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The Neoproterozoic and Palaeozoic palaeomagnetic data for the Siberian Platform: From Rodinia to Pangea

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Abstract

Using the most reliable palaeomagnetic data from the Siberian Platform we have constructed an apparent polar wander (APW) path extending between 1100 Ma and 250 Ma. From this we derive the palaeo-latitudinal drift history and orientation change of Siberia through the Neoproterozoic and Palaeozoic.

Comparison of selected palaeomagnetic data from Siberia north and south of the Viljuy basin confirms a mid-Palaeozoic anticlockwise rotation of northern Siberia relative to southern Siberia. The rotation of approximately 20 degrees was first proposed by Gurevich in 1984. The Viljuy basin runs approximately east–west along latitude 64°N. APW paths based on data compilations including, for example, Ordovician data from both the Lena river section (south) and Moyero river section (north) will be adversely affected by this relative rotation.

The palaeomagnetic data indicate an inverted orientation for Siberia in 'Rodinia times' (ca. 750 Ma) in a palaeo-latitudinal belt between 15°S and 20°N. This is inconsistent with a palaeo-position on the northern margin of Rodinia if the rest of Rodinia is located according to palaeomagnetic data from Laurentia, Baltica and East Gondwana.

The final convergence between Siberia and Baltica is poorly constrained by palaeomagnetic data. At 360 Ma Siberia was in an inverted position in mid-northerly latitudes, separated from Baltica (to the south) by an east–west oceanic tract approximately 1500 km wide. The next palaeomagnetic constraint on the position of Siberia is at 250 Ma which puts Siberia and Baltica together at the northern end of Pangea. The convergence of the two is characterised by the northerly drift of Baltica and clockwise rotation of Siberia.

Although the APW paths for Siberia, Baltica and Laurentia differ, they imply broadly similar palaeo-latitudinal drift trends for the three continents. During the time-period studied all three continents start in southerly/equatorial palaeo-latitudes, drift south, then drift north, changing drift sense at approximately the same time. The smaller scale differences in palaeo-latitude change reflect the opening and closing of intervening oceans. The overall pattern of movements may reflect a large scale (temporal and spatial) geodynamic system which survived the construction and destruction of supercontinents. If we hold to the concept that true polar wander is not significant, we conclude that large continents, although intermittently

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separated by oceanic tracts, may be driven across the globe in a weak union for periods of 800 Ma or more.

Keywords: Rodinia; rotation; Siberia; paleomagnetism; Neoproterozoic; Palaeozoic

1. Introduction

Under the umbrella of the EUROPROBE initiative, conceived to develop cooperation between eastern and western European earth scientists, we have critically reviewed the available palaeomagnetic data for the Siberian Platform. A certain mystery has surrounded such data sets in the minds of many Western palaeomagnetists, given language differences and sometimes limited documentation of the data. We attempt to clear up some of the mystery by presenting a selection of the most reliable data in a form familiar to Western palaeomagnetists and documenting our selection and rejection procedure.

Gurevich (1984) and Pavlov and Petrov (1996) proposed that northern Siberian north of ca. 64°N rotated anticlockwise through approximately 20 degrees relative to southern Siberia in Wenlock to Emsian times. We compare selected palaeomagnetic data from northern and southern Siberia and attempt to constrain further this interpretation (Fig. 1). Given the uncertain tectonic contiguity of the Siberian craton, we choose the southern (Aldanian) part for our analysis of APW for Riphean through Permian time. The majority of available data are from the southern region, enabling the construction of an APW path with maximum breaks not exceeding approximately 100 Ma.

In this account we use the data compilation to address the role of Siberia in a number of palaeogeographic scenarios through Neoproterozoic and Palaeozoic times. Of particular interest to us is the position of Siberia within the Neoproterozoic supercontinent Rodinia. Rodinia is thought to have come into being at around 1100 to 1000 Ma (Moores, 1991; Dalziel, 1991, 1992; Hoffman, 1991) and later underwent a protracted period of dismemberment lasting from approximately 750 Ma to early Cambrian times (Torsvik et al., 1996 and references therein). The position of Siberia in the Rodinia supercontinent configuration is the subject of debate, however the general consensus of opinion has been to place Siberia along the present northern margin of Laurentia (Dalziel, 1992; Condie and Rosen, 1994; Pelechaty, 1996). Our compilation of palaeomagnetic data for Siberia contradicts this fit. We stress, however, that the palaeo-position of Rodinia would benefit from a stronger foundation in data, a situation which dictates caution.

Comparing palaeomagnetic data from Siberia, Baltica and Laurentia, we notice that the motions of the three continents are broadly similar through post-Rodinia time, differing only in detail. We therefore look at the possibility of long-lived plate tectonic systems which survive smaller scale reorganisation of the continents.

In our analysis of palaeomagnetic poles we are required to convert stratigraphic ages to numerical ages in millions of years. Given the wide age range of data, we used the complete and familiar geological timescale of Harland et al. (1990) as a mainstay in this procedure. We recognise, however, that a series of new U–Pb zircon ages from Newfoundland and Britain significantly alters Cambrian and Ordovician chronology (Tucker and McKerrow, 1995) and we use this new timescale to constrain early Palaeozoic ages. Silurian ages are also affected by this timescale but not enough to alter the conclusions of the present investigation.

2. Palaeomagnetic data for the Siberian platform

We report a new palaeomagnetic data compilation for Siberia for late Riphean through Permian time. Gurevich (1984) and Pavlov and Petrov (1996) have proposed that the Siberian craton can be divided into two parts with different pre-Devonian rotation histories. These two parts meet along the Viljuy basin, running sub-latitudinally at approximately 64°N (Fig. 1). This basin encloses the Ygyatta and Viljuy grabens. The Viljuy graben is the larger of the two and runs southwest to northeast where it plunges beneath the Verkhoyansky orogenic belt. The Viljuy graben began to form in the Frasnian (mid-De-

