6.3 6.2)
Secondary overprint	335	358.9 (356.3)	70.6 72.8	-11.4 -11.1	-2.4 -2.4	2.0 2.0	4.1 4.2	121.6 119.5	239.3 239.3	80.1 79.6	15.6 16.1)	—	—
Worst estimate of primary direction	335	145.5 (145.7)	16.4 14.9	-11.4 -11.1	-2.4 -2.4	2.0 2.0	5.1 5.1	100.5 98.6	239.3 239.3	80.1 79.6	15.6 16.1	5.7 5.7	3.5 3.5)
Worst estimate by locality													
Isit	97/122	132.0 (132.0)	10.3 11.6	-10.0 -9.7	-2.6 -2.6	3.9 4.0	8.8 8.8	74.5 76.1	70.0 70.0	21.8 21.6	5.2 5.4	5.8 5.8	6.5 6.5)
Zhurinsky Mys	124/171	155.7 (155.3)	21.6 16.5	-11.8 -10.1	-2.7 -2.7	3.1 3.4	7.5 7.6	92.4 92.5	91.2 90.2	27.2 27.3	5.6 6.6	6.3 6.1	5.5 5.6)
Achchagy-Kyyry-Taas	71/90	146.0 (146.5)	15.9 16.6	-14.9 -15.1	-2.0 -2.0	3.7 3.7	12.6 12.7	99.1 98.8	49.4 49.3	19.1 19.2	2.5 2.5	5.2 5.2	8.2 8.2)
Achchagy-Tuoidakh	43/57	147.1 (147.0)	13.2 12.9	-15.1 -15.1	-3.6 -3.6	4.5 4.5	10.0 10.0	100.7 101.1	34.3 34.3	7.2 7.2	1.5 1.5	8.7 8.7	7.9 7.9)

Dec. and Inc. refer to the average declination and inclination as found by least-squares (Bingham, 1974).  $\kappa^1$  and  $\kappa^2$  are Bingham's (1974) precision parameters along with the minimum and maximum angles of 95% confidence and the azimuth of the long oval axis (Kirschvink, 1980).  $\lambda^1$ ,  $\lambda^2$ , and  $\lambda^3$  are the eigenvalues from the least-squares analysis. The second row of numbers enclosed in parentheses are results from directions after correction for local tilt of beds. Both the total number of samples used in the calculation and the total taken are given in summary by locality. The tilt-corrected Cambrian Primary Direction yields a pole at 16.6° N, 244.5° E, with dp and dm of 3.1 and 6.2.

