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NEW MIDDLE CAMBRIAN AND MIDDLE ORDOVICIAN PALAEOMAGNETIC DATA FROM SIBERIA: LLANDELIAN MAGNETOSTRATIGRAPHY AND RELATIVE ROTATION BETWEEN THE ALDAN AND ANABAR-ANGARA BLOCKS.

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Abstract

Whether Siberia was a coherent tectonic unit throughout the Phanerozoic or whether significant rotations occurred in early Palaeozoic times between the Anabar- Angara and Aldan blocks is still a matter of debate. Addressing this problem a detailed palaeomagnetic study of sections of mid Cambrian and Llandeillian age has been carried out along the river Lena, river Maya, river Kulumbe, and river Stolbovaya, with a total of 403 collected hand-samples.
A section of Llandeilian age was also investigated on the Russian Platform, near St. Petersburg. The studied rocks are carbonates or fine grained terrigenous sediments of reddish and greyish colors. Stepwise thermal demagnetization experiments reveal a rather simple directional behavior. In most samples, after removal of a secondary magnetizations at low to intermediate temperatures, a high temperature component is isolated, which is carried by magnetite and/or hematite. Positive reversal tests and fold tests clearly demonstrate the primary character of the latter component. While only reversed polarity directions are obtained in the lower two thirds of the Llandeilo, six magnetozones of normal polarity are found in the Upper Llandeilo, which mark the end of the Moyero reverse superchron.
Together with previously published paleomagnetic data our new results show rather systematic difference in declinations of ~20° between the Aldan and Anabar-angara blocks. This argues in favor of a relative rotation between these two blocks, with an Euler pole of rotation located at latitude ~ 62ºN and Longitude ~ 117°. Our interpretation is further supported by existing results from deep sounding seismic experiments, yielding a very similar pole of rotation.

Introduction

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The Siberian platform represents an important tectonic unit of the Earth crust and understanding its geodynamic history is of great importance for deciphering the geological evolution during the early Palaeozoic. Nevertheless, one of the key questions whether Siberia has to be treated as a coherent structural unit since its amalgamation during the Palaeoproterozoic, or whether independent units can be identified which have been subjected to subsequent relative rotation and/or translation remains unanswered.

Based on differences in the geological and structural inventory, the Siberian platform can be divided into three main tectonic elements (Fig.1). These are, the Anabar-Angara block, in the southwestern, western and northern part of the platform, the Aldan block, in the southeastern part and the v-shaped Vilyui syneclise separating Aldan from Anabar-Angara. The Vilyui syneclise itself is filled with a thick sequence of Palaeozoic and Mesozoic deposits and covers the NE trending Vilyui rift system of Middle Palaeozoic age.

Significant differences between palaeomagnetic pole positions for the Mid-Ordovician from Anabar-Aldan (Moyero river valley) and Angara (Lena river valley) have been noted earlier[1] and been interpreted as the consequence of post Middle Ordovician rotations between the two areas. However, whether these rotations are local or can be traced on a regional scale has so far not been unambiguously elaborated.

Subsequently, Pavlov and Gallet [2] carried out a detailed palaeomagnetic study of a Cambrian-Ordovician section along the Moyero river and confirming the above observation they indicated that systematic differences in palaeomagnetic pole positions with respect to the Apparent Polar Wander Path (APWP) for southeastern Siberia [3] are present throughout the sections, ranging from the Late Cambrian to the Early Silurian. Due to the variable quality of the palaeomagnetic data and uncertainties in temporal resolution of the different data sets, Pavlov and Gallet [2] did not fully support the block rotation model, but pointed out that more data are needed for Siberia before a final interpretation can be reached.

It has been shown earlier [4] that the discordant palaeomagnetic pole positions from nearly coeval sections of Middle Riphean age from the northwest of the Siberian Platform (Turukhansk) and the southeast (Uchur-Maya) can be matched if rotations between the southeastern part of the Siberian Platform (Aldan Block) and the rest of platform are allowed. These rotations, likely to be Mid Palaeozoic in age, can be related to the opening of the Vilyui rift about a rotation pole located on the southwestern margin of the Vilyui syneclise, approximately at 117˚E longitude and 62˚N latitude This interpretation was supported by Smethurst et al. [5], albeit with a slightly different rotation pole at Long. 100˚E, Lat. 60˚N. It should be pointed out, however, that Smethurst et al. [5], and, more recently, Cocks and Torsvik [6] point out relative rotations between the northern and southern Siberian platform whereas in the model proposed by Pavlov and Petrov [4] rotations of

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the Aldan block relative to Anabar-Angara are the main issue. In addition, the comparison of Middle to Late Cambrian palaeomagnetic poles from the northwest (Kulumbe river section), northeast (Olenek river section) and south of the Siberian platform (Angara river region) did not yield any significant differences between the palaeomagnetic data from these areas [7] therefore rendering significant rotations within the Anabar-Angara block, as postulated in Smethurst et al [5] as extremely unlikely. On the other hand, palaeomagnetic data for the Mid Ordovician from Aldan, satisfying modern quality standards [8], support rotations between Aldan and Anabar–Angara. Unfortunately, however, only two high quality data sets from coeval rocks from Aldan and Anabar-Angara are currently available and can be used to test the hypothesis described above. These are the results for the Malgina (Aldan block) and Linok (Anabar-Angara block) formations both of Middle Riphean age [2, 4, 7]and for rocks from the Moyero river section (Anabar-Angara block, [2]) and the Polovinka section (Aldan block, [8]), both of Llandeilian age [9].

Despite the fact that the synchronicity of the Malgina and Linok formations seems to be rather well established [10, 11], the contemporaneity was disputed and it was postulated that the different pole positions for the two formations can be explained by motions of the Siberian platform *in toto* without the need to invoke relative displacements between the two blocks [12]. Llandeilian pole positions from the Moyero river section (Anabar block, [13]) and from the Polovinka section (Aldan block, [8]) are difficult to be disputed as they meet modern quality requirements and the sections studied clearly cover the same age intervals [9].

Here, we present new palaeomagnetic results for the Middle Cambrian of the Aldan block, which will be compared to recently published results for rocks of the same age from the Anabar-Angara block [14, 15].

The first version of a regional Palaeozoic magnetic polarity time scale was published in a monograph by Khramov et al. [16]. . This magnetostratigraphic time scale was further refined by Khramov and Rodionov [17] and used, with minor modifications by Trench et al. [18] for the construction of a global Ordovician magnetic polarity sequence. However, the Russian data mentioned above are (a) based on very limited demagnetization experiments, (b) details of which are unpublished, (c) published details are rarely sufficient to match the magnetostratigraphic data to biostratigraphy and (d) almost all data used are from sediments from the Lena river valley. Therefore, resampling of Ordovician key sections in Siberia is required in order to improve the quality of the magnetostratigraphic database.

In two previous studies Pavlov et al. [8] and Gallet and Pavlov[13] published data for the Llandeilo of the Moyero and Polovinka key sections.In this paper we present new data from three additional sections of Llandeilian age from the Siberian platform. In addition, results from a magnetostratigraphic investigation of a Llandeilian section, exposed in the Alexeevka quarry

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(Leningrad Oblast, northwestern East-European platform) will be presented which are used to support the reliability of the Siberian data.

The magnetostratigraphy of the Ordovician of the East European platform was intensively studied by Claesson [19], Trench et al. [18], Torsvik and Trench [20, 21]. These studies, however, were limited to the limestones from South Sweden. The large area of Ordovician sedimentary rocks in the northwestern part of Russia was practically not studied with the noteworthy exception of the Arenig to Lower Llanvirnian sections of the Lava and Tosna rivers [5].

Geology and Stratigraphy

Middle Cambrian.

The Middle Cambrian deposits, studied here, are located in the Uchur-Maya region in the South-East of the Siberian platform (Fig. 2) and excluding the uppermost part of the Inican formations,. can be divided into the Chaya and Ust'-Maya formations. The Chaya formation reaches 60 m in thickness and is dominated by limestones, argillaceous limestones and marls of reddish, greenish and grey colour. This formation is exposed in two massif cliffs along the right bank of the Maya river (Supplementary file 8 in the Appendix for locations). Both cliffs were sampled for this study and will be referred to as outcrop A, where 50 and outcrop B, were 30 oriented hand samples were collected, respectively.

The Ust'-Maya formation, mostly greenish and grey-greenish limestones and clayish limestones is exposed in a series of outcrops of reduced thickness, predominantly along the left bank of the lower Maya river. The stratigraphic thickness of the Ust'-Maya formation, exposed along the Maya river valley totals up to about 500m. Nine outcrops of the Ust'-Maya formation were sampled and 113 oriented hand samples were taken.

Both, the Chaya and Ust'-Maya formations contain rich faunal assemblages of trilobites and acritarchs which define their biostratigraphic positions [22]. The Chaya formation corresponds to the trilobite index zones *Tomagnostus fissus/Paradoxides sacheri* (uppermost part of Amgian stage) and *Corynexochus perforatus/Anopolenus henrici* (lowermost part of Mayan stage). The Ust'Maya formation correlates with two upper trilobite index zones of Mayan stage – *Anomocariodes limbataeformis* and *Lejopyge laevigata/Aldanaspis truncata*.

All studied Middle Cambrian rocks are practically flat lying and maximum tilt does not exceed 3°.

Llandeilo.

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Based on recently published biostratigraphic time scales [23], the Llandeilo is interpreted to be the upper part of the Llanvirn and to correspond to graptolite zone *Glyptograptus teretiusculus*. The Ordovician of the Siberian platform is divided into 14 regional stages (horizons) three of which (from bottom to top the Volgian, Kirensky and Kudrian) are correlated with the *G.teretiusculus* zone [9] and, thus, correspond to the Llandeilo of the Fortey et al. [23] standard scale. Whereas both the Kirensky and Kudrinsky horizons can be definitely traced into the Ordovician of the Lena river, their stratigraphic differentiation is more difficult elsewhere on the platform and consequently, the Kirenskian and Kudrian beds are often grouped into the undifferentiated Kirinsko-Kudrian horizon.

During the field seasons of 1998-2001 three sedimentary sections of Llandeilian age from the NW, W and SSE of the Siberian platform were studied in detail.

The Kulumbe section (Fig.1, and Table 1) is situated along the Kulumbe river valley, downstream the “Silurian” rapids. Here, rocks of Llandeilian age (Kirensko-Kudrian horizon), composed of red and greenish-grey siltstones and mudstones with intercalation of grey marls, were sampled on the left bank of the river immediately below the Zagorninsky sill of Permian-Triassic age. Early Carboniferous deformation [24, 25] resulted in tilting between 15° to 25°.

In total, 35 hand samples were taken from the lower and middle parts of the Kirensko-Kudrian horizon with a sampling spacing between 0.2 and 1 m.

The second section is exposed on the left bank of river Stolbovaya, 6 km up-stream from its mouth. This section includes a continuous stratigraphic record spanning from Llandeilo (Volginsky horizon) to Lower Ashgill. It contains rich fossil assemblages [26] and is mainly composed by grey, greenish –grey limestones and marls with the exception of the red coloured Kirensko-Kudrinsky horizon, where more than 50 hand samples were taken in sampling intervals of 0.3 to 0.6m.

A third section studied is located in the upper valley of the Lena river near the village of Kudrino (Fig.1) and represents one of the most important Ordovician key sections on the Siberian platform [9]. The lower part of the section (Kirensky horizon) is represented by grey aleuritic sandstones and greenish mudstones, overlain by the Kudrinsky horizon, mostly brown and greyish brown aleuritic sandstones interbedded with greenish mudstones. The top of the section corresponds to the Chertovsky horizon (Caradoc) and consist of greenish-gray mudstones in the lower part and of red beds (mudstones and siltstones) in the upper part. 125 block samples were taken in the Kudrino section with a vertical sample spacing of 0.1-0.5 m.

The additionally studied European section is situated in the Leningrad oblast in a quarry near Alexeevka, Kingisp district, and represents almost the complete Llandeilo with the exception of the lowermost beds. The lower 3 m of the Alexeevka section belong to the Mednikova group of

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the Uhaku stage and are composed of bluish grey limestones and argillaceous limestones. The next 6m above correspond to the Viivikonna formation of the Kukruse stage and are made up by dark limestones, sometimes argillaceous and bituminous, with intercalations of kukersites (oil shales, rich in algae). Both the Mednikovo and Vivikonna formations are rich in benthic fauna and in microfossils [27]. In total, about 140 hand samples were taken here with sampling intervals of 0.05-0.1 m.

Laboratory Procedures

Oriented hand samples were cut into cubes of 8 cm^3 and directions and intensities of the Natural Remanent Magnetization (NRM) were measured using a vertically oriented 2G three axis cryogenic magnetometer in the Palaeomagnetic Laboratory of the Department for Earth and Environmental Sciences, Ludwig-Maximilians-University, Munich and in the Palaeomagnetic Laboratory of the Institut de Physique du Globe de Paris. All samples were subjected to stepwise thermal demagnetization experiments, reaching maximum temperatures of up to 680°C. Mineral alteration during heating was monitored by measurements of low field susceptibility with a mini-kappa susceptibility bridge. The magnetometers, as well as the furnaces used for thermal demagnetization (Schoenstedt, TSD-1 in Munich and laboratory-built oven in Paris) experiments, are housed in magnetically shielded rooms. The demagnetization results were analyzed using orthogonal vector plots [28] and stereographic projections. Linear and planar elements in the demagnetization data were identified by eye and subjected to principal component analysis [29].