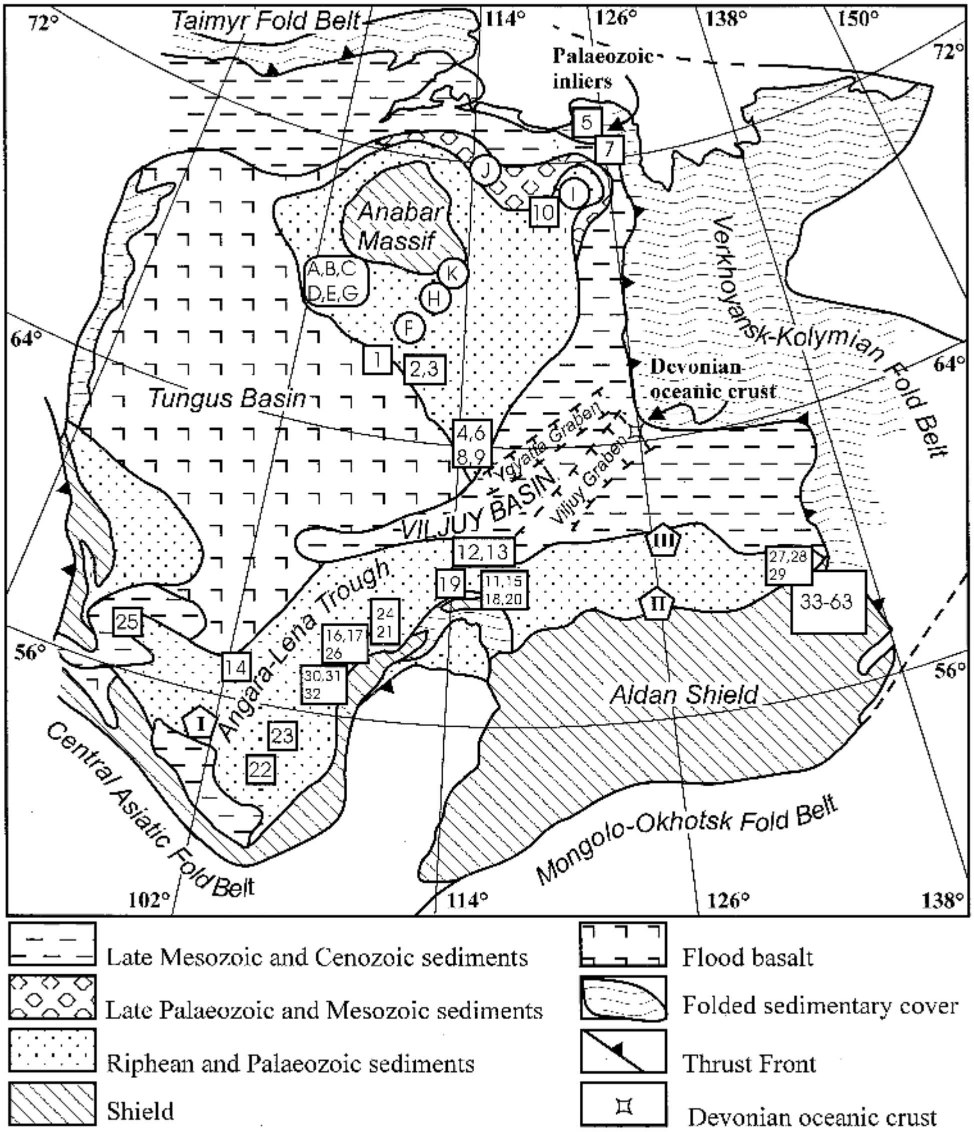


Fig. 1. Tectonic map of the Siberian Platform re-drawn and simplified from Zonenshain et al. (1990). Numbers in squares: sampling sites for selected palaeomagnetic studies in the southern *Aldanian* block and in post-Devonian rocks of the northern *Anabar* block. Numbers correspond to entries in Table 1. Letters in circles: sampling sites for selected palaeomagnetic studies in pre-Devonian rocks of the northern block (see Table 2). Roman numerals in pentagons: sampling sites for palaeomagnetic studies referred to in the text (see Table 1).

vonian) and accommodated an increasing amount of extension towards its northeast end where buried oceanic crust has been identified (Shtekh, 1965; Zonenshain et al., 1990). Pavlov and Petrov (1996) proposed that the block to the north of Viljuy rotated anticlockwise about a pole at approximately 60°N, 100°E relative to the southern block between the Wenlock (S_2) and Emsian (D_1) stages. We have evaluated palaeomagnetic data from both sides of the Viljuy basin but base our APW path for Siberia on the data from the southern (Aldanian) block for pre-Devonian time, and on data from both blocks for Devonian and later times (Fig. 1).

Many poles have been derived for the Siberian craton since palaeomagnetic investigation began there in 1959. Those data include what might fairly be termed key poles, along with less reliable poles derived from blanket cleaning experiments, and even simple low-field cleaning. The majority of palaeomagnetic investigations in Siberia were carried out to establish geomagnetic reversal stratigraphies and therefore sampling was usually performed in long traverses rather than in groups of discrete palaeomagnetic sampling sites. Investigations by Russian scientists dominate the data set; all of these used block sampling techniques in the field, usually measuring the dip direction and amount of dip of flat surfaces with magnetic compasses. The magnetic bearings were adjusted to True North using reference maps indicating magnetic deviation. In many cases between two and four block samples were taken from each stratigraphic horizon, and later two to four specimens were extracted from each block.

Two types of magnetometer were commonly used in the Russian investigations up to 1971; astatic magnetometers produced at the *All-Russia Petroleum Research and Geological Prospecting Institute* in St. Petersburg (VNIGRI), and spinner magnetometers of type ION-1 from the *Geologorazvedka* company. Since 1971, JR-3 and JR-4 spinner magnetometers produced by *Geofyzika Brno* were commonly used. Both thermal and alternating field (AF) demagnetisation techniques were applied in the Siberian studies. The majority of the furnaces in the Russian laboratories were shielded using between three and five mu-metal sheets, resulting in residual fields of 15 nanotesla or less. AF demagnetisation was usually performed using equipment incorporating two-axis tumblers mounted within three-axis Helmholtz coil systems. Up to 1971 it was usual to completely demagnetise only 10 to 15% of the specimens in a collection (at more than 6 demagnetising steps). Those results were used to guide bulk demagnetisation of the rest of the specimens. In these early Russian studies characteristic remanence component directions were determined through the application of Fisher statistics (Fisher, 1953) to ranges of vector differences in demagnetisation trajectories. From 1971 onwards it became usual to completely demagnetise all specimens in a collection and to use Zijderveld diagrams in conjunction with least-squares line fitting algorithms to identify characteristic remanence components. In the case of Russian magnetostratigraphy studies, overall mean remanence directions were calculated from mean directions at the block sample or stratum level.

In compiling the most reliable palaeomagnetic data for Siberia we started out by classifying palaeomagnetic poles according to the 7-point reliability scheme of Van der Voo (1988). The number of criteria met by a palaeomagnetic result, the Q factor, is sometimes used as a measure of quality or reliability. On the whole it is true that a key pole will have a high Q; it does not however follow that a pole with high Q is necessarily a key pole. The only general deduction we have made from Q is when Q is low. None of the poles selected have a Q lower than 3.

In our evaluation of palaeomagnetic data different weights were given to Van der Voo's seven reliability criteria. Criterion 5 concerning the tectonic coherence of the rock unit with the craton of interest was pivotal in our acceptance of data for use in constructing an APW path. Also pivotal was the application of *at least* partial progressive demagnetisation of rock specimens in the identification of ancient magnetic remanence directions.

The majority of palaeomagnetic results for Siberia are reported in Russian, often in summary form, in reports and journals with limited international circulation. We have therefore necessarily been lenient regarding failure to meet Van der Voo's criterion number 3: that the data are reported in sufficient detail for an independent assessment of reliability to be made. One of us (ANK) has a detailed knowledge of many of the available data for Siberia either through direct involvement in the acquisition of the data or though his efforts in maintaining a comprehensive and detailed pole list for the territory of the former Soviet Union (e.g. Khramov, 1975, 1982, 1984). Therefore, in the majority of cases where criterion 3 was not satisfied, we were nonetheless able to make a qualified assessment of analytical procedures followed and demagnetisation characteristics obtained therefrom.

