JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 105, NO. B6, PAGES 13,509-13,518, JUNE 10, 2000

Siluro-Devonian paleomagnetic results from the Tuva Terrane (southern Siberia, Russia): implications for the paleogeography of Siberia

V. Bachtadse,[1] V. E. Pavlov,[2] A. Y. Kazansky,[3] and J. A. Tait[1]

Abstract. New paleomagnetic data from seven sections of Siluro-Devonian age sedimentary sequences in the Tuva Terrane (south Siberia, Russia) reveal the presence of up to three different components of magnetization. Component A is of recent or Late Mesozoic-Cenozoic origin, and component B, identified unambiguously in 25 samples from one section, yields a sample mean direction (Declination/Inclination) of 300.6/-54.7 ($k = 42.2$, $\alpha_{95} = 4.5°$) in geographic and 283.9/-63.5 ($k = 45.4$, $\alpha_{95} = 4.3°$) in stratigraphic coordinates. However, since the results of the fold test are inconclusive, no further attempt has been made to assign an age to this magnetization. Component C, with unblocking temperatures of 500°-680°C, is identified in all seven sections and with dual polarity. After bedding correction, the section mean directions all plot along a common small circle in stereographic projection with a mean inclination of 42.1° ($N = 7$ sites, $k = 184.2$, $\alpha_{95} = 2.9°$). It passes the inclination-only fold test, the within-site fold test (both on the 95% significance level) and the reversal test and is thus interpreted as being primary in origin and Siluro-Devonian in age. Adopting the normal polarity option for component C yields a paleolatitude of 24° N (± 2°) for the Tuva Terrane. On the basis of geological evidence, the Tuva Terrane was clearly accreted to Siberia by early Silurian times. The results obtained in this study, therefore, indicate lower paleolatitudes for Siberia than those predicted from previously published Apparent Polar Wander Paths for the Siberian Platform and demonstrate that Siberia was positioned between the equator and 30° N during latest Silurian/earliest Devonian times. These new results are also supported by paleoecological and paleoclimatological evidence. The dispersion of declinations along a small circle is indicative of clockwise block rotations within the Tuva Terrane of up to 72° with respect to Siberia.

1. Introduction

The paleogeographic position of Siberia during Siluro-Devonian times is still unclear and a matter of debate. Whereas paleomagnetic data [*Khramov*, 1991; *Khramov and Rodionov*, 1980] indicate a position of southern Siberia between 40° and 50° N, the geographical occurrence of climatically sensitive sediments [*Scotese and McKerrow*, 1990], and the distribution of stromatoporoids [*Nestor*, 1990], gastropods [*Blodgett et al.*, 1990], rugose corals [*Pedder and Oliver*, 1990], algae [*Poncet*, 1990] and miospores [*Streel et al.*, 1990] point toward a significantly lower paleolatitude and a peri-equatorial position of Siberia during the mid-Paleozoic. In a recent paper, *Smethurst et al.* [1998] published an Apparent Polar Wander Path (APWP) for Siberia which indicates a shift of southern Siberia from 30° to 60°N between 435 and 360 Ma (absolute ages and using the timescale of *Harland et al.*[1990]). Unfortunately, however, no paleomagnetic data are available for the intervening time interval, i.e., from mid Silurian to mid Carboniferous times. Therefore, there is a need for new paleomagnetic data to fill this gap in order to differentiate between various paleogeographic models.

[1]Institut für Allgemeine und Angewandte Geophysik, Ludwig-Maximilians-Universität München, München, Germany

[2]United Institute of Physics of the Earth, Russian Academy of Science, Moscow, Russia

[3]United Institute of Geology, Geophysics and Mineralogy, Russian Academy of Sciences, Siberian Branch, Novosibirsk, Russia

Paper number 1999JB900429
0148-0227/00/1999JB900429$09.00

2. Late Silurian-Early Devonian Apparent Polar Wander Path for the Siberian Craton and Tuva Terrane

Despite the large number of paleomagnetic studies that have been carried out on the Siberian Platform and its surroundings, reliable data for the Paleozoic cover of Siberia are still rather sparse [*Smethurst et al.*, 1998]. Most of the paleomagnetic data for Siberia are accessible only through catalogue listings such as the Global Paleomagnetic Database (GPMDB [*McElhinny*, 1998]) and do not fulfill *Van der Voo*'s [1993] third reliability criterion, which requires adequate demagnetization and proper vector analysis of the results. Thus a substantial part of the Siberian data set is only of rather limited use for the construction of a reliable APWP during the mid-Paleozoic. In a recent paper, *Smethurst et al.* [1998], using the data available, constructed an APWP for Siberia. However, given the sparse and often poorly constrained data set and as discussed by the original authors, the mid-Paleozoic segment of this APWP can only be considered as a first approximation. This is particularly true for the Ordovician to Carboniferous segment which is basically anchored by the mid-Ordovician data of *Torsvik et al.* [1995] and a cluster of paleopoles of Late Devonian/Early Carboniferous age, the intervening time period being at present reliant on data of rather dubious quality.

For the Tuva Terrane itself, which had accreted to Siberia by Silurian times, only one paleomagnetic result is available, obtained from Upper Silurian-Lower Devonian red sediments [*Pogarskaya*

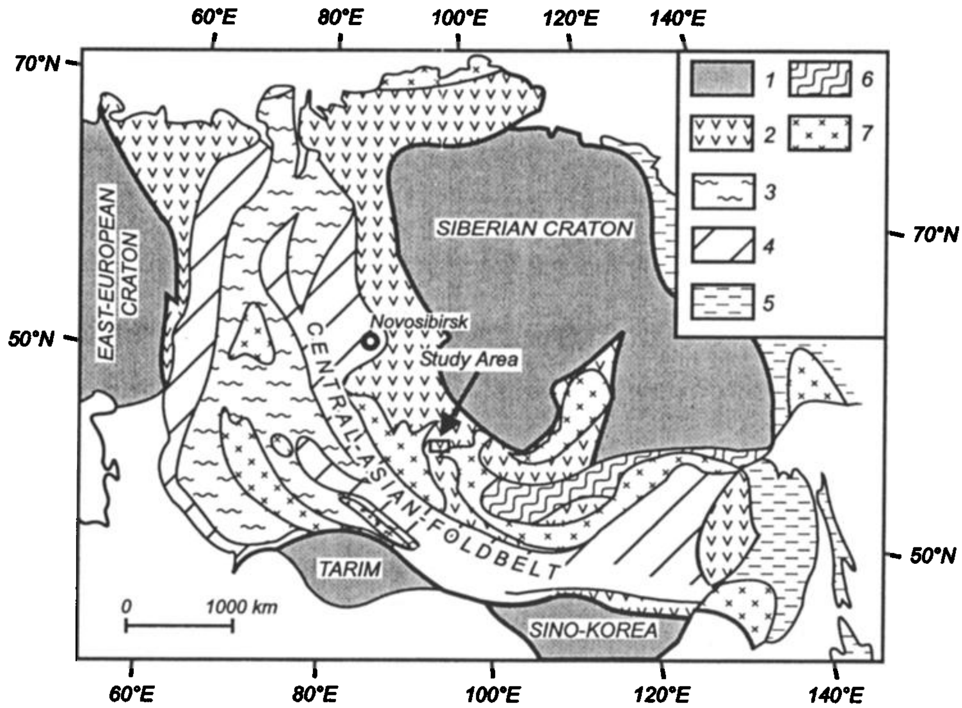

Figure 1. Simplified tectonic map of Siberia after *Berzin et al.* [1994].1, pre-Cambrian cratons; 2-7, accretionary systems with complexes of oceanic crust and island arcs of Late Proterozoic to Cambrian (2), Cambrian - Silurian (3), Ordovician to Early Carboniferous/Permo-Triassic (4), Late Paleozoic (5) and of undetermined Late Paleozoic to Mesozoic (6) age. 7 indicates Microcontinents and Precambrian sialic blocks. Also shown is the study area.