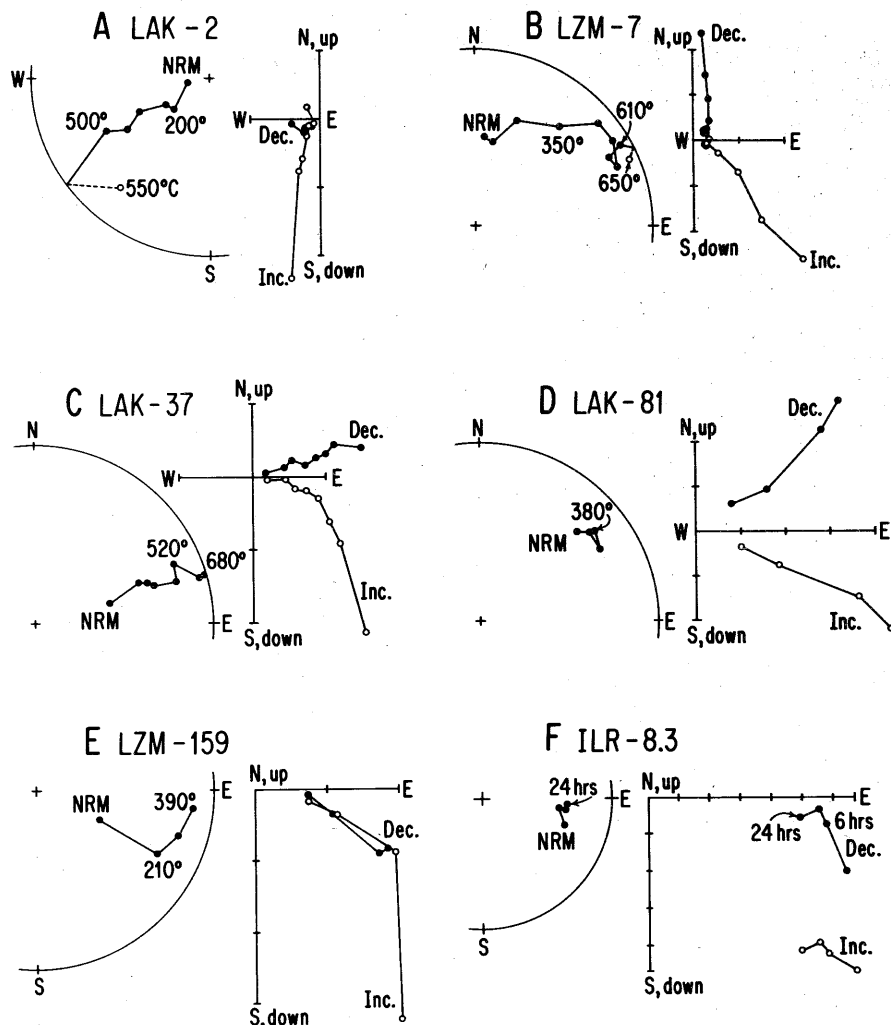


Figure 7. Progressive demagnetization of representative samples from the Siberian Platform. For each specimen the directional change of the magnetic vector is shown on an equal-area projection, while the intensity relationships are shown on a vector diagram (solid points are on the horizontal projection labelled 'Dec', and the horizontal vs. vertical intensity plot is labelled 'Inc'). For the vector diagrams, the scale is  $10^{-7} \text{ Am}^{-2}/\text{kg}$  on A, B and C and  $10^{-6} \text{ Am}^{-2}/\text{kg}$  for D, E and F.

Chemical demagnetization experiments indicate that the present field secondary component is carried by fine-grained ferric minerals such as haematite, rather than magnetite. Because conventional chemical demagnetization using concentrated HCl (Collinson, 1967, 1983) does not work very well on carbonate rocks, we used a strongly reducing sodium dithionite solution buffered to pH 7 with sodium citrate and sodium bicarbonate at room temperature (Kirschvink, 1981). Fine-grained ( $\sim 0.5 \mu\text{m}$ ) powders of magnetite remain apparently unchanged in this solution for several months. In contrast, ferric iron in haematite, pyrrhotite, maghaemite, and goethite is dissolved within a few hours or days and held in solution (chelated) by the citrate ions. Six samples of reddish limestone from the Pestrotsvet Formation were sliced into thin wafers and immersed for various intervals of time in this solution. Penetration of the solution into the samples was aided by initially immersing the samples, withdrawing internal air with a vacuum, and then repressurizing the vessel. The wafers rapidly

lost their reddish surface coloration, during which time part of the secondary magnetic component was also removed (Fig. 7F). However, even using the thin wafers it was difficult to produce a deep penetration of the chemical solution into the samples. As a result, the effectiveness of this method of chemical demagnetization decreased with time, and the method was judged to be both less effective and less efficient than thermal demagnetization for the samples with low porosity.

A Curie temperature analysis on one of the reddish carbonates from Isit was carried out under vacuum in a saturating magnetic field. The magnetic moment of the sample decreased with temperature up to  $450^\circ\text{C}$ , whereupon most of the reddish colour disappeared and the moment of the sample increased dramatically as shown in Figure 8. This new moment was lost abruptly at about  $590^\circ\text{C}$ , indicating that the ferric iron oxides had been reduced to magnetite. Upon cooling, the sample was far more strongly magnetized than it had originally been.

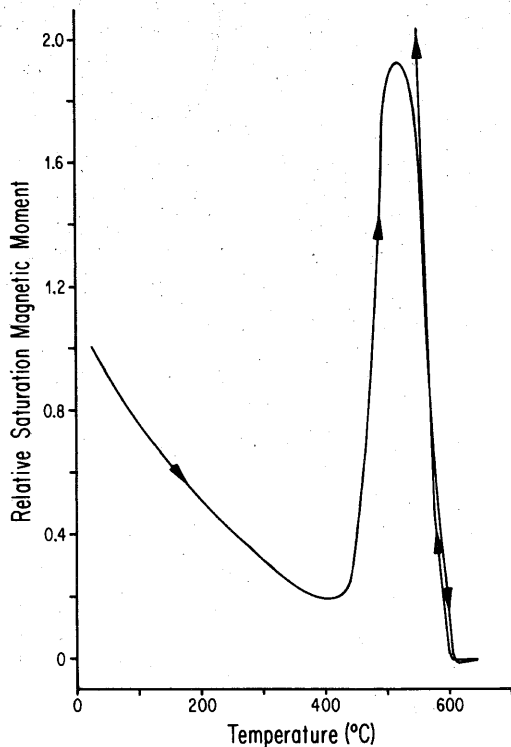


Figure 8. Curie temperature analysis of powdered material from Isit sample 47, a typical reddish carbonate from the Pestrotsvert Formation.