An appreciable number of the Siberian studies have revealed *stratigraphically zoned* dual polarity magnetisations. In our view this is a strong criterion for inferring a primary or near primary magnetisation mode (Van der Voo's criterion 6). Close antipolarity of dual polarity remanence is a good indication of the lack of contamination from an oblique overprint. Where possible we indicate results where mean normal and reverse directions are within 30 degrees of antipolarity and assign greater weight to those.

To make this a concise account of palaeomagnetic data we discuss only the distillation of data included in our brief pole lists (Tables 1 and 2), not those which failed to meet important reliability criteria. Significant poles which break with general trends in the data remain in the lists and are discussed at the appropriate time.

2.1. Riphean (ca. 1100–730 Ma)

The palaeomagnetic record for Siberia from 1100 Ma through 730 Ma, a period of 370 Ma, consists of results from just six suites of rocks—all but one of them sedimentary (poles 63 to 35: Table 1, Figs. 1 and 2). The majority of the data in this group are based on modern laboratory measurements incorporating complete thermal demagnetisation and the application of suitable vector subtraction techniques in the identification of remanence components. Only three of the six rock units are sufficiently well dated to pass Van der Voo's criterion 1. In all cases classical tests of palaeomagnetic stability such as fold, conglomerate and contact tests are absent. Results from the Maya River Groups are supported by the detection of field reversals within 10 degrees of exact antipolarity; encouraging evidence for a primary remanence mode.

The greatest weakness of this data set is age control: only 50% of the rocks units are well dated and few of the rocks studied yielded definitive evidence for a primary magnetisation mode. If the ages of the results are taken at face value, the APW for

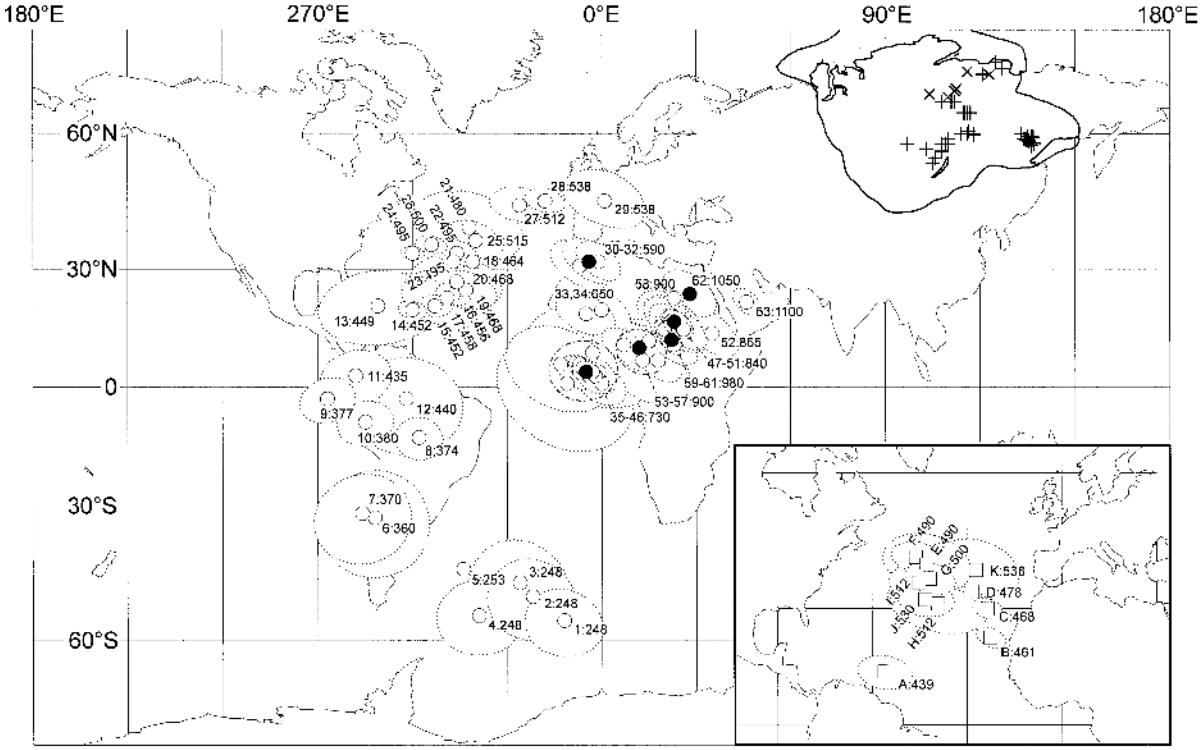


Fig. 2. Selected palaeomagnetic south pole positions for Siberia. Circles: palaeomagnetic pole positions for southern Siberia and post-Devonian poles for northern Siberia. Closed circles denote *combined* poles (see Table 1 for an explanation of combined poles). Pole numbers and ages (Table 1) are indicated alongside the pole positions. Sampling site locations for these poles are indicated by vertical crosses. Squares in inset: pre-Devonian palaeomagnetic pole positions for northern Siberia. Pole letters and ages (Table 2) are indicated alongside the pole positions. Sampling site locations for these poles are indicated by diagonal crosses in the main diagram. The present outline of the Siberian continent is given.

Table 1
Selected palaeomagnetic poles and statistically fitted APW path for southern Siberia

