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Ordovician palaeogeography of Siberia and adjacent continents

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Abstract: Ordovician palaeomagnetic data from the upper reaches of the Lena River, Southern Siberia, confirm and refine the earlier reported data sets. Ordovician palaeomagnetic poles from Siberia define a systematic southwesterly apparent polar wander (APW) trend during Ordovician times (mean south poles: 500 Ma: 42°N, 310°E; 467 Ma: 27°N, 314°E; 460 Ma: 23°N, 313°E; 448 Ma: 22°N, 301°E and 437 Ma: 0 N, 290°E). A primary or early magnetization age is verified by the reversal stratigraphy.

Siberia was geographically inverted at low southerly latitudes during the Latest Cambrian and Early Ordovician and drifted slowly northward and across the equator at an average palaeo-latitudinal velocity of *c.* 5cm/year. In Early Ordovician times, Avalonia and the European Massifs (e.g. Armorica and Bohemia) were located together with Gondwana in high southerly latitudes, Laurentia was positioned in equatorial latitudes whereas Baltica was located at intermediate southerly latitudes. Siberia was probably located north of Baltica in latest Cambrian–Early Ordovician times. Subduction-related, eclogite-facies metamorphism in latest Cambrian–Early Ordovician time in the Scandinavian Caledonides occurred in an ocean–continent transition zone marginal to Baltica but facing northern Siberia, and thus throws doubt on traditional Baltic–Laurentian correlations during this particular time period. With Baltica rotating counterclockwise during the Ordovician, the plate scenario allows for a Siberian source for Late Ordovician sedimentation in some areas of maritime Laurentia and perhaps even northern Norway. It also helps to explain the imposition of a deep-seated, sinistral strike-slip, fault regime between the obliquely converging Baltica and Laurentia, a transcurrent system which may have led to the permissive ascent of calc-alkaline granitoid magmas in favourable sites prior to the main stages of Scandinavian orogenic deformation.

Recent proposals that Laurentia formed a conjugate margin to the South American part of Gondwana during Ordovician times are permissible from palaeomagnetic data, but a tight continental fit during the entire Ordovician is contradicted by biogeographic data. The tight palaeomagnetic fit could perhaps be an artefact of inaccuracies in the palaeomagnetic record for Gondwana.

Keywords: Siberia, Ordovician, palaeomagnetism, palaeogeography, magnetostratigraphy.

Whereas the Ordovician drift history for Baltica, Laurentia, Avalonia and Gondwana and the development of the intervening oceans are constrained to a first order (Van der Voo 1988; Cocks & Fortey 1990; McKerrow *et al.* 1991; Torsvik & Trench 1991*a*; Torsvik *et al.* 1992; Cocks & McKerrow 1993), the palaeotectonic evolution of Siberia and its possible interaction with other continents is less well known. Notwithstanding these uncertainties, a significant amount of palaeomagnetic, palaeoclimatic, biogeographic and tectonic data is available for Siberia (cf. reviews in Khramov & Rodionov 1980 and Zonenshain *et al.* 1990). However, the reliability of the palaeomagnetic data cannot be adequately assessed given that they have not been recorded in diagrammatic detail. The data are generally available in the form of summary compilations (e.g. Khramov *et al.* 1981; McElhinny & Cowley 1977) or in digital form in The Global Palaeomagnetic Data Base (Lock & McElhinny 1991). Moreover, many of the palaeomagnetic data were gathered in the 1960s, prior to advancement in analytical and experimental methods and thus many of these early studies should be re-evaluated. We have therefore resampled selected Ordovician stratigraphic sections from the banks of the Lena River in order to examine the reliability of the existing Ordovician palaeomagnetic data-set from Siberia. This paper describes the characteristics of the palaeomagnetic data and discusses their integration with geological, biogeographic and tectonic data in developing an integrated geological model for the Siberian plate in Ordovician times.

Geology and sampling

Siberia is bordered to the west and south by the Northern Ural and Central-Asian fold belts (including the Kazakhstan microcontinent), which had formed by the end of the Palaeozoic era (Zonenshain *et al.* 1990; Svyazhina *et al.* 1992). To the northeast, the Siberian continental block is bounded by the Mesozoic Verkhogansk–Kolymian fold belt (Fig. 1). The Precambrian basement of the Siberian continent (Fig. 1) is exposed in its southern and central

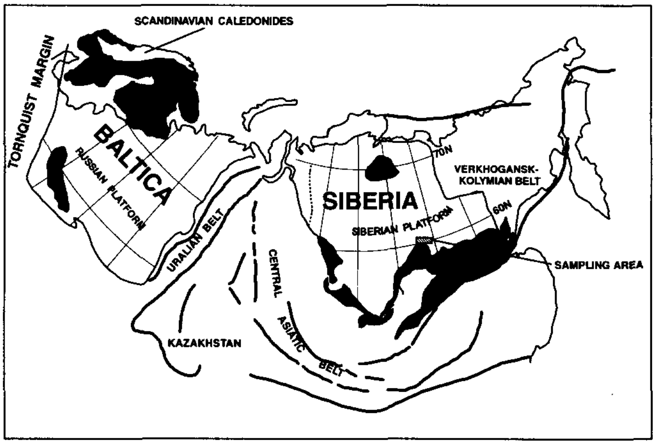

Fig. 1. Geographic sketch map of Siberia and Baltica (simplified after Zonenshain *et al.* 1990). Shaded areas show Precambrian basement regions. Sutures and/or major strike-slip faults associated within the Uralian, Central Asian and Verkhogansk–Kolymian belts are indicated by thick lines.