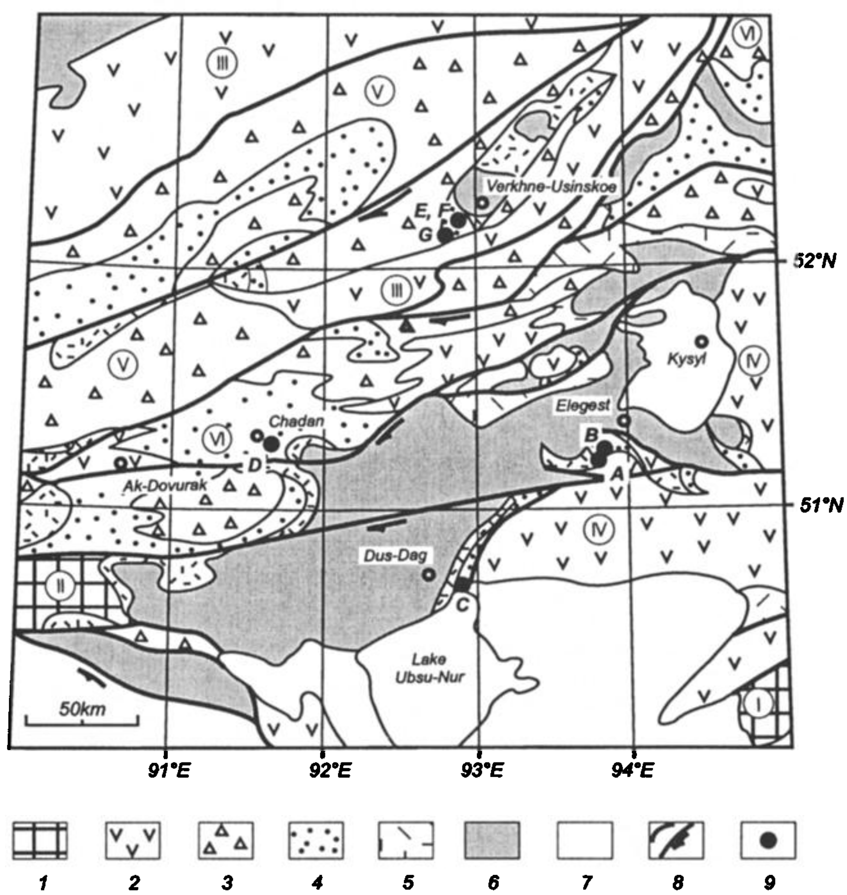

Figure 2. Sketch map of the Tuva and Sayan region, modified after *Berzin et al.* [1994] and *Berzin and Kungurtsev* [1996] 1, Precambrian microcontinents (I, Tuva-Mongolian; II, Mongun-Taiga); 2; Cambrian island arcs (III, North Sayan; IV, Tannu-Ola - Hamsarinskaya); 3, Mid-Cambrian to Late Ordovician collision complexes (V, Central and Western Sayanian zone; VI, Hemchig - Sistighemskaya zone); 4, Mid Ordovician to Silurian passive continental margin complexes; 5, Early Devonian volcanic complexes of an active continental margin; 6, Devono-Carboniferous terrigenous sediments of an active continental margin; 7, Mesozoic - Cenozoic depressions; 8, Major faults, including strike-slip faults; and 9, sampling localities: Elegest1 (A), Elegest2 (B), Kadvoy (C), Chadan (D), Us1 (E), Us2 (F), and Us3 (G).

Table 1. Stratigraphic, Lithological and Structural Data for the Sections Studied.

Section	Location (°N, °E)	Formation	Stratigraphic Age	Lithology	*N*	Strike	dip, deg.
Elegest1 (A)	51.2, 93.8	Baital	Upper Silurian (Pridolian)	grey, greenish-grey, occasionally red fine grained sandstones and siltstones	157	WNW	15-20
Elegest2 (B)	51.2, 93.8	Khondergay	Lower Devonian (Gedinnian)	red siltsones	30	WSW	10-15
Kadvoy (C)	50.7, 92.9	Kuzultash, Khondergay	Upper Silurian (Pridolian) to Lower Devonian (Gedinnian)	red siltstones and mudstones	30	SW	20-35
Chadan (D)	51.3, 91.7		Upper Silurian (Pridolian) to Lower Devonian (Gedinnian)	grey and greenish grey silt- and mudstones, occasionally limestones	37	N,NE	20-40
Us1 (E)	52.2, 92.9	Sosnovy	Upper Silurian (Ludlowian)	grey siltstones, red sandstones	10	N	15-20
Us2 (F)	52.2, 92.9	Sosnovy	Upper Silurian (Ludlowian)	grey siltstones, red sandstones	5	N	30-40
Us3 (G)	52.1, 92.8	Federovka	Upper Silurian (Ludlowian)	red and green sandstones	9	N	70-75

N, number of oriented samples taken at each section. Lettersin brackets in column "section" correspond to site locations in Figure 2. Note that strike and dip have been measured using the left-hand rule

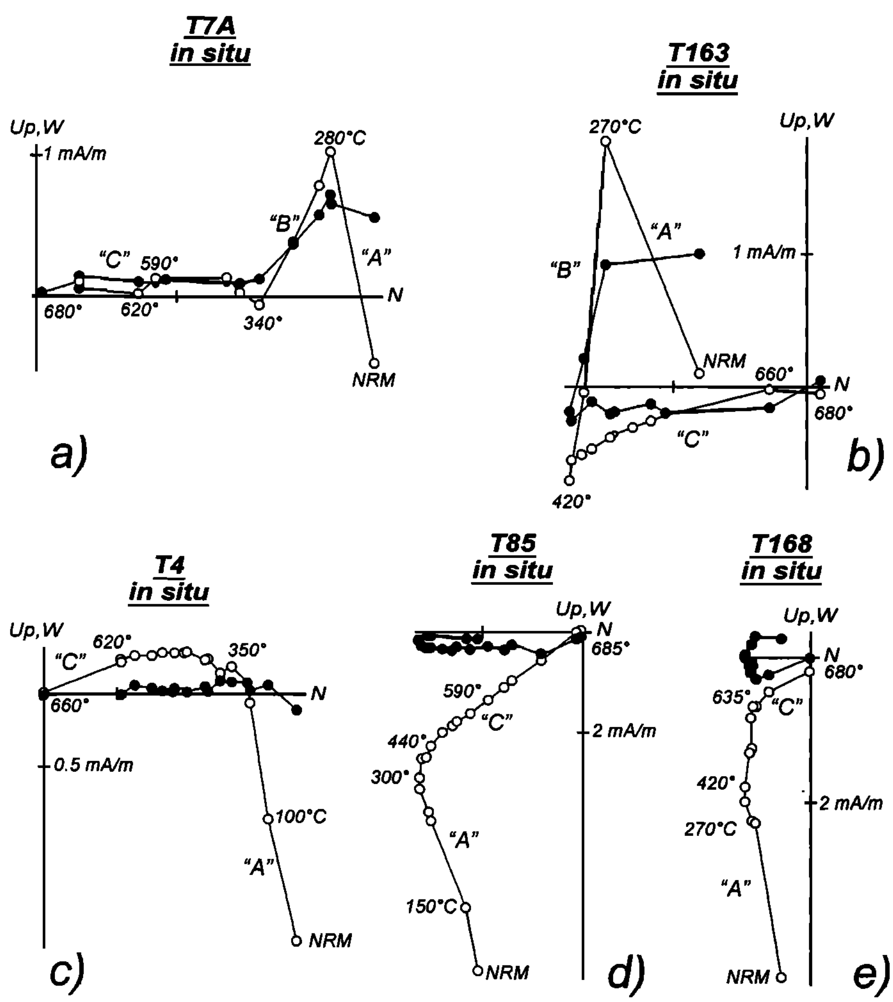

Figure 3. Orthogonal projection [*Zijderveld*, 1967] of stepwise thermal demagnetization results for representative samples from the (a), (b) Elegest2 and (c) - (e) Elegest1 section. Open (closed) symbols represent projections in the vertical (horizontal) plane. "A", "B", and "C" refer to the components of magnetization identified.