Siberia (south of 64°N before 408 Ma)				Remanence					Pole			
No.	Rock unit	Lat.	Long.	Dec.	Inc.	*N*	*k*	*a*95	Lat.	Long.	Dp	Dm
1	Upper Vilyui Intrusives (gabbro, dolerite)	66	108	261	−75	198	143	4	−56	348	7	7
2	Markha Region Volcanics and Intrusions (dolerite)	66	112	282	−75	298	56	5	−51	338	9	10
3	Upper Markha Region Intrusions (dolerite)	66	111	286	−75	338	154	6	−48	334	10	11
4	Ygyattin Region Intrusions (dolerite)	64	115	293	−82	446	56	4	−55	321	8	8
5	Lena River Sediments (various)	73	125	344	−75	35	18	19	−45	316	32	35
(I)	Angara River Intrusions and Sediments not used in APW path	55	101	275	−49	673	56	1	−21	350	1	1
(II)	Aldan Region Intrusions (syenite-porphyries) not used in APW path	59	126	322	−67	28	67	6	−23	331	8	10
6	Ygyattin Intrusives (dolerite)	64	115	12	−73	17	19	8	−33	288	13	14
7	Frasnian Volcanics and Sediments (red dolomite)	72	127	31	−66	286	21	8	−32	284	11	13
8	Ygyalta Series Volcanics and Intrusives (basalt, dolerite)	64	117	353	−58	66	13	5	−13	302	6	8
9	Ygyattin Series (basalt)	64	116	25	−45	20	22	7	−3	273	6	9
10	Olenek Region Intrusives (gabbro, dolerite)	71	121	17	−47	26	18	7	−9	285	6	9
11	Lena River Sediments (sandstone, siltstone)	60	116	15	−44	15	17	9	3	282	7	11
12	Lena River Sediments 5 (siltstone, mudstone, marl)	61	116	358	−52	9	16	13	−3	298	12	18
13	Lena River Sediments 4 (siltstone, mudstone, marl)	61	116	7	−16	17	5	17	21	289	9	18
14	Lower Bratsk Group (redbeds)	57	103	344	−23	133	10	4	20	300	2	4
15	Lena River Sediments (redbeds, clay)	60	118	351	−17	49	22	5	21	307	3	5
16	Makarovsk Group (redbeds)	58	108	338	−10	106	7	5	24	313	3	5
17	Lena River Sediments (sandstone, clay)	58	108	339	−14	20	8	13	23	311	7	13
18	Lena River Sediments 3 (mudstone, siltstone, marl, limestone)	60	118	342	7	26	82	3	32	319	2	3
19	Lena River Redbeds (sandstone, siltstone)	60	114	340	−5	21	11	9	25	317	5	9
20	Lena River Sediments (limestone, sandstone, clay)	60	118	346	−4	20	11	13	27	314	7	13
21	Ustkutsk Group (redbeds, limestone)	58	110	338	21	93	50	13	40	318	7	13
22	Verkholensk Group (redbeds)	54	105	337	4	192	33	6	34	314	3	6
23	Verkholensk Group (redbeds)	55	106	338	3	281	11	3	32	313	2	3
24	Irkutsk Sediments (red sandstone, siltstone, clay)	59	110	352	4	303	6	3	34	300	2	3
25	Evenkiisk Group (shale, sandstone, clay)	58	97	327	24	615	8	7	37	320	4	8
26	Lena River Sediments (redbeds)	58	109	346	13	193	270	4	36	306	2	4
27	Ust'Maya and Amga Groups (limestone, shale, marl)	60	133	345	32	21	30	6	45	334	4	7
(III)	Lena River Sediments (limestone) not used in APW path	61	127	238	−4	50	12	6	17	245	3	6
28	Inican River Sediments (limestone, shale)	59	135	161	−32	18	435	4	46	342	3	5
29	Pestrotsvetna Group (limestone, claystone)	60	135	148	−39	19	21	8	46	1	6	10
30	Baikalia Sediments (limestone, sandstone, shale)	57	108	123	−31	22	14	6	32	359	4	7
31	Baikalia Sediments (limestone, sandstone, shale)	57	108	127	−24	29	10	8	31	353	6	11
(32)	Baikalia Sediments Combined (poles 30 & 31) not used in APW path	57	108	125	−28	51	7	7	32	356	4	8
33	Ust–Kirbinskaya suite (red siltstone)	58	137	324	−14	21	11	9				
34	Ust–Kirbinskaya suite (red siltstone)	59	137	320	−6	24	10	9	20	360	5	9

Path			Age			Trt.	Classification										References
Lat.	Long.	Diff.	H	T	M		1	2	3	4	5	6	7	*Q*	R	K	
−53	333	9	248		S	a		X			X	X	X	4	N		Kamysheva, 1971
−53	333	4	248		S	a	X	X			X	X	X	5	Y	X	Kamysheva, 1971
−53	333	5	248		K–Ar	a	X	X			X	X	X	5	Y	X	Kamysheva, quoted in Khramov, 1984
−53	333	7	248		S	a		X			X	X	X	4	Y		Kamysheva, quoted in Khramov, 1984
−50	324	8	253		S	t,a	X	X		X	X		X	5			Pisarevsky, 1982
(−38)	(295)	(50)	300		S	a		X			X		X	3			Davydov and Kravchinsky, 1973
(−38)	(295)	(34)	300		S	a		X			X		X	3			Kamysheva, 1973
−27	291	7	360		K–Ar	a	X				X		X	3			Kamysheva, 1975
−19	290	14	370		F	a	X			X	X		X	4		X	Pisarevsky, 1982
−16	289	13	374		S	a	X	X			X	X	X	5	N	X	Kamysheva, 1975
−13	288	18	377		S	a	X				X		X	3			Kamysheva, 1975
−11	287	3	380		S	a		X			X		X	3			Kamysheva, 1973
10	291	11	435		F	T	X				X		X	3			Rodionov et al., 1982
12	294	16	440		F	T	X		X		X	X	X	5	Y		Torsvik et al., 1995
15	297	10	(443)	449	F	T	X		X		X		X	4		X	Torsvik et al., 1995
20	303	3	(450)	452	F	t	X	X			X		X	4			Rodionov, 1966
20	303	4	(450)	452	F	a	X	X			X		X	4			Rodionov, 1966
26	312	2	(460)	456	F	t	X				X	X	X	4	N		Khramov, 1982
28	314	5	(463)	458	F	a	X				X	X	X	4	N		Rodionov, 1966
30	316	3	(468)	464	F	T	X	X	X		X		X	5		X	Torsvik et al., 1995
31	317	6	(473)	468	F	T,A	X				X	X	X	4	N	X	Bucha et al., 1976
31	317	5	(473)	468	F	a	X				X	X	X	4	N		Rodionov, 1966
32	314	8	(488)	480	F	t,a	X	X			X	X	X	5	Y	X	Khramov, 1975
34	308	5	(510)	495	F	a		X	X		X	X	X	5	Y		Gurary and Trubikhin, 1968
34	308	4	(510)	495	S	t	X	X			X	X	X	5	Y	X	Kravchinsky et al., quoted in Khramov, 1982
34	308	7	(510)	495	S	a	X				X	X	X	4	N		Rodionov, quoted in Khramov, 1984
36	310	8	515		K–Ar	a	X				X	X	X	4	Y		Gurary, 1969
36	310	4	(515)	500	S	at	X	X			X	X	X	5	Y		Rodionov, quoted in Khramov, 1982
44	324	7	(530)	512	F	t	X	X			X	X	X	5	Y		Osipova, 1973a,b,c
(48)	(345)	(84)	(560)	537	F	T	X	X	X		X	X	X	6	Y		Kirschvink and Rozanov, 1984
46	351	6	(562)	538	F	t,a	X				X		X	3			Osipova, 1986
46	351	7	(562)	538	F	t	X				X	X	X	4	Y		Osipova, 1986
33	357	2	590		S	a	X				X		X	3			Gurevich, 1981
33	357	4	590		S	a	X	X			X		X	4			Gurevich, 1981
(33)	(357)	(1)	590		S	a	X				X		X	3			Gurevich, 1981
19	357	2	650		S, K–Ar	T	X		X		X		X	4		X	Pavlov, 1994
19	357	3	650		S, K–Ar	T	X		X		X		X	4		X	Pavlov, 1994

Table 1 (continued)