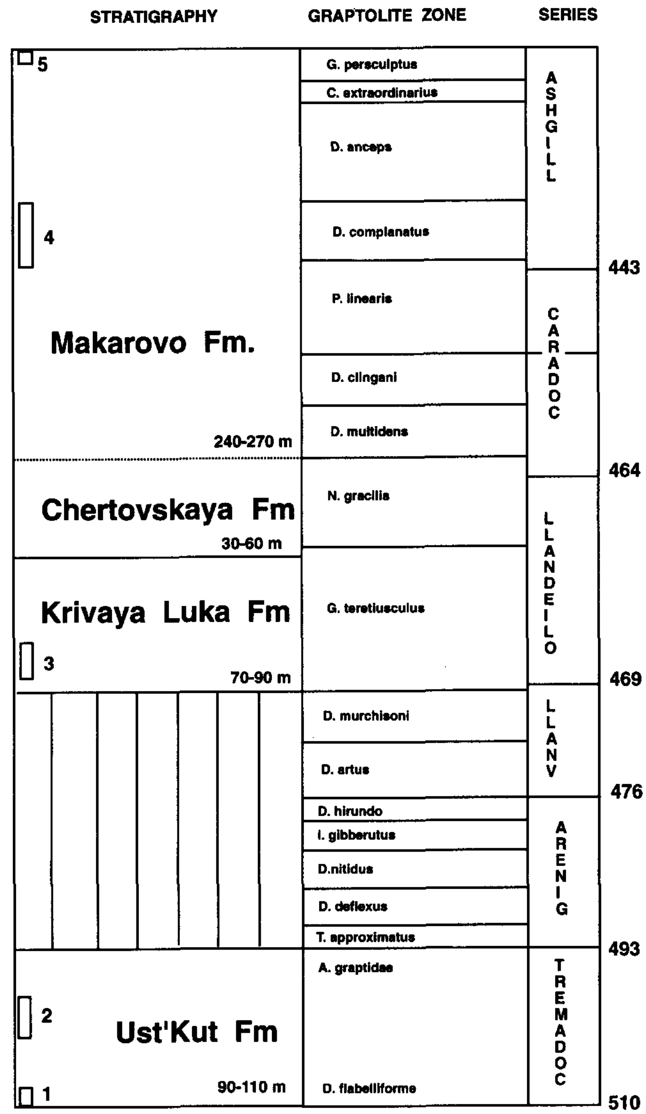

Fig. 2. Lena River stratigraphy, graptolite zonation (European system; see Fortey *et al.* 1991; Trench *et al.* 1991) and stratigraphic elements of the Ordovician period (modified after Kanygin *et al.* 1988). Time scale in million years after Harland *et al.* 1990. Sampling sections 1–5 are indicated in the left part of the diagram.

regions (Moralev 1981; Zonenshain *et al.* 1990). The remaining areas are covered by Riphean and younger sediments.

Cambrian and Ordovician sedimentary rocks are widespread throughout Siberia, and Lower–Middle Cambrian reefs indicate tropical climates (Kanygin *et al.* 1988). During Ordovician time the Siberian Platform was an area of shallow-water epicontinental sedimentation, represented by alternations of terrigenous, terrigenous–carbonate, carbonate rocks (dolomite and limestone), red beds and evaporates (Kanygin *et al.* 1988).

Palaeomagnetic samples from the Ordovician sediments were collected along the Lena River. The samples were drilled in the field and oriented with both sun- and magnetic compasses. The stratigraphy of the Lena River section (Kanygin *et al.* 1988; Lena Zone, Plate A) is divided into four formations (Fig. 2). Sampling was confined to five detailed vertical sections. Sections 1 and 2 include the Lower Ordovician Ust'kut Formation and are represented by grey, sandy, oolitic, stromatolitic dolomite, locally interbedded with sandstone, calcarous sandstone, sandy limestone and siltstone. Section 3 includes the Middle Ordovician Krivaya Luka Formation, which consist of grey and variegated red-grey mudstone, siltstone, marl and limestone. Finally, samples from sections 4 and 5 were collected from the Upper Ordovician Makarovo Formation, which comprises grey and variegated, red-grey, mottled siltstone, mudstone and marl.

The Ordovician System of the Siberian Platform depicted in Fig. 2 is similar to that of Kanygin *et al.* (1988) except for the position of the Caradoc–Ashgill boundary, which we have placed at the start of the *D. complanatus* graptolite zone (British standard: cf. Fortey *et al.* 1991; Trench *et al.* 1991).

Palaeomagnetic results

The natural remanent magnetization (NRM) was measured on a 2G cryogenic magnetometer (University of Michigan). The stability of NRM was tested by stepwise thermal cleaning, alternating field (AF) demagnetization or a combination of the two methods.

Approximately 40% of the samples yield NRM intensities below 0.25 mA m^{-1}. Red siltstone beds from section 3 yield the highest NRM intensities (1–10 mA m^{-1}) whereas the majority of the sample collection, grey sandstones, pale grey limestones and dolomites mostly possess intensities below 0.5 mA m^{-1}. The latter rock-types seldom proved suitable for detailed directional analysis. The NRM is often dominated by a present-day field component with low-unblocking temperatures. This component may carry 60–70% of the total NRM and following thermal treatment at 200–300 °C the intensity is typically reduced to about 0.05 mA m^{-1}, hence rapidly approaching the sensitivity of the magnetometer (*c.* 0.01 mA m^{-1}). The directional trends, however, made it possible to tentatively establish the palaeomagnetic polarity from section 2.

A total of 169 samples were stepwise demagnetized, but detailed directional analysis, including least square analyses for remanence component calculation, were accepted for only 52 samples. High-quality demagnetization results were obtained from red siltstone samples (section 3) from the Middle Ordovician Krivaya Luka Formation. The unblocking temperature spectra (T_b(max) = 680 °C) and Curie-temperature analysis (Fig. 3) indicate that

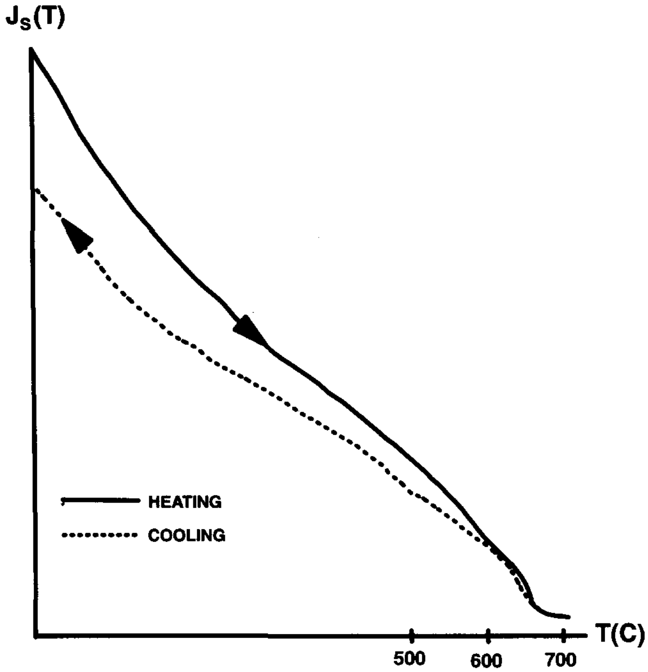

Fig. 3. Thermomagnetic analysis of a red siltstone sample from section 3: Krivaya Luka Fm.

