Tectonophysics 486 (2010) 65–80

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Paleomagnetism of the Precambrian Eastern Sayan rocks: Implications for the Ediacaran–Early Cambrian paleogeography of the Tuva-Mongolian composite terrane

Vadim A. Kravchinsky [a,*], Eugene V. Sklyarov [b], Dmitry P. Gladkochub [b], William P. Harbert [c]

[a] Physics Department, University of Alberta, Edmonton, Alberta, Canada T6G 2G7
[b] Institute of the Earth Crust, Siberian Branch of Russian Academy of Science, Irkutsk 664033, Russia
[c] Department of Geology and Planetary Science, University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA

ARTICLE INFO

Article history:
Received 13 June 2009
Received in revised form 10 February 2010
Accepted 15 February 2010
Available online 21 February 2010

Keywords:
Ediacaran
Mongolia
Paleomagnetism
Riphean
Sayan
Siberia

ABSTRACT

The Tuva-Mongolian Precambrian composite terrane is located within the complex Central Asian fold belt, which separates the Siberian portion of the Eurasian continent from other incorporated continental blocks. This terrane is one of the key elements that must be accurately modeled to reconstruct the Neoproterozoic–Paleozoic tectonic history of Eurasia. The reconstruction of the terrane's paleoposition after breaking up of supercontinent Rodinia relatively to other continental blocks has fundamental importance, as it is one of the missing blocks in most present day reconstructions.

We present a paleomagnetic study of rocks from several formations of the Eastern Sayan region south of Siberian platform (representative location $\lambda = 52.0°N$, $\phi = 100.5°E$), within the Tuva-Mongolian composite terrane. Sections of siltstone, fine grained sandstone and associated sills were sampled at several localities in this complex region. These units have been dated as Precambrian to Early Cambrian in age. The resulting collection was taken from three formations, representing a total of 33 sites, collected from this previously unsampled and remote region. Generally 6 to 11 samples per site were collected. Stepwise thermal demagnetization was completed using between 10 and 18 heating steps to up to temperatures of 680 °C. Principal component analysis of the stepwise thermal demagnetization data was successful in isolating two characteristic remanent magnetizations. The lower unblocking temperature component, component A, fails the fold test, is always of downward directed magnetic inclination, and may correspond to the present day Earth's magnetic field. The higher unblocking temperature magnetic component (B), was observed in the Dunzhugur Formation (B_{DF}, $N = 8$ sites) and the Bokson Formation (B_{BF}, $N = 11$ sites from 5 localities). The B component differs significantly from component A, and is recorded by sites of downward and upward directed magnetic inclinations in the Bokson Formation. Component B_{DF} is most likely a result of the regional remagnetization of the sediments and sills during multiple tectonic events in the area. Component B_{BF} yields a positive fold test and one site has reversed polarity direction. A virtual geomagnetic pole calculated from component B_{BF}, after rotating along a small circle, is coincident with other Ediacaran to Early Cambrian aged poles reported from nearby Mongolia and Siberia. This observation supports the earlier interpretation of Kravchinsky et al. (2001) postulating an adjacent position of the Tuva-Mongolian composite terrane and the Siberian continent in Ediacaran–Early Cambrian times.

1. Introduction

The Central Asian fold belt is one of the major tectonic features of the Asian continent and critically important to the accurate understanding of the accretionary tectonic history of this large and complex region. Plate reconstructions of the Eastern Sayan segment of the Central Asian fold belt are based on a very limited number of paleomagnetic studies (Zonenshain et al., 1990; Kravchinsky et al., 2001). Today, plate tectonic reconstructions of this region (Zonenshain et al., 1990; Belichenko et al., 1994; Berzin et al., 1994; Kravchinsky et al., 2001) are open to debate because of this lack of reliable paleomagnetic, and in some cases, any paleomagnetic data to constrain paleolatitude separation or relative rotation between tectonostratigraphic terranes.

* Corresponding author. Tel.: +1 780 4925591; fax: +1 780 4920714.
E-mail address: vkrav@phys.ualberta.ca (V.A. Kravchinsky).

0040-1951/$ – see front matter
doi:10.1016/j.tecto.2010.02.010

In earlier published plate tectonic reconstructions of this region, a number of ancient tectonostratigraphic terranes located south of the boundary of the Siberian platform (Tuva-Mongolian, Khamar-Daban, Barguzin) were regarded as a part of the Siberian continent in Precambrian until a number of Upper Riphean–Lower Cambrian ophiolitic zones separating the terranes from Siberia were documented (Sklyarov et al., 1994; Gusev and Khain, 1995). The ophiolitic zones define a Paleoasian Ocean separating the Siberian platform and Gondwanaland that was suggested by Zonenshain et al. (1976). The Tuva-Mongolian, Dzabkhan, Tarbagatay and Central-Mongolian tectonostratigraphic terranes are situated south of these ophiolite zones (Fig. 1) but their paleogeographic position relatively to Siberia is still a matter of discussions.

The south-eastern part of the East-Sayan Mountains in southern Siberia includes Early Precambrian, Late Precambrian and Early Paleozoic formations deformed by nappe-folds (Belichenko et al., 1988). In order to better constrain the Late Precambrian–Early Paleozoic tectonic history of the tectonostratigraphic terranes to the south of the edge of the Siberian platform we present new reconnaissance paleomagnetic results from the Neoproterozoic and Ediacaran–Early Cambrian aged formations of the Tuva-Mongolian terrane.

2. Geology and sampling

2.1. Geological description of the Tuva-Mongolian composite terrane

The Tuva-Mongolian composite terrane is one of a number of Precambrian terranes, located along the southern edge of the Siberia platform among the Paleozoic complexes of the Central Asian fold belt. The common feature of all of these Precambrian terranes is that an Ediacaran–Cambrian aged carbonate cover uncomfortably overlies them.

Several areas of distinct lithology and compositions form the northern part of the Tuva-Mongolian composite terrane. The main areas are the Gargan and Oka terranes, and the Shishkid island arc (Fig. 2). The Gargan terrane has a complex composition of crystalline basement overlain by sediments, ophiolite allochthons and also volcanic–terrigenous and intrusive complexes formed at an active continental margin (Sklyarov et al., 2001; Kuzmichev and Buyakaite, 1994; Kuzmichev et al., 2001). The basement of Archean age is composed of mafic granulites, amphibolites and gneisses with relic mineral paragenesis of granulite facies. The basement is overlain with stratigraphic and metamorphic discontinuity by a sedimentary cover interpreted to have formed in the paleogeographic setting of a passive

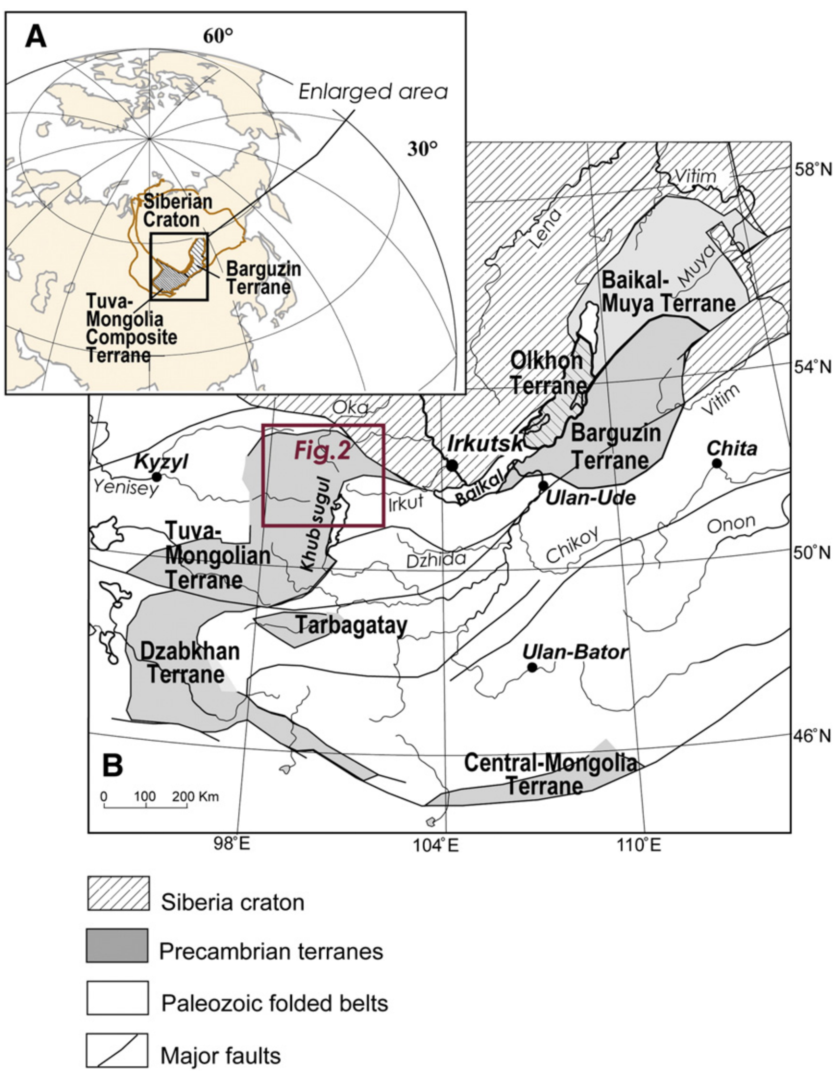

Fig. 1. (A) Reference geography map showing the area of investigation. (B) Reference terrane map of selected terranes relevant to the Precambrian tectonic history of the southern Siberia region (modified after Kuzmichev et al., 2001). The location of Fig. 2 is shown.