Palaeomagnetic Results

Maya River Section (Middle Cambrian)

Chaya formation

Thermal demagnetization experiments reveal the presence of two magnetic components (Supplementary file 1 in the Appendix) in almost all samples from the Chaya formation. A low-temperature component (LT) is isolated at demagnetization temperatures of up to 350-400ºC and has a direction very close to the direction of the present day Earth's magnetic field at the site. A high-temperature component (HT), carried by hematite, is observed above 400–450ºC and up to 680ºC. The HT component is of dual polarity, with south-southwest (north-northeast) declinations and upward (downward) moderate inclinations (Fig. 3a).

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A relatively large overlap between the LT and HT components often occurs in the intermediate to high-temperature range. Consequently, the HT component directions are sometimes biased by the LT component and cannot be determined by principal-component analysis (Supplementary file 1 in the Appendix, sample 3). Attempts using alternative field (AF) demagnetization to enhance the identification of components, failed. Finally, chemical alteration above 450°C and the formation of new magnetic phases often disguises the “true” direction of the HT component. Nevertheless, despite these difficulties we have managed to determine the direction of the HT component in the majority of the samples (Supplementary file 8 in the Appendix); mean directions calculated for normal and reversed directions [30] pass the reversal test with classification C [31]. This suggests that the resulting overall mean for the Chaya section is a rather reliable estimate of the magnetic field of time of acquisition of the HT.

Ust’-Maya formation

Generally, the magnetization of rocks of the Ust’-Maya formation is two to three times weaker, than the magnetization of rocks from the Chaya formation (Supplementary file 2 in the Appendix). The magnetization of the majority of the samples contains either solely one component of recent origin, removed at 300-400ºC, or is a composition of LT and HT components. The presence of HT is well defined by great circle tracks when plotted in stereographic projection. Rather weak magnetization in combination with chemical alteration above 440-460ºC, prevents the direct identification of HT in these samples.

Nevertheless, among the more than 100 samples from the Ust’-Maya formation studied, there are 24 with demagnetization properties allowing the identification of “end-point” directions for the HT component (Supplementary file 8 in the Appendix). Judging by the maximum unblocking temperatures observed (Supplementary file 2 in the Appendix) this component is mainly carried by magnetite. The majority of the “useable” samples originates from the lower part of the Ust’-Maya formation. It is interesting to note that there are examples indicating that in addition to LT, some samples can contain two, probably antipodal ancient components (see Supplementary file 2 in the Appendix, sample 123). This might indicate that occasionally the acquisition of magnetization spanned a prolonged time interval. Like the HT component identified in samples from the Chaya formation, the HT component, isolated in the Ust’-Maya formation is of dual polarity (Fig.3b) but does not pass the reversal test. This might be explained by some degree of contamination by a LT component.

The mean directions of the Chaya and Ust’-Maya formations are very close to each other, which can be expected on the basis of data published earlier for rocks of the Amgian and Mayan stage [14]. This also implies that averaging directions of normal and reversed polarities into a

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common mean reduces the influence of LT contamination significantly. This is in accord with the positive reversal test when all the HT directions from both the Chaya and Ust'-Maya formations are grouped together (Supplementary file 8 in the Appendix).

From the data presented here, it becomes evident that the Middle Cambrian section of the Maya river valley contains numerous intervals of normal and reversed polarity (Fig.2), which is compatible with magnetostratigraphic data obtained from north Siberian key sections of the Amgian and Mayan stage [14, 32]. This fact as well as the positive reversal test, the lack of resemblance to palaeomagnetic directions of younger age and the independence of the HT component from the magnetic mineralogy allow us to tie the acquisition of magnetization closely to the time of deposition of the rocks studied.

Kulumbe section (Llandeilo)

After removal of unstable magnetizations at low demagnetization temperatures, only one stable component of magnetization which is characterized by rather steep inclinations, can be identified in some part of samples, (Supplementary file 3 in the Appendix, sample 638-TC). The direction of this component is very close to the direction of the characteristic components identified in the Zagorninsky sill (Fig. 3c) [33], suggesting a Permian-Triassic age of remagnetization.

In addition, some samples show the presence of only one stable component with northwestern declinations and shallow to moderately positive inclinations. Usually, however, the magnetization of the samples studied is controlled by the combination of the components described above. Whereas the trap related remagnetization component is removed usually in the temperature interval 270-600˚C, the second component is more stable and shows maximum unblocking temperatures near the Curie point of hematite. The mean direction of this component (Supplementary file 9 in the Appendix) is close to mean directions obtained earlier for Llanvirnian rocks of the Kulumbe section [15] and coincides practically with the mean direction of Llandeilian rocks from the Moyero river[13], recalculated to the coordinates of the Kulumbe section (Fig. 3d). It should be noted, that the ChRM's from the various sections approach significantly after correction for local tilts, thus yielding a positive regional fold test and pointing towards a pre-Carboniferous age of magnetization.

Stolbovaya section (Llandeilo)

The magnetization of the sedimentary rocks of the Stolbovaya section is strongly affected by the trap intrusions [34]. Nevertheless, a considerable part of the redbeds within the Kirensky-Kudrian horizon preserved traces of an ancient magnetization. The various types of behaviour of the samples during thermal demagnetization are shown in Supplementary file 4 in the Appendix.

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While sample ST-233 is completely remagnetized, there are examples for successful isolation of a characteristic HT magnetization with northwesterly declinations and shallow inclination (sample ST-220 in Supplementary file 4 in the Appendix). However, the essential part of the studied collection is marked by a very strong overlap of the “trap magnetization” and, what is believed to be, an ancient component (Supplementary file 4 in the Appendix, samples ST-203, ST-206, ST-216).

However, this directional overlap does not preclude the determination of the polarity of the ancient component when regarding the trend of remagnetization circles. The combination of great circles and endpoint data [35] yields a mean direction for the Stolbovaya section (Fig.3, Supplementary file 9 in the Appendix) which is very close to the expected direction for the Llandeilo (based on the data from the Moyero and Kulumbe sections). This result indicates that the characteristic HT component was acquired during deposition or briefly after it.

Kudrino section (Llandeilo)

After removal of an unstable magnetization below 300°C, almost all samples from the Kudrino section show the presence of the dual polarity HT component together with an middle temperature component (MT) of normal polarity (fig. 4a,c,e). Whereas the HT component decays towards the origin of the orthogonal diagram, MT component practically always is intermediate (Supplementary file 6 in the Appendix, samples 24c-TC, 60-TC).

Maximum unblocking temperatures of both components are usually well above 600˚C, clearly indicating hematite as the principal carrier of the stable magnetization. The similarity in blocking temperature range does not facilitate distinction between both components, however the clear difference of their directions (Fig. 4f) as well as the comparison with stratigraphically adjacent samples allow to solve positively this question.

The mean direction for the intermediate (MT) component (Fig 4d,e, Supplementary file 9 in the Appendix) has about the same direction as the corresponding MT mean (Fig. 4 d,e,f) of the Mid Ordovician Polovinka section (middle valley of the Lena river), considered as being Late Ordovician or Early Silurian in age [8]. Therefore we suggest that the former is also of secondary origin.

The HT component isolated in rocks of the Chertovskian and the Kudrian horizons is of dual polarity and close to passing the reversal test (γ/γ_c= 15.0°/10.2° and 13.2°/10.3° correspondingly).

The comparison of the distributions of the HT vectors of reversed polarity of the Polovinka and Kudrino sections yields differences in mean declination in the order of 15-20° (Fig.4a,b,f). This is compatible with block rotation models proposed earlier [7] on the base of data for Middle-

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Late Cambrian rocks from the Lena river. All this allows us to interpret the HT component, isolated in the Kudrian and Chertovskian horizon to be of pre-rotational origin and having been acquired during deposition or soon after. No directions of the ChRM with normal polarity have been identified in the lower (Kirensky) part of the Kudrino section [see also 36].

Alexeevka section (Llandeilo)

Examples of demagnetization diagrams are represented in Supplementary file 6 in the Appendix. All samples from the Alexeevka quarry are rather weakly magnetized. Nevertheless, based on the intensity of magnetization and demagnetization behavior, the collection can be divided into two groups (Fig.3f).

The first group includes samples with magnetizations in the order of 3-6 $\cdot 10^{-5}$ A/m carrying either one or two components of magnetization. Single component samples are demagnetized between 250 and 300˚C and yield directions scattered around the direction of the modern field. If two components of magnetization are present, heating above 200°C reveals a directional component pointing to the south-southeast with rather steep positive inclinations. Maximum unblocking temperatures reach 400°C before the intensity of magnetization either drops below the sensitivity of the magnetometer or the directions are obscured by chemical alteration. AF – demagnetization experiments after initial heating up to 190° to 250°C reveal maximum coercitivities of the characteristic component of magnetization of about 10 to 50 nT, indicating magnetite as principal carrier of magnetization.

The resulting mean direction (Supplementary file 9 in the Appendix) is in excellent agreement with the expected direction for the Llandeilo (Fig.3g), calculated from the 463 Ma poles of the APWP for Baltica [5]. This supports our interpretation that this magnetization is indeed of Llandeilian age. The second group includes only a small number of samples; however these samples show a much stronger magnetization and behave more stable during demagnetization (Supplementary file 6 in the Appendix). The resulting directions of the ChRM strongly resembles directions associated with Mesozoic age remagnetizations which are typical for this region [5]. We therefore interpret the magnetizations observed in these samples to reflect a Mesozoic remagnetization event.

Magnetostratigraphy

The magnetostratigraphy of the sections studied is shown in Figures 5 and 6. Quite often stable end point directions could successfully be identified. Nevertheless, there are many samples, where this was prevented by either overlapping unblocking spectra or chemical alteration during

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thermal demagnetization. In the majority of these cases, however, it was possible to unequivocally establish the magnetic polarity based on the trend of remagnetization circles.

The most notable feature of all magnetostratigraphic records, obtained here, is the predominance of directions of reversed polarity. So far, no primary directions of normal polarity have been identified in the lower two thirds of the Llandeilo on the Siberian platform. Isolated samples from the Volginsky and the Kirensky horizons of the Polovinka section, carrying normal polarities have been considered to reflect Mid Palaeozoic remagnetizations [8].

The same reasoning can be applied to two zones of normal polarity isolated in the Volginsky horizon of the Kudrino section by Rodionov et al. [36] with mean directions very close to the ones of much younger sediments from the middle Lena river [37]. There are also no indications for the existence of a normal polarity zone in the Alexeevka quarry (Baltica) with exception of the uppermost levels. However, Torsvik and Trench [20, 21] found one sample with a normal polarity direction in the middle of the Llandeilo in the Hallekis section and some samples of normal polarity directions from two stratigraphic levels of the Gullhogen quarry, South Sweden also of Mid Llandeilian age. Hence, following Trench et al. [18] we include this zone in the composite magnetostratigraphic sequence of the Llandeilo. In agreement with Torsvik and Trench [21] we note, however, that at least the part of the data supporting the existence of this normal polarity zone, is only of moderate quality and more detailed sampling is required in the future in order to confirm this polarity zone.

The magnetostratigraphic record from the Llandeilo of the Kudrino section yields clear indication for the presence of at least three zones of normal polarity. The presence of several normal polarity zones in the upper part of the Llandeilo is also supported by the data from the Moyero, Polovinka and Alexeevka sections. Irrespectively whether three or more zones of normal polarity are present in the Llandeilian age sections studied so far, it is obvious that termination of the Llandeilo coincides with the termination of a long reversed polarity interval referred to as Moyero superchron by Pavlov and Gallet [38] which lasted ~20-30 Myr.

Furthermore, in the Kudrino section, a short period of normal polarity can be observed just above the Llandeilo-Caradoc transition. This short period of normal polarity is followed again by a short interval of reversed polarity before the onset of a rather long lasting interval of normal polarity. This pattern, two rather short intervals of normal and inverse polarity followed by a long interval of normal polarity is compatible with data from the Gullhogen quarry, South Sweden[21]

Palaeomagnetic data and the relative rotation between the Aldan and Anabar-Angara blocks.

Based on the magnetostratigraphy established results obtained in this study we can now compare palaeomagnetic data, which are exactly coeval and which have been obtained by applying

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modern laboratory and analytical techniques. In Fig.7a the Llandeilian palaeopoles of the Kulumbe, Moyero, Stolbovaya, Polovinka and Kudrino sections are presented as well as the palaeomagnetic pole, obtained by Torsvik et al. [37] for the Llandeilo of the mid stream Lena river valley. Paleopoles from the Anabar-Angara block (Siberian platform to the west of the axis of the Vilyui syneclise) form a tight group and are distinctly different from the poles derived from sections located in the south-eastern (Aldanian) part of the Siberian platform.

The Kudrino section, which is situated near the axis of the Vilyui syneclise yields an intermediate pole position. All the palaeomagnetic poles are close to or lie on a small circle centered about a pole of rotation located near the northern shore of lake Baikal. This location is very close to the Euler pole proposed earlier by Pavlov and Petrov [4] and used to match the palaeomagnetic poles of coeval Riphean formations from NW and SE of the Siberian platform. In addition, it is important to note that Mid-Riphean poles from Turukhansk and Uchur-Maya regions not only lie on small circles centered on the same pole of rotation (Fig.7a), but also the angle between the palaeomagnetic pole positions for the Llandeilo is comparable to the one for the Riphean poles (20–25°).

The Middle Cambrian paleomagnetic pole obtained in this study is a new strong argument for the existence of a significant angular difference between paleomagnetic data sets of the Anabar-Angara and Aldan blocks. This pole in combination with coeval and nearly coeval ones from the Angara –Anabar block defines a small circle segment covering 20° which is centered on the same pole of rotation as discussed above (fig.7a,b).

These observations agree very well with older palaeomagnetic data sets of considerably lower quality.