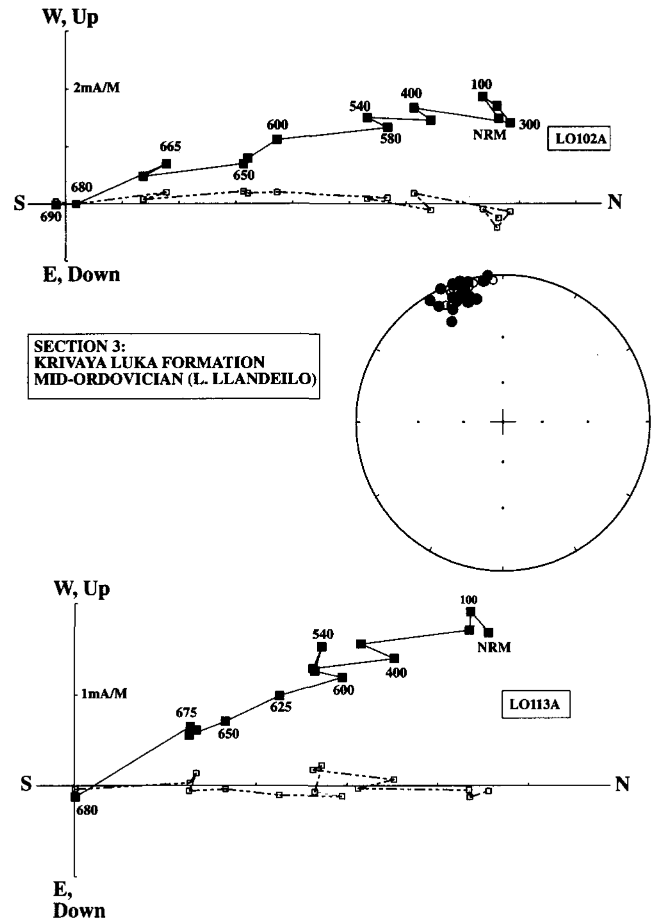

Fig. 4. Examples of thermal demagnetization of samples from section 3 and distribution of high unblocking components (stereoplot). In the Zijderveld diagrams, points in the horizontal (vertical) plane are shown as solid (open) squares. In the stereoplot, open (closed) symbols denote negative (positive) inclinations.

hematite is the main remanence carrier. These samples show almost univectorial behaviour, albeit noisy, with shallow inclinations and declinations toward NNE (Fig. 4). In some instances, however, it appears that the high- (>600 °C) and low unblocking components differ by approximately 5–15 degrees of arc. In the latter case, characteristic remanence components were calculated for the high-unblocking component.

Some variegated red and grey siltstone samples from the Upper Ordovician Makarovo Formation (section 4) also proved suitable for directional analysis. Note, however, the large directional scatter in the high-unblocking temperature components (Fig. 5). Most samples are dominated by steep downward components, typically demagnetized below 400 °C. The high-stability hematite components yield SE–SW declinations and widely dispersed inclinations.

Samples from the uppermost part of the Makarovo Formation (section 5) display dual polarity magnetizations (Fig. 6) that are carried by magnetite (T_b(max) = 575 °C). Note, however, that the inclinations recorded in the rock samples of uppermost Ordovician age are significantly steeper than those observed within the older strata (e.g. section 3; Fig. 4).

Isothermal remanent magnetization (IRM) curves for red (section 3) or variegated red and grey siltstone (section 4) show the dominance of high-coercivity phases, whereas sections 2 and 5 (grey limestone and dolomites) are governed by low-coercivity phases with saturation fields (J_s) in the order of 200–300 mT (Fig. 7). Subordinate high-coercivity phases, however, are also present in the two latter sections. This is clearly seen by thermal demagnetization of a three-component IRM (high = 1.2 T, intermediate = 0.4 T and low = 0.15 T). Low-coercivity phases are demagnetized below 580 °C whereas the high coercivity phases are demagnetized between 600 and 690 °C (samples from section 5, Fig. 7). Conversely, red or variegated red and grey samples (e.g. sample from section 3 in Fig. 7) are dominated by high/intermediate coercivity phases demagnetized between 100 and 680 °C, but they also have significant contribution of low-coercivity phases. These experiments agree with the NRM thermal unblocking spectra (cf. Figs. 4–6) and Curie-temperature analysis and indicate that whereas magnetite is the principal carrier for sections 2 and 5, hematite is the carrier for sections 3 and 4.