Alternating field demagnetization experiments were not very effective at isolating the low-inclination, two-polarity component. In particular, the red carbonates lost very little of their NRM in fields up to 100 mT. The pale carbonates responded somewhat better, losing most of their NRM in fields less than 70 mT, but the two-polarity component was never successfully isolated with this technique.

A straightforward interpretation of these results is that surface weathering during post-Mesozoic uplift and erosion of the Siberian Platform has oxidized some of the iron-bearing minerals into extremely fine-grained haematite, maghaemite or goethite. Although the Curie temperature of haematite is relatively high ( $\sim 680^\circ\text{C}$ ), submicron-sized crystals can have much lower blocking temperatures and could be responsible for some of the NRM held in the lower portion of the blocking temperature spectrum. Either of these three minerals could have been reduced to magnetite under the high vacuum conditions during the Curie run, although maghaemite and goethite both become chemically unstable at temperatures near this.

Of the original 440 samples, 335 have present-field and low-inclination components with severely overlapping blocking temperature spectra. Inspection of the 50 samples yielding discrete low-inclination components, however, reveals that the present field direction is mainly held in the 50 to 450  $^\circ\text{C}$  range, while the low inclination component peaks at higher temperatures. Under these conditions the remanence vectors

will be coplanar during demagnetization, and the arc will curve towards the direction of the more stable component. In this case the direction of this curvature indicates the polarity of the higher temperature component present within the sample, and it seems appropriate to use a right-handed convention based on this curvature to select the direction of the normal vector as was described before (Kirschvink, 1980). The directions of the normal vector to these demagnetization planes are shown on Figure 6C, and they clearly fall into two groups centred in the northnorthwest (NNW) and southsoutheast (SSE). Using the right-hand convention mentioned above, vectors in the NNW group indicate samples with vectors which are moving towards the southwest upon demagnetization, while the SSE group reflect those which are moving towards the northeast. The asymmetric girdle shape of this distribution is centred on the best estimate of where *neither* the present field nor the two-polarity, low-inclination components lie. Bingham statistics (Bingham, 1974; Onstott, 1980) can be used to place constraints on the orientation of the plane containing both of these components, and the swath of 95% confidence about this plane includes both the mean present-field component and that of the two-polarity component, as expected.

The geological age of the low-inclination, two-polarity component is a major question which remains at this point. If it formed during or shortly after deposition of the individual beds then the detailed polarity patterns within the sequence would be of use for stratigraphic correlation, and the direction of this component would specify the palaeolatitute and orientation of the Siberian Platform. On the other hand, if the magnetization was gained in a 'mottled' fashion during low-temperature diagenesis over several different polarity chrons, the polarity stratigraphy might not be strictly meaningful, while the mean axial direction might still represent the lower Cambrian of Siberia.

Several lines of laboratory evidence suggest that this magnetic component dates from at least lower Palaeozoic time. The demagnetization analyses suggest that it is carried in fine-grained magnetite and haematite, minerals which are capable of preserving a magnetic remanence over suitably long periods of time. Both groups of directions which form the low-inclination, two-polarity clusters are anti-parallel at the 95% confidence level, and indicate that the reversals were, in general, complete. Finally, low-inclination NNE–SSW trending directions have not been previously reported from the Phanerozoic strata on the Siberian Platform, and the Siberian APW path is reasonably well defined from upper Cambrian time onwards (Fig. 9). These arguments suggest that this magnetization is either of Early or Middle Cambrian age.

Unfortunately, these sediments are flat-lying and

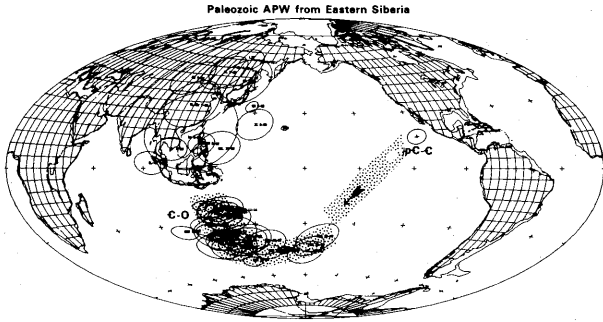


Figure 9. Lower Palaeozoic apparent polar wander path for the Siberian Platform. The pole labelled pε-ε was calculated from the data shown on Figure 6D and Table 1.