During the 60s and 70s many palaeomagnetic directions have been obtained for the rocks of the Upper Cambrian Verkholensk formation from outcrops along the valley of river Lena and along the upper stream of the Angara river. Despite the fact that these results do not meet modern quality criteria, we believe that they provide relatively reliable pole positions and can lend additional support to our interpretations. With the exception of the polarity transition zones, the NRM of these rocks is mainly carried by one component with minor overprinting by a very steep secondary component of recent origin [39]. The latter can considerably affect the inclination of the resulting total vector, with minor effects on the declination. We also note that the results for the Verkholensk formation were obtained by averaging of numerous directions of normal and reversed polarity which strongly reduces the bias due to overprints.

Plotting the distribution of declinations from the Verkholensk formation as a function of geographic position reveals that the variability in declination reflects clockwise rotation when moving from southwest to northeast (Fig. 7c). This is also true for the longitudes of the

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palaeomagnetic pole positions which are clearly controlled by the geographic location of the sampling sites (Fig. 7d). The corresponding pole positions are shown in Figure 7b. In concordance with the results for the Llandeilian, Middle Cambrian and Riphean, the distribution of pole position also describes a small circle centered around a common Euler pole.

In addition to the pole positions from the Verkholensk formation, recently published poles for the Upper and Middle Cambrian deposits of the Moyero, Kulumbe, Khorbusuonka and Olenek rivers sections [13-15, 40] are also shown in Fig.7b. We note that the rather tight cluster of all middle to upper Cambrian poles from the Angara-Anabar block, clearly indicates its crustal coherence since at least the Middle Cambrian. This observation is not compatible with the Euler pole positions suggested by Smethurst et al. [5].

Determination of the Euler Pole for the Aldan and Anabar-Angara blocks

In a first step, the data set (see Table 1) is divided into four subsets according to the stratigraphic ages: mid Riphean (two poles), Middle Cambrian (4 poles), Late Cambrian (17 poles) and Llandeilian (6 poles). In a second step, the surface of the globe is covered by a grid of evenly spaced points (for example 1 x 1°) and for each grid point as for centre of a circle the optimum small circle for each of the 4 subsets is calculated. As a measure of the quality of the fit, the residuals, which are the sum of squares of angular distances between the individual palaeomagnetic poles and the corresponding small circles, have been calculated for each grid point. The total residual value, calculated for each grid point, is considered as the estimate for the location of the Euler pole at a given grid point. Regions on the globe containing the grid points with the smallest residuals, are considered to be the most likely area where the location of the Euler pole is to be expected.

The distribution of calculated residual values on the Earth surface is shown in Supplementary file 7 in the Appendix. The area with the smallest residuals is centered at 54.5º N and 111.5º E, which, taking into account the accuracy of available palaeomagnetic data, is in quite good agreement with the Euler pole, proposed earlier by Pavlov and Petrov [41].

Geometry of the Vilyui basin's earth crust and the relative rotation of Aldan and Anabar-Angara blocks.

The hypothesis that the Aldan-Anabar block rotations are linked to the opening of the Vilyui rift system, was discussed and challenged by McElhinny and McFadden [42] and Pisarevsky and Natapov [12]. The main point raised by these authors is that such rotations should

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have induced a break up of the Siberian craton. This motivated us to look more closer at the geometry of the crustal basement of the Vilyui syneclise.

During the 1970s and 80s Siberian platform has been studied by long range refraction seismic experiments. Three of these seismic lines (CRATON, KIMBERLITE, BATHOLITE) crossed the Vilyui basin (Fig.1). Interpreted crustal cross-sections for the two first profiles [43, 44] are presented in Fig. 8. The geometry of the crustal boundaries allows us to estimate the amount of extension during the formation the Vilyui depression.

Continuous decrease, observed in the width of the Vilyui basin and in sedimentary thickness along its SW to NE axis suggests that the basin was opened in a scissors-like mode. Therefore, the amount of horizontal extension in different cross-sections may provide information on the position of the pole of opening.

In extensional basins, the thickness of the crust is controlled by external forces due to deformational changes in rock volume and in temperature. The changes in rock volume are small and neglected in most models. On the other hand, the temperature of the lithosphere increases during extension and then decreases afterward back to the steady state [45]. Assuming that the extension in the Vilyui basin occurred during the Palaeozoic [46] and that the 40 km-thick crust returns to the steady state temperature after about 55 my [45], we can consider that the temperature profile before extension was close to the present day one, and the thermal effect is negligible. Thus, we conclude that the difference between the basin axes crustal thickness prior to extension (referred to as $H_0(x)$) and after (referred to as $H_1(x)$) *is* mostly caused by deformation. Using the principle of mass conservation, we can pose the following equation:

$$\int_0^{L_1} H_1(x)dx = \int_0^{L} H_0(x)dx \qquad (1)$$

where L and L1 are respectively the length of the deformed area before and after extension.

The seismic profiles provide data on the present-day crustal thickness, while to estimating the crustal geometry before extension requires some assessments. Assuming that crustal thickness before extension changed linearly between the present-day thickness of the undeformed internal parts of the Anabar and Aldan blocks, the formula (1) then gives an estimate of the length of the extended area before deformation:

$$L = \int_0^{L_1} H_1(x)dx / H_{av} \qquad (2)$$

where H_{av} is the average value of the Aldan and Anabar crustal thickness.

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To estimate the amount of stretching along the seismic profiles it is necessary to estimate the present-day limits of the extended area. The thickness of the Earth crust at the end points of the chosen interval estimates the pre-extensional crustal thickness. Seismic data provide the depth to the crystalline basement and to the Moho. Crustal thickness within the basin is then derived by the difference between these values.

Possible sources of error are: incorrect seismic estimates of crustal thickness, variations of crustal thickness in the area of the Vilyui basin before extension and an erroneous choice in the limits of the extended area. An error analysis, however, shows that formula (2) is very robust (Supplementary file 11 in the Appendix).

Let us now estimate the amount of extension for two profiles crossing the Vilyui basin. For the profile CRATON, the thicknesses of the Anabar and Aldan crust are estimated to be 44 and 42 km, respectively, the width of the extended area to be 920 km, which gives an extension of ~234 km (~30%). This estimate can be compared to the McKenzie extension model [45]. Along this profile, the crustal thickness is ~20 km in the deepest part of the basin; the extension ratio is thus $\beta = (44+42)/(2*20) = 2.15$. According to [45], this would produces ~8.6 km of synextensional subsidence and ~4.7 km of thermal post-extensional subsidence. This corresponds well to the seismic data when suggesting densities of 3.2, 2.9 and 2.4 $* 10^3 kg/m^3$ for the mantle, the crust and the sediments, respectively.

The profile KIMBERLITE provides a smaller estimate of extension, ~45km for a present-day length ~662 km for the stretched area. This gives an average extension of ~7%. (The thickness is here ~38.7 km for the crust of Anabar and ~ 43.6 km for the crust of Aldan). The minimal crustal thickness along KIMBERLITE is 26.6 km, hence the maximum extensional ratio is equal to 1.55, which according to [45] yields a value of 5.5 km for the synextensional subsidence and of 3.1 km for the thermal subsidence. This values again appear in good agreement with the seismic data.

From the estimates above, one can find that the pole of basin opening was situated at a distance ~ 93 km to the south-west of profile KIMBERLITE (Fig. 9). We tested the robustness of these values by changing the parameters used in the model. In any cases, the distance does not exceed 100 km (Supplementary file 10 in the Appendix).

Discussion

If the determination of the position of the centre of opening of the Vilyui basin is correct, it would be manifested by compressional tectonics to the south-west from this location. Indeed, the actual interpretation of seismic data obtained for profile BATHOLITE indicates an elevated basement and crustal thickening, where the profile crosses the continuation of the Vilyui basin axis (A..Egorkin – personal communication). Post- Early Silurian SW-NE oriented folds are known in

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the southern part of the Siberian platform adjacent to north-northwestern areas of the Baikal – Patom fold-thrust belt (see Fig. 9). Recent data of industrial drill holes and seismic surveys in the region of the Nepsk-Botuobinsk antyclise (Fig. 9) indicate that the thrust and fold-nappes are widespread in this part of the Palaeozoic cover of the Siberian platform [47].

On the other hand the fan-like dyke swarms, rimming the Vilyui syneclise from NW and SE are evidence for the extensional formation of the Vilyui basin to the northeast from the suggested pole of opening. In the Middle of the 60s Shtekh [48] suggested the existence of buried oceanic crust under the northeastern margin of the Vilyui syneclise. Recent interpretation of seismic data [44] supports this conclusion which is compatible with the hypothesis of Aldan – Anabar-Angara blocks rotation.

The extensional pole lies within an area, where, according to palaeomagnetic data, the location of Euler pole is rather probable (Fig. 9). The boundary of this area corresponds to a value of the residual of R=1.6Ro, where Ro is the minimal value of the residual. Taking into account the accuracy of the palaeomagnetic data, the compatibility is rather high. It is important that the angle of opening of the basin based on extensional data is about the same as predicted from palaeomagnetism. The rotation pole derived from extensional data (Lat ≈62ºN; Long≈117ºE) seems to be rather robust as it satisfies both geological and palaeomagnetic data.

Conclusion

Our new magnetostratigraphic results combined with published data allow to propose a magnetic polarity sequence for Llandeilian times, which is characterized by the predominance of reversed polarity in its early part and by alternation of intervals of normal and reversed polarity (6 at least) in its later part.

The comparison of palaeomagnetic poles from the Aldan and Anabar-Angara blocks of the Siberian platform obtained for four age levels (Middle Riphean, Middle Cambrian, Late Cambrian and Middle Ordovician) demonstrates significant angular differences in declination.

This difference may be explained by relative rotation in the order of 20-25º of the Aldan and Anabar-Angara blocks in post-Ordovician time about an Euler pole located somewhere to the north-east from the northern shore of lake Baikal. Such a rotation requires imperatively the extension of the Earth crust under the Vilyui basin, with increasing amounts from south-west to north-east.

Extension rates along two crustal cross sections, based on results from long-range seismic profiles, are compatible with the palaeomagnetic data and allow the definition of a rotation pole at: Lat ≈62ºN; Long≈117ºE.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:????????

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Figure and table captions

Table 1. Palaeomagnetic pole positions for the Siberian platform.
Lat and Long – are the geographic location of the studied sections; Plat and Plong – are latitude and longitude of the palaeopole positions; dp/dm – semi axis of 95% confidence oval around the mean pole. GPMDB - result numbers from Global Palaeomagnetic Database [49].

Figure 1. Geological sketch map of the Siberian platform and the location of the sections studied and discussed. 1- Cretaceous deposits; 2 – Jurassic deposits; 3- Permo-Triassic trap basalts; 4 – Palaeozoic cover; 5 – Precambrian sedimentary rocks and basement; 6 –axis of the Vilyui syneclise; 7 – location of the long-range seismic profiles "Craton", "Kimberlit"; "Batholit". Stars and circles identify the location of the sections studied and discussed: grey stars – studied sections of Llandeilian age; open stars – other sections of Llandeilian age; solid circles- sections of the Upper Cambrian Verkholensk formation; open circles – other Middle and Upper Cambrian sections. The sections are labeled as in the Table 1. Hatched rectangles show the location of Uchur-Maya and Turukhansk regions.

Figure 2. Geographic and stratigraphic position of the sections of Middle Cambrian age studied. Outcrops of Chaya formation (A and B) are marked by stars; open circles show outcrops of the Ust'-Maya formation (NN 1-9). Also shown is the magnetostratigraphy. Normal (reversed) polarities in black (white).

Figure 3. Orthogonal plots [28] of demagnetization behaviour of specimens from Middle Cambrian and Llandeilan rocks from the sections studied.
a, b - Characteristic directions identified in rocks from the Chaya (a) and Ust'-Maya (b) formations (Maya river valley). Solid (open) circles here and hereinafter are vector projections onto lower (upper) hemisphere.
c - Characteristic directions and great circles identified in rocks from the Kulumbe section; white star denotes the location of the resulting non-trap mean direction for Llandeilian rocks. The grey star shows the mean direction of the nearby Zagorninsky sill, related to the Permo-Triassic trap basalts. All data are tilt corrected. Also shown are the corresponding 95% confidence areas [30];
d - Comparison of mean Kulumbe direction in situ (geo) and in stratigraphic coordinates (str) to the direction, derived from the Llandeilian palaeomagnetic pole from Moyero section[13].
e - Comparison of great circles and stable endpoint directions from the Stolbovaya river section with nearby trap's direction (open circle with confidence circle) and Llandeilian directions (closed circles with confidence circles) recalculated from Moyero (1) and Kulumbe (2) sections.

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f - Characteristic directions from the Alexeevka section.

e - Comparison of mean Alexeevka direction with direction, expected from the 463 Ma pole from the APWP of Smethurst et al. [5].

Figure 4. Orthogonal plots [28] of demagnetization behaviour of specimens from the Kudrino (a, c, e) and Polovinka (b, d) sections;

a, b: directions of the high temperature components (HTC) isolated in the Kudrinsky horizon (fossil zone); c: directions for HTC, identified in the Chertovsky horizon; d and e: directions of the intermediate component of magnetization; f: resulting high temperature mean directions (with oval of 95% confidence) for the Kudrinsky fossil zone of Kudrino (1, only reversed directions) and Polovinka (2), for the intermediate temperature component of magnetization from the Kudrino section (3) and the HTC for the Kudrinsky horizon of Kudrino (4, only normal directions). Note that (1) and (2) display reversed polarity, whereas (3) and (4) are of normal polarity. Downward (upward) directions are shown as filled (open) circles.

Figure 5. Magnetic polarities recorded in the sections studied. Normal (reversed) polarities are shown in black (white). Lithology: 1 - mudstones, siltstones and marls alternation; 2 - alternation of marls and limestone; 3 – alternation of limestone and argillaceous limestone; 4 – siltstones; 5 – mudstones; 6 – sandstones. Closed (open) circles in the declination and inclination diagrams identify data from stable endpoint (great circle) analysis.