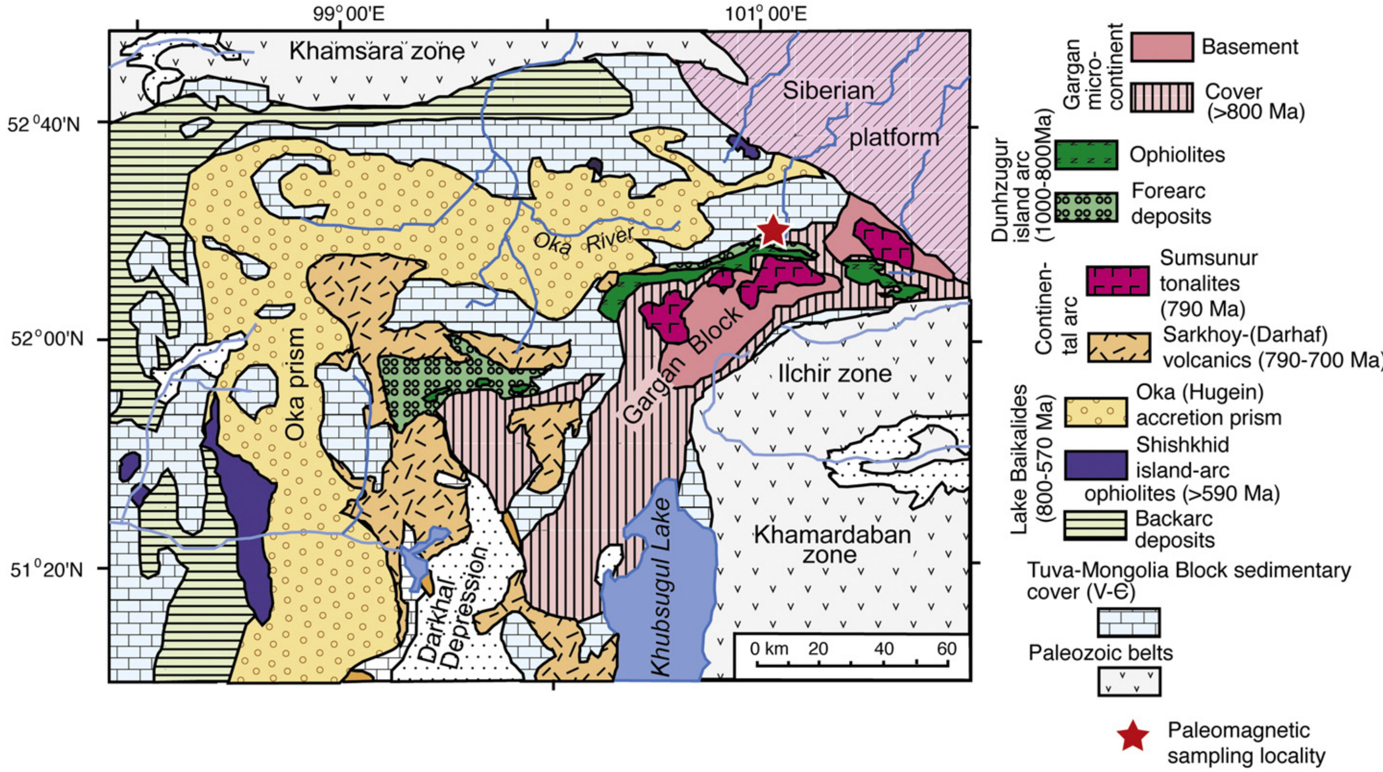

Fig. 2. Simplified tectonostratigraphic terrane map of the Tuva-Mongolian composite terrane (modified after Kuzmichev et al., 2001). Paleozoic granites, Cenozoic sediments and volcanics (except for where present in a large depression) are not shown to simplify the figure. The star symbol shows the location of our study area.

margin. The lower stratigraphic unit of the metamorphosed sedimentary cover consists of marbles and the upper one is composed predominantly of schists.

The Tuva-Mongolian composite terrane includes rocks that are interpreted to be an active continental margin represented by the volcanics of the Sarkhoy and Shishkhid Formations composing a broad differentiated series from rhyolite through andesite to basalt. A wide range of rocks, often variegated, including conglomerates, sandstones, siltstones and dolomites, represents the sedimentary series. The Sarkhoy Series has been dated as 718 ± 30 Ma (Kuzmichev and Buyakaite, 1994); the age of the Shishkhid Formation has been reported as 590 ± 20 Ma (Kuzmichev, 2004) and both correspond to important stages in the Neoproterozoic buildup of the Tuva-Mongolian terrane.

2.2. Ophiolite complex of the Dunzhugur Formation

The ophiolite allochthon makes up a complete sequence that is tectonically dismembered and coupled in common thrust slices with a sedimentary series. The structural position of the allochthon within the present structure implies that the Precambrian basement was overlain by these ophiolites. Rocks of the lower part of the ophiolite sequence (ultrabasites) are widespread in the eastern portion, while in the western portion, rocks composing the upper unit of the ophiolite section (basalts associated with sedimentary series) are predominant and overlain by turbiditic sedimentary units intruded by numerous sills of gabbro–diabase composition. The sills are widespread among the Dunzhugur island-arc association. Khain et al. (2002) use petrologic and geochemical data to demonstrate that all members of the ophiolite succession (layered sequence of pyroxenite and gabbro, sheeted diabase dykes and basaltic pillow lavas) originally belonged to the same cogenetic mafic–ultramafic crustal section and support a suprasubduction zone setting in a forearc rifted environment. Khain et al. (2002) reported the age of 1019.9 ± 0.7 Ma for plagiogranite from the Dunzhugur ophiolite sequence.

Field observations enable us to conclude that the deep-water sediments of the Dunzhugur Suite were deposited straight onto the pillow lavas and we assume that they directly overlie the ophiolite section. The sediment age may therefore be considered to be the same, or very close to, the age of the ophiolite.

There were two Neoproterozoic amalgamation stages at ~800 Ma and 600–550 Ma along the East-Sayan edge of the Tuva-Mongolian terrane (Kuzmichev et al., 2001). These events involved two terranes, the Gargan terrane and the Dunzhugur oceanic arc terrane, with the latter represented by island-arc ophiolites of ~1020 Ma now overthrusting the Tuva-Mongolian terrane. The Dunzhugur arc faced the terrane and the arc–continent collision occurred at around 800 Ma (Kuzmichev et al., 2001).

2.3. Sills in the sedimentary sequence

Within the Dunzhugur oceanic arc terrane the volume of sills exceeds that of the interleaved sedimentary sequence overlying the ophiolitic volcanics. Cross cutting diabase dykes, possibly feeder dikes, are present in the underlying volcanics. Within the lower part of the ophiolite sequence, dykes of the same geochemical composition occur. Sills are enriched in light REE and are characterized by moderate to high concentrations of TiO_2, FeO, and related trace elements (Kuzmichev et al., 2001). In most cases, sills form subparallel layers of thicknesses ranging from 10 m up to several hundred meters. Contacts are generally conformable with the layering of the interleaved sedimentary rocks although detailed studies of well-exposed sites sometimes show more complex morphology. We have sampled two Dunzhugur sills with thicknesses of a few dozen meters. A number of attempts to date the sills were unsuccessful but the work may be repeated in the future (Kuzmichev, personal communication).

2.4. Ediacaran–Early Cambrian carbonate sediments of the overlapping complex

The Bokson Formation has been geologically studied since the 1950s, when the first bauxite deposit and phosphorite deposits were geologically mapped. The unit is well-exposed, and in our opinion, is the only stratigraphic unit of the Eastern Sayan region which has valid stratigraphical subdivisions based on fossil evidence. Carbonate rocks of the Bokson Series are divided into five distinct Suites: Zabit, Tabinzurta, Khuzhirtai, Nurgata and Khyuten (Belichenko et al., 1988). The first two Suites are composed of dolomites and the others are composed of limestones.

The terrigenous sediments of the Mangatgol Formation conformably overlie the sediments of the Bokson Formation and the relics of *Claudina* and *Ediacara* fauna constrain a Late Vendian (Ediacaran)–Early Cambrian age for these sediments (Belichenko et al., 1988; Kheraskova and Samygin, 1992). We have sampled the Tabinzurta Suite dolomites and bauxites for this study. The Tabinzurta Suite (thickness ~1300 m) is sedimentologically similar to the underlying Zabit Suite and is represented predominantly by phytolite (fossilised plants) and stromatolite dolomites with different extents of silification and with minor layers of quartz sandstones and breccias. The Ediacaran–Early Cambrian age of the Tabinzurta sediments has been determined by Ediacaran microphytolithic (*Osagia*, *Volvatella*, *Vesicularites*, *Nubecularites*, and *Glebosites*) and stromatolitic (*Linella* and *Stratifera*) dolomites with a variable degree of silicification and subordinate quartz sandstone interbeds (Letnikova and Geletii, 2005). The upper part of the Suite encloses Early Cambrian algae *Renalcis* and silicified archaeocyatheans.

A hiatus defined by a weathering crust is observed between these Suites in the Bokson River area and expressed by a fragmented bauxite layer from 1 to 10 m thick. This crust consists of a sedimentary package of red-coloured clay and sandstone. There is no well-defined

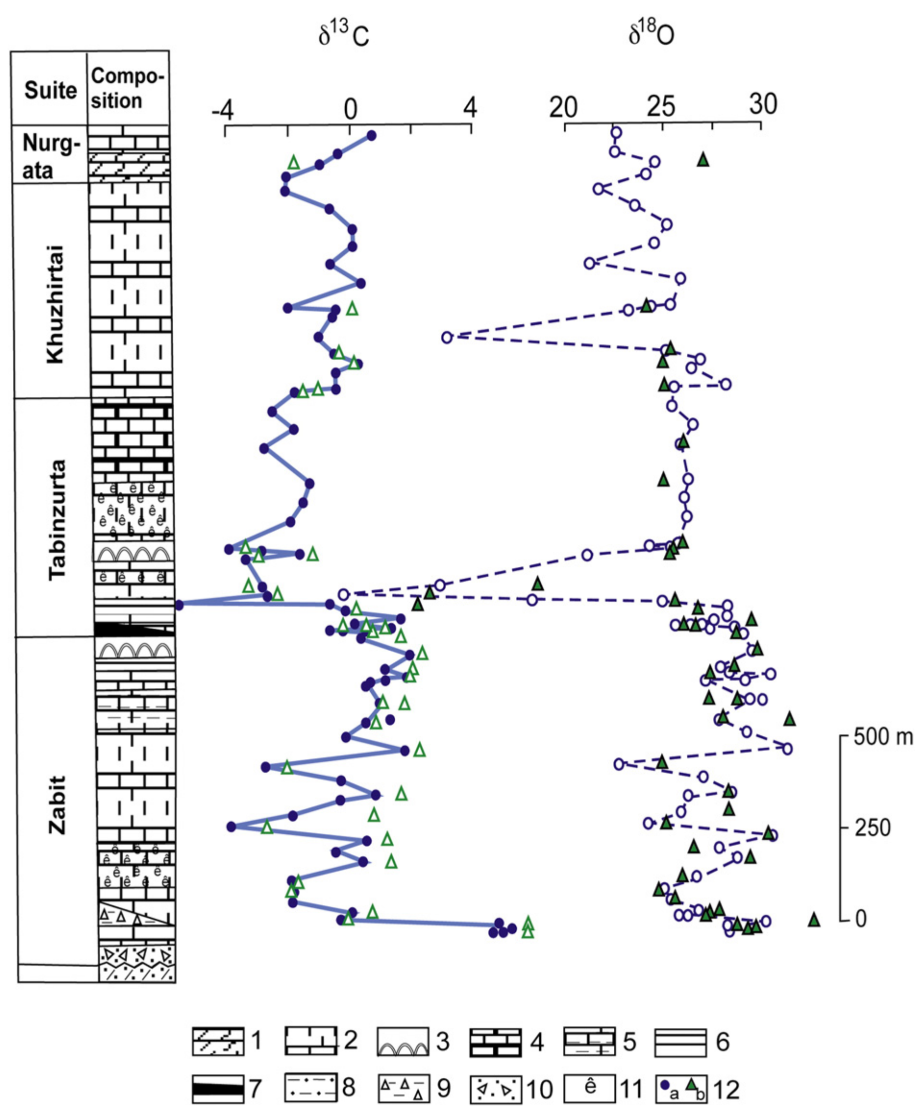

Fig. 3. Stratigraphic column and isotopic characteristics of carbonates from Bokson Formation (modified from Pokrovsky et al., 1999). Symbols used in legend are the following: 1 — limestones; 2 — gray massive dolomites, sometimes with phytolites; 3 — stromatolithic dolomite; 4 — black and gray dolomite, calcarenites and calcirudites; 5 — phosphorous calcarenites; 6 — marlaceous schists; 7 — bauxite horizon; 8 — argillites and aleurolites; 9 — diamictites; 10 — alluvial sediments; 11 — silicification; 12 — (a) circles and (b) triangles represent the samples collected from calcite and dolomite.

lithologic boundary between the uppermost unit of the Tabinzurta Suite and the overlying Khuzhirtai Suite.