Interpretation

Palaeomagnetic south poles calculated for sections 3 to 5 (Fig. 8; Tables 1 & 2) compare favourably with Ordovician palaeomagnetic data reported by Rodionov (1966). A stratigraphically-linked reversal pattern (Fig. 9; based on Khramov *et al.* 1965) confirms a primary or early diagenetic origin for the remanence. We note a minor directional asymmetry in the earlier reported data sets (cf. Rodionov 1966, figs 2 & 3) which probably relates to inadequate AF (30–40 mT) and thermal cleaning (100 °C) of the samples. Rodionov's (1966) data, however, were to a large extent derived from 'stable red sediments', probably largely of a 'single-component' nature or NRM directions close to the characteristic high unblocking remanence component (see Fig. 4), hence their limited stability testing were most likely sufficient for estimating remanence components. As a result, we consider it valid to incorporate the results of previous demagnetization experiments into overall mean-pole positions (Table 2). Rodionov (1966) also pointed out that the

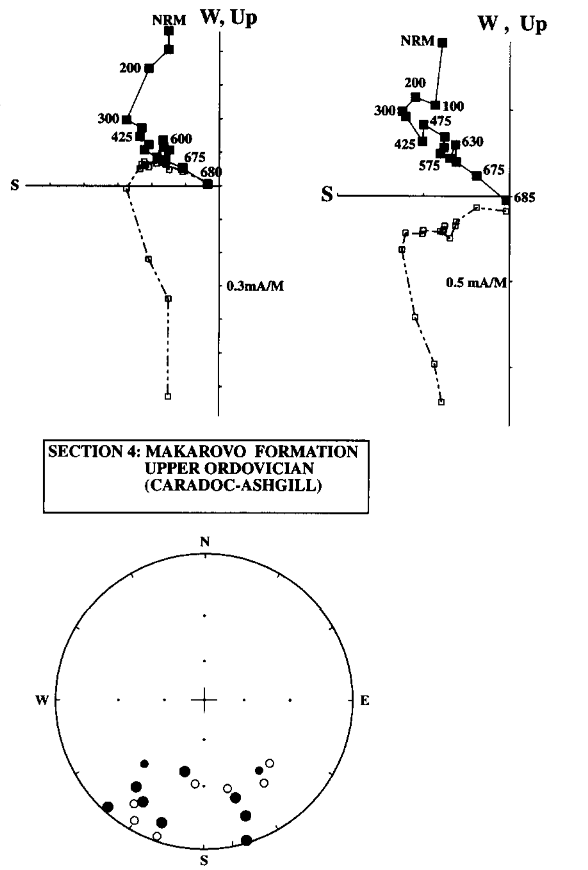

Fig. 5. Examples of thermal demagnetization of samples from section 4 and distribution of high unblocking components. Legend as Fig. 4.

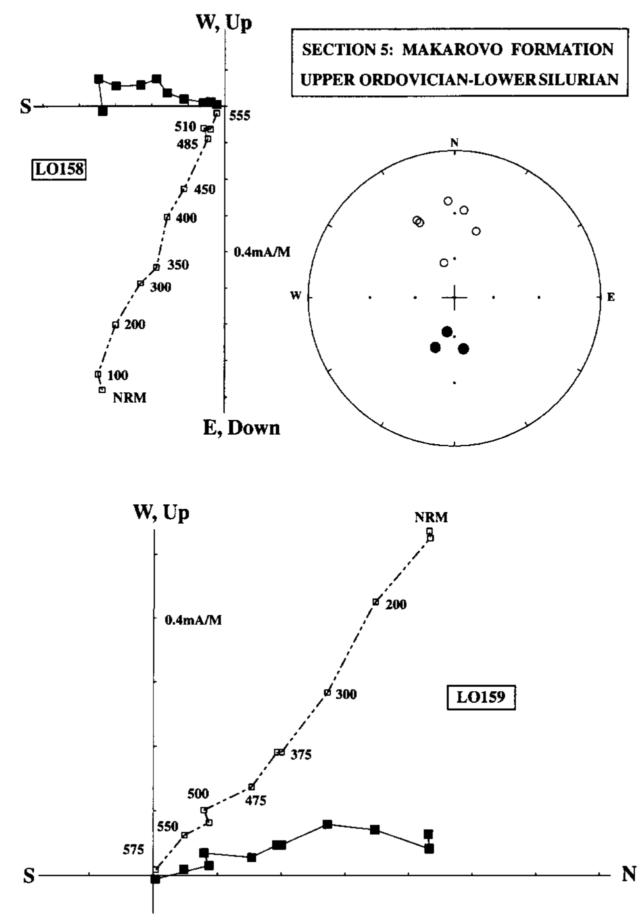

Fig. 6. Examples of thermal demagnetization of samples from section 5 and distribution of high unblocking components. Legend as Fig. 4.

pale limestones and dolomites proved unsuitable for their analysis because of NRM intensities below the noise level of their astatic magnetometer.

Trench *et al.* (1991) have noted that the Siberian reversal pattern, based on Khramov *et al.* (1965), can be reconciled with that of Baltica (Torsvik & Trench 1991*b*) and the rest of the world if one assumes that Siberia was geographically inverted in Ordovician times (Fig. 10), so that the Mongolian margin was facing north (see also Khramov *et al.* 1981; McKerrow *et al.* 1991; Torsvik & Trench 1991*a*). Shallow NNW directions observed for example in the Krivaya Luka Formation (section 3) are therefore of reverse polarity. The reversed magnetic polarity indicated by the noisy data for section 2 and well-defined reverse directions obtained from section 3 agree with the previously published polarity scale for the Siberian Platform (Khramov *et al.* 1965; Fig. 9). Furthermore, normal polarity directions for early Ashgill times from section 4 match the world Ordovician magnetostratigraphic compilation of Trench *et al.* (1991). Section 5, however, suggests a polarity reversal (from normal to reversed) in latest Ordovician–Early Silurian times (Fig. 9), but the extent of the reverse polarity zone is as yet uncertain since the Early Silurian (Llandovery) magnetostratigraphy is relatively unconstrained. Note that the Siberian polarity scale (Fig. 9) differs slightly from that presented by Khramov *et al.* (1965) due to the contrasting correlation's between the European and Siberian stages (cf. Trench *et al.* 1991 for details).

Palaeomagnetic constraints on palaeogeography

The Ordovician palaeogeographic scenarios depicted in Figs 11a–c are based on those published by Torsvik & Trench (1991*a*) and Torsvik *et al.* (1992). The position of Siberia has been adjusted to take account of our new data (Table 2).

In Early Ordovician time (490–500 Ma), Avalonia and the European Massifs (e.g. Armorica and Bohemia) were located close to Gondwana in high southerly latitudes. Avalonia had rifted away from Gondwana by Llanvirn time while Armorica and Bohemia remained in high latitudes together with Gondwana throughout the Ordovician. The Tornquist Sea, separating Avalonia and Baltica, narrowed gradually during the Ordovician as indicated by the increasing faunal affinity, whereas faunal bonds between Avalonia and Gondwana declined during the same interval.