Figure 6. Magnetostratigraphic correlation of the data from the Siberian and East-European platforms and a resulting tentative composite magnetostratigraphic time scale for the Llandeilo-Early Caradoc.

Figure 7.

a - Location of the palaeomagnetic poles of Middle Riphean age (stars), Middle Cambrian age (open circles, pole, obtained in this study surrounded with eight-pointed black star, poles, obtained in other studies surrounded with black rim) and Llandeilian (rectangles) age. The poles are numbered according to table 1. The angular distance along (between?) Aldanian and Angara-Anabarian poles is constantly about 20-25º.

b - . Location of the palaeomagnetic poles of Upper (circles) and Middle Cambrian (see notation above) age. Note: these poles are distributed along a small circle, centered on the same Euler pole (denoted by 12-pointed star) as the circles in Figure 7a. The numbering of the poles refers to Table 1.

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c,d - Distribution of the palaeomagnetic directions (c) and the palaeomagnetic poles (d) from the Upper Cambrian Verkholensk Formation as a function of the location of the sampling sites. K is the corresponding correlation coefficient.

Figure 8. Crustal cross-sections for profiles “Craton” [43] and “Kimberlit” [44] 1,2,3 – seismic boundaries with the boundary velocities of P-waves (first number) and S-waves (numbers in brackets); 4 – layer velocities of P-waves (upper number) and S-waves (numbers in brackets); 5 – basement surface (BS); 6- Mohorovichich boundary (MB). Thick lines represent the estimated average upper and lower limits of the basement.

Figure 9. Determination of the extension pole position and its comparison with location of the Euler pole, obtained from palaeomagnetic data. SE-NW trending thick lines denote the estimated extension rates in areas, where seismic profiles cross the axis of the of Vilyui syneclise (SW-NE trending thick line); 12-pointed star denotes the estimated position of the pole of extension; 5-pointed star denotes the Euler pole position, estimated from palaeomagnetic data. Light grey semi-transparent area denotes the region of Earth surface where the location of Euler pole according to the palaeomagnetic data are most probable (residual values $\leq 1.6R_o$, where R_o is the minimal value of residual).

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Table 1. Palaeomagnetic pole positions for the Siberian platform.

Pole number	Locality	Lat [°N]	Long [°E]	Plat [°N]	Plong [°E]	dp/dm	GPMDB	Reference
Llandeilo								
1	Moyero	67.5˚	104.0˚	-22.7	157.6	2.0/3.8		[13]
2	Kulumbe	68.0˚	88.8˚	-24.1	152.4	2.4/4.5		This study
3	Stolbovaya	62.1˚	92.5˚	-22.0	158.0	2.9/5.5		This study
4	Kudrino	57.7˚	108.0˚	-21.1	143.4	2.7/5.3		This study
5	Polovinka	60.1˚	113.7˚	-31.2	133.2	2.3/4.6		[7]
6	Middle Lena	59.8˚	118.1˚	-32.0	139.4	1.6/3.1		[38]
Upper Cambrian								
7	Moyero (Cm3)	67.5˚	104.0˚	-37.0	138.4	3.6/6.4		[13]
8	Kulumbe (Cm3)	68.0˚	088.8˚	-36.1	130.7	2.0/3.4		[15]
Verkholenskaya formation (Upper Cambrian)								
9	Angara river valley	54.3	104.6	-34.0	134	3.0/6/0	5390	[50]
10	Lena river valley	55.0	105.0	-29.0	129	5.6/11.1	5437	[51]
11	Lena river valley	54.5	105.5	-32.0	133	1.5/3.0	5445	[52]
12	Lena river valley	54.5	105.5	-36.0	134	1.5/3.0	5403	[53]
13	Lena river valley	57.0	107.0	-39.0	125	4.7/9.2	5391	[16]
14	Lena river valley	58.0	108.8	-36.0	126	2.1/4.1	5446	[52]
15	Lena river valley	58.0	109.0	-39.0	129	2.1/4.1	5411	[54]
16	Lena river valley	58.0	109.5	-39.0	135	2.7/5.2	5413	[54]
17	Lena river valley	58.5	109.8	-38.0	124	2.4/4.6		[39]
18	Lena river valley	58.5	110.0	-36.0	121	3.1/6.1	5415	[54]
19	Lena river valley	58.5	110.0	-38.0	118	5.2/10.2	5414	[54]
20	Lena river valley	58.6	110.3	-34.0	120	1.5/3.0	5447	[52]
21	Lena river valley	58.7	111.0	-30.0	119	2.0/4.0	5438	[55]
22	Lena river valley	59.0	112.0	-40.0	114	1.1/2.1	5439	[55]
23	Lena river valley	60.0	114.0	-34.0	103	3.6/7.0	5407	[52]
Middle Cambrian								
24	Kulumbe river	68.0˚	088.8˚	-41.9	136.2	1.8/2.9		[15]
25	Khorbusuonka river	71.5˚	124.0˚	-43.7	140.5	2.0/3.3		[14]
26	Olenek river	71.0˚	122.5˚	-36.4	139.6	3.0/5.2		[40]
27	Maya river			-45.8°	115.0	3.3/5.9		This paper
Middle Riphean								
28	Uchur-Maya region, Malgin formation			-25.4	230.5	2.6		[11]
29	Turukhansk region, Linok formation			-15.2	256.2	7.5		[11]

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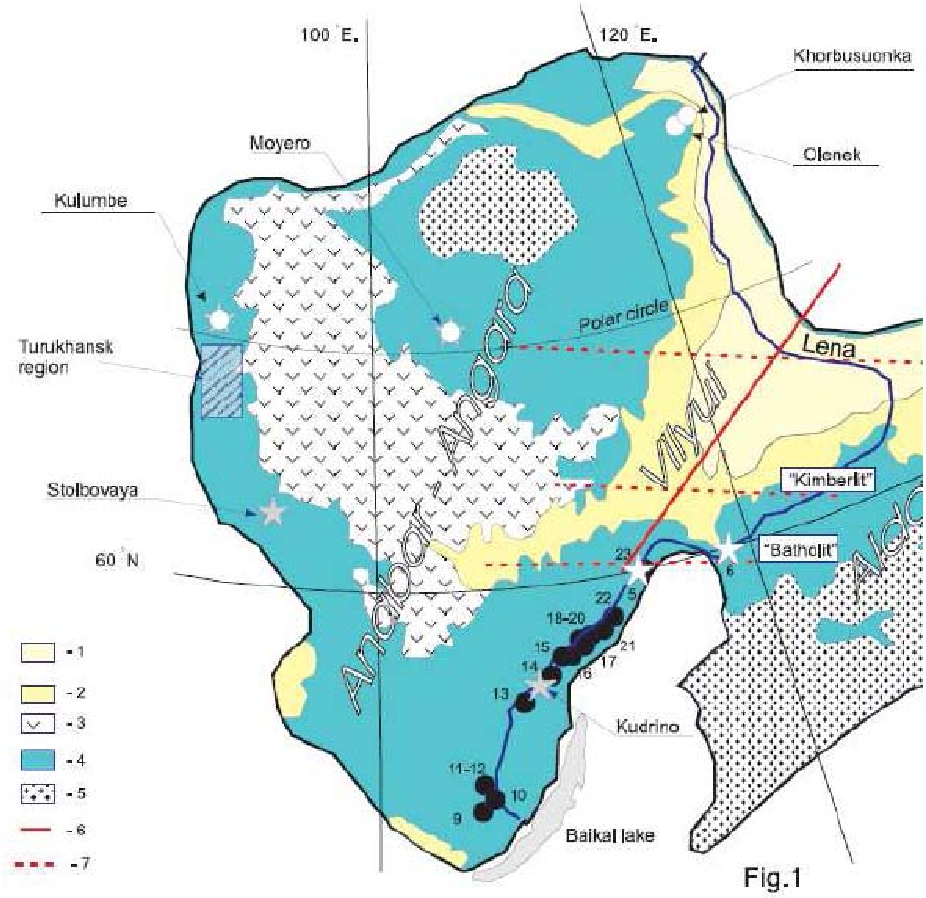

Fig.1

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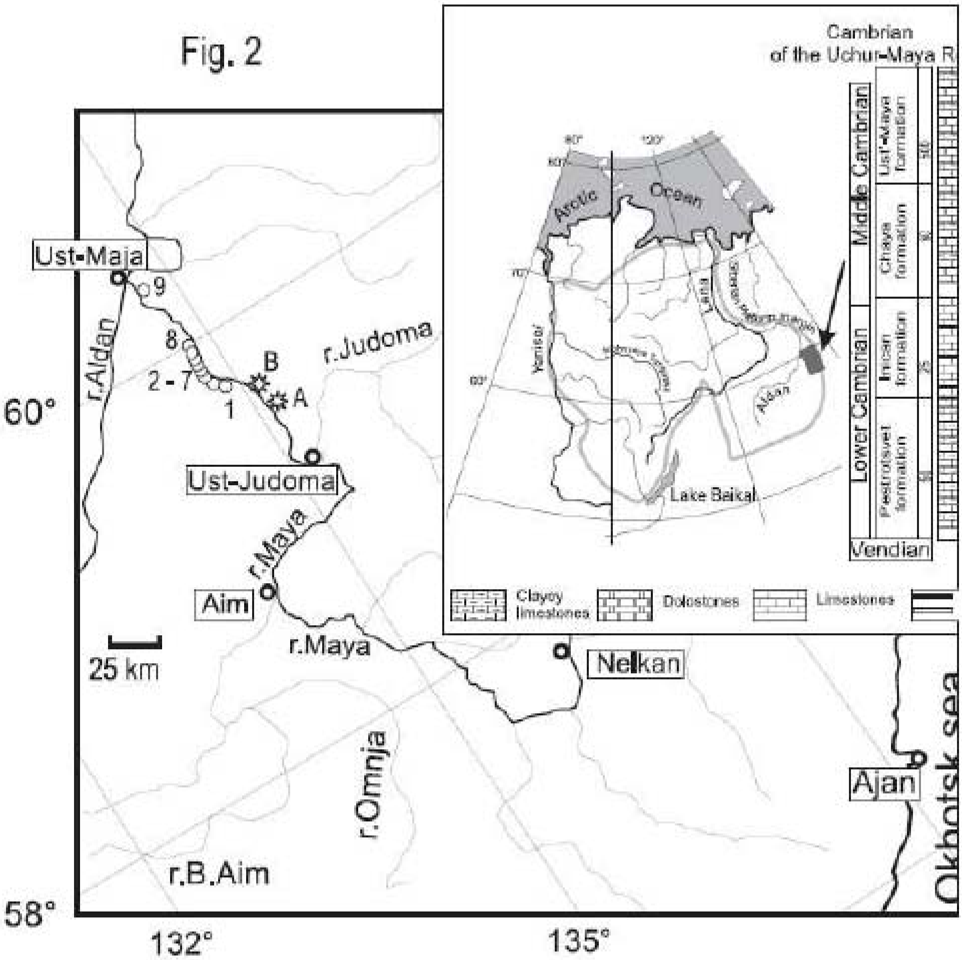
Fig. 2


Cambrian
of the Uchur-Maya R
Middle Cambrian
Lower Cambrian
Vendian
Ust'-Maya formation
Chaya formation
Inican formation
Pestrotsvet formation
Arctic
Ocean
Lena
Yenisei
Aldan
Lake Baikal
Clayey limestones
Dolostones
Limestones
Ust-Maja
9
8
2 - 7
1
B
A
r.Aldan
r.Judoma
Ust-Judoma
r.Maya
Aim
r.Maya
Nelkan
25 km
r.Omnja
r.B.Aim
Ajan
Okhotsk sea
60°
58°
132°
135°

ACCE

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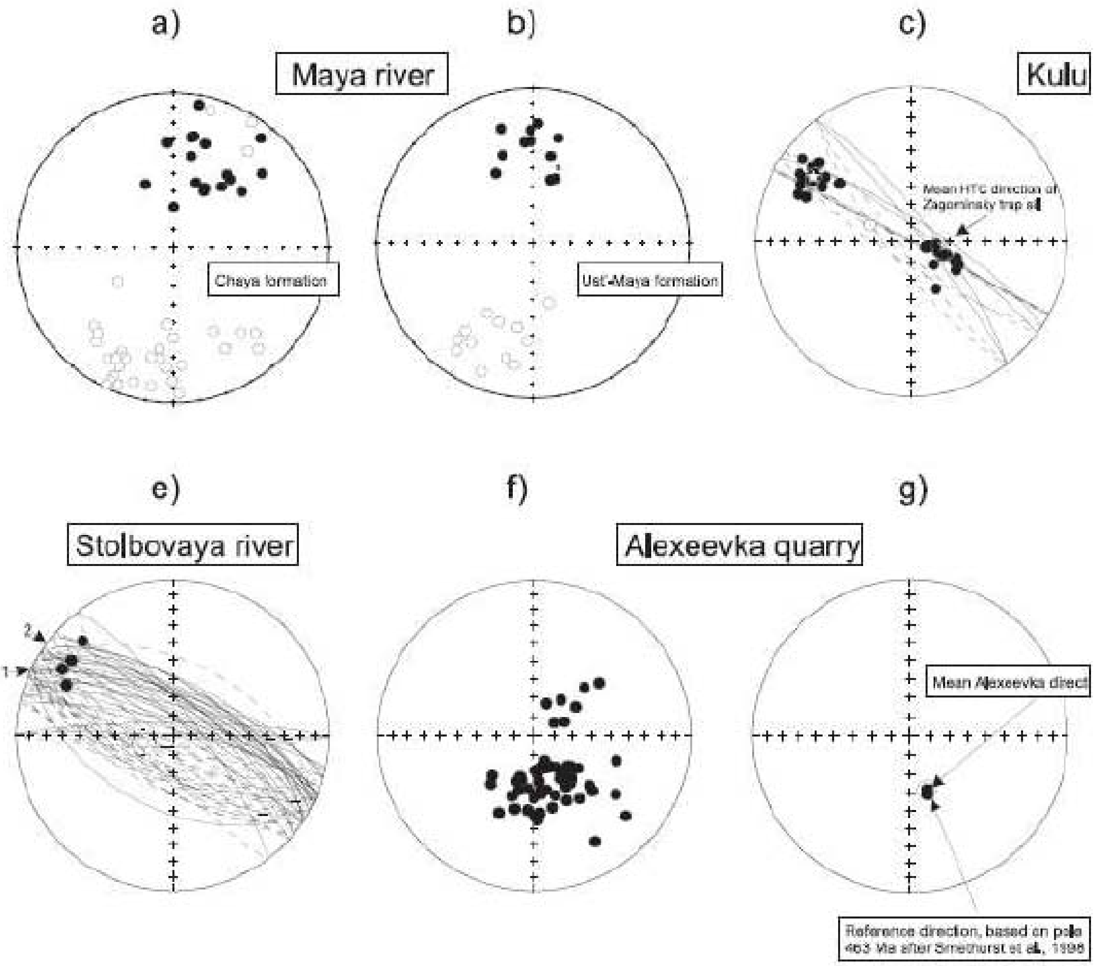