An Ediacaran–Early Cambrian age for the carbonate sediments has been shown by isotopic data (Pokrovsky et al., 1999; Fig. 3). Oxygen and carbon isotopic curves indicate an evolution of the Bokson Series correlating with analogous curves obtained from rock series of contemporaneous age in the Siberian platform and the Tsagan-Olom Suite in nearby Western Mongolia. The correlative features of the curves are anomalously high values $\delta^{13}C$ and $\delta^{18}O$ at the base of the section which are typical of the lower unit of the West Mongolian Tsagan-Olom Suite of the Ediacaran age. The other main feature is the abrupt decrease of values of $\delta^{13}C$ and $\delta^{18}O$ in the lower part of the Tabinzurta Suite, comparable to that obtained in sections of the Siberian continent and West Mongolia and corresponding to the beginning of the Nemakit-Daldyn Stage that corresponds to the Ediacaran age (Pokrovsky et al., 1999). Consequently we can compare our same age paleomagnetic results from Eastern Sayan and Western Mongolia in order to perform plate tectonic reconstructions.

3. Laboratory experiments

We have studied sediments and sills of the Dunzhugur Formation (39 samples from sediments and 21 samples from sills) and sediments of the Tabinzurta Suite of the Bokson Formation (107 samples). Coordinates for the localities were taken from maps, and we applied magnetic azimuth corrections to bedding and the sample orientation (the center of the sampling areas is at 52.0°N, 100.5°E).

We sampled 10 localities at which one outcrop usually represented a locality. Depending on the size of the outcrop, one locality is represented by between one and three paleomagnetic sites. Generally two 8 cm^3 cubes (referred to as samples) were cut from each oriented hand block. We obtained the results from 167 samples (17 sites).

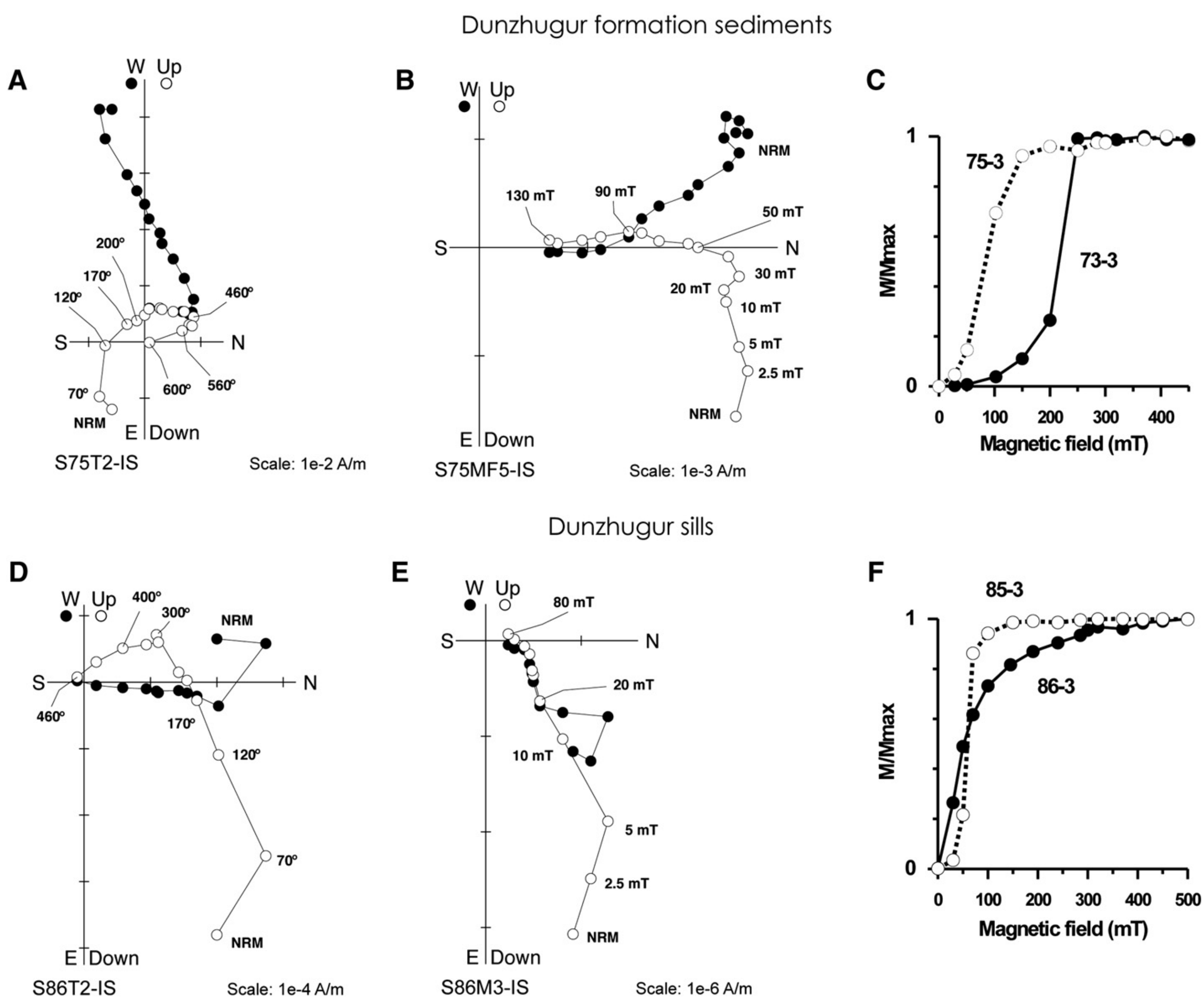

Fig. 4. Results of thermal and alternating field demagnetization, and rock magnetic experiments for the Dunzhugur Formation sediments and sills. A and B — thermal and alternating field demagnetization for two sediment samples from the same oriented block. C — normalized isothermal remanent magnetization (IRM) acquisition curves for two different sediment samples. D and E — thermal and alternating field (AF) demagnetization for two sill samples from the same oriented block. F — normalized IRM acquisition curves for two different sill samples. Typical orthogonal vector plots during thermal (A, D) and alternating field (B, E) demagnetization are *in-situ* coordinates (Zijderveld, 1967). Closed (open) symbols in orthogonal plots: projections onto the horizontal (vertical) plane; temperature steps are indicated in degrees Celsius, AF demagnetization steps are in mT.

Stepwise thermal demagnetizations and magnetic measurements of the samples were carried out by V.A.K. at the Physics Department of the University of Alberta (60% of the samples), Institute of Geochemistry in Irkutsk (Russian Academy of Sciences, Siberian Branch; ~10% of the samples) and the University of Pittsburgh Paleomagnetic Laboratory (~30% of the samples).

The samples were demagnetized thermally in ovens housed in permalloy (Alberta), two-layer high-permeability steel magnetically shielded room (Pittsburgh) or in the 3-layer cylindrical μ-metal shielded oven (Irkutsk). The residual field was approximately 8–12 nT in the center of the ovens. The samples were demagnetized using twelve −50 °C steps to around 690 °C, and remanent magnetizations were measured with a 3-axis 2G cryogenic or SCT magnetometers (Alberta and Pittsburgh respectively), or a JR-4 spinner magnetometer (Irkutsk). Magnetic susceptibility was measured using a Kappabridge KLY-2 (Irkutsk) and a Bartington susceptibility-meter (Alberta and Pittsburgh).

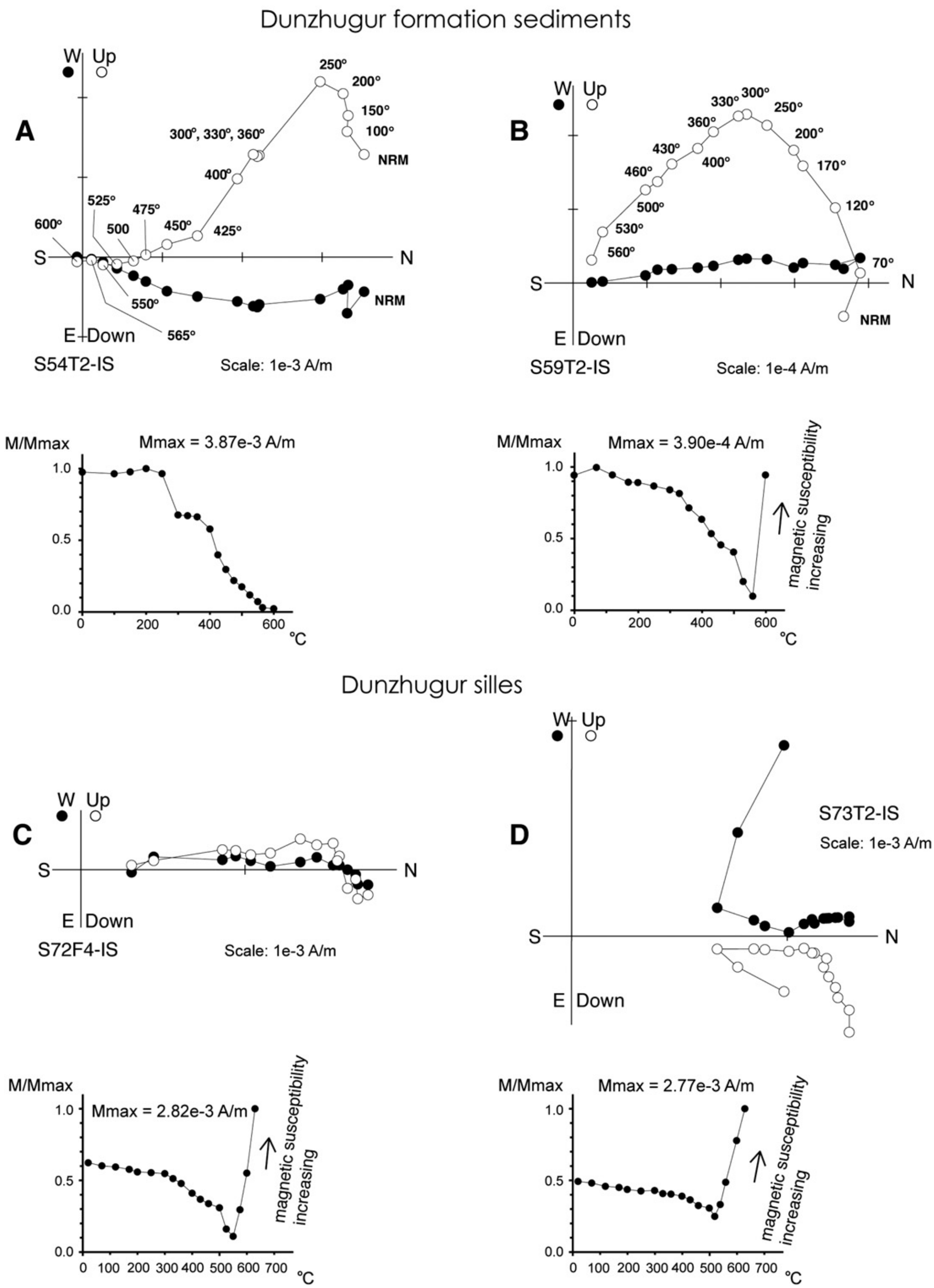

Fig. 5. Results of thermal demagnetization of Dunzhugur Formation sediment (A, B) and sill (C, D) samples and magnetic intensity decay curves for the same samples. Magnetic susceptibility and intensity increasing indicate magnetomineralogical transformations during the experiment. Same abbreviations as Fig. 3.