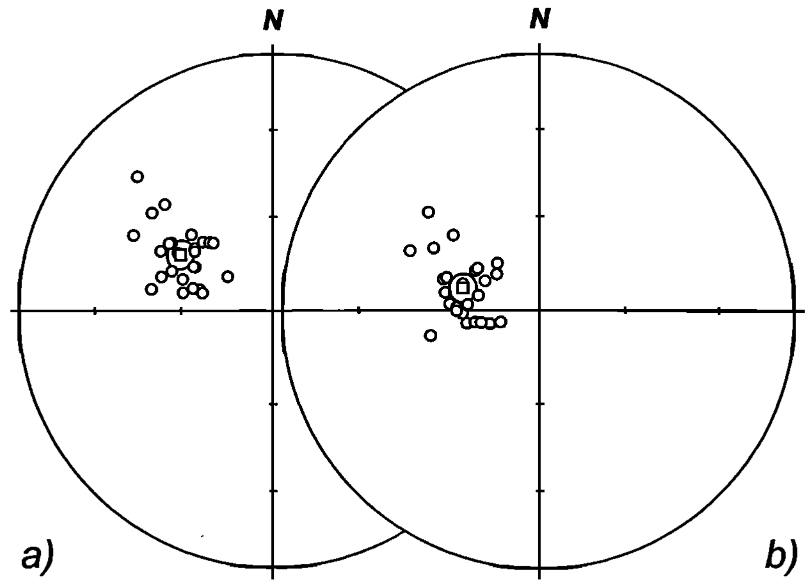

Figure 4. Equal-area projection of sample directions of component B. (a) in situ and (b) after bedding correction. Also shown is the resulting mean direction (square) and the cone of 95% confidence (α_{95}, *Fisher* [1953]). Open symbols are upper hemisphere projections.

and Goncharov, 1982] and which is marked by rather shallow inclinations. Despite the reported presence of normal and reversed polarities, however, the reversal test is negative, and the statistical parameters [*Fisher*, 1953] associated with the resulting mean direction indicate the rather low quality of the data (k = 4, α_{95} = 19°). Furthermore, this pole position is based on only 18 samples from four sites which, according to the information given in the GPMDB, have not been adequately demagnetized. Thus these data do not meet modern quality criteria and cannot be considered reliable. New paleomagnetic data are required to decipher Siberias drift history during Middle Paleozoic times. With this aim, a detailed paleomagnetic study of Siluro-Devonian age sediments from the Tuva Terrane, SW Siberia, has been carried out.

3. Geology and Sampling

The Tuva Terrane forms part of the central Asian Altai-Sayan Foldbelt which is draped around the western and southern margins

Table 2. "Section Mean Directions" for Component B and C

Section	Stratigraphic Age	n/N	N_n	N_r	Geographic coordinates Dec	Inc	k	α_{95}	Stratigraphic coordinates Dec	Inc	k	α_{95}	FT	Paleopole Lat, Long (°N, °E)
Component B														
(A) Elegest1, (B) Elegest 2 combined	S2-D1	25/187		25	300.6	-54.7	42 4	4.5	283 9	-63.5	45 4	4.3	F?	26 3, 144.0
Component C														
(A) Elegest1	S2	60/157	51	9	174 4	20.7	18.9	4 3	173.6	37.6	21 3	4.0	F+,R+	17 5, 100.1
(B) Elegest2	D1	10/30	10		169 3	41 4	22 3	11	173.4	48.6	25.7	9.7	F+	9.0, 99.6
(C) Kadvoy	S2-D1	21/30	17	4	192.1	30 4	15.3	8.4	210.6	37.6	25 3	6.4	F+	13.3, 63.7
(D) Chadan	S2-D1	23/37	21	2	202.5	60.8	6.6	13	156.9	41.8	14 3	8.3	F+	11.9, 113.2
(E) Us1	S2	10/10		10	355.3	-47.3	34.7	8.3	337.7	-43.4	37.1	8.0	F?	10 1, 113.3
(F) Us2	S2	5/5		5	336	-66 0	18.0	19	302.5	-44.5	25 1	15.6	F?	3.0, 142.2
(G) Us3	S2	9/9	9		221.1	-0.4	61.8	6.6	193.1	40.8	60.9	6.7	F?	13.7, 80.4
Mean inclination (Component C)		7				42.1	3.8	21.6		42.1	184.2	2.9		

n/N, number of samples used for calculation of mean direction/number of samples measured; N_n and N_r number of samples with normal and reversed polarity, respectively; k, α_{95} parameters of *Fisher* [1953] statistics; Dec and Inc, declination and inclination (in degrees), respectively. FT, field tests. "F" and "R" denote fold [*McEllhinny*, 1964] and reversal test [*McFadden and McElhinny*, 1990]. The results of field tests are indicated by a cross if positive and a question mark if no significance on the 95% significance level was achieved. Note that the resulting mean inclination for component C and the associated statistical parameters were calculated after *Enkin and Watson* [1996].

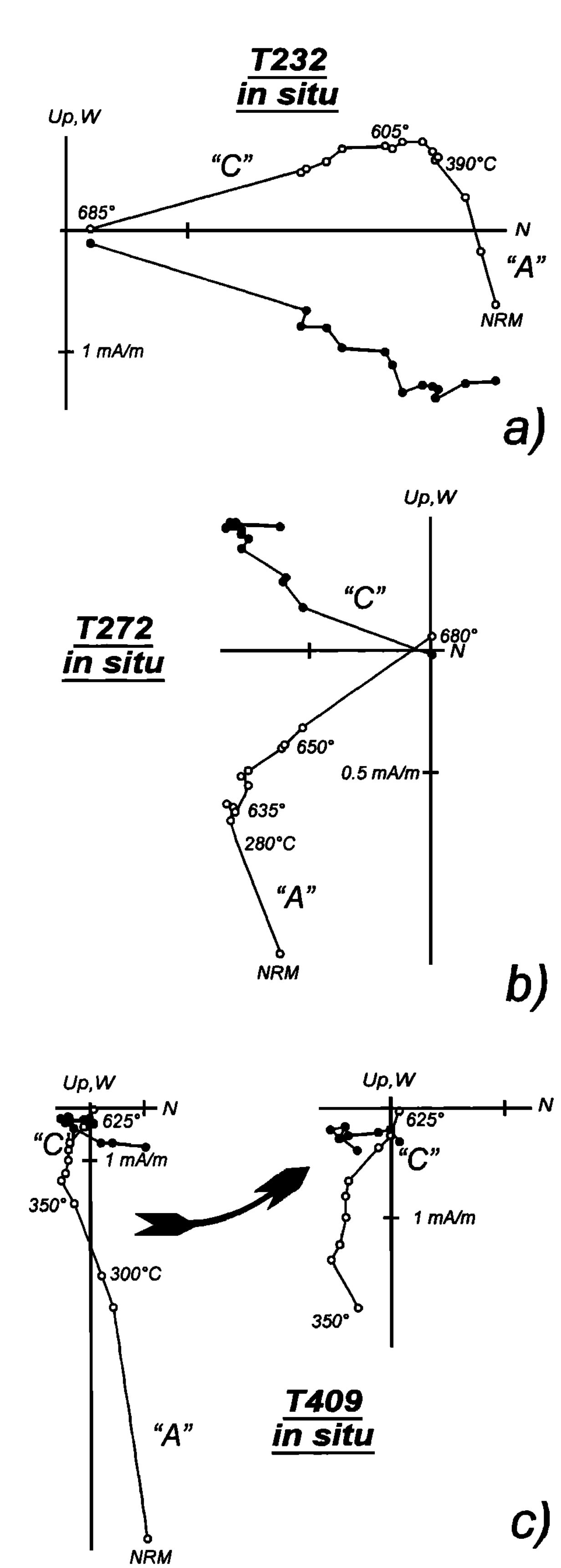

Figure 5: Thermal demagnetization results for representative samples from the (a), (b)Kadvoy and (c) Chadan sections. "A" and "C" refer to the components of magnetization identified. Conventions same as in Figure 3.