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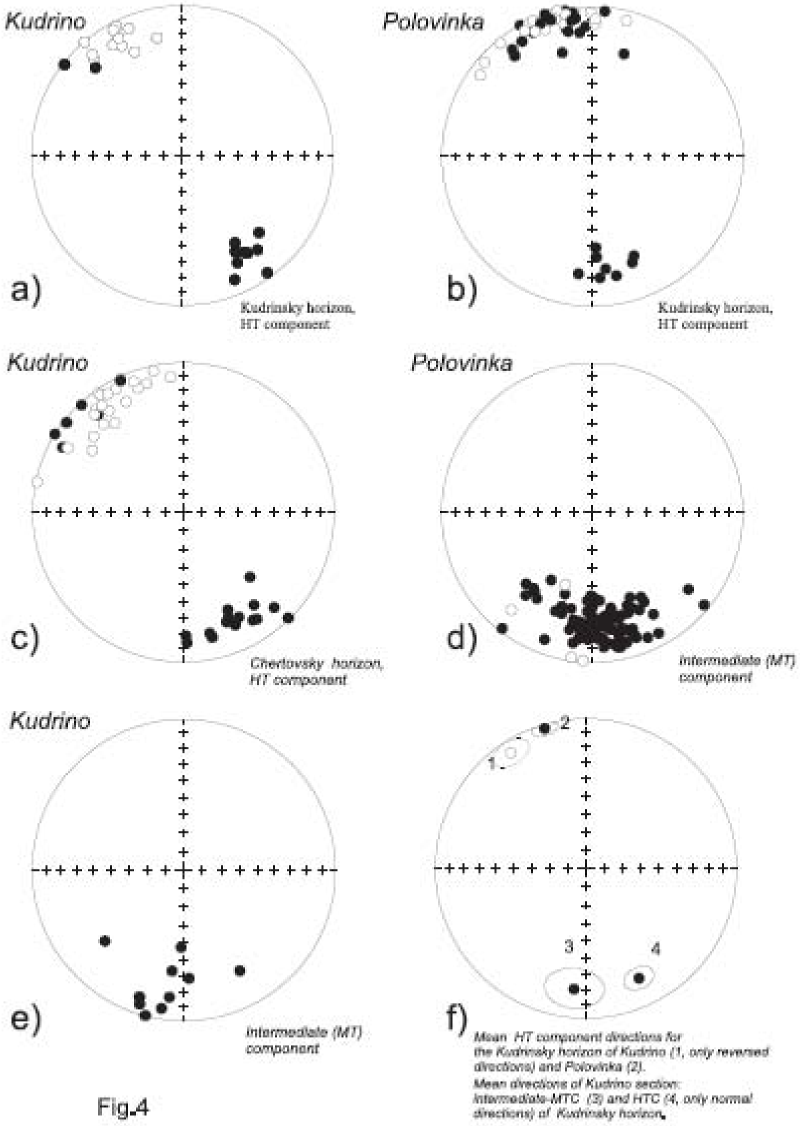

Fig.4

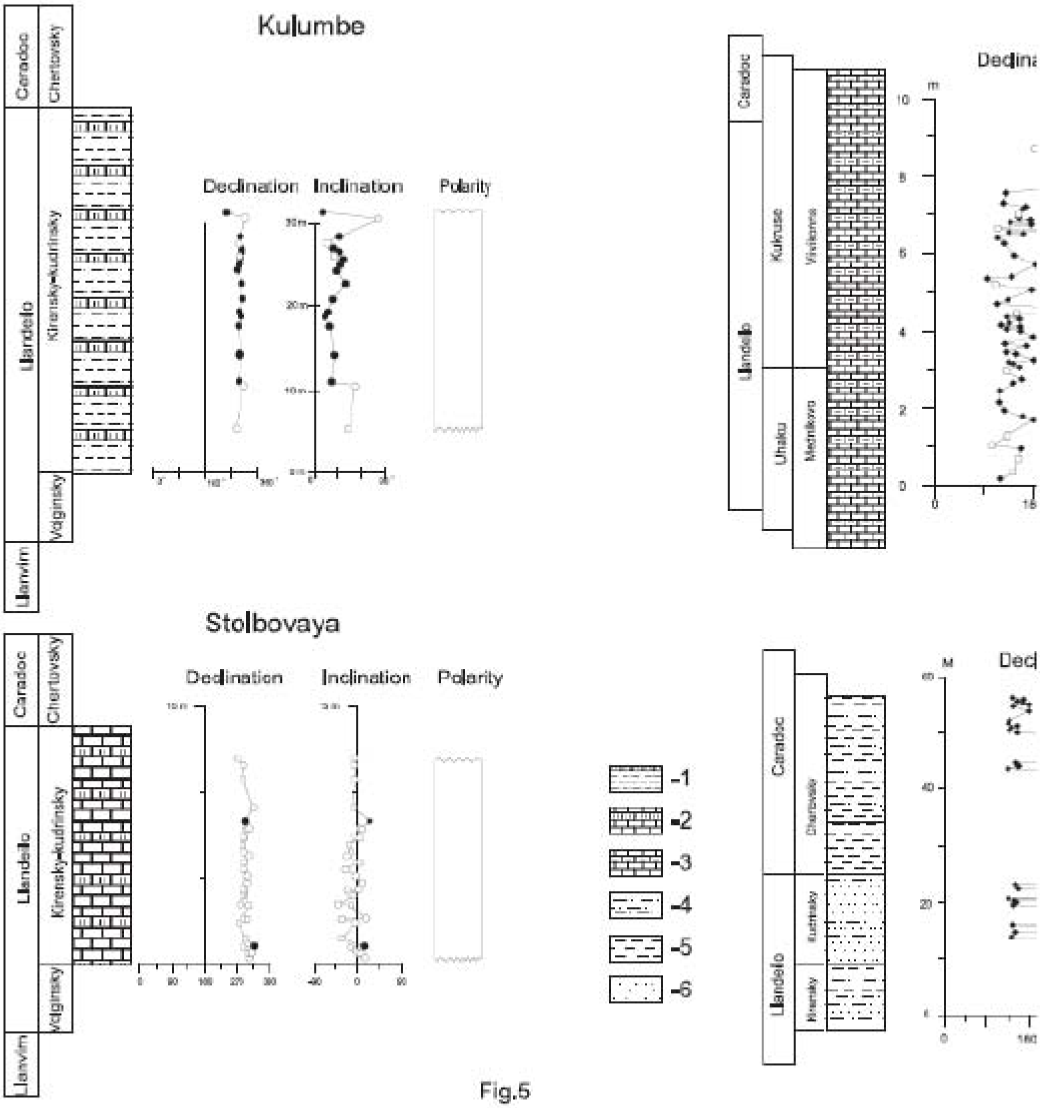
Kulumbe
Caradoc
Chertovsky
Llandeilo
Kirensky-kudrinsky
Volginsky
Llanvirn
Declination
Inclination
Polarity
Stolbovaya
Caradoc
Chertovsky
Llandeilo
Kirensky-kudrinsky
Volginsky
Llanvirn
Declination
Inclination
Polarity
-1
-2
-3
-4
-5
-6
Caradoc
Llandeilo
Kukruse
Uhaku
Mednikovo
Declina
Caradoc
Llandeilo
Dec

Fig.5

ACC

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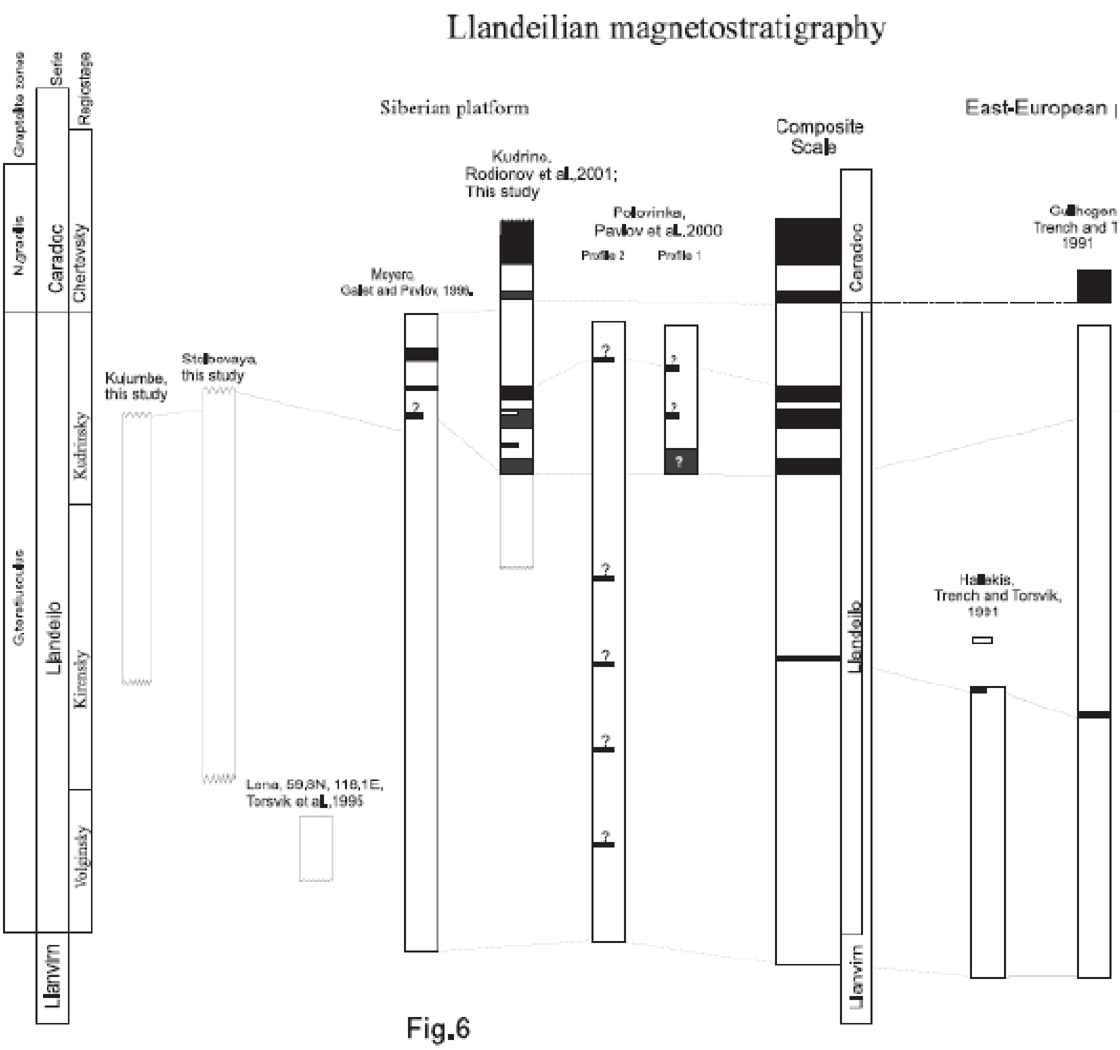
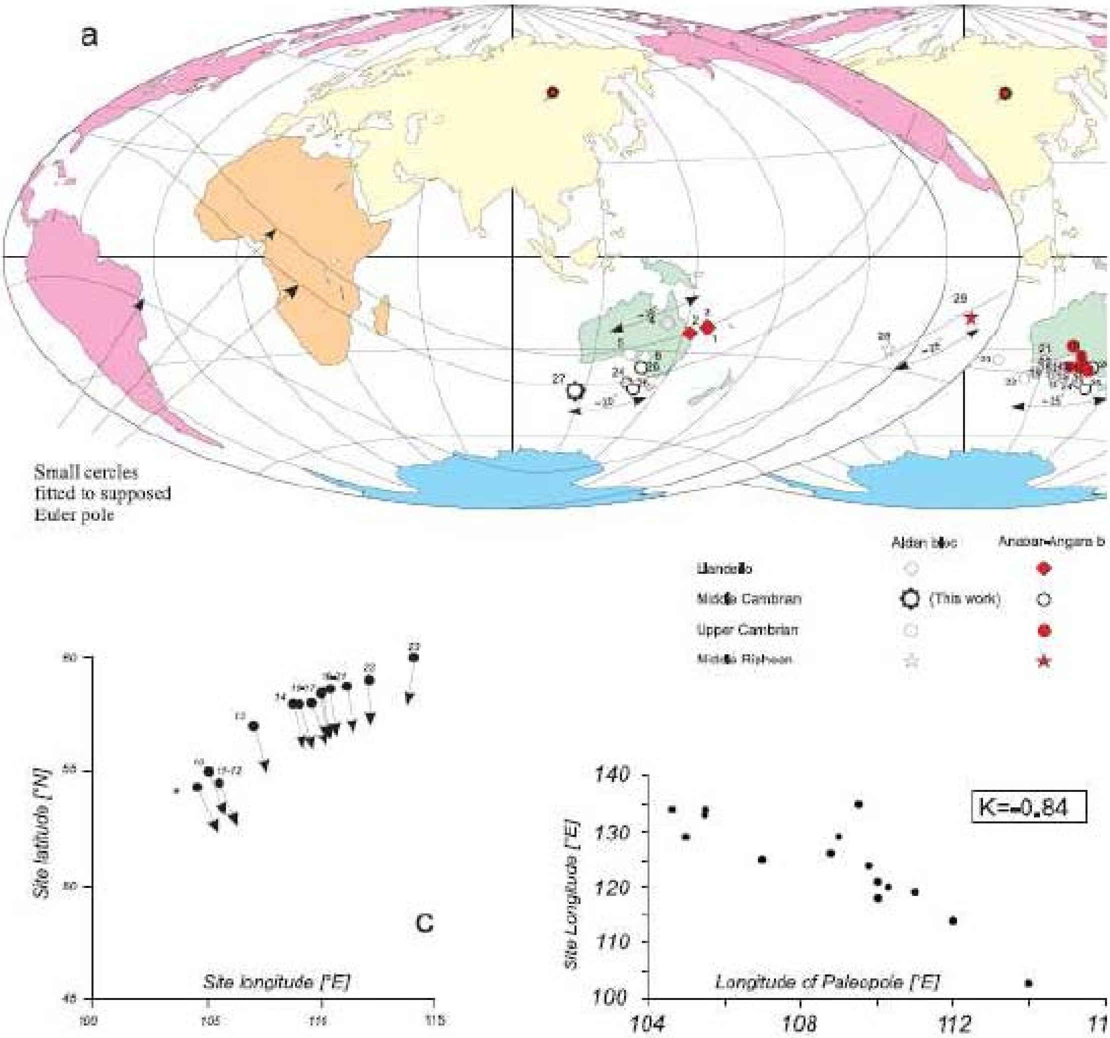