Siberia (south of 64°N before 408 Ma)				Remanence					Pole			
No.	Rock unit	Lat.	Long.	Dec.	Inc.	*N*	*k*	*a*95	Lat.	Long.	Dp	Dm
35	Kandykskaya suite sediments (chert)	59	136	327	−36	3	28	15	6	347	10	17
36	Kandykskaya suite intrusions (gabbroic diabase)	59	136	318	−27	7	7	19	9	357	11	21
37	Kandykskaya suite intrusions and baked contacts (gabbroic diabase, chert, sandstone)	59	136	312	−37	11	34	7	1	360	5	8
38	Kandykskaya suite sediments (siltstone, sandstone)	59	136	321	−37	7	73	6	4	353	4	7
39	Kandykskaya suite sediments (siltstone, sandstone)	59	136	323	−42	10	6	18	1	349	14	22
40	Kandykskaya suite intrusions and baked contacts (gabbroic diabase, chert, sandstone)	59	136	317	−34	21	48	4	4	357	3	5
41	Kandykskaya suite intrusions (gabbroic diabase)	59	136	315	−36	14	34	6	3	358	4	7
42	Kandykskaya suite intrusions (gabbroic diabase)	59	136	321	−33	21	115	3	6	353	2	3
43	Kandykskaya suite intrusions (gabbroic diabase)	59	136	317	−36	16	31	6	3	356	4	7
44	Kandykskaya suite intrusions (gabbroic diabase)	59	136	320	−35	22	52	4	5	354	3	5
45	Kandykskaya suite intrusions (gabbroic diabase)	59	136	315	−34	28	25	5	4	359	3	6
(46)	Kandykskaya suite combined (poles 36,37, 40–45) not used in APW path	59	136	319	−35	140	266	3	4	355	2	4
47	Ignicanskaya suite (red dolomite)	58	136	295	5	18	17	8	15	26	4	8
48	Ignicanskaya suite (red dolomite)	59	135	298	7	17	12	10	17	23	5	10
49	Ignicanskaya suite (red dolomite)	59	135	299	7	30	14	7	17	22	4	7
50	Ignicanskaya suite (red dolomite)	59	135	298	7	11	13	12	17	23	6	12
(51)	Ignicanskaya suite combined (poles 48, 49 & 50) not used in APW path	59	135	298	7	58	999	9	17	22	1	1
52	Nelkanskaya suite (limestone)	58	136	287	12	18	13	9	14	35	5	9
53	Milkonskaya suite (limestone)	59	135	308	−17	21	19	7	11	7	4	7
54	Milkonskaya suite (limestone)	59	136	302	−19	15	16	16	7	13	9	17
55	Milkonskaya suite (limestone)	59	135	302	−8	12	22	9	12	15	5	9
56	Milkonskaya suite (limestone)	58	136	298	−17	23	13	8	7	18	4	8
(57)	Milkonskaya suite combined (poles 53,54 & 55) not used in APW path	59	135	304	−15	48	145	10	10	12	5	11
58	Maya River Groups (limestone, siltstone, shale)	59	134	300	18	94	19	3	23	23	2	3
59	Kumahinskaya suite (red argillite)	59	135	299	2	17	48	5	15	20	3	5
60	Kumahinskaya suite (dolomite)	59	135	295	−4	16	49	8	11	23	4	8
(61)	Kumahinskaya suite combined (poles 59,60 & other) not used in APW path	59	135	296	−2	41	346	7	12	22	3	7
(62)	Maya River Groups combined (poles 58, 63 & other) not used in APW path	59	135	295	28	338	50	8	24	28	5	9
63	Maya River Groups (limestone, siltstone, shale)	59	135	281	35	206	8	4	22	46	3	5

Palaeomagnetic poles from rocks north of 64°N with ages older than 408 Ma are listed separately in Table 2 due to a suspected tectonic rotation between northern and southern Siberia (see text).

No. = pole number used in Figs. 1 and 2 and in the text. Poles numbered in parentheses (I, II, III, 62, 61, 57, 51, 46 and 32) were not used to generate the APW path. Our reasons for excluding poles I, II and III are presented in the text. Poles 62, 61, 57, 51, 46 and 32 are published/reported combined poles based other data in the pole list (see *Rock Unit* for a list of the data sets included in the combined poles); Details of the APW path appear in parentheses alongside the excluded poles; *Lat., Long.* = site latitude, longitude; *Dec., Inc., N, k, a95* = remanence declination, inclination, number of observations, the precision parameter k by Fisher (1953), and 95% error parameter; *Pole Lat., Long., Dp, Dm* = south palaeomagnetic pole latitude, longitude and 95% error parameters; *Path Lat., Long., Diff.* = statistically fitted APW path latitude, longitude and great circle angle from palaeomagnetic pole; *Age* = Rock and pole age (Ma) according to two time scales *H* = Harland et al. (1990), *T* = Tucker and McKerrow (1995); *M* = Dating method (S = stratigraphic, F = fossil, K–Ar and Pb–S = radiometric); *Trt.* = laboratory demagnetisation procedure (a/A = partial/complete AF demagnetisation, t/T = partial/complete thermal demagnetisation, at = combined AF and thermal treatment, A,T = complete AF on some samples and thermal on others); *1,2,3,4,5,6,7,Q* = reliability classification scheme of Van der Voo (1988); *1* = good age, *2* = firm statistical foundation, *3* = detailed laboratory analysis, *4* = field tests of stability, *5* = tectonic coherence with craton, *6* = reversals, *7* = not like younger results, *Q* = score 0 to 7, *R* = antipolar reversals (*Y* = within 30 degrees of antipolarity, *N* = not); *K* = key pole.

Path			Age			Trt.	Classification										References
Lat.	Long.	Diff.	H	T	M		1	2	3	4	5	6	7	*Q*	R	K	
4	355	8	730		S, K–Ar	T	X		X		X		X	4			Pavlov, 1994
4	355	5	730		S	A	X		X		X		X	4			Pavlov, 1994
4	355	6	730		S,K–Ar	A	X		X		X		X	4			Pavlov, 1994
4	355	2	730		F,K–Ar	T	X		X		X		X	4			Pavlov, 1994
4	355	7	730		F,K–Ar	T	X		X		X		X	4			Pavlov, 1994
4	355	2	730		S,K–Ar	A	X		X		X		X	4			Pavlov, 1994
4	355	3	730		S	A	X		X		X		X	4			Pavlov, 1994
4	355	3	730		S	A	X		X		X		X	4			Pavlov, 1994
4	355	2	730		S	A	X		X		X		X	4			Pavlov, 1994
4	355	1	730		S	A	X		X		X		X	4			Pavlov, 1994
4	355	4	730		S	A	X	X	X		X		X	5			Pavlov, 1994
(4)	(355)	(0)	730		F,S,K–Ar	T,A	X	X	X		X		X	5		X	Pavlov, 1994
(16)	(24)	(3)	840		K–Ar,Pb, S	T			X		X		X	3			Pavlov, 1994
(16)	(24)	(1)	840		K–Ar,Pb, S	T			X		X		X	3			Pavlov, 1994
(16)	(24)	(2)	840		K–Ar,Pb, S	T		X	X		X		X	4			Pavlov, 1994
(16)	(24)	(1)	840		K–Ar,Pb, S	T			X		X		X	3			Pavlov, 1994
(16)	(24)	(2)	840		K–Ar,Pb, S	T		X	X		X		X	4			Pavlov, 1994
(16)	(30)	(5)	865		F,K–Ar	T	X		X		X		X	4		X	Pavlov, 1994
(18)	(25)	(8)	900		F,K–Ar	T			X		X		X	3			Pavlov, 1994
(18)	(25)	(15)	900		F	T			X		X		X	3			Pavlov, 1994
(18)	(25)	(11)	900		F	T			X		X		X	3			Pavlov, 1994
(18)	(25)	(12)	900		F	T			X		X		X	3			Pavlov, 1994
(18)	(25)	(14)	900		F	T		X	X		X		X	4			Pavlov, 1994
(18)	(25)	(6)	900		F K–Ar	t	X	X			X		X	4		X	Osipova, 1971
(18)	(25)	(5)	980		S	T			X		X		X	3			Pavlov, 1994
(18)	(25)	(7)	980		F,K–Ar	T			X		X		X	3			Pavlov, 1994
(18)	(25)	(6)	980		F, K–Ar	T		X	X		X		X	4			Pavlov, 1994
(20)	(25)	(5)	1050		F K–Ar	t	X	X			X	X	X	5	Y	X	Osipova, 1971
(22)	(46)	(0)	1100		F K–Ar	t	X	X			X	X	X	5	Y	X	Osipova, 1971