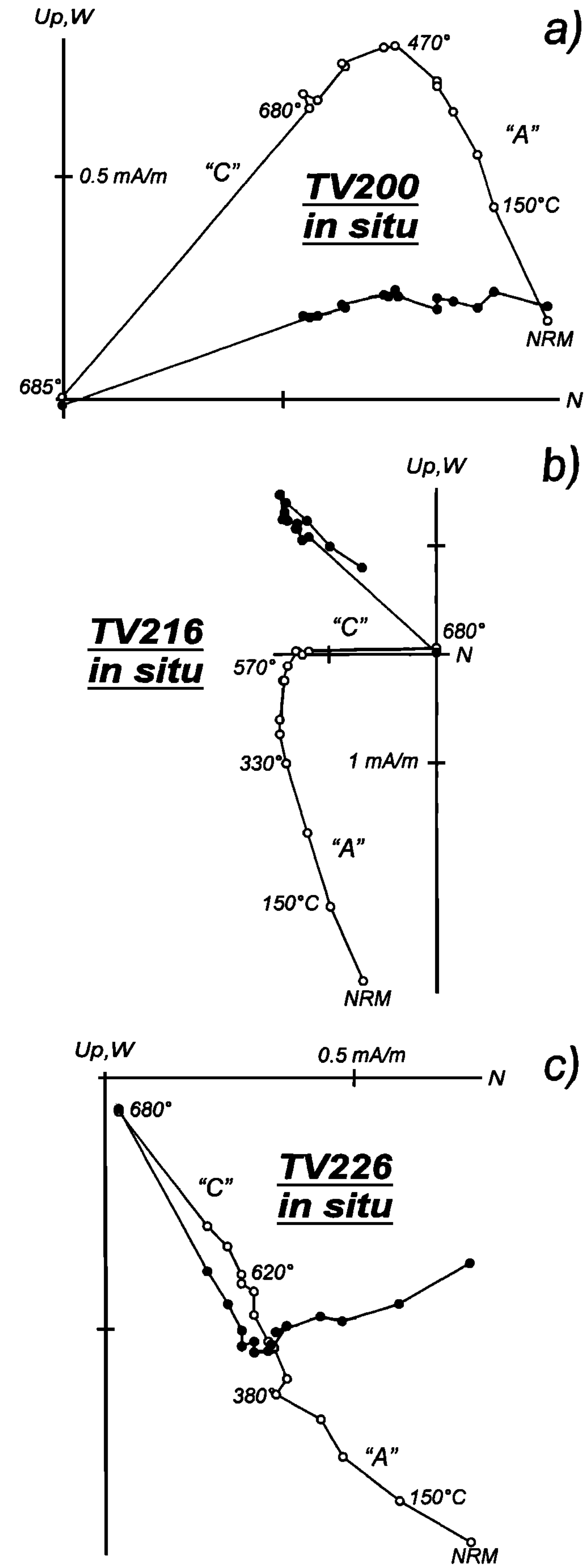

Figure 6. Orthogonal projection of the results of stepwise thermal demagnetization experiments of samples from section (a) Us1, (b) Us2 and (c) Us3. "A" and "C" refer to the components of magnetization identified. Conventions same as in Figure 3.

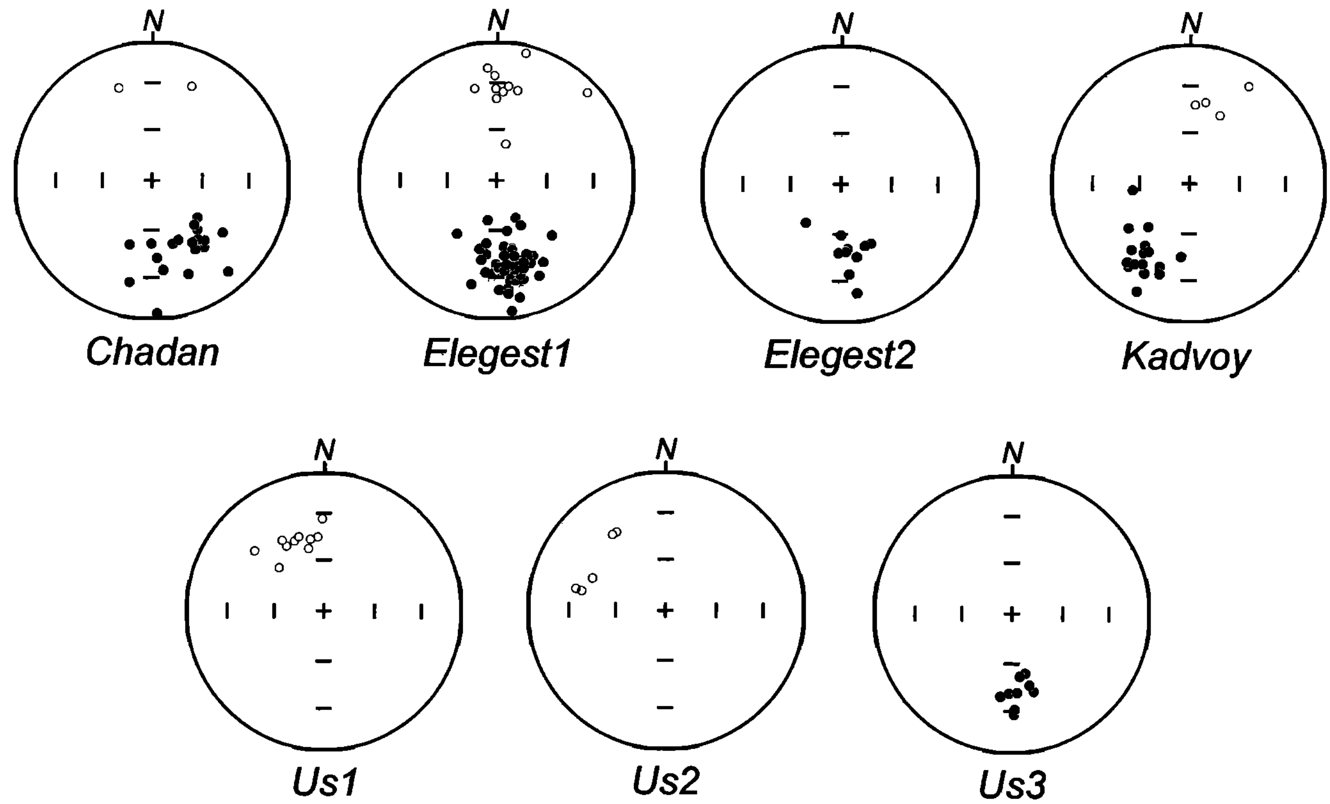

Figure 7. Stereographic projection of the characteristic sample directions identified for component C for the individual sections after bedding correction. Open (solid) symbols are projections on the upper (lower) hemisphere.

of the Siberian Platform (Figure 1). Although a variety of models for the timing and mode of accretion of the Tuva Terrane to the (present day) southern margin of Siberia have been proposed [*Belichenko et al.*, 1994; *Berzin et al.*, 1994; *Berzin and Dobretsov*, 1993; *Didenko et al.*, 1994; *Dobretsov et al.*, 1987; *Dobretsov and Ignatovitch*, 1989; *Mossakovsky et al.*, 1993; *Sengör et al.*, 1993; *Zonenshain et al.*, 1990; *Zorin et al.*, 1994], they all agree that by early Silurian times, the Tuva Terrane had already amalgamated to Siberia.

The Ordovician to Silurian sediments of the Tuva Terrane were deposited in a restricted basin with increasing depth from east to west [*Kulkov et al.*, 1985] in present-day coordinates. Thus the sediments of the easterly sections (Elegest, Kadvoy, Us-River) were deposited in shallow-sea and near-shore environments, whereas the sediments of the western section (Chadan) reflect a deep-sea environment. During the Early Devonian, the sea level was significantly reduced, as marked by the deposition of terrigenous sediments, indicating the transition from littoral to continental conditions. Starting in Late Gedinnian times, the Tuva Terrane acted as an active continental margin and was fragmented into smaller tectonic units, separated by dextral strike-slip faults. From abundant field evidence, however, it is clear that deformation peaked in mid-Carboniferous times [*Zonenshain et al.*, 1990] during the collision of Baltica, Siberia and the Kazakh Terrane Agglomerate in the sense of *Sengör et al.* [1993].