The data were processed using the software of Enkin (1996) and Cogné (2003) and orthogonal projections of vector behavior diagrams (Zijderveld, 1967) were constructed for each sample to aid in the interpretation of the demagnetization data. Resolved components were analyzed using principal component analysis (PCA) (Kirschvink, 1980) and site-mean directions were calculated using Fisher (1953) statistics. For mixed populations of directions and remagnetization of great circles, the combined analysis technique of McFadden and McElhinny (1988) was also used in the analysis. Tables in this paper include only samples with directions used for our statistical analysis.

In addition, rock magnetic measurements were completed to aid in the identification of magnetic mineralogy and changes to this mineralogy, which occurred during thermal demagnetization. These measurements included temperature dependent magnetic susceptibility, using the Bartington system, isothermal remanent magnetization (IRM) acquisition, and hysteresis loops. These measurements were completed at the Physics Department Paleomagnetic Laboratory at the University of Alberta.

4. Paleomagnetic results

4.1. Dunzhugur Formation, Middle—Late Riphean

We sampled 6 sedimentary sites at 3 localities (locality 5, 7 and 8) and two sills (locality 6-1 and 6-2). The total number of studied samples was 60. Although sills cut through sediments, the outcropped contacts have not been found in the field and therefore the baked contact test is unavailable. Sediments have been sampled, however, in a few dozen meters from the sills, and the thickness of the sills is from a few first meters to a dozen of meters.

IRM acquisition experiments were dominated by saturation magnetizations of between 250 and 300 mT, in both sediment and diabase (Fig. 4) samples. We interpret these results to show that the natural remanent magnetization (NRM) is most likely carried by magnetite grains.

A low temperature component (component A) (Figs. 4 and 5, Table 1) was defined between 20 °C and 300–400 °C on the basis of PCA analysis of the stepwise thermal demagnetization data. This magnetic component has a northerly declination and steep downward inclination in *in-situ* coordinates, and displays only normal polarity for both sediments and diabases. The average direction of component A using *in-situ* coordinates is $D=17.6°$, $I=67.1°$ ($\alpha95=11.1°$, $N=8$ sites), which is very close to the present day geomagnetic field (PDF) direction in the region ($I_{PDF}=71.3°$, $D_{PDF}=-0.4°$). We therefore conclude that component A is a recent overprint (Fig. 6). The medium temperature component (MTC) is noticeably present in 7 samples within the temperature range between 250 and 300° and 400 and 450°C (Fig. 5A). The MTC component is always observed to have a negative inclination but is very scattered. Because of the inconsistency in this component we do not interpret it and have focused on a higher temperature magnetic component, component B_{DF}.

The high temperature component (component B_{DF}) was isolated during thermal demagnetization steps between 400 and 600 °C (Fig. 5) and always displays shallow inclinations and declinations directed to the northeast (Fig. 6). Increasing magnetic susceptibility values at temperatures above 520—540 °C are typical of approximately 80% of the thermally demagnetized samples, and interpreted to indicate mineralogical changes occurring within the samples during demagnetization resulting from thermal oxidation. Only one polarity was observed at all sampled sites (Table 1).

The average of 8 component B_{DF} site directions of this component (Table 1, and Fig. 6) is $D_g=7.0°$, $I_g=-23.2°$ ($k=27.2$, $\alpha95=10.8°$) *in-situ* coordinates, and $D_s=28.9°$, $I_s=-7.1°$ ($k=23.7$, $\alpha95=11.6°$) in tilt-corrected coordinates (6 sites from sediments and 2 sites from sills). No fold test could be performed on these populations due to the similar bedding orientation of the sampled sediments, the absence of a reversal test, and the unavailability of a baked contact test. Although component B_{DF} is a reconnaissance result, it is the only presently available paleomagnetic result from a well-dated unit of ~1020 Ma age.

The similarity of sill and sediment directions could be interpreted either to be the result of regional overprinting caused by later tectonics and metamorphism, or as recording a short time interval between sediment deposition and later sill intrusion. Radiometric dating of the sills has not been successful, although their age is currently considered to be only marginally younger than sediments (Kuzmichev, 2004). The sills have the same bedding orientation as the intruded sediments. Because of the absence of metamorphism or clearly observed evidence for reheating of the sediments by sills in the sampling locality, we cannot rule out the possibility that the higher temperature component B_{DF} could represent a primary magnetization of ~1020 Ma or slightly younger age. Nevertheless, given the reconnaissance nature of our field work in this region and the lack of evidence in favor of the primary nature of the high temperature component, we prefer to interpret the component B_{DF} as the complete remagnetization of the Dunzhugur sediments and interbedded sills by later tectonic processes.

Table 1
Site-mean paleomagnetic directions for the low (A) and high (B_{DF}) temperature components of magnetization of the Dunzhugur Formation (52.0°N, 100.5°E).

Locality–site	*n*	D_g	I_g	D_s	I_s	*k*-value	α_{95}	Polarity
A component								
5-1	6d	52.0	56.4	–	–	14.5	18.2	N
(Sediment)		–	–	306.5	35.5	15.9	17.3	
5-2	4d	10.3	63.4	–	–	95.7	9.4	N
(Sediments)		–	–	310.6	8.5	68.8	11.2	
5-3	7d	334.0	54.8	–	–	10.5	19.6	N
(Sediments)				309.6	−14.2	9.8	20.3	
6-1								
(Diabases)	10d	5.4	67.6	302.7	10.3	27.1	9.5	N
6-2	11d	348.4	66.4	–	–	9.2	16.0	
(Diabases)		–	–	300.4	20.1	4.5	24.4	N
7	10d	6.6	62.2	–	–	43.9	7.4	
(Sediments)		–	–	299.1	31.1	32.3	8.6	N
8-1	9d	83.0	69.9	–	–	16.0	13.3	
(Sediments)		–	–	265.9	53.5	11.5	15.9	N
8-2								
(Sediments)	3d	45.5	65.7	297.2	34.2	98.0	12.5	
Overall	8/70	17.6	67.1	–	–	25.8	11.1	N
Mean	Sites/samples	–	–	300.8	22.9	12.1	16.6	
B_{DF} *component*								
5-1	5d	17.8	−16.2	–	–	38.9	12.4	N
(Sediments)		–	–	26.4	5.2	75.9	8.8	
5-2	5d	17.6	−16.9	–	–	43.4	11.7	N
(Sediments)		–	–	29.7	2.4	39.0	12.4	
5-3	7d	4.6	−34.4	–	–	21.8	13.2	N
(Sediments)		–	–	44.2	−9.2	19.1	14.2	
6-1								
(Diabases)	10d	343.7	−38.0	46.4	−28.6	24.3	10.0	N
6-2	8d	357.6	−8.8	–	–	57.9	7.3	N
(Diabases)		–	–	11.5	−17.2	59.7	7.2	
7	7d	12.8	−15.9	–	–	20.1	13.8	N
(Sediments)		–	–	18.3	5.0	18.2	14.5	
8-1	9d	17.1	−35.7	–	–	114.1	4.8	N
(Sediments)		–	–	34.9	−3.0	25.3	10.4	
8-2	6d	1.8	−16.9	–	–	20.5	15.2	N
(Sediments)		–	–	21.7	−12.5	32.5	11.9	
Overall	8/50	7.0	−23.2	–	–	27.2	10.8	N
Mean	Sites/samples	–	–	28.9	−7.1	23.7	11.6	

Locality/site and lithology sampled, (*n*) number of sites and samples, which contributed directions (*d*) or great circles (cc) in the calculation of the site-mean, coordinates of geographic (*in-situ*) declination and inclination (D_g, I_g) and stratigraphic declination and inclination (D_s, I_s), Fisher estimate of kappa (*k*-value), and the half angle radius of the 95% probability confidence cone (α_{95}), observed polarity normal (N) or reverse (R).

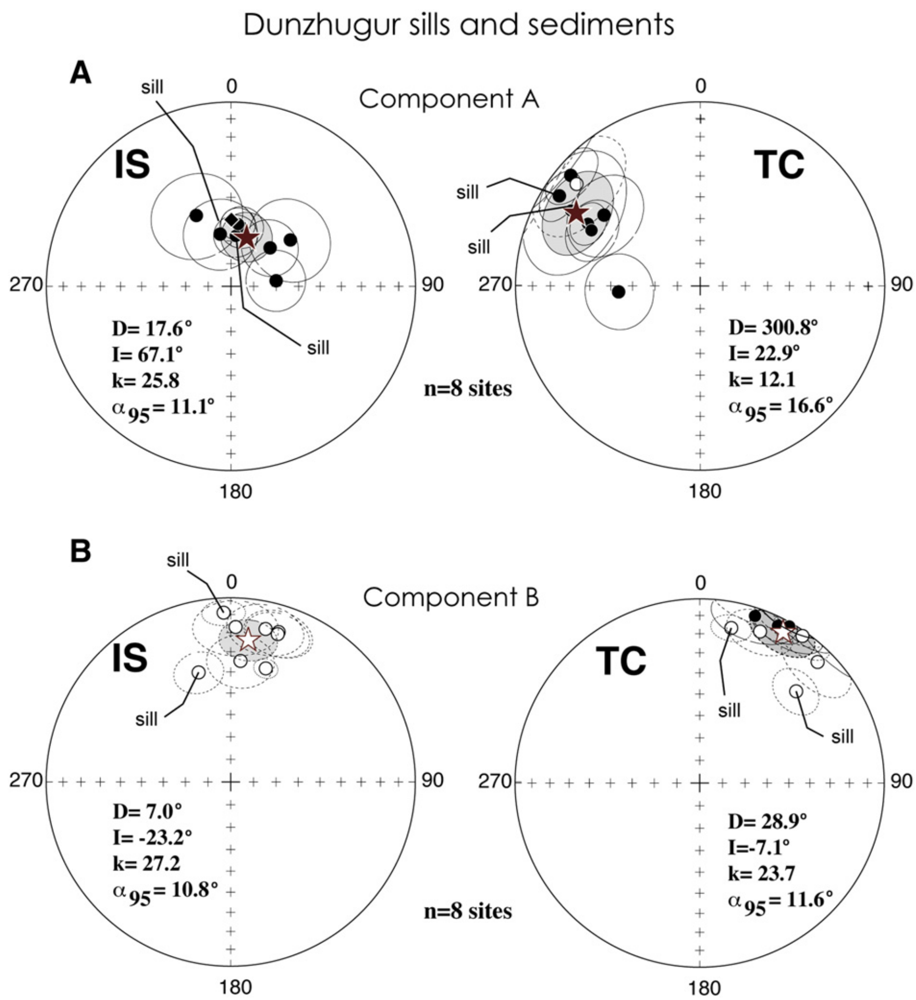

Fig. 6. Equal-area projections of Dunzhugur Formation sediment and sill site-mean directions of low (A) and high (B) temperature components, calculated at the site level, with their α_{95} circles of confidence, shown in *in-situ* (IS, left) and tilt-corrected (TC, right) coordinates. Closed (open) symbols: downward (upward) inclinations. Stars: formation mean direction.