1100 to 730 Ma appears to zigzag backwards and forwards a number of times while traversing very little of the globe. More likely, given the comparatively poor age control on rock and remanence, APW for Riphean through Sturtian time follows a more direct path from the Maya river pole 63 (rocks well dated, ca. 1100 Ma) to the Kandykskaya suite poles 46 to 35 (dated at ca. 730 Ma, Fig. 2). The Kandykskaya results from south-east Siberia (Fig. 1) are of special interest because the majority are from a suite of diabase intrusions which has been correlated with the Franklin dyke swarm in Canada (Condie and Rosen, 1994). The Kandykskaya microgabbros and dolerites were emplaced in the lower strata of the Kandykskaya suite sediments. According to the review of radiometric dates of Semikhatov and Serebriakov (1983), pebbles from the dolerites occur in upper strata which have been dated to between 700 and 760 Ma (K–Ar age on glauconite). These rocks were later cut by intrusions of the Ingili massif dated to between 640 and 690 Ma (K–Ar on biotite) and 650 Ma (Pb–Pb).

The shortness of this path segment is notable given the long time it represents (370 Ma). Either Siberia remained quite static excepting longitudinal movement during that time or the ages of the rock

Table 2
Potentially rotated palaeomagnetic poles from rocks in northern Siberia older than 408 Ma

Siberia (south of 64°N before 408 Ma)				Remanence					Pole			
ID	Rock unit	Lat.	Long.	Dec.	Inc.	*N*	*k*	*a*95	Lat.	Long.	Dp	Dm
A	Moyero River Sediments VI (limestone)	68	104	340	−14	20	17	8	14	304	4	8
B	Moyero River Sediments V (limestone)	68	104	311	17	32	48	4	23	338	2	4
C	Moyero River Sediments IV (red marl + limestone)	68	104	315	28	45	31	4	30	337	2	4
D	Moyero River Sediments III (red marl + limestone)	68	104	320	32	144	29	2	3	332	1	3
E	Moyero River Sediments II (red marl + limestone)	68	104	333	37	15	26	9	40	318	6	11
F	Alakit River Sediments (limestone)	67	110	341	36	27	24	5	42	314	3	6
G	Moyero River Sediments I (red marl + limestone)	68	104	332	33	22	30	6	37	318	4	6
H	Olenek River Sediments (limestone, siltstone, marl)	68	112	336	24	102	44	13	31	321	7	14
I	Olenek River Sediments (limestone)	71	123	349	32	73	7	7	36	315	4	8
J	Udzha River Sediments (limestone, sandstone)	72	116	341	28	40	11	7	32	317	4	8
K	Emyaksa Group (limestone)	69	113	327	40	20	12	9	39	333	7	11

ID = pole letter used in Figs. 1 and 2 and in the text. Other symbols and abbreviations are as in Table 1. Note that (1) these data are passed on Van der Voo's criterion 5 even though their tectonic coherence with southern Siberia is in doubt, (2) a polar wander path has *not* been fitted to the data in this table, the APW path listed under *Path Lat., Long*. is for *southern* Siberia. *Path Diff*. is the angle between the northern data of this table and the path for southern Siberia.

units and/or remanences are wildly wrong. Given that we only have the shortness of the path to suspect incorrect dating of the results, we favour the static or lethargic explanation of Siberia for the Riphean.

The greatest uncertainty in the locus of this part of the APW path lies between the 840 Ma (and older) results and the tight group of 730 Ma (key) results from the Kandykskaya suite. Without data to guide us, we presume that APW follows the shortest route across this 110 Ma gap. Although the gap is long in the temporal frame, it is narrow in pole-space (15 degrees of arc).

2.2. Vendian through Early Cambrian (ca. 650–535 Ma)

An 80 My gap in the palaeomagnetic record ends with poles of ca. 650 Ma age. The eight palaeo-poles in our list with ages between 650 and 535 Ma come from well dated limestones and redbeds (poles 34 to 28 and pole III: Table 1, Figs. 1 and 2). The pole of Kirschvink and Rozanov (1984) (ca. 537 Ma) is an outlier and will be discussed later. The other palaeopoles describe a noisy arc from the tight cluster of 730 Ma poles (Kandykskaya suite) towards 320°E 30°N (Fig. 2). It is notable that only one of the seven remaining results in the 650 to 530 Ma range has a good statistical foundation. This could well be the principal reason for the irregular procession of poles through this time window. None of the poles are supported by field tests of palaeomagnetic stability, and only one is supported by the observation of field reversals (29: Pestrotsvetna Group). The course of APW described by these seven surviving data is, however, supported by a number of data which were excluded from our selection due to the use of only cursory demagnetisation techniques. These are studies from the Lena, Belaya and Maya rivers (e.g. SU130075 and SU130041 in the Russian pole list) supported by reversal stratigraphies. The Emyaksa Group pole (K: Table 2, Fig. 2 inset lower right) falls into the present time window but comes from rocks north of Viljuy and will be discussed later.

We list an outlying palaeo-pole by Kirschvink and Rozanov (1984) with a reported age of ca. 537 Ma (pole III, Table 1). Being one of as yet very few results for Siberia from joint projects between Eastern and Western scientists we explain our reasons for its exclusion from our APW analysis. The authors indicate that the result from the Lena river section is supported by a ‘‘correlatable and consistent magnetic polarity stratigraphy’’ (see also Kirschvink, 1992). The conundrum, then, is why does the pole not fall anywhere near, and preferably between, older and younger results from the Lena river section, or other sedimentary sections on the Siberian craton? Kirschvink (1992) proposed that APW for Siberia