During the field season of 1996 a total of 278 oriented hand samples from five sections at Elegest, Chadan, Kadvoy and Us (Figure 2) were collected by two of the authors (VEP and AYK). The stratigraphic age of these rocks has been established on the base of detailed conodont [*Vorojbitov*, 1992] and brachiopod biostratigraphy [*Kulkov et al.*, 1985]. A brief description of the stratigraphic ages, formations and rock types sampled as well as the structural attitudes is given in Table 1.

4. 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 Department of Geophysics, Munich. All samples were subjected to stepwise thermal demagnetization experiments, reaching maximum temperatures of up to 690°C. Mineral alteration during heating was monitored by measurements of low field susceptibility with a KLY-2 susceptibility bridge after each heating step. The magnetometer, as well as the furnaces used for thermal demagnetization (Schoenstedt, TSD-1) experiments, are housed in a magnetically shielded room to reduce magnetic contamination. The demagnetization results were analyzed using orthogonal vector plots [*Zijderveld*, 1967] and stereographic projections. Linear and planar elements in the demagnetization data were identified by eye and subjected to principal component analysis [*Kirschvink*, 1980].

5. Paleomagnetic Results

Visual inspection of the orthogonal projections reveal the presence of up to three stable components of magnetization. Component A, directed to the north with rather steep downward pointing inclinations, is considered to reflect a magnetic overprint of the local present day or Late Mesozoic/Cenozoic geomagnetic field in the area studied. Maximum unblocking temperatures for compo-

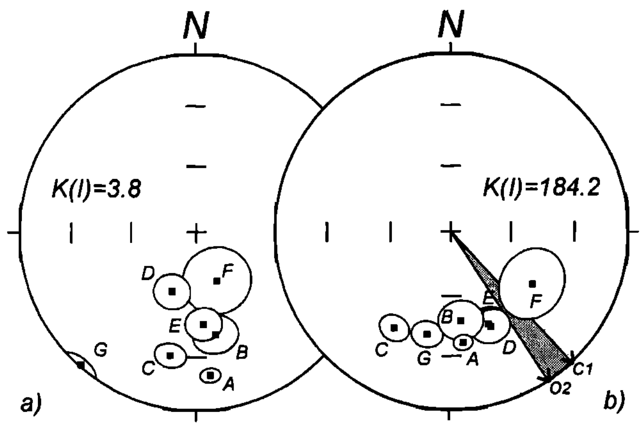

Figure 8. Stereographic projection of the "section mean directions" for component C (a) before and (b) after correcting for structural tilt. Inverse mean directions are converted to normal polarity. Also shown are the cones of confidence for the individual mean directions (α_{95}, [*Fisher*, 1953]). Note the significant increase in *k(I)* after applying the inclination-only fold test [*Enkin and Watson*, 1996]. Letters refer to the individual sections: A, Elegest1; B, Elegest2; C, Kadvoy; D, Chadan; E, Us1; F, Us2; G, Us3. Shaded area in (b) is defined by the expected declination values for mid-Ordovician (O2, declination: 147°) and early Carboniferous (C1, declination: 137°) times for the Tuva Terrane, calculated from reference pole positions for Siberia.

nent A reach 420°C. Component B, identified only in 25 samples from Elegest1 and Elegest2, between temperatures of 270° and 420°C, is directed to the WNW (Figures 3a and 3b) and yields a sample mean direction of 301°/-54° (Declination/Inclination) in geographic coordinates and 284°/-64° after bedding correction (Figure 4, Table 2). Due to only minor differences in bedding attitude between the sections Elegest1 and Elegest2, both the classical *McElhinny* [1964] fold test and the tectonic correlation fold test [*McFadden*, 1990] are inconclusive (Table 2). Thus no further attempts have been made to assign a magnetization age to this component.

A dual polarity component of magnetization, characterized by southerly or northerly declinations with shallow to intermediate inclinations (component C) and maximum unblocking temperatures of 685°C, is identified after heating at 420°C in samples from Elegest1 and 2 (Figure 3), Kadvoy, Chadan (Figure 5), and Us river (Figure 6). The maximum unblocking temperatures of component C (685°C) are in accord with the reddish color of the material studied and the dominance of hematite as carrier of this magnetization. In the Us river sections, component C can be identified in almost 100% of the samples. For the other sections studied (Chadan and Elegest1), however, mineralogical changes at higher temperatures often result in erratic behavior of the magnetization directions. As a result, component C can only be identified in ~15% (Chadan) to 70% (Kadvoy) of the samples measured (see also Table 2).

Despite only minor variations in bedding attitude within the different sections studied (Table 1), the values for *Fisher*'s [1953] precision parameter *k* increase upon unfolding for all sections with the exception of Us3 where no improvement is observed upon unfolding. The observed increase in *k* is significant at the 95% probability level for sections Chadan, Kadvoy, Elegest1, and Elegest2 (Table 2) yielding positive fold tests [*McElhinny*, 1964]. In addition, dual polarity directions are identified in samples from the Chadan, Kadvoy, and Elegest1 sections (Figure 7). Although, not enough observations are available for Chadan and Kadvoy, the reversal test [*McFadden and McElhinny*, 1990] is positive (classification B) for section Elegest1.

In geographic coordinates the section mean directions for component "C" generally yield southerly declinations, after converting to a common, normal polarity (Figure 8a). Upon tilt correction, however, the inclinations converge toward a common mean of about +40° (Figure 8b) but with a large scatter of declination values such that all the mean directions plot along a common small circle. This is indicative for significant rotations about vertical axes of the various sections. Application of the inclination-only fold test [*Enkin and Watson*, 1996] results in an increase of *k* from 3.8 (in situ) to 184.2 (100% bedding corrected) yielding a positive inclination-only fold test on the 95% confidence level (Figure 9). This result, in conjunction with a positive within site reversal test (Elegest1) and the occurrence of dual polarities in the other sections studied, is considered diagnostic for the prefolding age of component C and provides encouraging evidence for the primary character of magnetization. This is also supported by conodont alteration indices which do not exceed values of 2 [*Vorojbitov*, 1992] thus indicating maximum burial temperatures of 140°C [*Epstein et al.*, 1977]. This is not sufficiently high to cause the acquisition of secondary thermal remanent magnetizations (TRM) stable at intermediate to high demagnetization temperatures.

6. Interpretation and Discussion

The resulting paleopole positions for the individual tectonic units of the Tuva terrane, based on component C, plot on latitudes comparable to the one of the lowermost Silurian segment of the

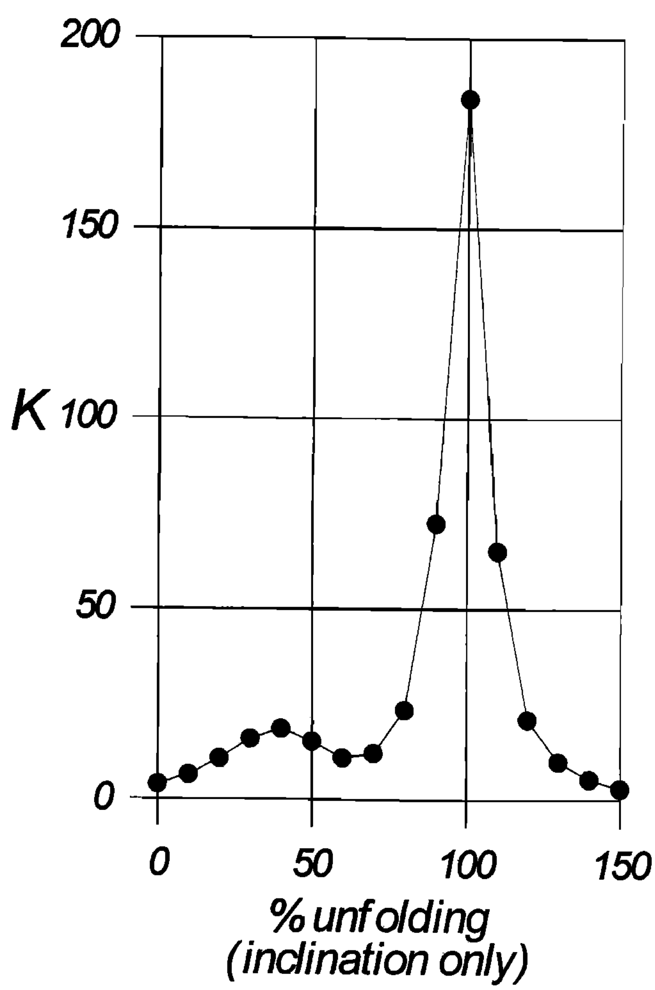

Figure 9. *Fisher*'s [1953] precision parameter *k* for the overall mean inclination (inclination-only fold test, *Enkin and Watson* [1996]) as a function of stepwise unfolding.