lack intraformational conglomerates. It was therefore not possible to conduct either of the classic fold or conglomerate tests which might otherwise be used to help bracket the age of their remanent magnetism. The archaeocyathid biostratigraphy in the field area shown on Figure 5, however, provides an alternative method of determining whether or not the strata were magnetized at or near the time of their deposition. The fossil assemblages permit the same zone boundaries (approximate times lines) to be recognized in different localities, despite the wide geographical separation and the pronounced facies variations discussed earlier. At the four localities sampled along the Lena River, most parts of the Tommotian and Atdabanian stages are present in at least two places. If this two-polarity magnetization is penecontemporaneous with deposition, the magnetic polarity patterns with each zone ought to agree reasonably well from section to section. On the other hand, if the magnetization was acquired in an irregular fashion at some later time during diagenesis, it would be unlikely for similar patterns to emerge.

Figures 10 and 11 show the magnetic polarity interpretations based on the progressive demagnetization data from the four localities along the Lena River. The vertical scale on the side of each column gives the stratigraphic position in metres, and for each

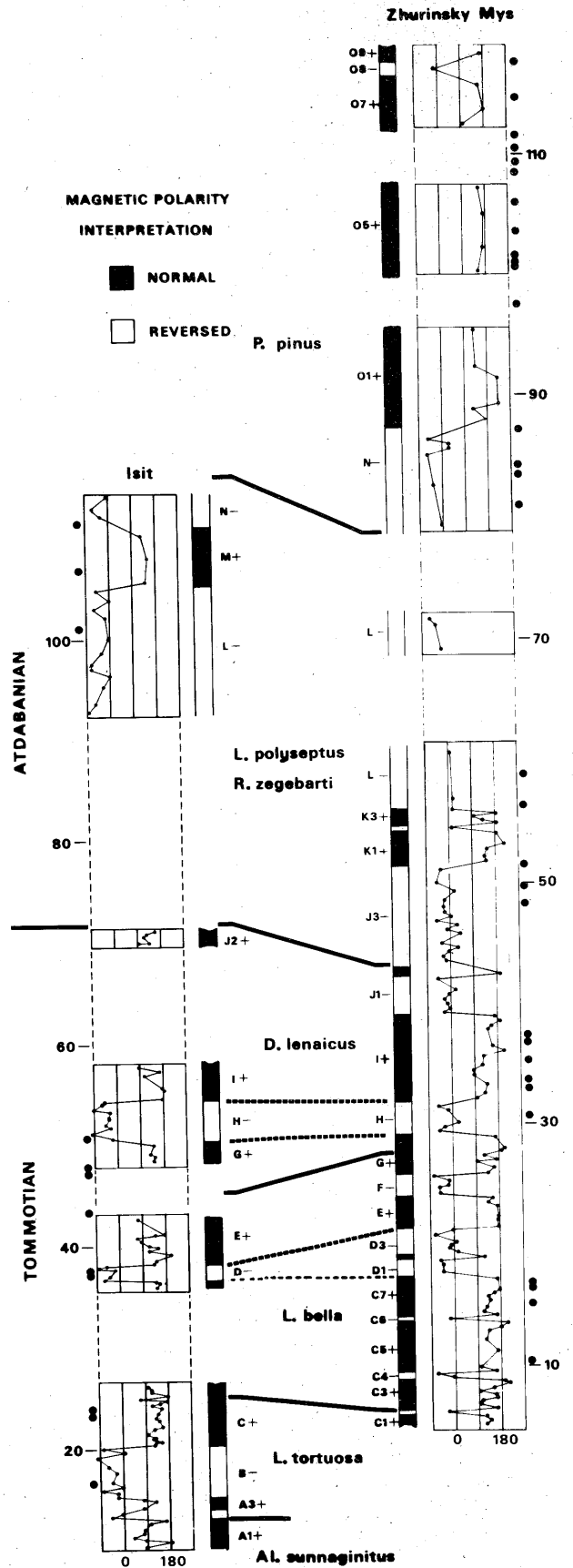


Figure 10. Comparison of magnetic polarity zonation between Isit and Zhurinsky Mys, localities 1 and 2 of Figure 1. Solid lines drawn between the vertical columns indicate the biozone boundaries shown on Figure 5. The black and white stripes indicate regions of normal and reversed polarity of the characteristic magnetic component. Dashed lines show the probable magnetostratigraphic correlation between these sections. Large black dots on the outside along the metre scale indicate the stratigraphic positions of samples which were unstable or totally remagnetized by recent weathering. Declination points shown alongside the polarity interpretation pattern for each locality represent the direction of the right-handed normal vector to plane of least-squares fit as described by Kirschvink (1980). The small letters, numerals, and +/- sign are the designations of the magnetochrons shown on Figure 13, using the system of nomenclature adopted by Alvarez *et al.* (1977).