Path			Age			Trt.	Classification										References
Lat.	Long.	Diff.	H	T	M		1	2	3	4	5	6	7	*Q*	R	K	
(11)	(293)	(11)	439		F	T	X		X		X		X	4			Gallet and Pavlov, 1996
(29)	(315)	(21)	(466)	461	F	T	X	X	X		X	X	X	6	Y		Gallet and Pavlov, 1996
(31)	(318)	(16)	(473)	468	F	T	X	X	X		X		X	5			Gallet and Pavlov, 1996
(33)	(316)	(13)	(485)	478	F	T	X	X	X		X		X	5			Gallet and Pavlov, 1996
(32)	(309)	(11)	(500)	490	F	T	X		X		X	X	X	5	Y		Gallet and Pavlov, 1996
(32)	(309)	(11)	(500)	490	F	t,a	X	X			X		X	4			Rodionov, 1966
(36)	(310)	(6)	(515)	500	F	T	X		X		X		X	4			Gallet and Pavlov, 1996
(44)	(325)	(13)	(530)	512	F	at	X	X			X	X	X	5	Y	X	Osipova, quoted in Khramov, 1982
(44)	(325)	(11)	(530)	512	F	T	X				X	X	X	4	Y		Pisarevsky and Gurevich, quoted in Khramov, 1986
(47)	(341)	(24)	(553)	530	S	T	X	X	X		X		X	5		X	Komissarova, quoted in Khramov, 1986
(46)	(347)	(12)	(562)	538	F	t	X				X	X	X	4	Y		Osipova, 1986

passed from his outlying Vendian/early Cambrian pole through ca. 90 degrees of arc, not punctuated by other data, to pass through mid-Cambrian poles, also included in our list. To incorporate the pole of Kirschvink and Rozanov (1984) into our APW model, APW would first have to pass through 90 degrees to get to the outlying Kirschvink and Rozanov pole, and then 90 degrees in the opposite direction to get back again (Table 1, pole III, *Path Diff.*), within a very short time period. This being unlikely, we view the single outlying pole with some trepidation, a point of view strengthened by the fact that the pole becomes entirely consistent with the others in Table 1 if 90 degrees is added to the declination of the mean remanence direction (058.1 + 90 = 148.1, yielding a pole at 22.4°S, 161.7°E which is equivalent to a south pole at 22.4°N, 341.7°E, a pole position which would not be out of place in our data compilation at 540 Ma).

In an attempt to resolve the discrepancy between early Cambrian results Pisarevsky, Gurevich and ANK obtained new palaeomagnetic data for Lower Cambrian sediments outcropping along the Olenek river (northern Siberia, Pisarevsky et al., 1997). Their results confirm the Cambrian poles included in our data selection while the Kirschvink and Rozanov (1984) pole remains unsubstantiated.

2.3. *Early–Cambrian through Late Ordovician/Early Silurian (ca. 530–439 Ma)*

There are 16 poles in our list with reported ages between 530 and 439 Ma, all from sedimentary rocks (Poles 27 to 12: Table 1, Figs. 1 and 2). Ten results were selected for this time period from north of the Viljuy basin, poles J to A: Table 2, Figs. 1 and 2. None of the 16 results are supported by positive field tests, however, rock ages are well determined and a primary mode for many of the results is supported by the presence of reversals. The majority (13) of the results come from Russian laboratories, seven of those obtained before 1975. We will discuss the older Russian results first, and then the results of two recent studies from Western laboratories (Torsvik et al., 1995; Gallet and Pavlov, 1996).

The Russian results for this time have a significantly firmer statistical foundation than for earlier time windows. This is because many of the results are from long stratigraphic sections subjected to detailed sampling and not because of the application of more detailed or modern demagnetisation procedures. Of the ten studies reporting dual polarities only five approach true antipolarity (> 150 degrees). The simplest explanation for this phenomenon is contamination—the incomplete separation of the normal and reverse primary components from an oblique overprint. Averaging the two polarities might reduce the bias but will not eliminate it completely. This is disturbing but does not completely invalidate the data. There are many results for the time window which describe a fairly noisy but consistent trend in APW swinging from 40°N 315°E (Cambro–Ordovician boundary) through 25°N 315°E (Llandeilo) to 5°N 280°E (Ashgill/Llandovery)(Fig. 2). We therefore take this to be an acceptable indication of the actual APW path for Siberia.

The recent study of Torsvik et al. (1995) along the Lena river section yielded the remaining three palaeo-poles in this time window with Lower Llandeilo (464) Lower Ashgill (449) and Upper Ashgill/Llandovery (440) ages (Poles 18, 13 and 12: Table 1, Figs. 1 and 2). The palaeo-poles are based on few samples, but all were subjected to detailed and complete demagnetisation. On the whole the Torsvik et al. (1995) results confirm the earlier Russian results, reinforcing this section of the APW path. Unfortunately, greatest reinforcement is required at the younger end of the APW segment, at approximately 440 Ma. Torsvik et al.'s 440 Ma pole (12) is the weakest of the three, based on only nine (mixed polarity) specimens. Still, it lies not far from the Upper Ashgill/Llandovery pole of Rodionov et al. (1982) and therefore suggests that the definition of the younger end of this part of the Siberian APW path is 'firm' if not 'solid'.

Five palaeo-pole positions ranging in age from Upper Cambrian to Lower Silurian from the study of Gallet and Pavlov (1996) are included in Table 2 for Siberia north of Viljuy. The remanences themselves appear to be primary, however the data are from the Viljuy (triangle) basin, which explains why their Lower Silurian pole (Pole A: Table 2, Fig. 2 inset) lies 25 degrees east of similar aged poles from the southern part of the platform (Fig. 2). Gallet and Pavlov (1996) recognise the similarity in the shape of the APW path described by their data and the earlier compilation of Khramov (1991). They attribute the differences between their data and the reference path to a difference in the time resolution of the data sets. We attribute the apparent offset of their data to significant mid-Palaeozoic relative tectonic rotation.

2.4. Silurian through Permian (ca. 435–250 Ma)

There are 13 poles in our list (poles 11 to 1: Table 1, Figs. 1 and 2) including 2 poles (I and II) which are not used in our APW path. Unlike the previous time windows, poles from sedimentary rocks are in the minority (4). The rocks are generally well dated and, unlike any other time window, the majority of results have a firm statistical foundation. Most of the studies are old and did not incorporate detailed progressive demagnetisation and/or analytical procedures (criterion 3). Partial AF cleaning was the predominant laboratory treatment used. Palaeomagnetic stability tests support the magnetisation ages of two of the results (7 and 5). The reversals reported in studies 2, 3 and 4 are close to antipolar, supporting the overall pole positions despite less than ideal laboratory demagnetisation for palaeo-pole determination.

We notice that the older poles in this time window (8, 9, 10 and 11) follow on from the general trend in the data in the preceding time window (Fig. 2). We presume, therefore, that APW passes through central South America late in the Devonian period. The course of APW becomes unclear through Carboniferous time into the Permian. A consistency between palaeo-pole positions re-emerges in the Zechstein where 5 comparatively strong results (1 to 5, Table 1) are in good agreement. The data in our selection with ages in the range Late Devonian to Mid-Permian (Poles 6, 7, I and II: Table 1) present two conflicting courses of APW in the uncertain region. Either APW passes south into central Chile (Poles 6 and 7) and then swings southeast to pass though the Zechstein poles, or it traverses southeast to pass through poles I and II and then on to the Permian poles. After some deliberation we chose to accept poles 6 and 7 as the most reliable of the four poles. In their favour, the rocks are well dated, the studies are more recent and one of the poles is supported by a remanence stability test. Poles I and II come from poorly dated rocks, no evidence exists for a primary magnetisation mode and both studies are old.