Following Kuzmichev et al. (2001), the Dunzhugur arc and seafloor volcanics have a long and complex tectonic history in the study area, which includes a suprasubduction episode between 1000 and 800 Ma, collision and obduction at 800 Ma, another suprasubduction episode at 790 Ma, and then accretion of the Oka prism at 790–700 Ma. It is unlikely that this prolonged tectonism, lasting into the Cambrian, had not left a magnetic imprint on the Dunzhugur Formation. We, therefore, assume at this stage of the study that the magnetization of the Dunzhugur is an overprint and likely to be much younger than 1020 Ma.

4.2. Bokson Formation of Ediacaran–Early Cambrian age

During thermal demagnetization experiments we observed substantial viscous magnetization in the dolomite samples. In addition, these samples were only very weakly magnetized and exhibited unstable magnetic directions during stepwise thermal or alternating field demagnetization. Because of these factors, it was not possible to distinguish any consistent stable magnetic components from the dolomite samples and therefore these data were excluded from further analysis.

The paleomagnetic samples from the bauxite-bearing horizon of the Tabinzurta Formation were stable during stepwise demagnetization and we have studied 6 localities (17 sites, 107 samples). Fig. 7 illustrates thermal demagnetization behavior (A, C), hysteresis loop (B, D), isothermal remanent magnetization (IRM) acquisition curves (E), and Curie point thermomagnetic curves *Js(T)* (F) for two samples (B016T3 and B199F1). Both the thermomagnetic curves (*Js*(*T*)) and IRM acquisition experiments are dominated by hematite characteristics with a Curie point at 675 °C and a continuous increase of IRM intensity above an applied field of 100 mT. We also observed a small inflexion in the thermomagnetic curve (Fig. 7F, sample B199F1) at about 580 °C, which we interpret to suggest that component B could be carried by a small fraction of magnetite and/or large-grain size hematite. We also observe that the thermomagnetic curve (Fig. 7F) is not reversible, and displays a sharp increase in magnetization intensity upon cooling. This behavior is typical of redbed samples, in which heating may produce new magnetite by mineralogical changes occurring at high thermal demagnetization temperatures (Dunlop and Özdemir, 1997). This type of magnetic property behavior had been noted for Siberian platform redbeds of late Ediacaran age in an earlier study (Kravchinsky et al., 2001). The shape of the hysteresis curve is compatible with a relatively narrow distribution of single or pseudo-single domain grains.

Stepwise thermal demagnetization of the redbed samples can be interpreted with respect to the presence of two magnetic

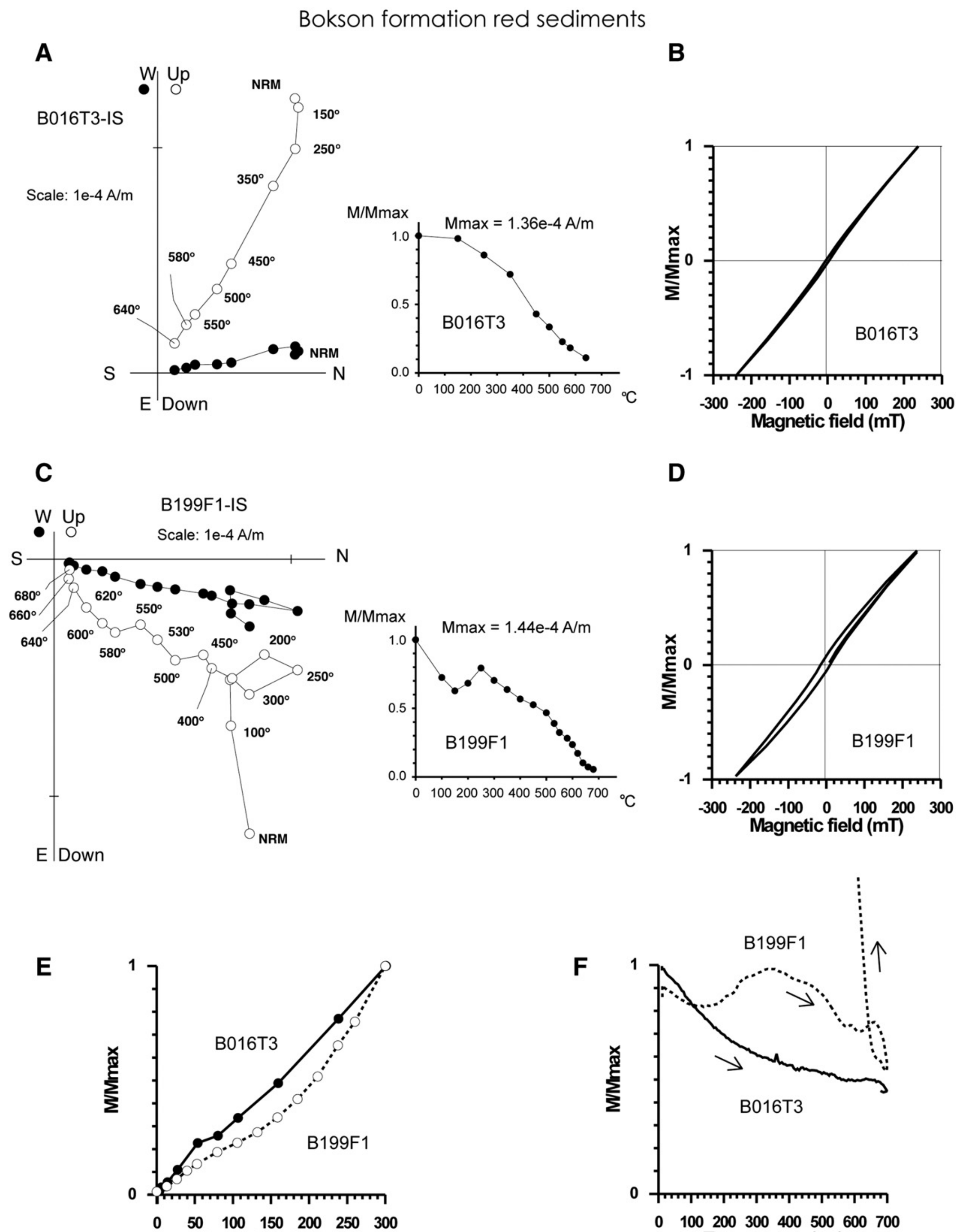

Fig. 7. Results of thermal and alternating field demagnetization, and rock magnetic experiments for the Bokson Formation (Tabinzurtin Suite) bauxites. A and C — thermal demagnetization and magnetic intensity decay curves for samples B016 and B199F1. B and D — hysteresis loops for the same samples. E — normalized IRM acquisition curves for samples B016 and B199F1. F — Curie point thermomagnetic curves $J_s(T)$ for the same samples. Same abbreviations as Fig. 6.

components (Figs. 7 and 8) for 69 of the 115 samples (17 sites). The lower unblocking temperature component, component A, was observed at all localities except at locality 1 (Table 1). Component A observed in sites 15-1, 15-2, 15-3, and 15-4 quite scattered so we have combined the directions to calculate an average for locality 15.

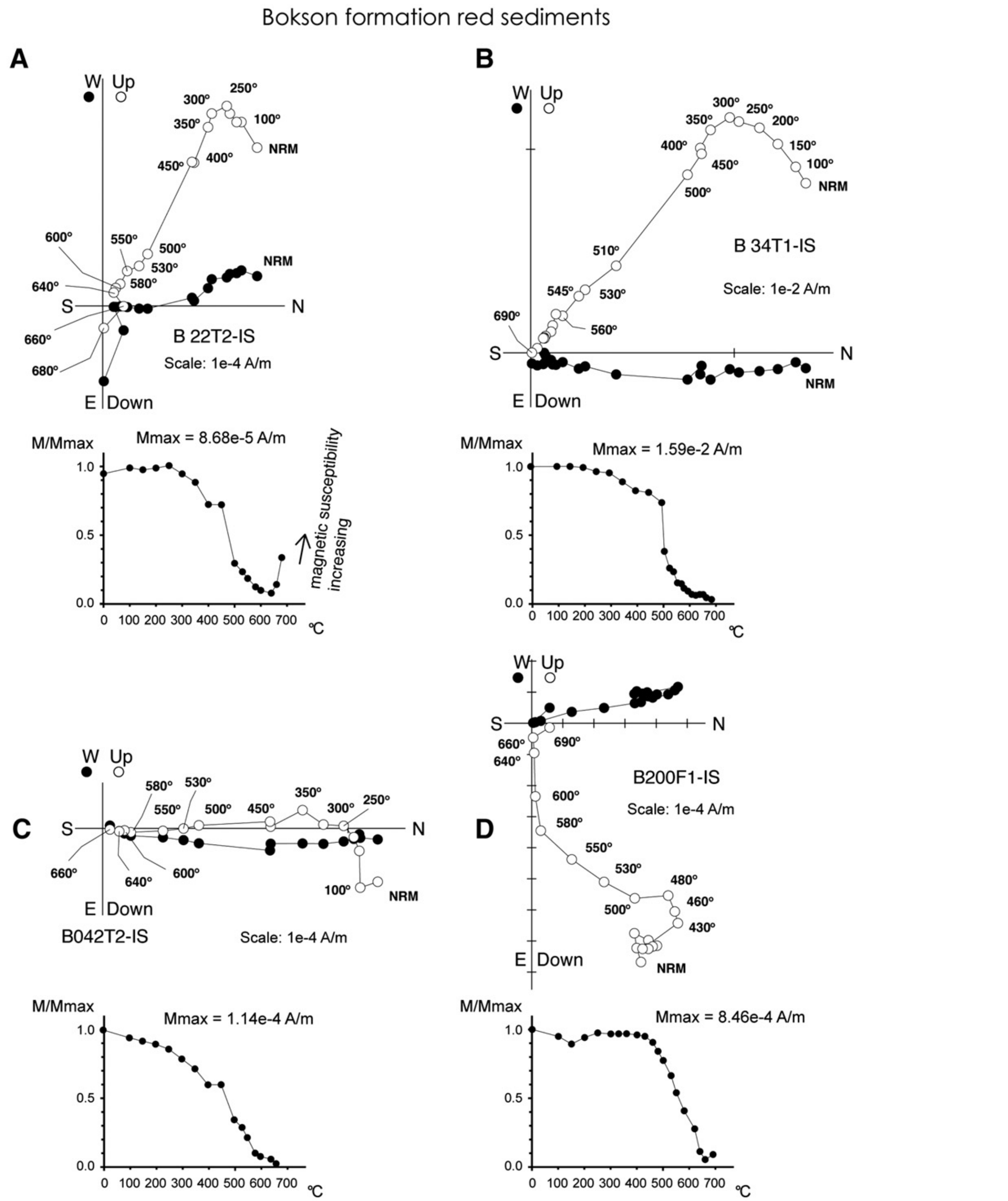

Fig. 8. Results of thermal demagnetization and magnetic intensity decay curves for Bokson Formation (Tabinzurtin Suite) bauxites. Magnetic susceptibility and intensity increasing indicate magnetomineralogical transformations during the thermo-demagnetization experiment. Same abbreviations as Fig. 6.