Palaeomagnetic and palaeoclimatic data (Webby 1984; Witzke 1990; Van der Voo 1988) suggest that Laurentia was positioned in equatorial latitudes during most of the Ordovician. Conversely, Baltica was initially located at intermediate southerly latitudes and drifted northwards while undergoing an anticlockwise rotation during Ordovi-

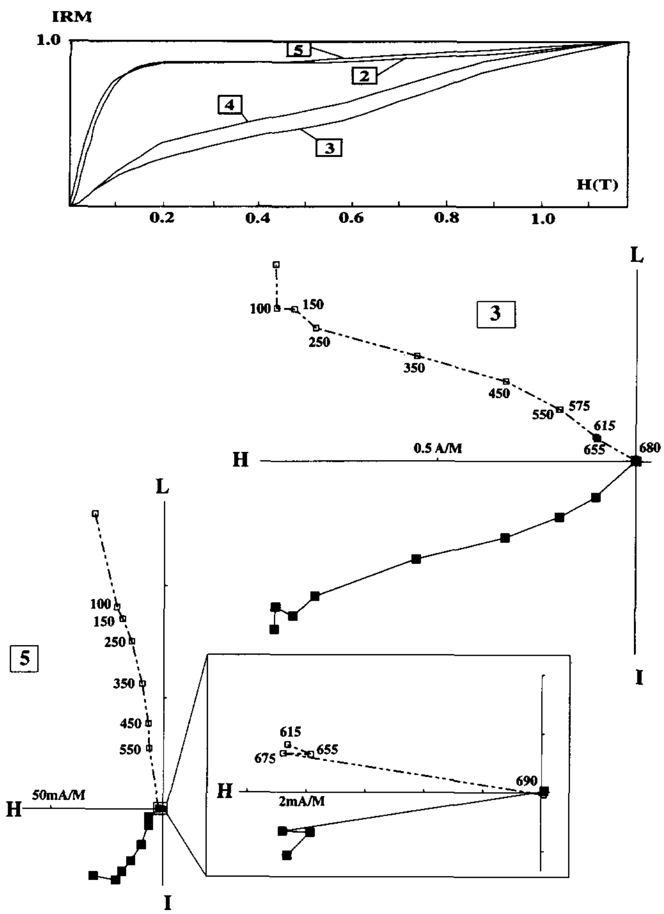

Fig. 7. Isothermal-remanent magnetization (IRM) curves obtained from samples from sections 2–5 (top diagram) and thermal demagnetization of a three-component IRM from sections 3 and 5 (cf. text). Lower right diagram represent an expansion of the diagram to the left. H = high field component (D/I = 270/0); I = intermediate field component (D/I = 180/0); L = low field component (I = − 90). Zijderveld legends as Fig. 4.

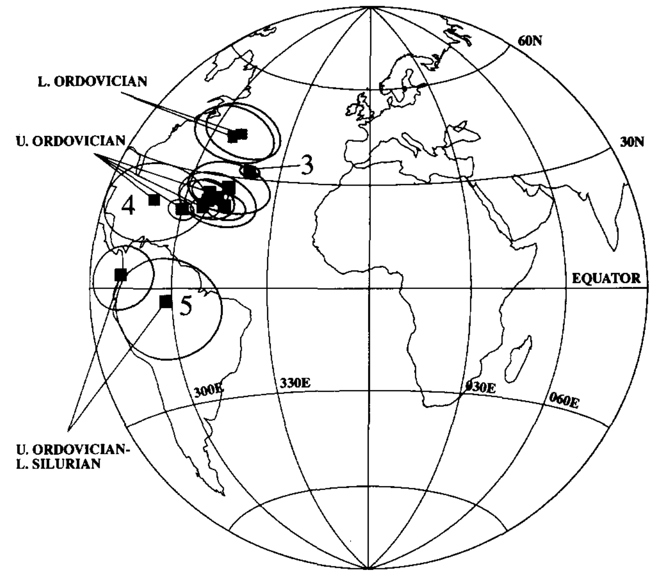

Fig. 8. Ordovician palaeomagnetic south poles from Siberia (cf. Table 2). New data from sections 3, 4 and 5 of the present study are indicated.

cian times (Torsvik *et al.* 1992). By the end of the Ordovician, the Tornquist Sea between Avalonia and Baltica had closed sufficiently to form Balonia (Torsvik *et al.* 1993); and finally by Early–Mid-Silurian times (*c.* 425 Ma) Balonia collided with Laurentia during the Scandian Orogeny. As a consequence of continuing, though diminishing anticlockwise rotation of Balonia (ex-Baltica) and a coeval southward drift of Laurentia, sinistral transpressive deformation prevailed (Hutton 1987; Soper *et al.* 1992) and Scandian thrust-related orogenesis continued on into Early–Mid-Devonian time in northern areas (Roberts & Sundvoll 1990; Anderson *et al.* 1992).

The Ordovician APW path for Siberia (Fig. 8), including our new data, signifies that Siberia was geographically inverted at low southerly latitudes during the Early Ordovician (*c.* 500 Ma). The Siberian plate then drifted slowly northward (Fig. 10) and across the equator at an average palaeo-latitudinal speed of *c.* 5 cm/year. During Late Ordovician (Ashgill)–Early Silurian times, however, an increased northward velocity (up to 18 cm/year) is recognized. The low palaeolatitudes for Siberia during most of the Ordovician are supported by palaeoclimatic data (Kanygin *et al.* 1988).

Refinements to palaeogeography based on geological observations

Siberia has usually been placed to the north of Baltica in Palaeozoic reconstructions, and by some authors near the eastern margin of Laurentia in Mid- to Late Ordovician times (McKerrow *et al.* 1991). The latter solution is based on the suggestion that the Late Proterozoic–Ordovician Mongolian volcanic arc of Siberia (Mossakovsky & Dergunov 1985) may represent a Late Ordovician offshore igneous source to eastern Laurentia, i.e. the Southern Uplands (McKerrow *et al.* 1991). Palaeomagnetically derived palaeolatitudes may support this tectonic scenario (Fig. 11a–c).