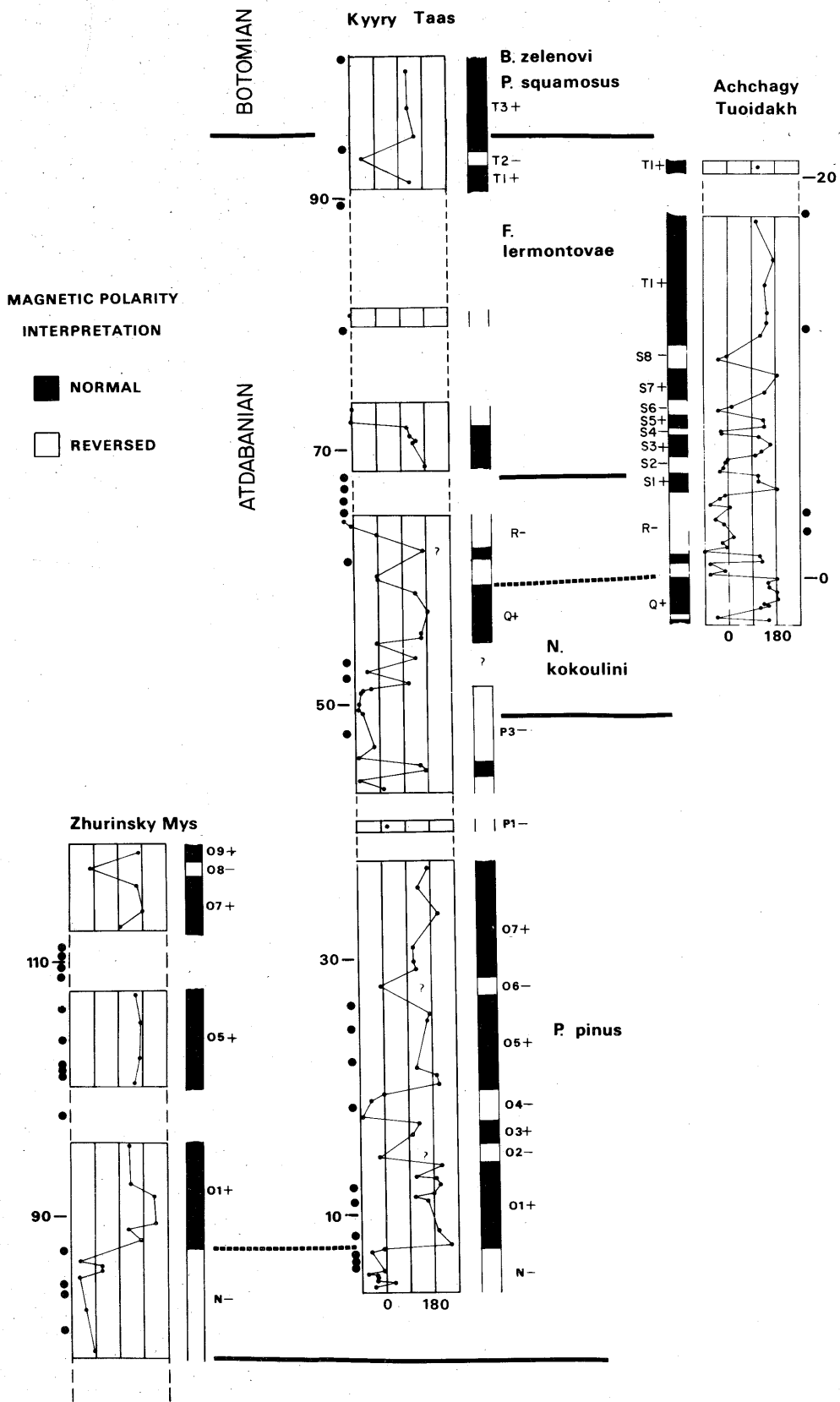


Figure 11. Atdabanian and Botomian magnetostratigraphic correlation between the top of Zhurinsky Mys, Achchagy-Kyryy-Taas, and Achchagy Tuoidakh. All symbols are as described for Figure 10.

sample the declination value for the normal vector to the demagnetization plane of best least-squares fit (like those in Fig. 6C) is shown to indicate the polarity. Demagnetization planes from the 50 samples which yield the stable two-polarity directions have been included, although they are not shown in Figure 6. The stratigraphic positions of samples which were totally remagnetized or magnetically unstable are shown by black circles. Solid lines drawn between the columns show the biostratigraphic correlation between the sections.