The mean direction of the component A for the whole formation was observed between thermal demagnetization steps from 20 °C to 200–400 °C, and was always of downward directed inclination, and when Fisher averaged using *in-situ* coordinates has $D_g = 356.5°$, $I_g = 68.8°$ ($k = 49.4$, $\alpha_{95} = 8°$, 8 sites; Fig. 9A). This *in-situ* direction is very similar to the expected PDF direction earlier discussed. In addition, the significant decrease in the precision parameter k of the average direction during unfolding from *in-situ* coordinates ($k_g/k_s = 10.1$) indicates that the fold tests of McElhinny (1964) and Enkin (2003) are negative at 95% probability for these 8 sites. We consider that the component A represents a PDF overprint on the basis of these observations (Table 2).

After removing component A during stepwise thermal demagnetization we could isolate a higher unblocking temperature component, component B_{BF}, in demagnetization temperature ranges between 200° and 400 °C and 600° and 700 °C (Fig. 8). An increase in sample magnetic susceptibility above a temperature of 620 °C was observed in less than 10% of the measured samples. An intermediate unblocking temperature magnetic component could only rarely be isolated (for example in sample B200F1 shown in Fig. 8D) and the scatter of these rarely observed components was very large. We therefore did not interpret any intermediate unblocking temperatures from these samples.

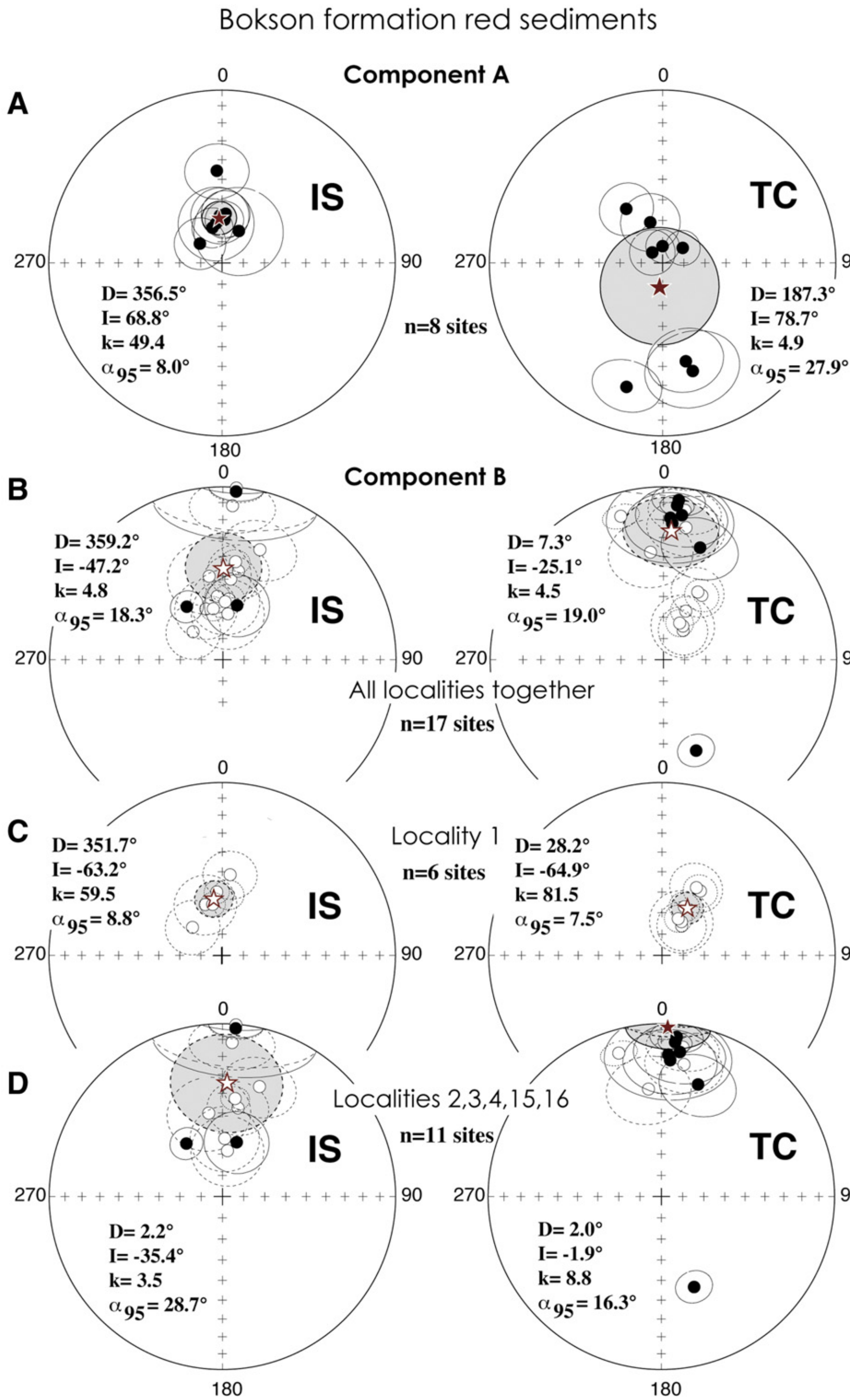

Fig. 9. Equal-area projections of Tabinzurtin Suite bauxites. Site-mean directions of low (A) and high (B) temperature components, calculated at the site level, with their α_{95} circles of confidence, shown in *in-situ* (IS, left) and tilt-corrected (TC, right) coordinates. C — 6 sites of the locality 1 in *in-situ* coordinates. D — 12 selected sites with tilt-corrected coordinate best fitting (localities 2, 3, 4, 15, and 16). Same abbreviations as Fig. 8.

The mean component B_{BF} direction for all 17 sites has a very low precision parameter ($k = 4.5$, see Fig. 9B) and is quite scattered in both geographic and stratigraphic coordinates, although within each particular locality this component is well clustered with associated tilt-corrected coordinate precision parameter, *k*, varying between 6.2 and 24.5 (Table 3). We could not apply the fold test within localities because the bedding was generally homoclinal at each sampling locality. Nevertheless, we are able to apply the fold test at the inter-locality level if locality 1 is separated from the remainder. The stepwise thermal demagnetization characteristics observed from this locality are quite different from the other studied samples, specifically there were no low or mid temperature components and only component B_{BF} is present. The bauxite horizon has the largest thickness compared with the other localities and the regular layering of the red sandstones is not always easy to observe in the field. The direction of component B_{BF} is also different from other sites at this locality and has a steep negative inclination in both *in-situ* and tilt-corrected coordinates with $k_s/k_g = 1.37$ (Table 3, Fig. 9C). This yields

Table 2
Site-mean paleomagnetic directions for the low temperature (A) component of magnetization of the Tabinzurta Suite (52.0°N, 100.5°E).

Locality–site	n	D_g	I_g	D_s	I_s	k-value	α_{95}	Polarity
A component								
2	7d	357.5	67.6	–	–	21.4	13.4	N
				326.2	59.1	24.3	12.5	
3-1	6d	356.8	45.6	–	–	23.8	14.0	N
				343.2	70.0	24.7	13.8	
3-2	6d	3.2	69.6	–	–	57.2	8.9	N
		–	–	359.9	82.1	74.6	7.8	
4-1	5d	344.8	72.8	–	–	66.3	9.5	N
				53.1	78.2	87.7	8.2	
4-2	5d	4.2	66.7	–	–	47.6	11.2	N
				315.8	83.1	52.4	10.7	
15-1 ÷ 15-4	23d	311.3	76.2			7.3	12.1	N
		–	–	196.2	26.3	5.6	14.1	
16-1	11d	27.7	73.0	–	–	5.7	20.9	N
		–	–	164.4	35.4	6.1	20.1	
16-2	6d	351.4	71.2	–	–	15.5	17.6	N
				166.7	41.2	17.7	16.4	
Overall	8/69	356.5	68.8	–	–	49.4	8.0	N
Mean	Sites/samples	–	–	187.3	78.7	4.9	27.9	

Same abbreviations as defined in Table 1.

an inconclusive fold test at the 95% probability following McElhinny (1964) and Enkin (2003) and we cannot therefore be sure which coordinate system is preferable. We interpret this component as a possible remagnetization of the bauxite horizon at locality 1 during one of the tectonic processes that has influenced the region. This is supported by the observation that the bauxite layer is folded and cut by minor strike-slip faults and the larger thickness of this horizon at location 1 could also be a signature of tectonic reworking of the outcrop.

In contrast to the first locality, component B_{BF} from other five localities (2, 3, 4, 15 and 16) clusters better in tilt-corrected coordinates. The average direction in tilt-corrected coordinates is: $D=2°$, $I=-1.9°$ ($k=8.8$, $\alpha_{95}=16.3°$, 11 sites, see Table 3 and Fig. 9D). The fold test is positive at the 95% level with $k_s/k_g=2.45$ with a maximum unfolding at 80.9% (McFadden, 1990). The fold test of Enkin (2003) is also positive.

Only one site, 15-1, has reversed polarity, and we cannot therefore apply the reversal test of McFadden and McElhinny (1988) and the angular separation between the normal polarity sites and the reversed polarity site is 127.8°. We therefore interpret the component B_{BF} for localities 2, 3, 4, 15 and 16 as possibly a pre-folding primary component based on the positive fold test and one reversed polarity site. The thick carbonate sediments appeared to be unsuitable for paleomagnetism, so the thin bauxite horizon is a uniquely well-dated layer suitable for obtaining a possible Ediacaran–Early Cambrian paleomagnetic pole for the Eastern Sayan.

Table 3
Site-mean paleomagnetic directions for the high temperature (B_{BF}) component of magnetization of the Tabinzurta Suite (52.0°N, 100.5°E).

Locality–site	n	D_g	I_g	D_s	I_s	k-value	α_{95}	Polarity
B_{BF} component								
Locality 1								
1-1	6d	313.3	−70.8	–	–	28.4	12.8	N
				34.0	−73.4	35.0	11.5	
1-2	4d	5.6	−61.1	–	–	164.3	7.2	N
		–	–	30.8	−54.3	139.8	7.8	
1-3	6d	355.1	−59.8	–	–	138.1	5.7	N
		–	–	24.7	−64.7	93.5	7.0	
1-4	5d	341.6	−64.7	–	–	29.4	14.4	N
				30.0	−71.7	27.6	14.8	
1-5	8d	349.4	−65.5	–	–	91.9	5.8	N
				23.9	−71.1	76.0	6.4	
1-6	5d	5.6	−51.3	26.9	−53.8	41.5	12.0	N
Overall	6/34	351.3	−63.2	–	–	59.5	8.8	
Mean	Sites/samples	–	–	28.2	−64.9	81.5	7.5	
Localities 2, 3, 4, 15, 16								
2	9d	3.6	−11.7	–	–	11.7	15.7	N
		–	–	8.2	−13.7	15.4	13.6	
3-1	8d	10.0	−46.8	–	–	17.8	13.5	N
				9.7	−23.5	14.0	15.4	
3-2	7d	350.7	−49.5	–	–	11.6	18.5	N
				353.2	−37.4	12.3	17.9	
4-1	5d	4.5	−0.4	–	–	71.0	9.1	N
		–	–	5.5	8.0	65.3	9.5	
4-2	4d	4.5	2.7	–	–	11.3	28.5	N
				2.8	18.9	15.0	24.5	
15-1	6d	14.7	63.4	–	–	21.2	14.9	R
				160.1	43.7	69.3	8.1	
15-2	9d	6.3	−68.2	–	–	10.3	16.8	N
		–	–	7.3	16.8	9.6	17.5	
15-3	6d	2.3	−62.5	–	–	18.9	15.8	N
		–	–	3.7	22.0	14.2	18.4	
15-4	5d	7.4	−42.3	5.1	11.3	154.3	6.2	N
16-1	4d/5 cc	18.6	−33.3	–	–	12.4	15.7	N
				18.1	32.3	11.8	16.2	
16-2	4d	325.9	59.6	–	–	145.9	7.6	N
				343.5	−14.5	174.9	7.0	
Overall	11/67	2.2	−35.4	–	–	3.5	28.7	
Mean	Sites/samples	–	–	2.0	−1.9	8.8	16.3	

Same abbreviations as defined in Table 1.