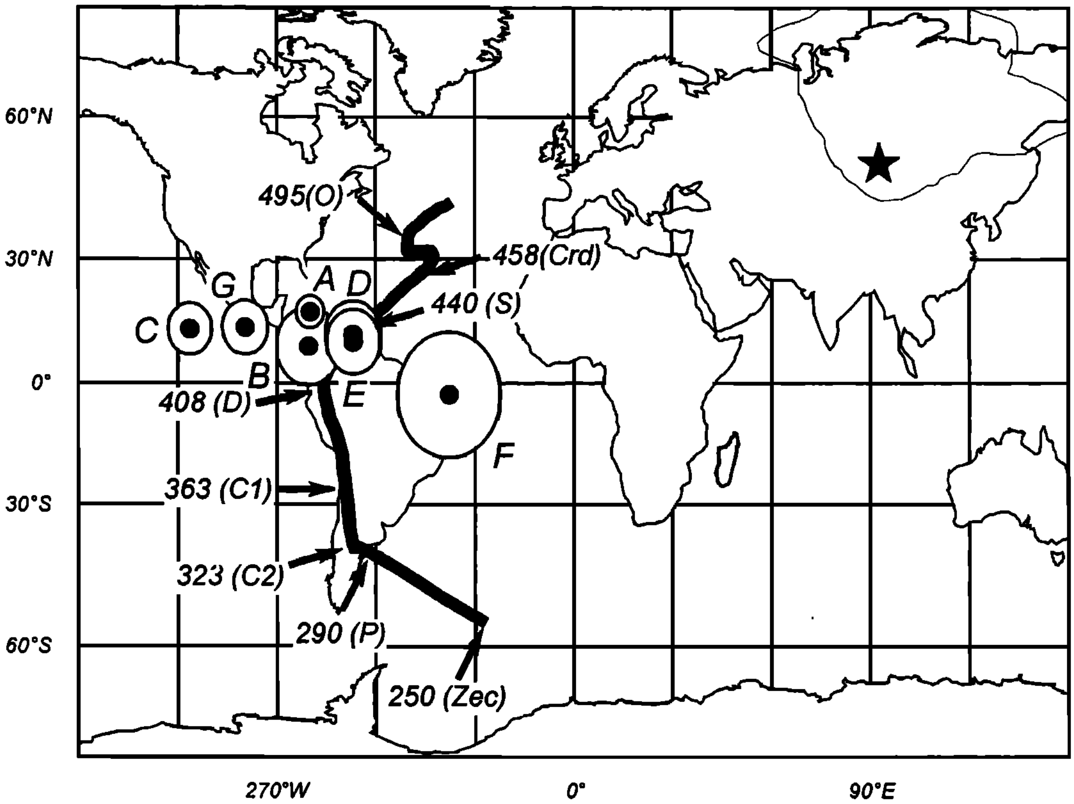

Figure 10. Paleopole positions for the Siluro-Devonian of the Tuva terrane (labeled A to G, see also Table 2). Also shown is the APWP for Siberia [*Smethurst et al.*, 1998] for Ordovician to latest Permian times. Numbers on the reference path refer to time in My. O, Ordovician; Crd, Caradoc; S, Silurian; D, Devonian; C1 and C2, early and late Carboniferous, respectively; P, Permian and Zec: Zechstein. Also shown are the sampling location (star) and the outline of Siberia.

Smethurst et al. [1998] APW path for Siberia (Figure 10). With the exception of the paleopole for the river Us section ("F" in Tables 1 and 2 and on Figure 10), all paleopoles plot either directly on or are displaced to the west of the APW path, defining a small circle path.

On the basis of the structural evidence cited above that by Silurian times the Tuva Terrane formed a coherent part of the Siberian platform, the data presented here can be used to refine the paleogeographic position of Siberia during latest Silurian/earliest Devonian times. The mean inclination for component C of +42° (N = 7 sites, k = 184.2, α_{95} = 2.9°) translates into a paleolatitude of 24° (±2°) for the Tuva region. These new data place Siberia between the equator and 30°N (Figure 11). This is ~20° lower than implied from previously published APWPs for Siberia [*Khramov and Rodionov*, 1980; *Khramov*, 1991] and still 15° lower than the interpolated position of Siberia given by *Smethurst et al.* [1998].

With regards to the possibility of inclination shallowing it is now generally considered that the main controlling factors are the clay content in sediments together with the amount of compaction [see *Kodama*, 1997, and references therein]. In the present study, however, a large variety of sedimentary rocks with varying clay content, ranging from mudstones to coarse grain sandstones, have been studied, but no significant variation of inclination as a function of grain size has been observed. Thus inclination shallowing is very unlikely to have affected our results. Additional support arises from a recent paleomagnetic study of volcanic rocks of early Mid Devonian (Lower Eifelian) age in the Minusa Terrane, yielding a paleopole position of 11°S, 125°E [*Solodovnikov*, 1996]. Geological data indicate that, comparable to the Tuva Terrane, Minusa was amalgamated to Siberia by Early Devonian times [*Yolkin et al.*, 1994], thus allowing us to calculate the expected inclination for the Tuva Terrane during early Mid Devonian times. The resulting inclination of +39° is comparable to the mean inclination determined for component C (this study).

Using the new paleomagnetic data presented here to refine the paleogeographic position of Siberia during Siluro-Devonian times, problems arise if the conventional longitudinal relationship between Baltica and Siberia is maintained. In most reconstructions Siberia is situated immediately to the North of Baltica (see reconstructions by *Torsvik et al.* [1995]), our new results cause significant overlap of these crustal blocks. This can be avoided by moving Siberia further to the East. This solution is supported by paleontological data [*Nikiforova and Andreeva*, 1961] which indicate that Siberia was in fact separated from both Laurentia and Baltica [*Lieberman, B.S.*, 1999, personal communication].

The small circle distribution of declinations (Figure 8b) reflects rotations of individual tectonic blocks making up the Tuva Terrane. In the absence of reference data for cratonic Siberia in Siluro-Devonian times, however, the magnitude and sense of rotation cannot be easily determined. In their recent synthesis of paleomagnetic data, *Smethurst et al.* [1998] propose constant northward directed drift and simultaneous continuous clockwise rotation of Siberia during the Paleozoic. Therefore it is a rather safe assumption that the "true" Siluro-Devonian reference declination for the Tuva terrane should be located between the expected reference directions for the region based on the mid Ordovician and Carboniferous key pole positions (poles 12 and 8 of *Smethurst et al.* [1998]). This defines a field between 137° and 147° (shaded area in Figure 8b) for the "true" Siluro-Devonian declination. Thus