In general, there seems to be an overall similarity in the magnetic polarity pattern between overlapping sequences, particularly between the Isit and Zhurinsky Mys localities compared on Figure 10. In these two sections the sampling density was high enough to resolve most of the polarity structure present, although a few thin events appear in one section that were not recognized in the other. This general agreement lends support to the hypothesis that the magnetization was acquired at or shortly after deposition of the individual beds in these units, although this strict interpretation is not as clear higher in the sequence around the Tommotian/Atdabanian boundary. Comparison with the Siberian APW path (Fig. 9) indicates that the northwest and southwest directions (Fig. 6D) are of normal and reversed polarity respectively, and these correspond in turn to normal vectors in the southeast and northwest groups of Fig. 6C. These polarity interpretations are shown on Figures 10 and 11 as black and white, respectively.

At the Zhurinsky Mys locality, the sequence extends into the lower portion of the *Porocyathus pinus* zone and is characterized by a prominent switch from reverse to normal polarity. A similar switch in polarity is observed at the base of the Achchagy-Kyyry-Taas locality (Fig. 11), which from biostratigraphic and regional lithostratigraphic considerations is also near the base of the *P. pinus* Zone; it is therefore straightforward to suggest that it is the same event at both localities and provides a basis for detailed correlation between them.

We should note that there is one portion of this sequence within the *F. lermontaovae* Zone for which the Achchagy-Kyyry-Taas and Achchagy-Tuoidakh polarity patterns do not agree very well. In particular, Achchagy-Tuoidakh has eight small magnetic zones which are not seen in Achchagy-Kyyry-Taas. Part of the problem is certainly due to the large fraction of samples which were unstably magnetized or remagnetized along the present field direction (black dots on Fig. 11), which in turn is largely a result of poor outcrop exposure and prolonged surface weathering in this portion of the Achchagy-Kyyry-Taas locality. Another interpretation, however, is that some of the sediments in this part of the sequence gained their remanence inhomogeneously during diagenesis, and the data at hand cannot as yet distinguish between these possibilities.

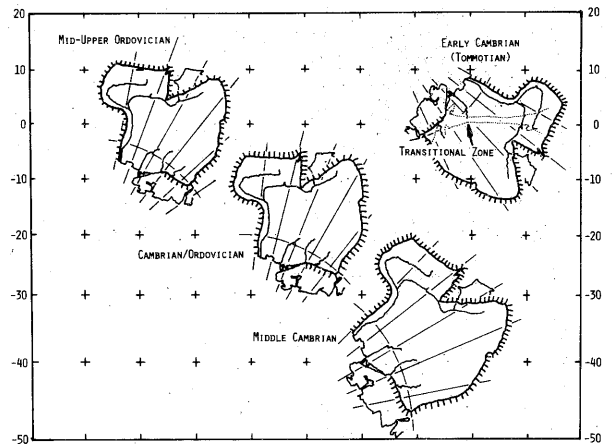


Figure 12. Palaeoposition of the Siberian Platform for the lower Palaeozoic. The Tommotian position is based on the palaeomagnetic data from this study, and the Middle Cambrian, Cambrian/Ordovician, and mid-upper Ordovician orientations are from data given by Khramov, Petrova & Pechersky (1981). The location of the transitional facies zone discussed in the text is shown by dotted lines in the Tommotian figure, and is on the equator within the limits of the palaeomagnetic data.