The overturned palaeo-orientation of Baltica during Early Ordovician time (Fig. 11a) calls into question the traditional correlations of the Ordovician evolution of the eugeoclinal assemblages of Baltica and Laurentia (cf. discussion in Torsvik *et al.* 1991). The Scandinavian Caledonides embody four major allochthonous complexes (Gee *et al.* 1985; Roberts & Gee 1985), the two lowest of which consist of rock types indigenous to Baltica and its miogeoclinal margin. In the Upper Allochthon, protoliths for medium- to high-grade gneisses, schists and amphibolites, including eclogites, in the Seve Nappes were formed in the Baltoscandian continent–oceanic transition zone. Early Caledonian eclogitization, in Tremadoc times (Mørk *et al.* 1988), relates to westward subduction of Baltic continental crust (Dallmeyer & Gee 1986); a subduction event, with inferred arc development locally, that was closely followed by uplift and retrogression of the eclogites and obduction of Early Ordovician ophiolites (Sturt & Roberts 1991). The Seve Nappes are superseded by oceanic basin-and-arc systems in the exotic or suspect terranes of the Køli Nappes; these include fragmented ophiolites in several areas. Higher

Table 1. *Palaeomagnetic results obtained from sections 3–5*

Section	*P*	Bedding	IDEC	IINC	*N*	α_{95}	*k*	CDEC	CINC	VGP N°	VGP E°	dp/dm
3	R	025/7	341	+2.0	26	3.1	82.1	342	+7	32.0	319.4	1.6/3.1
4	N	253/14	186	+3.0	17	17.3	5.2	187	+16	21.1	289.0	9.2/17.8
5	N	260/9	187	+55.0	3	18.4	45.9					
	R		352	−36.0	6	17.1	16.3					
	Mix	260/9	356	−43.0	9	13.1	16.4	358	−52	−3.1	298.1	12.3/17.9

P = polarity; IDEC/IINC = *in situ* declination/inclination; *N* = number of samples; α_{95} = 95% confidence circle; *k* = precision parameter; CDEC/CINC = bedding corrected declination/inclination; VGP = virtual geomagnetic pole; dp/dm = semi-axes of the 95% ovals.

up, the heterogeneous Uppermost Allochthon has been considered to be of probably Laurentian affinity (Roberts *et al.* 1985; Stephens & Gee 1985).

The overturned palaeo-orientation of Baltica during Early and Mid-Ordovician times and the latitudinal drift-history for Siberia and Baltica suggest a palaeo-ocean between Baltica and Siberia and not latest Cambrian to Early Ordovician subduction and Early Ordovician obduction between Laurentia and Baltica (Iapetus Ocean). From Mid-Ordovician to Silurian times Baltica experienced a gradual but pronounced anticlockwise rotation (Torsvik *et al.* 1992). This eventually gave rise to a deep-seated, strike-slip fault regime in the narrowing oceanic tract between Baltica and Siberia, and ultimately between the obliquely converging plates of Baltica and Laurentia (cf. Hutton 1987; Soper *et al.* 1992). This developing fault system may have influenced and possibly controlled the generation and ascent of Late Ordovician (Ashgill), mainly calc-alkaline granitoids in the Uppermost Allochthon (Nordgulen 1993). These particular granites and granodiorites have earlier been taken to be solely subduction related (Sturt *et al.* 1984), but more recent geochemical studies allow for a more complex interplay of subduction and strike-slip tectonics (Nordgulen 1993).

An alternative palaeogeographic approach

Details in the 'archetypal' palaeogeographic scenario outlined above have been questioned by Dalla Salda *et al.* (1992) and Dalziel *et al.* (1994). These authors propose that Laurentia formed a conjugate margin to Gondwana in Cambro–Ordovician times and that Taconic (Laurentia) and Famatinian (South America) deformation resulted from a Mid-Ordovician (*c.* 450 Ma) collision between Laurentia and the South American part of Gondwana. They also contend that the Cambrian platform carbonates with olenellids in the Precordillera of NW Argentina represents a detached fragment of Laurentia during subsequent rifting in Late Ordovician times. This novel model is permissible from the palaeomagnetic data (Fig. 11d–f), but is apparently contradicted by some of the biogeographic evidence

Table 2. *Selected Ordovician palaeomagnetic south-poles from the Siberian Platform*

Series	Age	Area	Sampling N°	Sampling E°	α_{95}	D°	I°	VGP N°	VGP E°	Ref
U. Ashgill–Sil.	435	Lena	60.3	116	9.0	015	−44	3	282	2
U. Ashgill–Sil.	439	Lena	60.5	116.4	13.1	358	−52	−3	298	1
Mean	437			A95 = 38.0				0	290	
L. Ashgill	443	Lena	60.5	116.4	17.3	187	16	21	289	1
U. Caradoc	450	Ilim	57	103	4.2	164	23	20	300	2
U. Caradoc	450	Lena	58	108	6.0	162	10	25	308	2
U. Caradoc	450	Lena	60	118	4.5	171	17	21	307	2
Mean	448			A95 = 9.6				22	301	
U.Ll–L. Caradoc	460	Lena	58	108	12.7	159	12	24	311	2
U.Ll–L. Caradoc	460	Lena	60	118	6.5	165	14	22	314	2
Mean	460			A95 = 7.4				23	313	
M. Llandeilo	466	Lena	58	108	9.0	162	14	23	308	2
M. Llandeilo	466	Lena	60	118	13.1	166	4	27	314	2
L. Llandeilo	468	Lena	59.8	118.1	3.1	342	7	32	319	1
Mean	467			A95 = 10.2				27	314	
Tremadoc	500	Lena	57	107	12.7	164	−19	41	308	2
Tremadoc	500	Lena	57	104	11.8	160	−23	42	311	2
Mean	500			A95 = 5.4				42	310	

Ref, references: 1, this study; 2, Rodionov (1966); see Table 1 for legend.