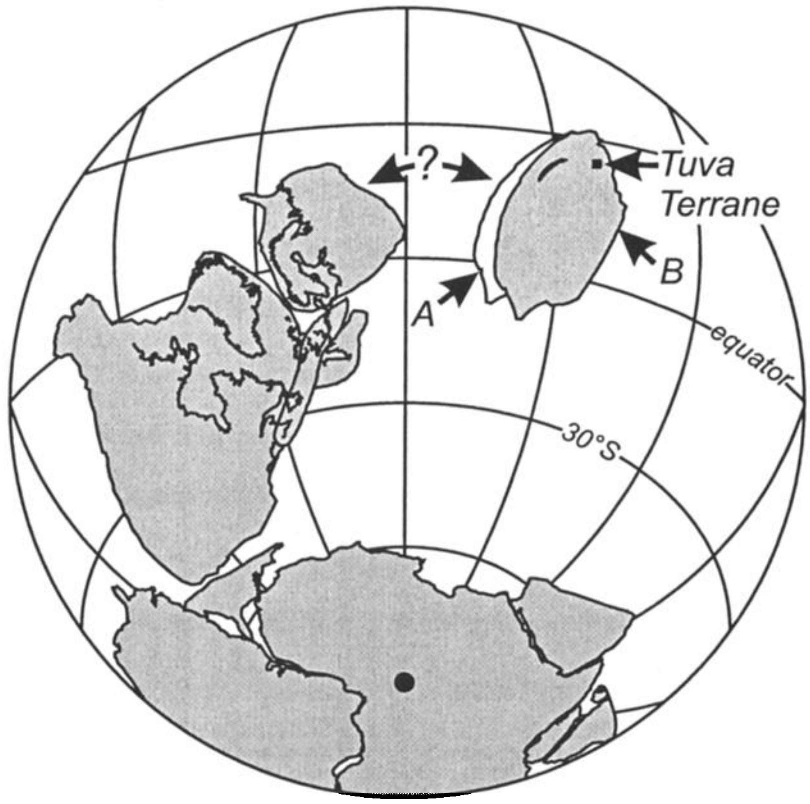

Figure 11. Siluro/Devonian paleogeographic reconstructions of Siberia based on the mean inclination value obtained in this study and the early Carboniferous (A) and mid-Ordovician (B) reference declinations for the Siberian platform. The Tuva Terrane is marked by a square. Also shown are the paleogeographic relationships between the major circum-Atlantic continents based on paleomagnetic data (Gondwana [*Bachtadse et al.*, 1987], Laurentia [*MacNiocall and Smethurst*, 1994], Baltica, [*Torsvik et al.*,1992], Avalonia [Channell et al., 1992], Armorica [*Tait*, 1999]). The question mark reflects the uncertainty in the longitudinal position of Siberia.

the various blocks within the Tuva Terrane may have rotated up to a maximum of 72° clockwise with respect to the Siberian platform, with increasing amounts of rotation from North to South. We note, however, that the mean direction for section US2 (labeled "F" on Figure 8) does not follow this pattern and is displaced 13° to 23° to the east of the Carboniferous and Ordovician reference directions, respectively (Figure 8). Whether this deviation from the general rotation pattern is caused by local second order tectonic rotations is unclear. Nevertheless, we postulate that clockwise rotations of the individual blocks, making up the Tuva Terrane, control the structural inventory of the area. This scenario is comparable to that proposed by *Wells and Heller* [1988] for the western United States, where clockwise rotations are controlled by dextral strike-slip fault systems. We also note that our observations are in agreement with the *Sengör et al.* [1993] model for the formation of the Altaids which postulates the existence of major dextral strike-slip faults between the Tuva-Mongolian block and the Siberian platform.

Acknowledgments. VEP expresses his thanks to H. Soffel and N. Petersen for allowing access to the paleomagnetism laboratory of the Department of Pure and Applied Geophysics, Ludwig-Maximilians-University Munich. The authors are grateful to V.Gonikberg, L.V.Kungurtsev, A.S.Gibsher, and V.D.Zaltsman, for valuable advise on the geology of the study area. We are also grateful to Bruce Lieberman for giving us valuable advice on the palaeobiogeographical relations between Siberia, Baltica, and Laurentia. M. Schaetz and A. Zwing read earlier versions of the manuscript; their constructive criticism is greatly appreciated. Mark Smethurst, Jean-Pascal Cogné, and Tim Rolph (Associate Editor) are thanked for their constructive review and advice. This work was supported by Russian Fund of Basic Researches, grants 95-05-14519 and 96-05-79019. VB and JAT were partly supported by grants So72/58-1, So72/58-2, and TA193/1-3 from the German Research Council (DFG). VEP is grateful to the DFG for financial support for his visit to the paleomagnetic laboratory in Munich.

References

Bachtadse, V., R. Van der Voo, and I.W. Haelbich, Paleozoic paleomagnetism of the western Cape Fold Belt, South Africa, and its bearing on the Paleozoic apparent polar wander path for Gondwana, *Earth Planet. Sci. Lett.*, *84*, 487-499, 1987.

Belichenko, V.G., E.V. Sklarov, N.L. Dobretsov, and O. Tomurtogoo, Geodynamic map of Paleoasian Ocean. East segment, in *Geodynamic Evolution of the Paleoasian Ocean*, edited by N.L. Dobretsov, R.G. Coleman, and N.A. Berzin, *Geol. Geophiz.*, *35*, 29-40, 1994.

Berzin, N.A., and N.L. Dobretsov, Geodynamic Evolution of Southern Siberia in Late Precambrian - Early Paleozoic time, in *Reconstruction of the Paleoasian Ocean.*, pp. 67-69, VSP Intern. Sci., Zeist, Netherlands, 1993.

Berzin, N.A., and L.V. Kungurtsev, Geodynamic interpretation of Altai-Sayan geological complexes, in *Geodynamic Evolution of the Paleoasian Ocean*, edited by N.L. Dobretsov, R.G. Coleman, and N.A. Berzin, *Geol. Geophiz.*, *35*, 57-73,1994.

Berzin, N.A., R.G. Coleman, N.L. Dobretsov, L.P. Zonenshain, Xiao-Xuchang, and E.Z. Chang, Geodynamic map of the western part of the Paleoasian Ocean, in *Geodynamic Evolution of the Paleoasian Ocean*, edited by N.L. Dobretsov, R.G. Coleman, and N.A. Berzin, *Geol. Geophiz.*, *35*, 5-22, 1994.

Blodgett, R.B., D.M. Rohr, and B. A.J., Early and Middle Devonian gastropod biogeography, in *Paleozoic Paleogeography and Biogeography*, edited by W.S. McKerrow and C.R. Scotese, pp. 277-284, Geol. Soc.of London, London, 1990.

Channell, J.E.T., C. McCabe, and N.H. Woodcock, Early Devonian (pre-

Acadian) magnetization directions in Lower Old Red Sandstone of south Wales (UK), *Geophys. J. Int.*, *108*, 883–894, 1992.

Didenko, A.N., A.A. Mossakovsky, D.M. Pechersky, S.Y. Rushentsev, S.G. Samygin, and T.N. Kheraskova, Geodynamics of Paleozoic oceans of Central Asia, in *Geodynamic Evolution of the Paleoasian Ocean*, edited by N.L. Dobretsov, R.G. Coleman, and N.A. Berzin, *Geol. Geophiz.*, *35*, 48-61, 1994.

Dobretsov, N.L., and V.I. Ignatovitch, *Geology and ore depositing of East Sayan* (in Russian), 127 pp., Nauka, Novosibirsk, 1989.

Dobretsov, N.L., R.G. Coleman, J.G. Liou, and S. Maruyama, Blueschist belts of Asia and periodicity of blueschist metamorphism, *Ophioliti*, *12*, 445-456, 1987.

Enkin, R.J., and G.S. Watson, Statistical analysis of palaeomagnetic inclination data, *Geophys. J. Int.*, *126*, 495-504, 1996.

Epstein, A.G., J.B. Epstein, and L.D. Harris, Conodont color alteration-An index to organic metamorphism, *U. S. Geol Surv. Prof. Pap.*, *995*, 1–27, 1977.

Fisher, R.A., Dispersion on a sphere, *Proc. R. Soc. London, Ser. A*, *217*, 295-305, 1953.

Harland, W.B., R.L. Amstrong, A.V. Cox, L.E. Craig, A.G. Smith, and D.G. Smith, *A Geologic Time Scale*, 131 pp., Cambridge Univ. Press, New York, 1990.

Khramov, A.N., Standard series of paleomagnetic poles for Northern of Eurasia: Connection with problems of paleogeodynamics of the USSR territory, in *Paleomagnetism and Paleogedynamics of the USSR Territory*, edited by A.N. Khramov, pp. 154-176, Rus. Res. Inst. of Geol. Oil Explor., St. Petersburg, 1991.