Fig.6

838
839
840


a
Small circles
fitted to supposed
Euler pole
Aldan bloc
Anabar-Angara b
Llandeilo
Middle Cambrian
(This work)
Upper Cambrian
Middle Riphean
Site latitude [°N]
Site longitude [°E]
c
Site Longitude [°E]
Longitude of Paleopole [°E]
K=-0.84

ACC

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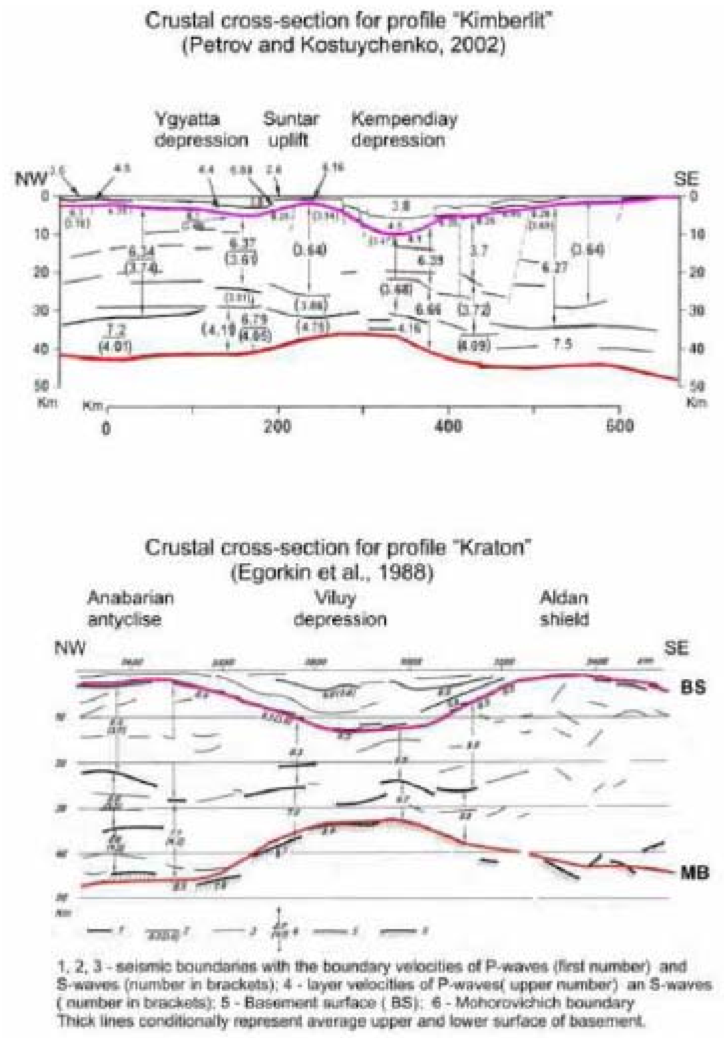

Fig.8

844
845
846

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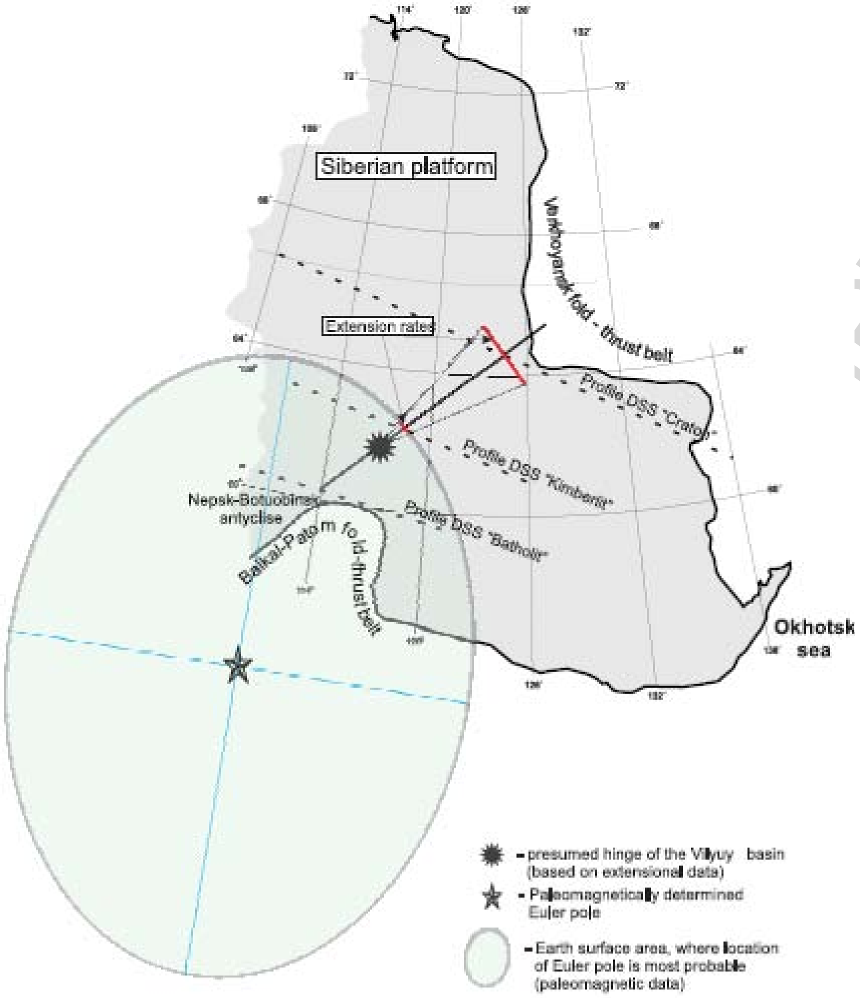

Fig.9

847

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SUPPLEMENTARY FILES.

Supplementary file 1.

Representative orthogonal diagrams of thermally demagnetized samples from the Chaya formation. All data are shown in situ. Solid (open) symbols are projected onto the horizontal (vertical) plane. Also shown are the demagnetization data for sample 3 in stereographic projection. Here closed (open) circles are projections onto the lower (upper) hemisphere for stereoplot. Temperatures are in degrees Celsius.

Supplementary file 2.

Representative orthogonal plots of thermally demagnetized samples from the Ust'-Maya formation. Also shown are the demagnetization data for samples 97 and 123 in stereographic projection. Conventions as in Supplementary file 1.

Supplementary file 3.

Representative orthogonal plots of thermally demagnetized samples of Llandeilan rocks from Kulumbe section. All data are shown in stratigraphic coordinates. Conventions as in Supplementary file 1.

Supplementary file 4.

Representative orthogonal and stereographic plots of thermally demagnetized samples from the Stolbovaya river section. Conventions as in Supplementary file 1.

Supplementary file 5.

Representative orthogonal plots of thermally demagnetized samples of Llandeilan and Caradocian age from Kudrino section. Conventions as in Supplementary file 1.

Supplementary file 6.

Representative orthogonal plots and stereographic plots of thermally (a,c) and combined af and thermally (b) demagnetized samples from Alexeevka section. Conventions as in Supplementary file 1.

Supplementary file 7.

Distribution of the residual values (chosen as a measure of probability for the location of the Euler pole at a given point) on the Earth surface. The dark region within the red area corresponds to the region with the smallest value for the residuals. The values of the residuals decrease from blue to green to red. The darkness of each color is proportional to residual values.

Supplementary file 8.

Paleomagnetic directions and paleomagnetic pole position of the Middle Cambrian from the lower Maya river valley.

N, number of samples, D, declination, I, inclination, k is the precision parameter and $\forall_{95}$ the 95% precision cone around the mean direction [34] . γ/γ_c is the ratio of the observed and critical angular difference between the two antipodal directional distributions [35]. The geographic location of the sampled sections is given by φ (northern latitude) and λ (eastern longitude). Φ and Λ are latitude [°N] and longitude [°E] of the resulting palaeopole positions. dp/dm – semi axis around the mean pole.

Supplementary file 9.

Paleomagnetic directions of the studied Llandeilian sections.

See supplementary file 8 for notation.

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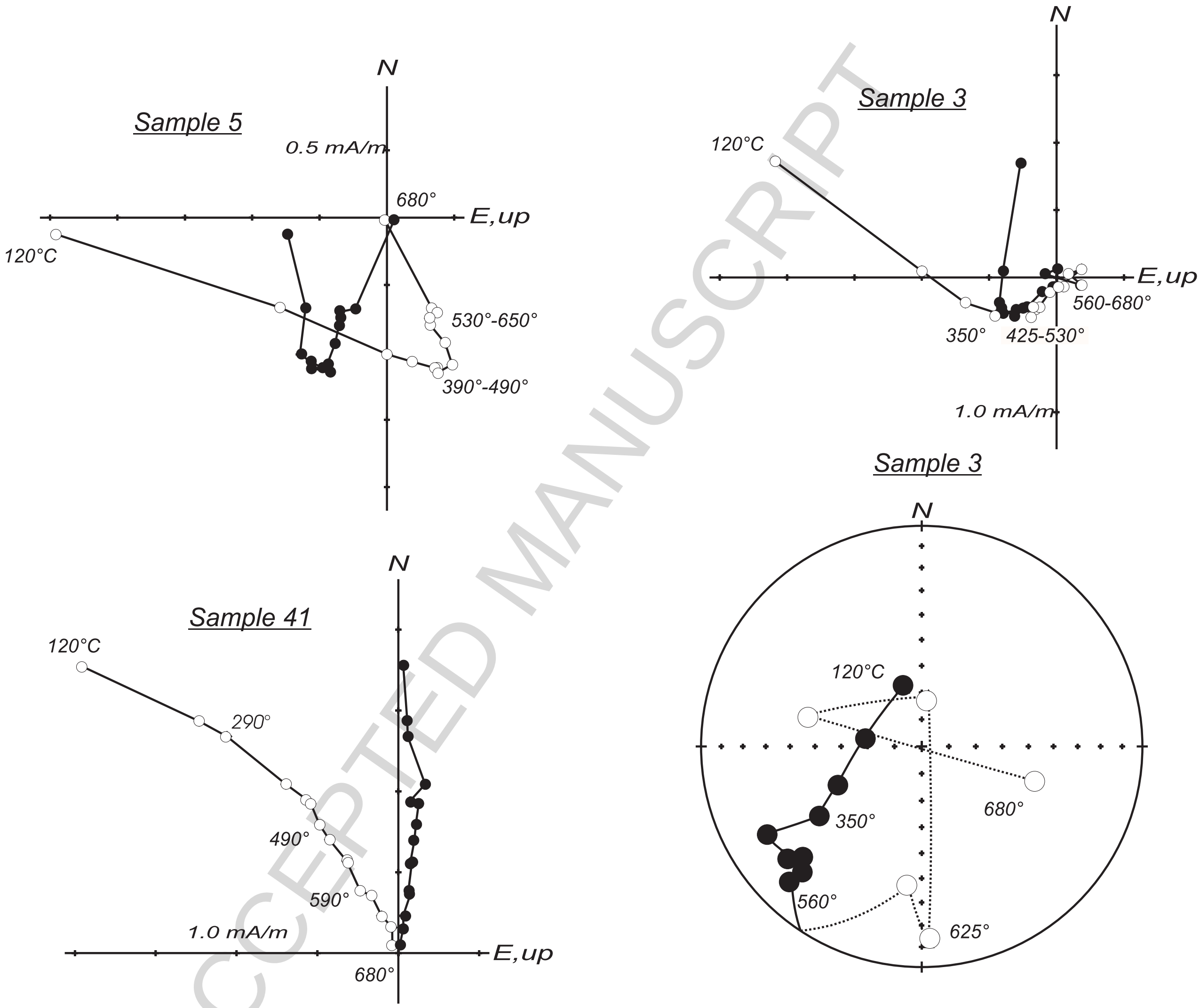
Chaya formation