5. Discussion

Using component B_{DF} we have calculated a paleomagnetic pole for both sediments of the Dunzhugur Formation and closely associated intrabedded sills (Table 4). For this result, unfortunately, there are no paleomagnetic reliability tests to constrain the origin of the B_{DF} component. As mentioned earlier in this manuscript, because component B_{DF} is observed in both sediments and sills it may be explained either by rather a short time gap between the sedimentary sequence formation and sill intrusions, suggesting a primary magnetization origin for B_{DF}, or by complete remagnetization of sediments during sill intrusion, or by later overprint of both.

Here we choose a model in which a complete remagnetization of both sediments and sills has occurred, this constrains the age of the B_{DF} component to be much younger than 1020 Ma (the age of the ophiolite sequence). The paleomagnetic pole for component B_{DF} in tilt-corrected coordinates is 29.3°S/66.9°E (with semiaxes of the 95% confidence ellipse about the paleomagnetic pole of dp/dm = 5.9°/11.7°) and *in-situ* coordinates is 25.6°S/92.9°E (with semiaxes of the 95% confidence ellipse about the paleomagnetic pole of dp/dm = 6.1°/11.5°) (Fig. 10). The paleolatitudinal position of the Tuva-Mongolian terrane can then be calculated as 12.1°S ± 6.1°.

Relative tectonic rotation of the Tuva-Mongolian terrane about a vertical axis could place the Dunzhugur *in-situ* pole anywhere on an appropriate positioned small circle (Fig. 10). The comparison of this pole location with observed APWP poles from the Siberian platform taken from the recent overview of Cocks and Torsvik (2007) (Fig. 10) shows that the small circle of possible positions for our result intercepts Siberian APWP at 450–460 Ma. For reference we also show Ediacaran–Early Cambrian poles of the Siberian platform selected by Pisarevsky et al. (2008) and list these poles in Table 4. The small circle of the Dunzhugur pole intercepts the majority of Ediacaran–Early Cambrian Siberian poles (Fig. 10). At the same time there is a considerable disagreement between Siberian Ediacaran–Early Cambrian poles which is still not explained; it allows us to perform only preliminary comparison. Overall we may conclude that the possible remagnetization age of the Dunzhugur sediments and sills is Ediacaran–Early Cambrian or Upper Ordovician.

For the Ediacaran–Early Cambrian component B_{BF}, we have calculated two poles: one for locality 1 and one for localities 2, 3, 4, 15, and 16. Considering the component B_{BF} locality 1 to be remagnetized, we calculate a pole using *in-situ* coordinates at 7°N/

Table 4
Selected Precambrian paleomagnetic poles from the Siberian platform and Tuva-Mongolian composite terrane.

No.	Age (Ma)	Geological age	Pole latitude	Pole longitude	A_{95} (dp/dm)	Area/geological formation	Authors
Siberian platform							
1	537	Early Cambrian	−40.5	157.4	–	Mean pole for Siberian platform	Cocks and Torsvik (2007)
2	542–630	Ediacaran–Early Cambrian	−33.7	37.2	12.7	Minya Formation, Chaya River, South Siberia	Kravchinsky et al. (2001)
3	542–630	Ediacaran–Early Cambrian	−32.0	71.1	13.8	Shaman Formation, Irkut River, South Siberia	Kravchinsky et al. (2001)
4	542–630	Ediacaran–Early Cambrian	−2.7	168.2	9.2	Lena River redbeds, South Siberia	Pisarevsky et al. (2000)
5	608–618	Ediacaran	−25	121	14/28	Biryusa dykes, South Siberia	Metelkin et al. (2005)
Tuva-Mongolian block							
11	545–518	Early Cambrian	−21.4	167.1	9.6/19.1	Bayan-Gol Formation	Kravchinsky et al. (2001)
12	518–630	Ediacaran–Early Cambrian	−27.9	48.2	6.5/13	Urigal-Gol, Udzeltu-Gol Rivers, West. Mongolia	Pechersky and Didenko (1995)
13	548–590	Ediacaran	−35.5	37.6	3.5/6.7	Udzeltu-Gol River, Western Mongolia	Pechersky and Didenko (1995)
14	420–440	Age of remagnetization (420–440 Ma)	7.0	106.7	10.9/13.9	Location 1; Tabinzurta Suite Eastern Sayan, Russia	This study
15	518–630	Ediacaran–Early Cambrian	−38.9	97.9	8.2/16.3	Locations 2, 3, 4, 15, and16. Tabinzurta Suite, Eastern Sayan, Russia	This study
16	518–630	Ediacaran	−22.8	28.4	10.8/21.6	Tsagan-Olom formation	Kravchinsky et al. (2001)
17	<1020 possibly	Upper Early Riphean	−25.6	92.9	6.1/11.5	Dunzhugur fm. (sediments and basalts), Eastern Sayan, Russia	This study

Notes: No.: number of pole corresponding to Figs. 10 and 11; Age: age of sampled units; Pole latitude, Pole longitude: latitude, longitude of the paleomagnetic pole; A_{95} (dp/dm): radius of the 95% confidence circle (semiaxes of the 95% confidence ellipse) of the virtual paleomagnetic pole.

106.7°E (dp/dm = 10.9°/13.9°) although there is little change in spatial position when applying the tilt correction. The position of the locality 1 paleomagnetic pole is very close to a remagnetized pole from Early Cambrian Mongolian sediments of 4°N/115°E (A_{95} = 4.6°, Evans et al., 1996, Fig. 11).

Comparing our *in*-situ pole and the pole of Evans et al. (1996) with the Paleozoic part of the Siberian APWP (Cocks and Torsvik, 2007), we suggest that a possible remagnetization process took place around 420–440 Ma in the Eastern Sayan and Mongolia. It is too early to speculate about the precise nature of this remagnetization on the basis of just one locality, more data are required for the future discussion.

Another component B_{BF} pole calculated in tilt-corrected coordinates for localities 2, 3, 4, 15, and 16 (38.9°S/97.9°E; dp/dm = 8.2°/16.3°) from the Tabinzurta Suite is compared to Ediacaran–Early Cambrian selected poles from the global paleomagnetic database

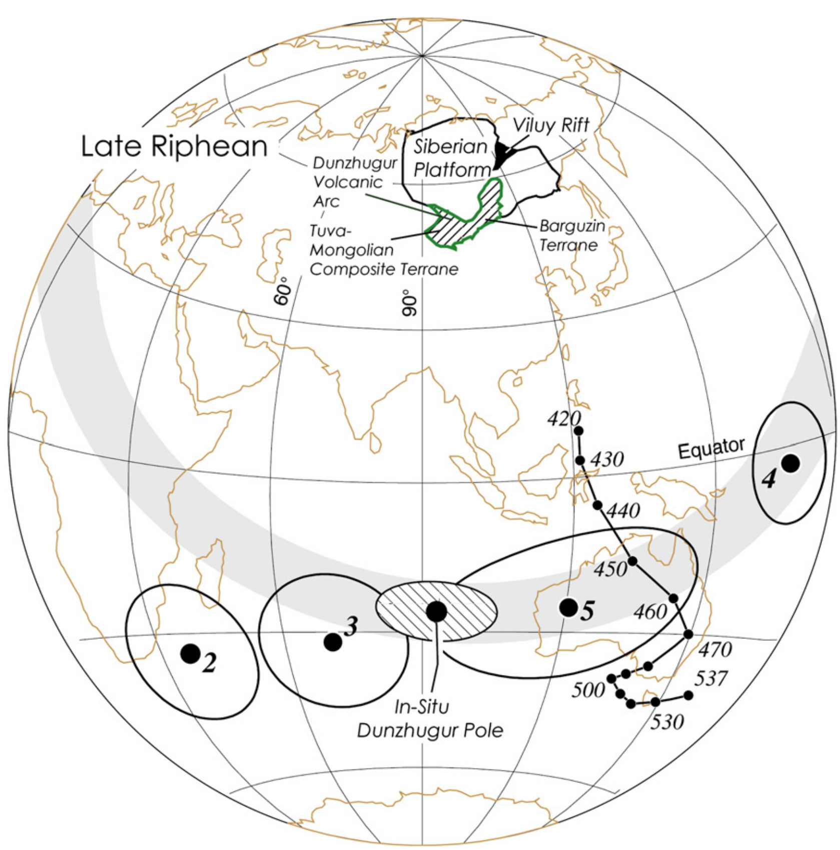

Fig. 10. Equal-area projection of Late Riphean Dunzhugur Formation paleomagnetic pole for Tuva-Mongolian terrane and the Siberian platform paleomagnetic poles of approximately corresponding age (see Table 4) with their 95% ellipses of confidence. Small gray circle illustrates possible rotation of the Dunzhugur Formation pole. The small circle does not intercept the poles with ages of >1000 Ma indicating that Tuva-Mongolian terrane could be close to Siberia but most likely separated from it.