#### 4. Discussion and conclusions

##### 4.a. Siberian apparent polar wander path and the palaeoposition of the Siberian Platform

The apparent polar wander path for the Siberian Platform is relatively well defined for most of Phanerozoic time, but as mentioned earlier the reliable Palaeozoic data reported to date (Khramov, Petrova & Pechersky, 1981) only extend down to the lower Middle Cambrian (Fig. 9). The palaeomagnetic pole for the Tommotian reported here lies approximately 45° to 60° away from the nearest later Cambrian direction and implies that the Siberian Platform was then located on the equator with approximately the orientation shown for it on Figure 12. The equatorial position most likely contributed to the high organic diversity mentioned earlier and described at length by Rozanov *et al.* (1969). An interesting and unexpected result of this investigation is that the archaeocyathid reef-bearing belt which separates the two facies zones shown on Fig. 3A was approximately on and aligned with the earth's equator when it formed. We do not know of any other mid-continent belt of reef-life organisms in the Phanerozoic which was constrained in this fashion, but it seems plausible that its position was controlled by east-west trending oceanic circulation patterns like those discussed by Parrish *et al.* (1983).

Palaeomagnetic data for Middle Cambrian time imply that Siberia was located in mid-southerly latitudes, so our Tommotian result implies that the Siberian Platform moved into the southern hemisphere between Early and Middle Cambrian time. It is interesting to note that the archaeocyathid-bearing transitional zone remains in roughly the same

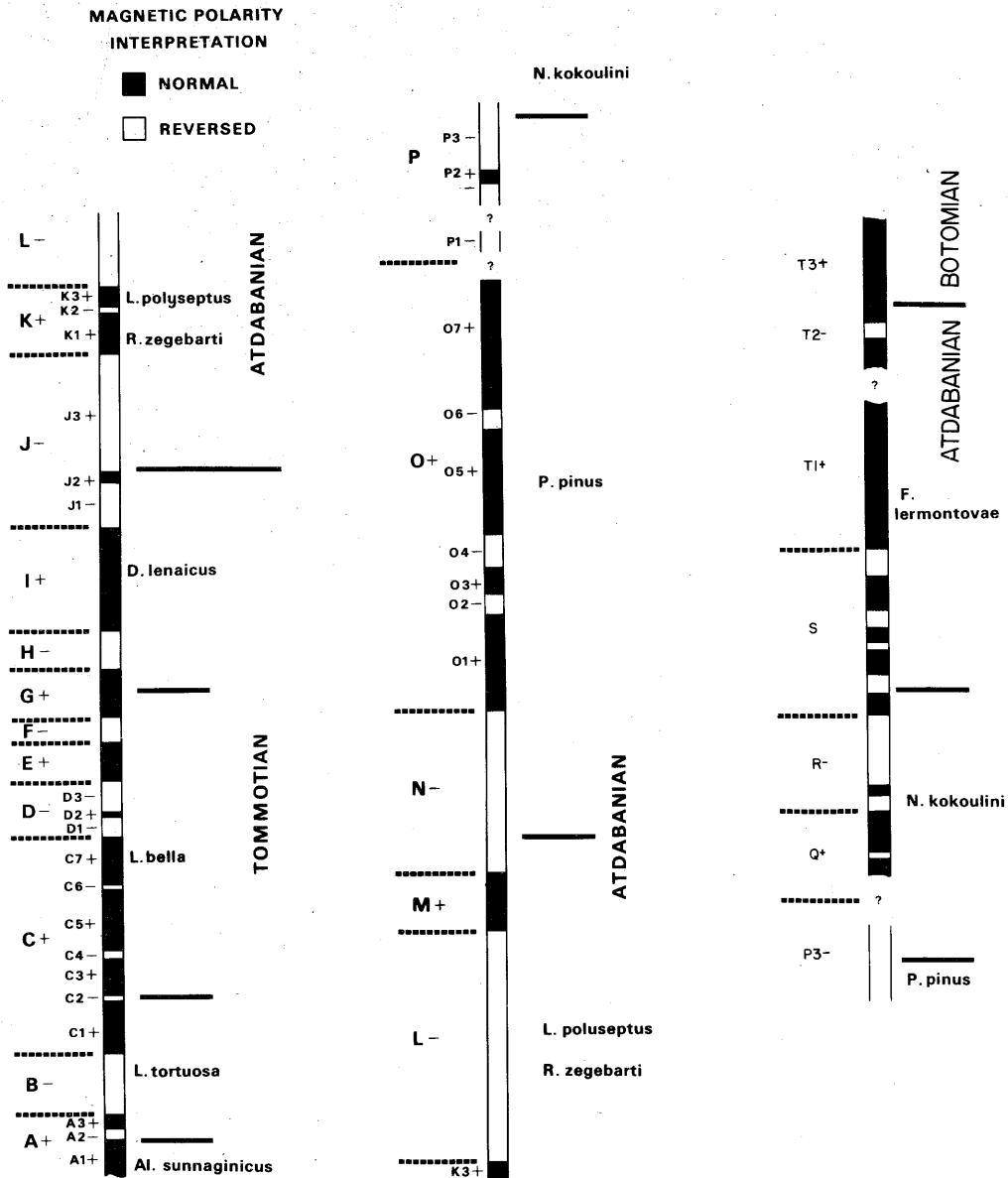


Figure 13. Summary of the preliminary magnetic polarity time scale from the Lena River of the Siberian Platform.