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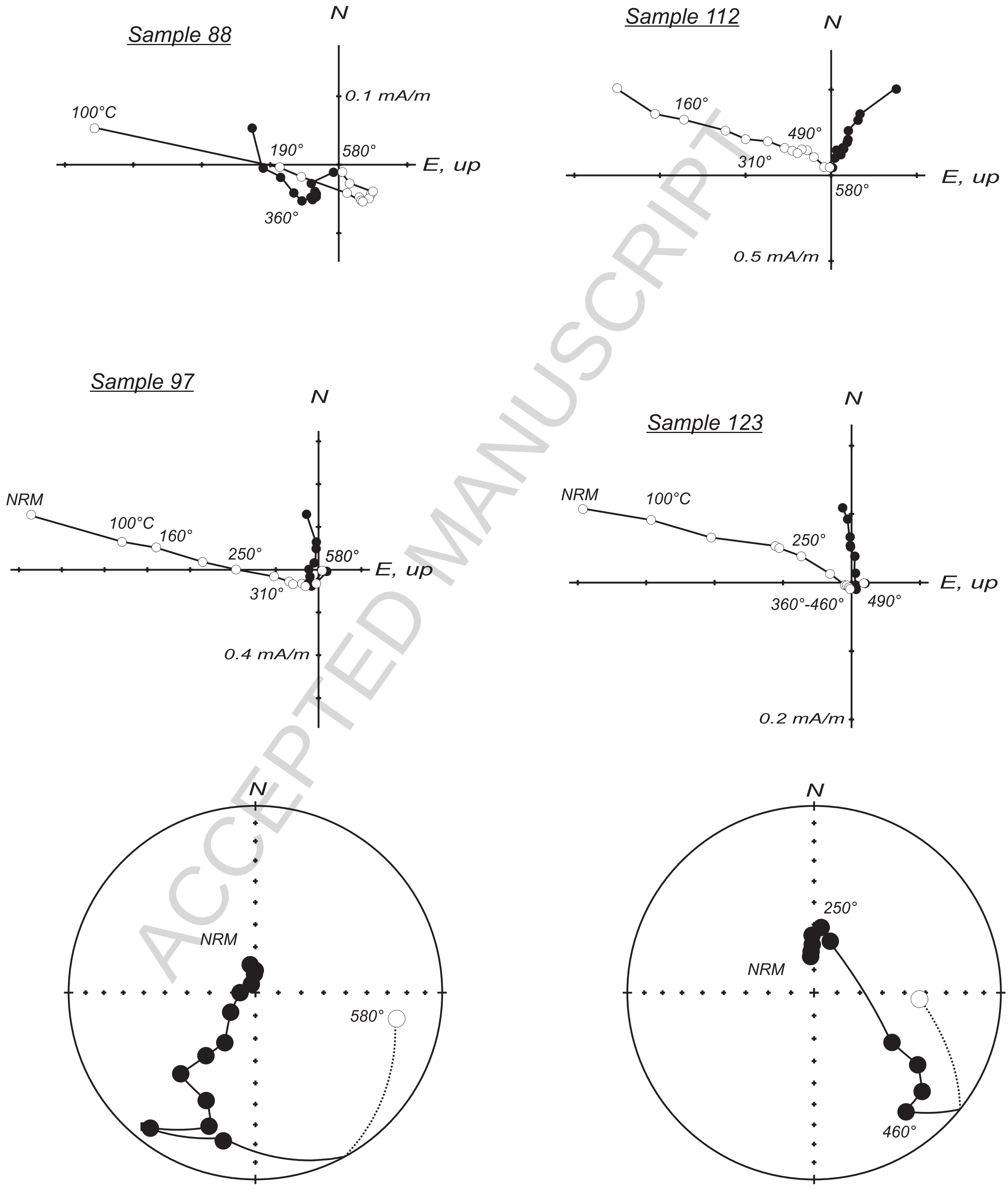
Supplementary file 1

Representative orthogonal plots (for sample 3 also stereoplot) of thermally demagnetized samples from the Chaya formation. All data are in situ. Solid (open) symbols are projected onto horizontal (vertical) plane for orthogonal plots and onto lower (upper) hemisphere for stereoplot. Temperatures are in degrees Celsius.

Ust'-Maya formation



Supplementary file 2

Representative orthogonal plots (for samples 97 and 123 also stereograms) of thermally demagnetized samples from the Ust'-Maya formation. All data are in situ. Solid (open) symbols are projected onto horizontal (vertical) plane for orthogonal plots and onto lower (upper) hemisphere for stereogram. Temperatures are in degrees Celsius.

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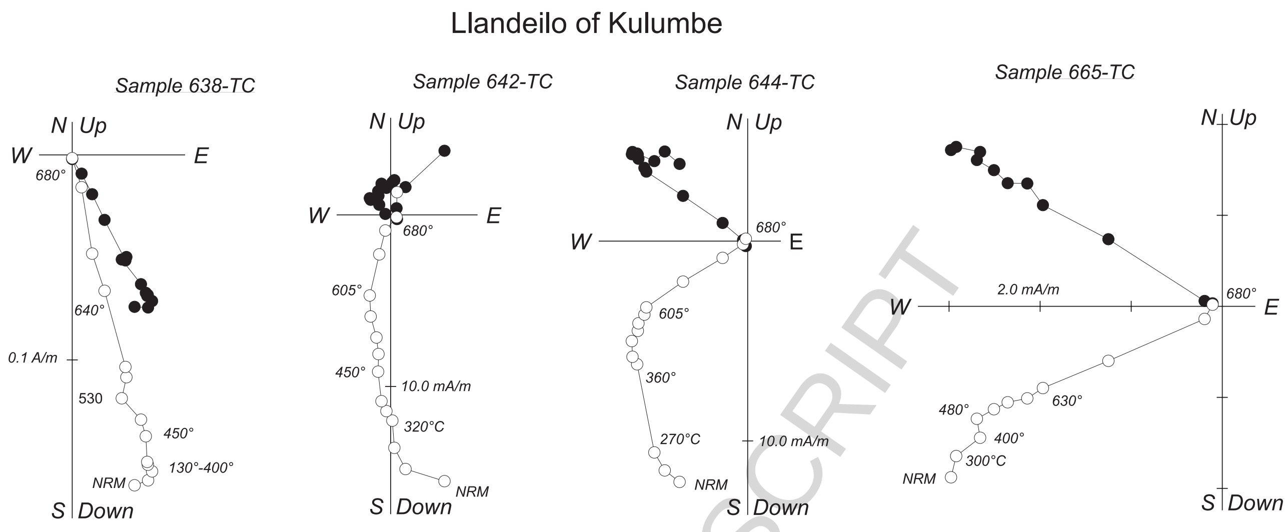

Supplementary file 3

903 Representative orthogonal plots of thermally demagnetized samples from Llandeilo of the Kulumbe section. All data are shown in stratigraphic coordinates. All notations as in supplementary file 1.

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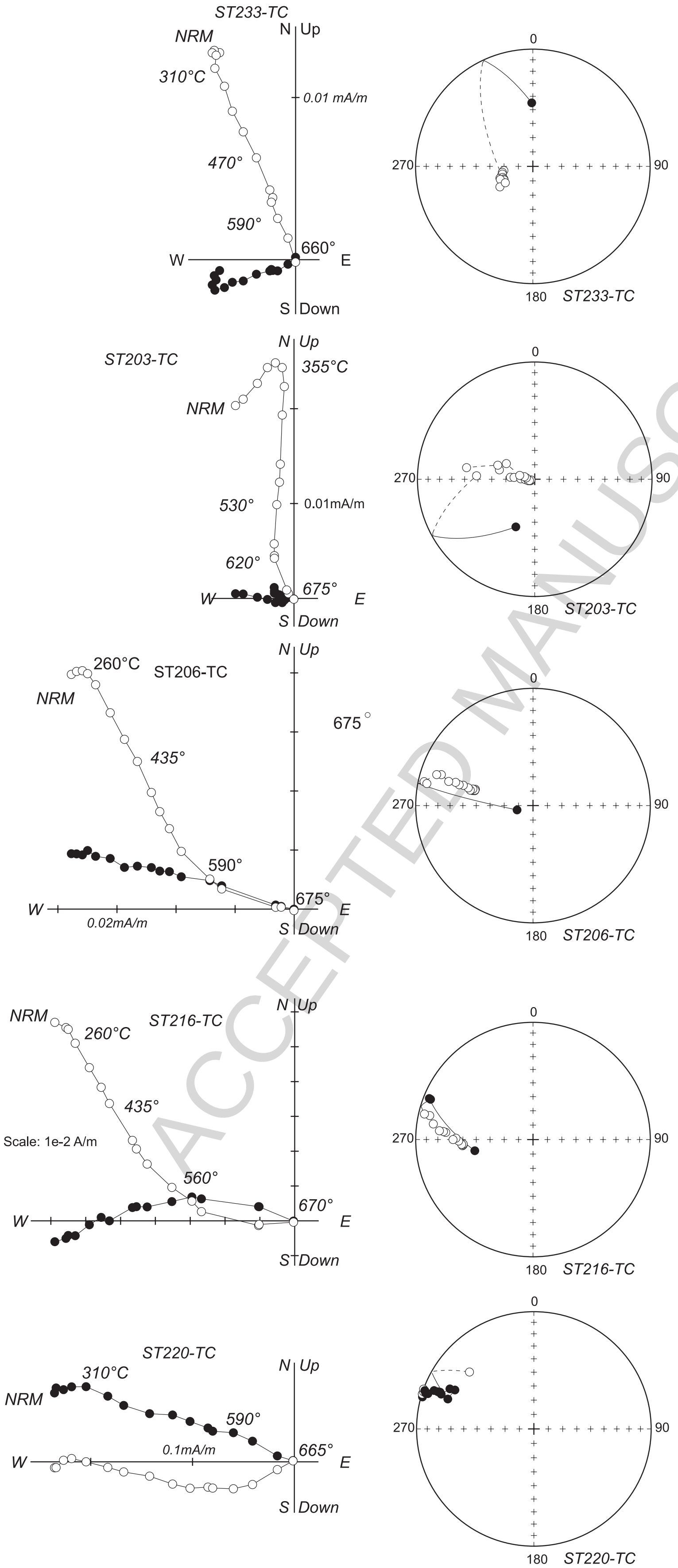
Llandeilo of Stolbovaya



Supplementary file 4

Representative orthogonal plots of thermally demagnetized samples from Llandeilo of the Stolbovaya section. All notations as in supplementary file 1.

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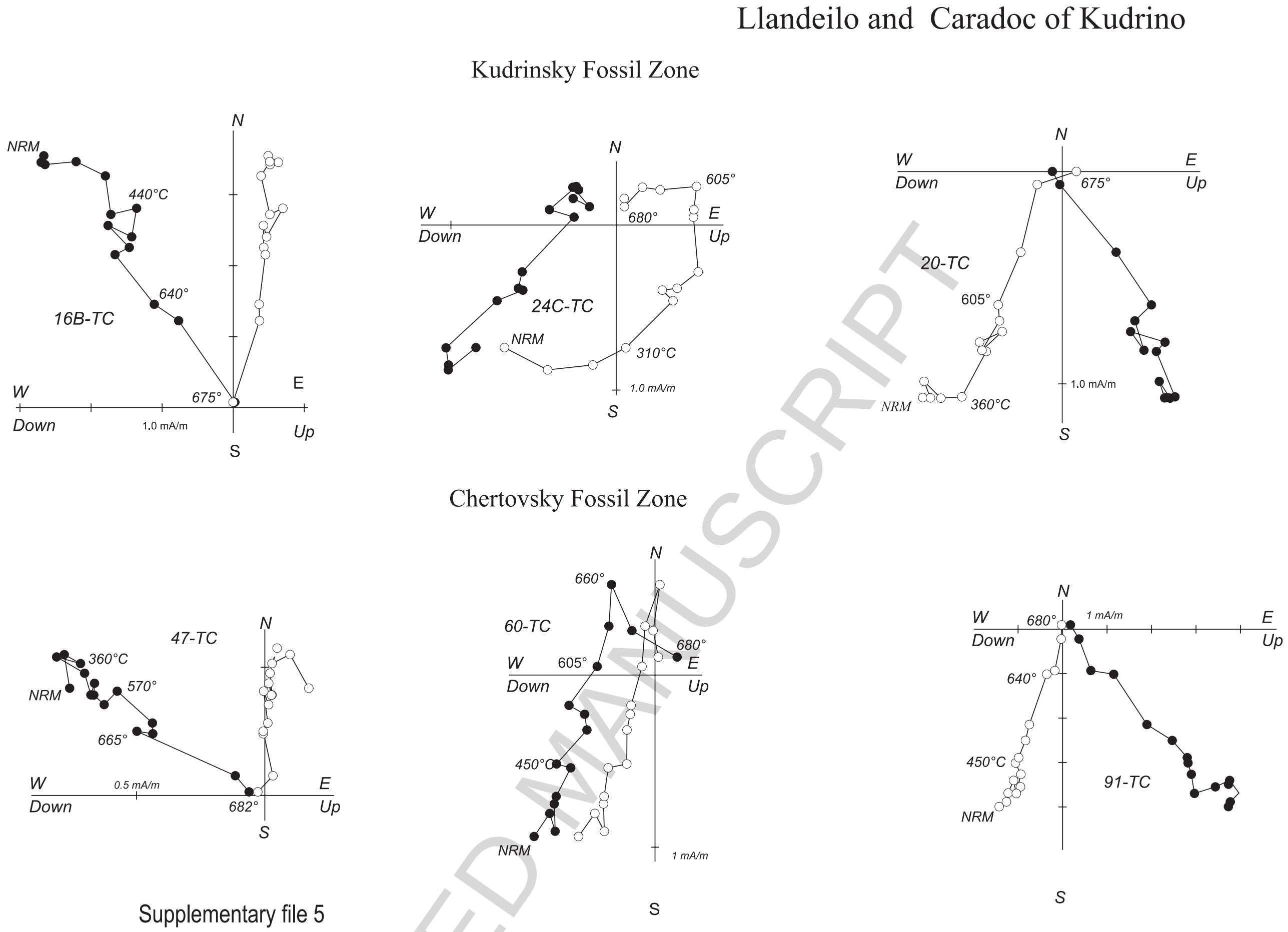

Supplementary file 5

Representative orthogonal plots of thermally demagnetized samples from the Kudrino section. All notations as in supplementary file 1.