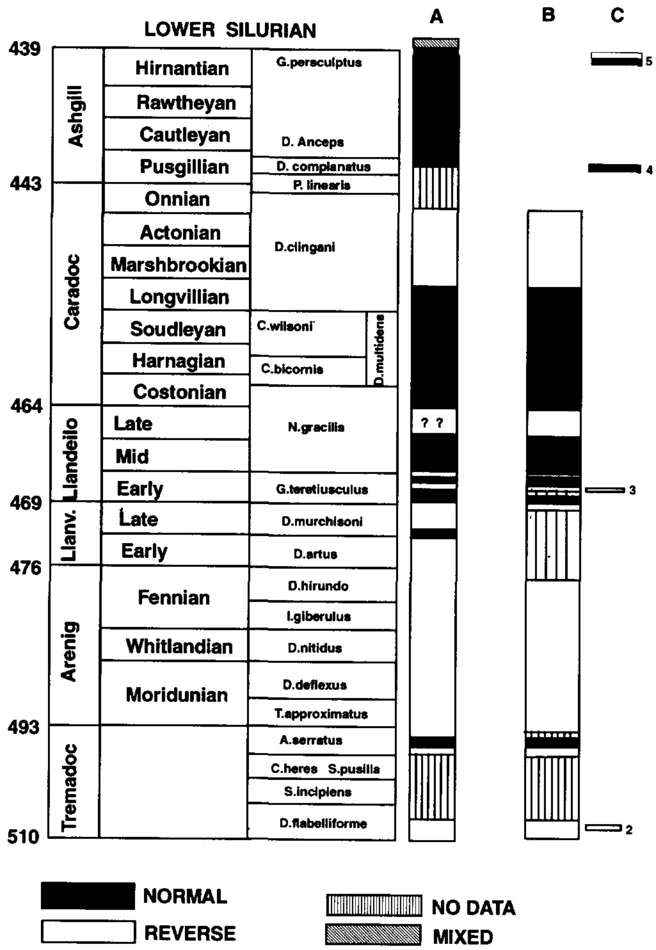

Fig. 9. Ordovician stage names, faunal sub-divisions (European system) and magnetostratigraphy. Column A is world Ordovician magnetostratigraphy after Trench *et al.* (1991); Column B is Siberian magnetostratigraphy (Khramov *et al.* 1965); Column C is present study. Lower Silurian (mixed data; column A) after Trench *et al.* (1993).

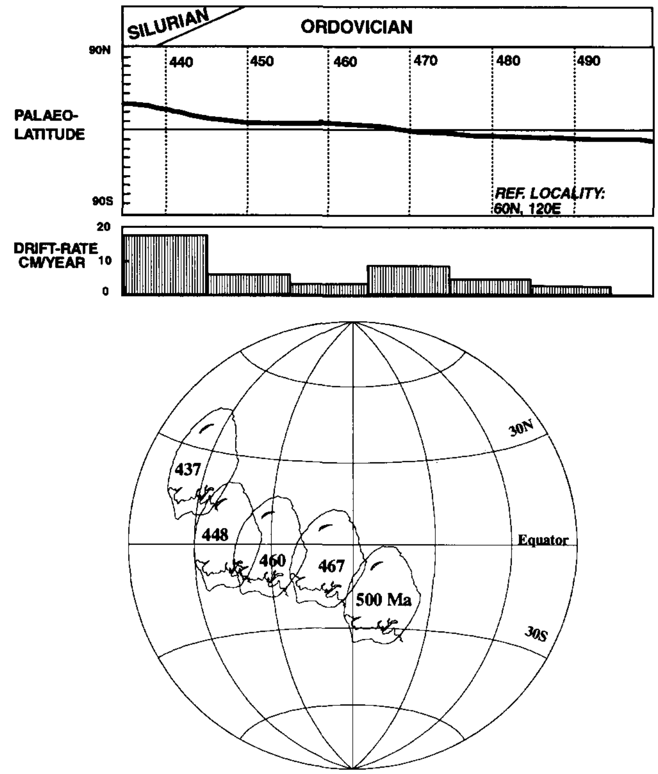

Fig. 10. Ordovican and Early Silurian palaeo-latitudinal drift curve for Siberia (based on data listed in Table 2) and estimates of latitudinal drift-rates (cm/year). The latter represent minimum velocities for the Siberian plate. The lower diagram shows Ordovician palaeo-reconstructions for Siberia during the 500–437 Ma interval (Table 2).

(McKerrow *et al.* 1992; Cocks & Fortey 1990). In Fig. 11d–f we have kept the relative position between Laurentia and Siberia as the 'traditional model' (Fig. 11a–c), while accommodating the palaeolongitude of the remaining continents in order to test this proposal. These alternative reconstructions, however, pin-point some biogeographic enigmas. Most importantly, the existing palaeomagnetic data indicate a tight fit (oceanic separation <300–500 km) between Laurentia and South America during the Early Ordovician, hence indicating unabridged faunal exchange. However, the Early Ordovician (480 Ma) platform faunas in Laurentia were quite different from those of Gondwana (Cocks & Fortey 1990) indicating at least 1500 km of seperation until the late Caradoc (*c.* 450 Ma). In addition, the Early Ordovician continental slope faunas indicate deep margins along the Appalachian edge of Laurentia and the Andean edge of South America (Cocks & Fortey 1990, fig. 3). The tight palaeomagnetic fit, could perhaps be assigned to inaccuracy in the palaeomagnetic data-set, particularly that of Gondwana.

The Taconic Orogeny appears to be a product of an arc–continent collision. The volcanic arc outcrops in New England and Newfoundland (McKerrow *et al.* 1991). The collision took place during the Caradoc in New England and during the Llandeilo in Newfoundland; in both cases prior to the mixing of the platform faunas. Thus the Taconic Orogeny was confined to Laurentia, and cannot have been related to a continent–continent collision involving a second continent.