palaeogeographical position during the Tommotian (Fig. 3 B), but starts to move off towards the northeast during Atdabanian time. This is precisely what would happen if the entire Siberian Platform began to move towards the south while the reef-building organisms tried to remain behind on the equator.

**4.b. A preliminary polarity time scale**

The positions of the magnetic polarity zone boundaries relative to the archaeocyathid zones are summarized on Figure 13, using the data from Figures 11 and 12. In order to minimize the effects of slightly varying sedimentation rates, the average thickness of individual biozones from overlapping sections has been used to provide a relative vertical scale, and the average thickness of each magnetic zone has been interpolated relative to them. The physical magnetic polarity units found in these correlative sequences have been

designated alphabetically in a fashion similar to that used by Alvarez *et al.* (1977), where major groups of beds characterized by a common polarity are given letter designations, with '+' standing for normal polarity and '-' reversed. In accordance with the recommendation of the Subcommittee on Magnetostratigraphic Nomenclature (1973) and the International Stratigraphic Guide (Hedberg, 1976; Hedberg, Salvador & Opdyke, 1979), some of the thinner polarity units are considered to be polarity subzones and are distinguished by numerals such as C1+, J2-, etc. This labelling scheme is identical on Figures 10, 11 and 13. We interpret these physical zones to represent global periods of normal or reversed geomagnetic polarity during which the sediments were deposited, and hence the term 'polarity chron' applies.

As of now, we must stress that the data underlying Figure 13 are derived from at most two overlapping intervals in the stratigraphic succession of the Lena

River, and it is quite probable that some magnetic subzones of short duration have been missed. Similarly, we cannot rule out the possibility that some of the zones which are of short duration, based on only one sample, and which have only been identified at a single locality might be a result of remagnetization during later diagenesis; examples of this include C2—, C6—, K2—, etc. At best the scheme shown on Figure 13 should be considered provisional until results from several additional, biostratigraphically constrained stratigraphic sequences are available, principally those from the Aldan River and Mongolia (Drozdova *et al.* 1981), where the zones of the Tommotian Stage have been recognized.

#### 4.c. Comparison with the lower Cambrian of Australia

Despite the limits of the present data, it seems worthwhile to attempt a comparison of these results with those reported for lower Cambrian sediments in the Amadeus and Georgina basins of Australia (Kirschvink, 1978; Burek, Walter & Wells, 1979). These authors found an interval of mixed polarity in Late Precambrian strata immediately beneath a widespread regional disconformity. This portion of the sequence had been palaeontologically assigned to the Late Precambrian owing to the presence of an assemblage of soft-bodied metazoan fossils similar to the Ediacaran fauna (Glaessner & Walter, 1975). Sediments of presumed early Cambrian age which disconformably overlie these rocks were also of mixed polarity, and both mixed intervals displayed a prominent bias towards normal polarity.

A major problem that arises in the attempt to compare these magnetic polarity patterns, however, is the lack of an adequate biostratigraphic framework for the lowermost Cambrian in Australia. Australian archaeocyathids which are found in the Todd River Dolomite (near the top of the Australian palaeomagnetic sequence) have been correlated with the Botomian Stage of the Siberian Platform (Rozanov & Debrenne, 1974). On biostratigraphic grounds alone it is not clear whether or not sediments of Tommotian age were deposited or preserved in the central Australian sequence.

The observation that the lower Cambrian sediments of Australia have a normal-polarity bias helps to reduce the number of possible correlations. In particular, it seems unlikely that strata of the *L. polyseptus*-*R. zegebarti* Zone at the base of the Atdabanian Stage of Siberia could be present in Australia, as there are no equivalents of the Lena River J-, L- and N- reversed magnetochrons. Either there is another as yet unrecognized disconformity in the Australian sequence (perhaps at the Arumbera II/III contact) or the earliest Cambrian rocks (Arumbera II) were deposited after the Lena River N-magnetochron. This latter possibility implies that

strata of Tommotian age are probably not present in central Australia, with the possible exception of the uppermost Arumbera I at Laura Creek.

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