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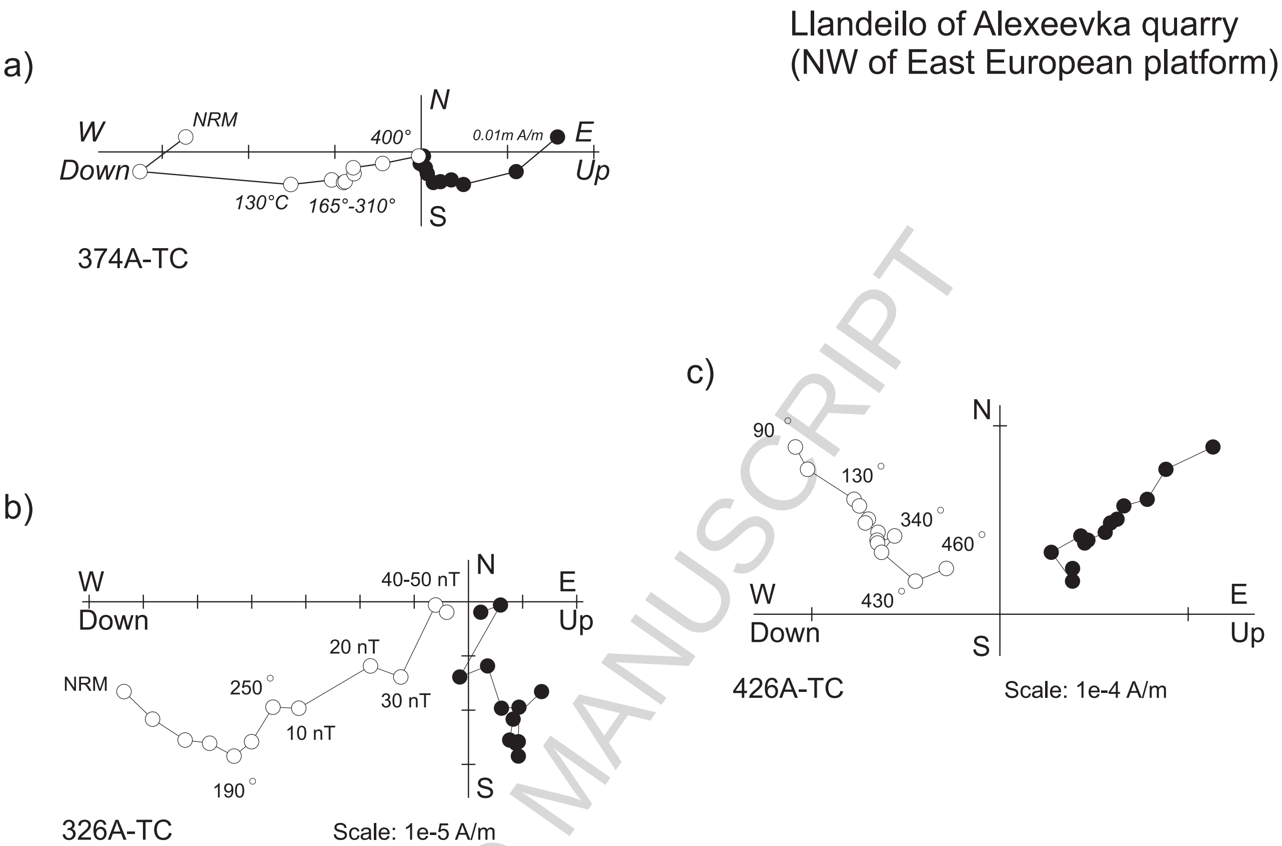

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Supplementary file 6

Representative orthogonal plots of thermally (a,c) and thermally-af (c) demagnetized samples from Llandeilo of the Alexeevka section. All notations as in supplementary file 1.

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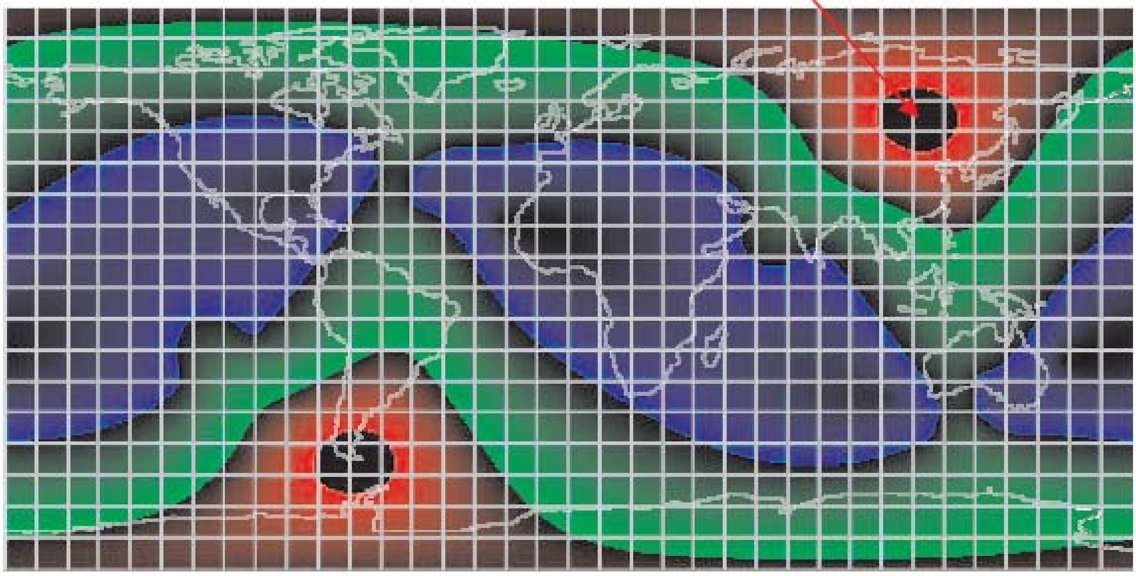

Supplementary file 7

Distribution of residual value (chosen as a measure of probability for the location of the Euler pole at a given point) on the Earth surface. The dark spot inside of red area corresponds to region with the smallest value of residual value. Red area residual values are smaller then values corresponding to green area, which, in its turn, are smaller then values corresponding to blue area. The darkness of each color is proportional to residual values.

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Supplementary file 8.
Paleomagnetic directions and paleomagnetic pole position of the Middle Cambrian from the lower Maya river valley.

Formation	Outcrops	N	In situ				Tilt corrected				Reversal test
			D [°]	I [°]	K	α_{95} [°]	D [°]	I [°]	K	α_{95} [°]	γ/γ_c [°]
Chayskaya formation	**Outcrop A** (φ=59°24’48’’; λ=135°06’04’’)										
	Normal	10	197.5	-22.5	18.4	11.6	197.4	-22.1	18.4	11.6	11.8/18.1
	Reversed	20	23.2	33.3	8.5	11.9	22.9	32.9	8.5	11.9	
	Total	30	201.1	-29.5	10.1	8.7	200.9	-29.2	10.1	8.7	
	Outcrop B (φ=59°29’12’’; λ=135°05’58’’)										
	Normal	21	188.5	-25.5	8.3	11.8	188.5	-26.3	8.3	11.8	
	Reversed	-	-	-	-	-	-	-	-	-	
	Total	21	188.5	-25.5	8.3	11.8	188.5	-26.3	8.3	11.8	
	Outcrop A + Outcrop B										
	Normal	31	191.6	-24.6	10.1	8.6	191.6	-24.9	10.1	8.6	12.7/14.1
	Reversed	20	23.2	33.3	8.5	11.9	22.9	32.9	8.5	11.9	
	Total	51	195.9	-28.0	9.1	7.0	195.8	-28.1	9.1	7.0	
Ust-Maya formation	**Outcrops 1,2,3,4,5,7,8** (φ=59°40’02’’-60°00’05’’; λ=135°00’34’’-134°48’41’’)										
	Normal	12	203.5	-31.4	19.9	10.0	202.5	-32.0	18.4	10.4	20.3/13.1
	Reversed	12	359.6	39.2	25.9	8.7	359.0	39.0	25.6	8.7	
	Total	24	192.1	-35.9	16.9	7.4	191.2	-36.1	16.6	7.5	
Chayskaya + Ust-	Normal	43	195.0	-	11.3	6.8	194.6	-	11.2	6.8	
	Reversedl	32	14.4	26.6	10.0	8.4	14.0	27.1	10.0	8.5	8.8/10.7

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Maya formations	Total	75	194.7	36.1 - 30.7	10.5	5.3	194.4	- 35.9 - 30.8	10.5	5.3	
Paleomagnetic pole Plat =-45.8° Plong = 115.0° dp/dm=3.3°/5.9° A95=4.4°											

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Supplementary file 9.

Paleomagnetic directions of the studied Llandeilian sections.

Stratigraphic position	Component	N	In situ				Tilt corrected			
			D [°]	I [°]	K	α_{95} [°]	D [°]	I [°]	K	α_{95} [°]
Kudrino										
Kudrinsky horizon	HTC normal	10	147.3	18.5	53.8	6.6	147.7	22.1	61.3	6.2
	HTC reversed	13	326.9	-6.2	35.7	7.0	327.2	-8.9	27.4	8.1
	HTC combined	23	327.1	-11.6	34.8	5.2	327.4	14.7	30.1	5.6
Chertovsky horizon	HTC normal	16	153.4	14.1	26.1	7.4	154.4	19.9	28.2	7.1
	HTC reversed	27	322.3	-1.7	17.8	6.8	322.4	-8.5	17.8	6.8
	HTC combined	43	326.4	-6.4	17.2	5.4	326.8	-12.8	17.6	5.3
	MTC	9	182.7	14.0	15.1	13.7	185.7	20.2	16.2	13.2
Polovinka (Pavlov et al., 1999)										
Kudrinsky horizon	HTC reversed	39	343.4	-3.2	19.0	5.4	343.5	2.9	20	5.2
Kirensky+ Kudrinsky horizons	MTC	90	178.4	30.0	16.5	3.8	177.0	25.4	18.2	3.6
Kulumbe										
Kirensko-kudrinsky horizon	HTC reversed	14	303.0	8.0	58.5	5.2	302.9	25.0	88.7	4.2
Stolbovaya										
Kirensko-kudrinsky horizon	HTC reversed	32[1)]	300.7	18.1	24.5	5.3	300.7	18.1	24.5	5.3
Alexeevka										
Llandeilo	HTC reversed	47	162.8	60.6	19.3	4.9	162.8	60.6	19.3	4.9

[1)] based on the combination of 2 stable endpoints and intersecting great circle data for 30 samples.

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Supplementary material.

Analysis of stability of estimates of total extension using formula (2).

Possible sources of error in total extension estimates are: incorrect seismic estimates of crustal thickness, variations of crustal thickness in the area of the Vilyui basin before extension and erroneous choice of limits of the extended area. As formula (2) uses the integral of the crustal thickness it is robust to local (short-term) variations of the crustal thickness. Significantly more important, however, are systematic errors in estimates of the depth of the Moho. Suppose that the depth determination for the Moho is wrong by a value of ΔH, then the estimate of the initial crustal thickness will be wrong by the the same value, and the error in the estimate of the value L will be in order of $(\Delta H/H)^2 L$. If the depth of the Moho is misidentified by 5 km, when the true depth is about 45 km, then the error associated with the estimate of L will be about 1%. Suppose that when applying formula (2) the left boundary of the extended area is shifted by values of δL_1 and the right was shifted by δL_2 compared to the real limits of the extended area. Substituting into formula (2) shows that the error in the estimate of the amount of stretching $\Delta L = L_1 - L$ will be equal to $(\delta L_2 - \delta L_1) * \delta H/(2H_{av})$, where δH is the difference in crustal thickness at the left and the right end of the profile. Thus, when limits of the extended area are shifted to the same distance the error is equal to zero. Suppose that $(\delta L_2 - \delta L_1)$ =100 km (which is very unlikely) and δH =2 km (the real value for the Vilyui basin), then ΔL is about 2 km, which is very small in comparison to the width of the basin.

Another possible source of error are changes in crustal thickness during the process of extension caused by intrusion of magmatic rocks. These changes should be proportional to the amount of extension. To estimate the position of the pole of opening we use the extensional ratio along different profiles. It is easy to demonstrate that errors proportional to the extension do not shift the location of the pole of rotation. Thus, we conclude that estimate (2) is very robust to different sources of errors.