We also note from Fig. 11d & e that Baltica must have been located far away from Laurentia (>5000 km) during the Early and Mid-Ordovician in the scenario of Dalla Salda *et al* (1992). Hence, Mid-Ordovician (450 Ma; Taconian) collision between Laurentia and South America would require subsequent rifting (cf. Dalziel *et al.* 1994) and dextral shear during Late Ordovician times (Fig. 11f) in order to (1) furnish the well-established initial stage of Scandian collision (*c.* 425 Ma) between Laurentia and Baltica, and (2) to close the British Iapetus sector by Early–Mid-Silurian times (Trench & Torsvik 1992; Torsvik *et al.* 1993). World reconstructions of continental distributions through the Palaeozoic (e.g. Scotese & McKerrow 1990) suggest that, if the Precordillera include exotic terranes derived from Laurentia, the most probable time of transfer appears to be the Devonian, when parts of South America were adjacent to the Appalachian margin.

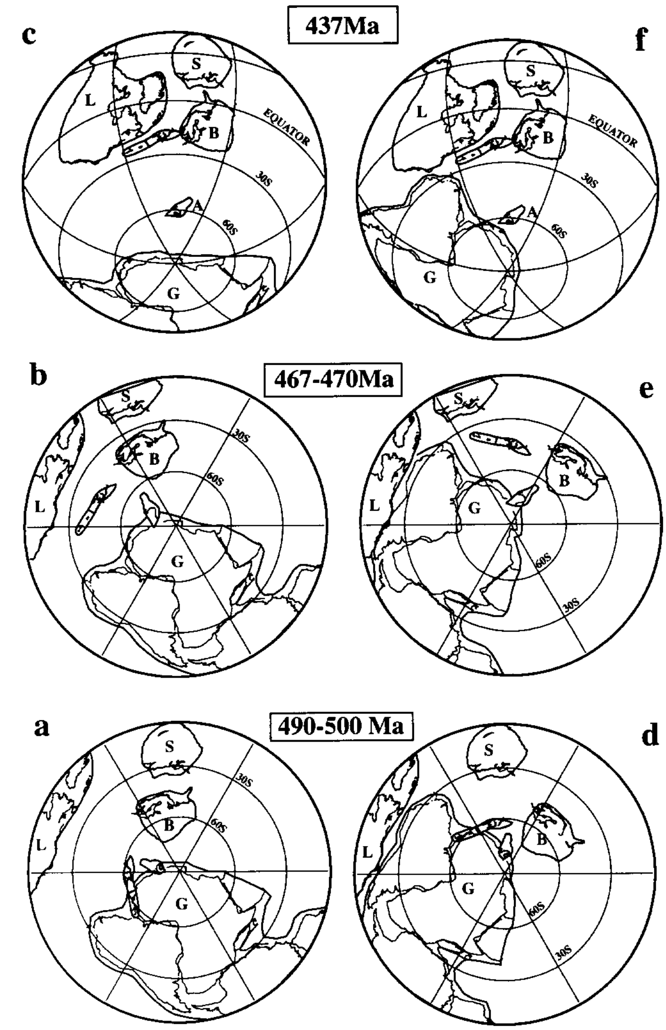

Fig. 11. Ordovician palaeo-reconstructions, including Laurentia (L), Siberia (S), Baltica (B), Armorica (A), Gondwana (G) and Avalonia (unmarked). D–F represent alternatives to A–C, i.e. Laurentia is shown as a conjugate margin to Gondwana (cf. text for details). Reconstructions are based on palaeomagnetic data/poles listed in Table 1 (Siberia); Van der Voo (1988); Torsvik *et al.* (1990); Torsvik & Trench (1991) and Torsvik *et al.* (1992). Note that all the reconstructions for Gondwana are based on a common Ordovician palaeomagnetic pole (Van der Voo 1988) since it appears to be relatively minor APW/change in palaeolatitude during this time interval (cf. Van der Voo 1993).

Conclusions

Our analysis of samples of Ordovician sediments from the Siberian plate confirms and refines the earlier reported data sets, and along with geological evidence, forms the basis for our palaeogeographic reconstructions.

Siberia was geographically inverted at low southerly latitudes during the Early Ordovician. During Early and Mid-Ordovician times, Siberia drifted northwards at comparable or somewhat slower latitudinal drift-rates than Baltica. In our reconstructions we tentatively infer that, during this time period, the present northern margin of Siberia was a comparatively passive conjugate margin facing the then northern active margin of Baltica (Fig. 11a & b), where the Scandinavian Caledonides are now located. Hence, latest Cambrian/Early Ordovician subduction-related eclogite metamorphism in the Upper Allochthon of the Scandinavian Caledonides and Arenig–Llanvirn ophiolite obduction occurred in an ocean–continent zone between Baltica and Siberia. This calls into doubt the traditional correlations of the eugeoclinal, Ordovician, volcanosedimentary assemblages of Baltica and Laurentia where plate tectonic reconstructions have been made between essentially 'static' non-rotational continental blocks. At this time, the Uralian margin of Baltica (Fig. 1) was a passive margin (Zonenshain *et al.* 1990) and supposedly facing the Kazakhstan microcontinent or alternatively Gondwana. Conversely, the northern margin of Siberia comprised a volcanic arc which may have been the source area for 'eastern' Laurentian sedimentation in Late Ordovician time (McKerrow *et al.* 1991). It is also of interest here that Middle to Upper Ordovician conglomerates overlying the Lyngen Gabbro Complex (? ophiolite) in northern Norway contain abundant clasts of exotic, mainly felsic, magmatic arc rock-types of hitherto unknown provenance (Minsaas & Sturt 1985). In the new plate reconstruction scenario (Fig. 11 b & c), a likely magmatic arc source thus presents itself in the Cambro-Ordovician volcanic and plutonic rocks of Taimyr Peninsula of northern Siberia.

During the Late Ordovician we note increased latitudinal velocities for Siberia whereas Baltica rotated anticlockwise. This rotation may have been controlled by deep-seated transcurrent faults, originating at the site of a former subduction zone, which in turn may have governed magma generation and the emplacement of granitoid plutons what is now the Uppermost Allochthon in the Scandinavian Caledonides.

Recent proposals that Laurentia formed a conjugate margin to the South American part of Gondwana during Ordovician times are permissible from presently available palaeomagnetic data, but an inferred tight continental fit during the entire Ordovician is contradicted by biogeographic data. The tight palaeomagnetic fit could perhaps be an artefact of inaccuracies in the palaeomagnetic record, most probably for Gondwana.

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