Khramov, A.N., and V.P. Rodionov, Paleomagnetism and reconstruction of paleogeographic position of the Siberia and Russian plates during the Late Proterozoic and Paleozoic, *J. Geomagn. Geoelectr*, *32*, suppl. III, 23-27, 1980.

Kirschvink, J.L., The least-squares line and plane and the analysis of paleomagnetic data, *Geophys. J. R. Astron. Soc.*, *62*, 699-718, 1980

Kodama, K.P., A successful rock magnetic technique for correcting paleomagnetic inclination shallowing: Case study of the Nacimiento Formation, New Mexico, *J. Geophys. Res.*, *102*, 5193-5205, 1997.

Kulkov, N.P., E.V. Vladimirskaja, and N.K. Rybkina, *The Brachiopods and Biostratigraphy of Upper Ordovician and Silurian of Tuva*, 208 pp., Nauka, Novosibirsk, 1985.

MacNiocall, C., and M. Smethurst, Palaeozoic palaeogeography of Laurentia and its margins: A reassessment of palaeomagnetic data, *Geophys. J. Int.*, *116*, 715-725, 1994.

McElhinny, M.W., Statistical significance of the fold test in paleomagnetism, *Geophys. J. R. Astron. Soc.*, *8*, 338-340, 1964.

McElhinny, M.W., Six new paleomagnetic databases released, *Eos Trans. AGU*, *79*, 387, 1998.

McFadden, R.L., A new fold test for palaeomagnetic studies, *Geophys. J. Int.*, *103*, 163–169, 1990.

McFadden, R.L., and M.W. McElhinny, Classification of the reversal test in paleomagnetism, *Geophys. J. Int*, *103*, 725-729, 1990.

Mossakovsky, A.A., S.Y. Rushentsev, S.G. Samygin, and T.N. Kheraskova, Geodynamic evolution of the Paleoasian Oceans, in *UNESCO Int. Sump. Metallog. Mafic Ultramfic Complexes East. Mediterr.-West. Asia Areas, Ist Comp. Similar Metallog. Environ. World, Proc.*, *4*, 105 - 107, 1993.

Nestor, H., Biogeography of Silurian stromatoporoids, in *Paleozoic Paleogeography and Biogeography*, edited by W.S. McKerrow, and C.R. Scotese, pp. 215-222, Geol. Soc. of London, London, 1990.

Nikiforova, O.I., and O.N. Andreeva, Stratigraphy of the Ordovician and Silurian of the Siberian Platform and its paleontological basis (Brachiopods), *Biostratigraphya Paleo. Sibirskov Platformy*, *1*, 1-412, 1961.

Pedder, A.E.H., and W.A. Oliver Jr., Rugose coral distribution as a test of Devonian paleogeographic models, in *Palaeozoic Biogeography and Palaeobiogeography*, edited by W.S. McKerrow and C.R. Scotese, pp. 267-275, Geol. Soc. of London, London, 1990.

Pogarskaya, I.A., and H.I. Goncharov, Pole number 90066, in *Paleomagnetic Directions and Paleomagnetic Pole: Data for the USSR*, edited by A.N. Khramov, Soviet Geophysical Committee, World Data Center, B, Moscow, 1982.

Poncet, J., Biogeography of Devonian Algae, in *Paleogeography and Biogeography*, edited by W.S. McKerrow and C.R. Scotese, pp. 285-290, Geol. Soc. of London, London, 1990.

Scotese, C.R., and W.S. McKerrow, Revised world maps and introduction, in *Palaeozoic Palaeogeography and Biogeography*, edited by W.S. McKerrow and C.R. Scotese, pp. 1-21, Geol. Soc. of London, London, 1990.

Sengör, A.M.C., B.A. Natal'in, and V.S. Burtman, Evolution of the Altaid tectonic collage and Palaeozoic crustal growth in Eurasia, *Nature*, *364*, 299-307, 1993.

Smethurst, M.A., A.N.Khramov, and T.H.Torsvik., The Neoproterozoic and Paleozoic drift history of the Siberian Platform, *Earth Sci. Rev.*, *43*, 1-24, 1998.

Solodovnikov, G.M., Paleointensity of the geomagnetic field in Early and Middle Devonian time *Izv Russ. Acad. Sci. Solid Earth, Engl. Transl.*, *7*, 64-71, 1996.

Streel, M., M. Fairon-Demaret, and S. Lobosiak, Givetian-Frasnian phytogeography of Euramerica and western Gondwana based on miospore distribution, in *Palaeozoic Biogeography and Palaeobiogeography*, edited by W.S. McKerrow and C.R. Scotese, pp. 291-296, Geol. Soc. of London, London, 1990.

Tait, J., A palaeomagnetic study of Early Devonian sequences in the Armorican Massif, NW France, *J. Geophys. Res.*, *104*, 2831-2839. 1999.

Torsvik, T.H., M.A. Smethurst, R. Van der Voo, A. Trench, N. Abrahamsen, and E.J. Halvorsen, BALTICA - A synopsis of Vendian-Permian palaeomagnetic data and their palaeotectonic implications, *Earth Sci. Rev.*, *33*, 133-152, 1992.

Torsvik, T.H., J. Tait, M. Moralev, W.S. McKerrow, B.A. Sturt, and D. Roberts, Ordovician palaeogeography of Siberia and adjacent continents, *J. Geol. Soc., London*, *152*, 279-287, 1995.

Van der Voo, R., *Paleomagnetism of the Atlantic, Tethys and Iapetus Ocean*, 411 pp., Cambridge Univ. Press, New York, 1993.

Vorojbitov, A.M., Conodont and brachiopoda of Silurian-Lower Devonian of "Chadan" section (Tuva) (in Russian), *Izv Russ. Acad., Series Geol.*, *2*, 82-96, 1992.

Wells, R E , and R.L. Heller, The relative contribution of accretion, shear and extension to cenozoic tectonic rotation in the Pacific North West, *Geol. Soc. Amer. Bull.*, *100*, 325-338, 1988.

Yolkin, E.A., N.V. Sennikov, M.M. Buslow, A. Yu. Yazikov, R.T. Gratsianova, and N.K. Bakharev, Paleogeographic reconstruction of the western Altai-Sayan area in the Ordovician Silurian and Devonian and their geodynamic interpretaion, in *Paleozoic Evolution of the Paleoasian Ocean*, edited by N.L. Dobretsov, R.G. Coleman, and N.A. Berzin, *Geol. Geofiz.*, *35*, 100-124, 1994.

Zijderveld, J.D.A., AC demagnetization of rocks: analysis of results, in *Methods in Paleomagnetism*, edited by D.W. Collinson, K.M. Creer, and S.K. Runcorn, pp. 254-287, Elsevier, New York, 1967.

Zonenshain, L.P., M.I Kuzmin, and L.M. Natapov, *Tectonics of Lithospheric Plates of the USSR Territory* (in Russian), 328 pp., Nedra, Moscow, 1990.

Zorin, Y.A., V.G. Belichenko, E H. Turutanov, V.V. Mordvinova, V.M. Kozhevnikov, H. P., O. Tomurtogoo, N. Arviasbaatar, G. S., and P. Devis, Baikal-Mongolian transect, in *Paleozoic evolution of the Paleoasian Ocean*, edited by N.L. Dobretsov, R.G. Coleman, and N.A. Berzin, *Russ. Geol.Geofiz.*, *35*, 78-92, 1994.

V. Bachtadse, J.A. Tait, Institut für Allgemeine und Angewandte Geophysik, Ludwig-Maximilians-Universität München, Theresienstraße 41, 80333 München, Germany. (valerian@geophysik.uni-muenchen.de, jenny@geophysik.uni-muenchen.de

A. Y Kazansky, United Institute of Geology, Geophysics and Mineralogy, Russian Academy of Sciences, Siberian Branch, Akademik Koptug ave. 3, Novosibirsk, 630090, Russia. (kaz@uiggm.nsc.ru)

V.E. Pavlov, United Institute of Physics of the Earth, Russian Academy of Sciences, Bolshaya Gruzinskaya str.10, Moscow, 123810 Russia. (pavlov@uipe-ras.scgis.ru)

(Received February 22, 1999; revised November 17, 1999; accepted November 30, 1999.)