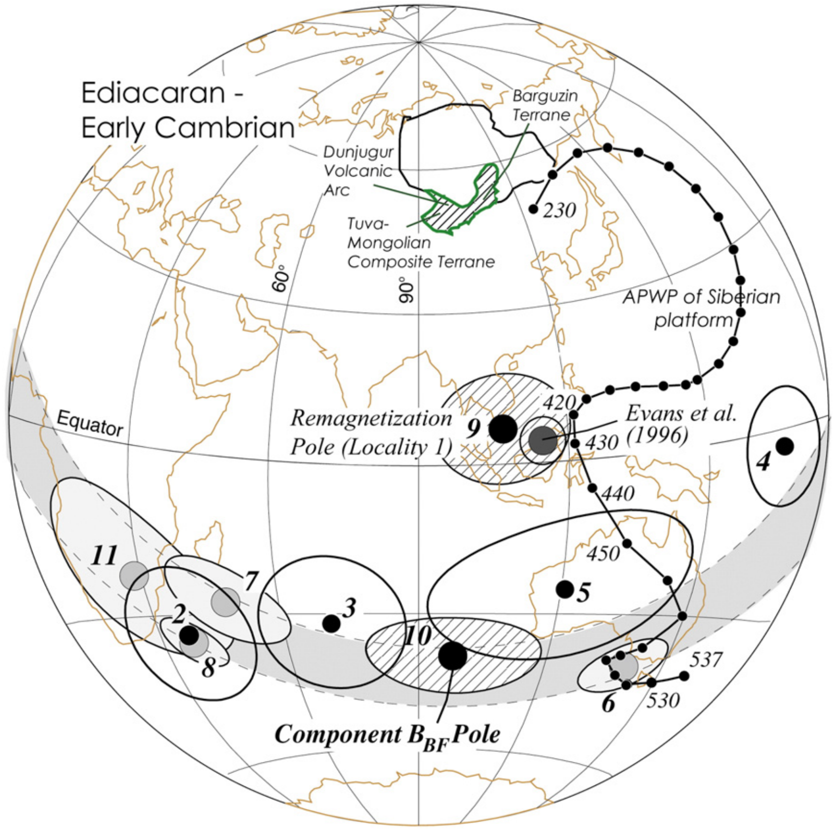

Fig. 11. Equal-area projection of Ediacaran–Early Cambrian paleomagnetic poles for the Tuva-Mongolian terrane (from Table 4), with their 95% ellipses of confidence. Small black dots are the Siberian platform APWP from Cocks and Torsvik (2007) with ages indicated in Ma. Siberian platform reference poles for 540–620 Ma are from Table 4. The small gray circle illustrating possible relative rotation of Tabinzurtine Suite intercepts other Mongolian reference APWP poles of the same age supporting an already formed single Tuva-Mongolian terrane. At the same time the small circle does not intercept Siberian poles of similar ages (540–550 Ma) indicating that Tuva-Mongolian terrane was possibly not fully accreted to the Siberia platform.

version 4.6 (see Fig. 11 and Table 4). The B_{BF} paleomagnetic pole is in agreement with the analogous Ediacaran Tsagan-Olom Suite and Early Cambrian Bayan-Gol Suite poles from the southern part of the Tuva-Mongolian terrane if to assume that the magnetization was acquired before considerable rotations occurred in the region, i.e. to rotate the B_{BF} pole along the small circle shown in Fig. 11. Large tectonic rotations could have taken place but all the paleomagnetic poles from the sediments lie along a small circle with the pole of rotation in the central region of the Tuva-Mongolian terrane. The observed paleolatitude of the Tabinzurta Suite (1.0°S ± 8.2°) corresponds to a paleoposition of the Tuva-Mongolian terrane derived from other locality paleomagnetic poles from Table 4.

Paleomagnetic poles of Ediacaran–Early Cambrian age for the Siberian platform are quite scattered and problematic (see the relevant discussion in Cocks and Torsvik, 2007 and Pisarevsky et al., 2008). Following Pisarevsky et al. (2008) we have chosen to use only four Siberian platform poles (Table 4). Comparison of the Tabinzurta pole with analogous age poles of the Siberian platform illustrates that the confidence circle radii for the Siberian poles overlap with the small circle for the Tuva-Mongolian terrane (Fig. 11). Using this comparison we may confirm an earlier conclusion of Kravchinsky et al. (2001) that the Tuva-Mongolian terrane and the Siberian platform occupied closely adjacent positions in the Ediacaran–Early Cambrian. Large relative post Early Cambrian rotations took place because the poles are spread along the small circle of rotation for the Tabinzurta Suite (Fig. 11). From paleomagnetic data alone we can not firmly speculate about a still open or already closed oceanic space between the two continents. We prefer a model in which the Tuva-Mongolian terrane was already accreting with the Siberian continent in the Ediacaran and probably connected to the Siberian continent by the Ediacaran. Continued collision processes, however, could have taken place in the Late Cambrian and subsequent times and been responsible for further shortening, folding and relative rotation of different parts of the Tuva-Mongolian terrane, both relative to each other, and to the Siberian continent.

Fig. 12 illustrates reconstructions for the Ediocarion–Early Cambrian that summarize our paleomagnetic results. The paleopositions of Laurentia and the North China terrane are taken from Li et al. (2008) and the Siberian platform from Pisarevsky et al. (2008). The Siberian platform is shown in the configuration before the Viluy rift opening (Pavlov et al., 2008). The Tuva-Mongolian terrane paleoposition is taken from this paleomagnetic study result and the Barguzin terrane reconstruction that incorporates the tectonic reconstruction of the Olkhon terrane (the present day marginal part of the composite Barguzin terrane) from Gladkochub et al. (2008). There are no reliable paleomagnetic data with which to reconstruct the paleoposition of the highly metamorphic Barguzin terrane composed from the island-arc and back-arc volcanics and sediments (Zorin et al., 2009). At the present day, the Olkhon terrane is situated between the Barguzin terrane and the Siberian platform (Fig. 1).

Gladkochub et al. (2008) and Zorin et al. (2009) discuss an option for the successive accretion of the smaller oceanic terranes of different age and composition (including island-arc and back-arc basin complexes) alongside the Siberian platform margin to generate a larger Barguzin terrane to the east of Lake Baikal in present day coordinates. Alternatively Gladkochub et al. (2008) suggest that the Barguzin terrane could already have existed as a composite tectonostratigraphic terrane before the accretion with the Siberian

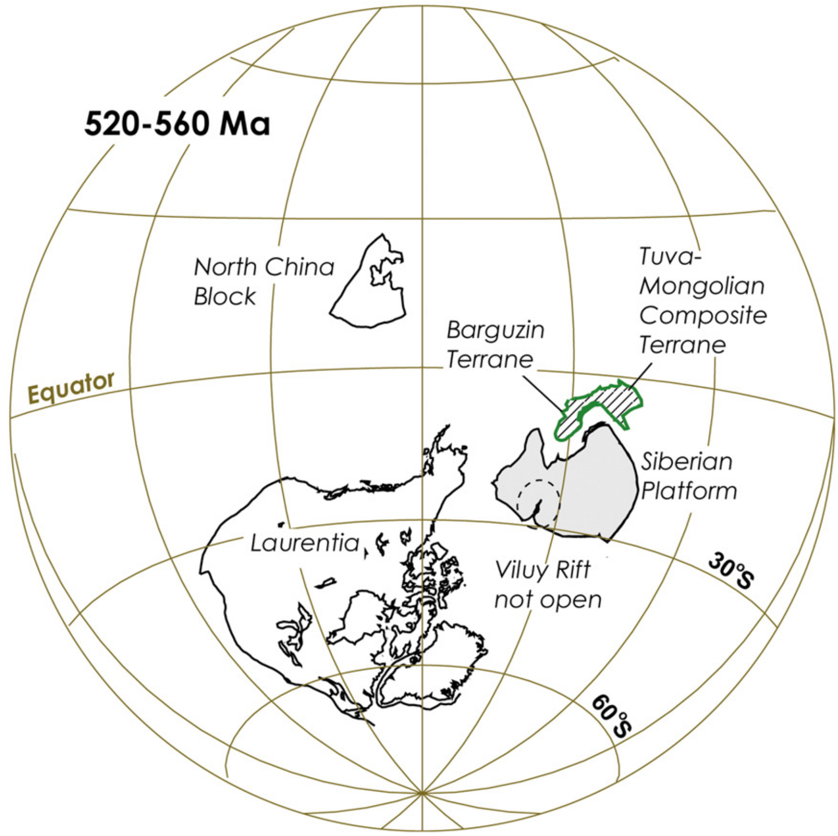

Fig. 12. Tentative reconstructions of relative paleoposition of the Tuva-Mongolia terrane and the Barguzin terrane relatively to Siberia, Laurentia and North China. The paleoposition of Laurentia and North China platforms is taken from Li et al. (2008) and of the Siberian platform from Pisarevsky et al. (2008). Siberian platform is shown in the configuration before the Viluy rift opening (after Pavlov et al., 2008).

platform, although Zorin et al. (2009) doubt such possibility. The petrological and geochronological data of Gladkochub et al. (2008) support an age of accretion of the smaller oceanic terranes of different age with the Siberian platform at approximately ~500 Ma, although collisional processes could have occurred after this time. In Fig. 12 on the reconstruction for Ediacaran–Early Cambrian we show the Tuva-Mongolian and the Barguzin composite terranes in their present day relative configuration and attached to each other for simplicity, although their relative position and attachment are only speculative. The Tuva-Mongolian terrane is shown in the close proximity to the Siberian platform; the paleomagnetic data, however, allow some spacing between both continental blocks. Probably the Tuva-Mongolian terrane was in the final stage of accretion with Siberia.

Kuzmichev et al. (2001) alternatively suggested that a detachment of the Tuva-Mongolian terrane from the Siberian platform took place around 650–550 Ma. Although the paleomagnetic data does not allow us to fully accept or exclude the alternative interpretation of Kuzmichev et al. (2001), the close position of the Ediacaran–Early Cambrian paleomagnetic poles for Siberia and Tuva-Mongolia (Fig. 11) suggests that there was no considerable latitudinal difference between the Siberian platform and the Tuva-Mongolian terrane by the beginning of the Phanerozoic. Therefore in our reconstruction on Fig. 12 we display Tuva-Mongolia in the closest position to Siberia.

Our finding implies some additional features for the recent Ediacaran–Early Cambrian reconstructions (Li et al., 2008; Pisarevsky et al., 2008). While there is common agreement that the present day southern Siberian margin could face northward, the paleolatitude position of Siberia is uncertain. A model incorporating an adjacent position of Siberia and Tuva-Mongolia during Ediacaran–Early Cambrian suggests the Siberian plate was located in near equatorial latitudes rather than middle latitudes. That could be an important factor to take into account when evaluating possibilities for interaction between major continental blocks neighboring Siberia during that period (Laurentia and the Russian platform with the Baltica shield).

6. Conclusion

New reconnaissance paleomagnetic data from the Tuva-Mongolian terrane suggest that amalgamation of the Eastern Sayan, Tuva and central part of the Mongolian terranes (possibly also with the Barguzin terrane) occurred before the Ediacaran–Early Cambrian because available paleomagnetic poles for this time interval plot along the same small circle (see Fig. 11). Collisional processes continued after the accretion event, leading to the relative rotations of the tectonostratigraphic terranes expressed as a dispersion of the poles along the small circle. The relatively large age uncertainties for the Tabinzurta Formation and Siberian poles do not enable us to make more precise reconstructions, however we hope future paleomagnetic work will result in a clearer understanding of the paleogeography and tectonic history of this region.

Acknowledgments

The authors wish to sincerely thank to N.L. Dobretsov and M.I. Kuzmin for their help in the beginning of the study. We are thankful to K.M. Konstantinov, A.V. Tyzhinov, V.N. Medvedev, A.M. Rogachev and S.V. Sherstyannikov for their participation and help in the field trip. M.Z. Khuzin, A.S. Zasipkin, and N.A. Sadovnikova measured samples in Irkutsk. Special thanks to J.-P. Cogné (Institut de Physique du Globe de Paris) and R. Enkin (Geological Survey of Canada) who provided their paleomagnetic software. Constructive and scrupulous assessment of R. Van der Voo, J.D.A. Piper and an anonymous reviewer helped us to improve the manuscript considerably. Part of the project was completed with the financial support of the Natural Sciences and Engineering Research Council of Canada and the Siberian Branch of the Russian Academy of Sciences.

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