3. The APW path

The 'spherical spline' algorithm of Jupp and Kent (1987) as implemented in the GMAP program of Torsvik and Smethurst (http://www.ngu.no/geophysics/index.html) was used to fit a smooth curve to palaeomagnetic poles. The spline is constrained to lie in the unit sphere and takes the ages of poles and their reported angular uncertainties into account. A smoothing parameter is used to control the sinuosity of the path. The selected poles for Siberia in Table 1 were used in the analysis, consisting of poles of all ages from south of Viljuy, and only post-Devonian data from north of Viljuy. Poles I, II and III were excluded from the analysis for reasons already noted. The combined poles 62, 61, 57, 51, 46 and 32 were also excluded because they are based either wholly or partly on other data in the pole list (see notes in Table 1). In the case of the Siberian data set, the shape of the fitted path was insensitive to adjustments in the smoothing parameter.

The locus of the fitted path is given in digital form alongside the original palaeomagnetic poles in Table 1 (*Path Lat.* and *Path Long.*). The great circle angle between original palaeomagnetic poles and their time-equivalent positions in the path are given in column *Path Diff*. The path details corresponding in time to poles which were *not* used to derive the fitted path are shown in parentheses. It was noted in an earlier discussion that if the ages of the pre-730 Ma data are taken at face value the course of APW would track back and forth a number of times to accommodate all of the data. Being suspicious of potential dating inaccuracies we chose to deal with this section of the path in two ways. The first was simply to take the data at face value and produce a path with a tight loop in it. This 'objective' approach was used to derive the path segment indicated in parentheses in Table 1 for poles 47 to 63. The second was to re-assign ages to the data in order to obtain a smooth path passing straight through the data, essentially ignoring details in their time progression. The result of this second 'eyeball' approach is shown only in Fig. 3.

Fig. 3 shows the fitted path displayed together with the selected palaeomagnetic poles. The smooth curve describes the palaeomagnetic poles satisfactorily, taking into account the error ovals associated with the poles. The inset in Fig. 3 has a similar

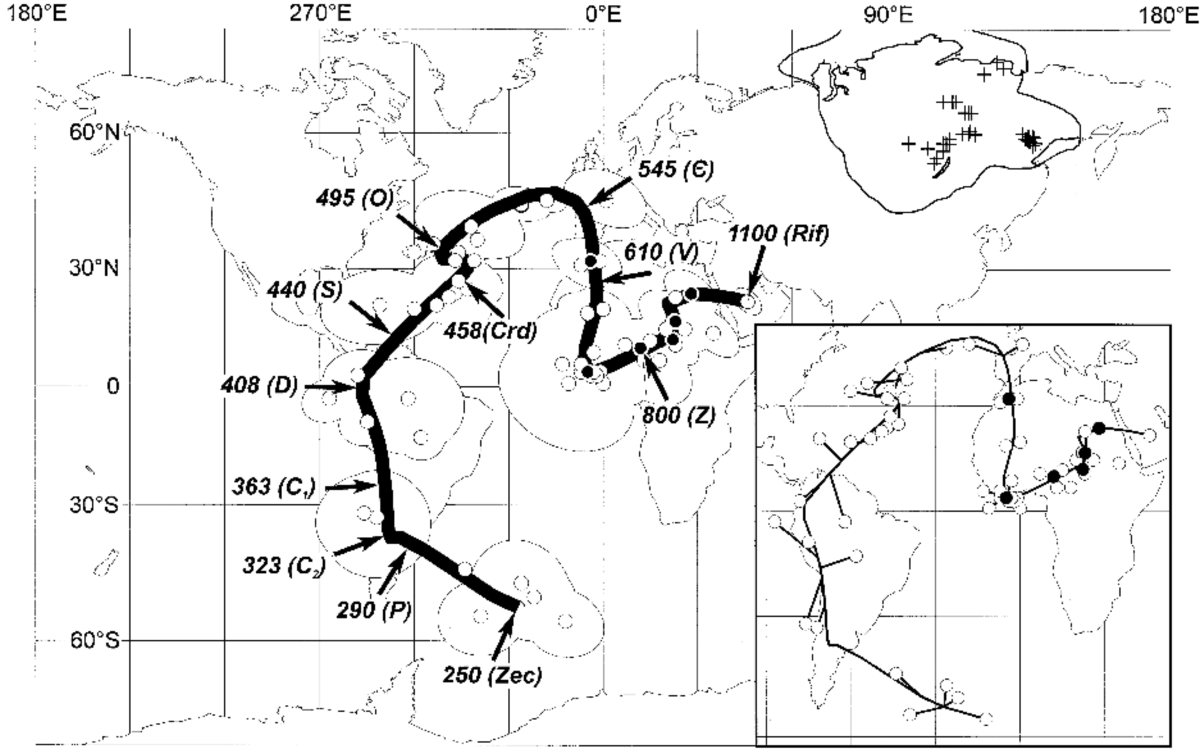


Fig. 3. The south polar wander path for Siberia (southern block plus northern block for post-Devonian time only; *Path Lat. Long.* in Table 1). Main diagram: 95% error envelopes are indicated around palaeomagnetic poles (see Fig. 1 for the identities of poles). The polar wander path is indicated by a thick black line. Combined poles (closed circles) were not used to generate the APW path (see Table 1 for an explanation of combined poles). Times for the path are indicated in italic lettering (numerical ages and stratigraphic abbreviations). Inset: palaeomagnetic poles linked to the path according to time (see *Path Diff.* in Table 1).

content but shows the individual poles linked to the path according to their reported ages, illustrating the effect each pole has on the time calibration of the path — not easily seen in the more conventional representation of the main figure. The path, representing 800 Ma of APW, has a simple form traversing from Arabia (1100 Ma) towards the Ivory Coast (730 Ma) where it turns sharply to swing through Spain (540 Ma) towards a characteristic double kink in the mid-Atlantic (lasting from 500 to 450 Ma). Somewhat less well constrained by data the path continues southwestward to Ecuador (430 Ma) where it turns south, now very loosely constrained by data, to end firmly anchored amid the Permian (248 Ma) poles.

4. Anticlockwise rotation of northern Siberia relative to southern Siberia

Our list of pre-Devonian poles for the northern block extends in age from approximately 540 to 440 Ma (Table 2). This APW path segment is compared with the time-equivalent segment for the southern tectonic block in Fig. 4a. There is clearly a systematic difference between parts of the two data sets. On average the southern poles deviate from the fitted APW path by 5.5 degrees (Table 1, *Path-Diff.*). The northern poles deviate from the same path by an average of 15 degrees (Table 2, *Path-Diff.*).

We attempted to define a rotation pole which would reconcile the two data sets but quickly discovered that the geometry of the paths and the scatter in the data make it difficult to define a rotation pole. Instead we took a geological model as a starting point. We assumed that the observed discrepancy in palaeomagnetic poles from north to south is associated with the formation of the Viljuy Graben and associated structures. In this case one would anticipate a rotation pole somewhere near Viljuy, presumably near its western end, since extension across the graben was greatest in the east. We attempt to match the data sets using a rotation pole at 60°N, 100°E just west of the Viljuy basin (Fig. 1). Fig. 4b shows the northern data set rotated clockwise through 20 degrees, 'correcting' for an ancient *anticlockwise* rotation of the block, in agreement, as far as it is possible, with the southern data set. Note the convergence of the 461 Ma pole for the northern block (pole B, Table 2) with the 468 Ma poles for the southern block (poles 19 and 20, Table 1).

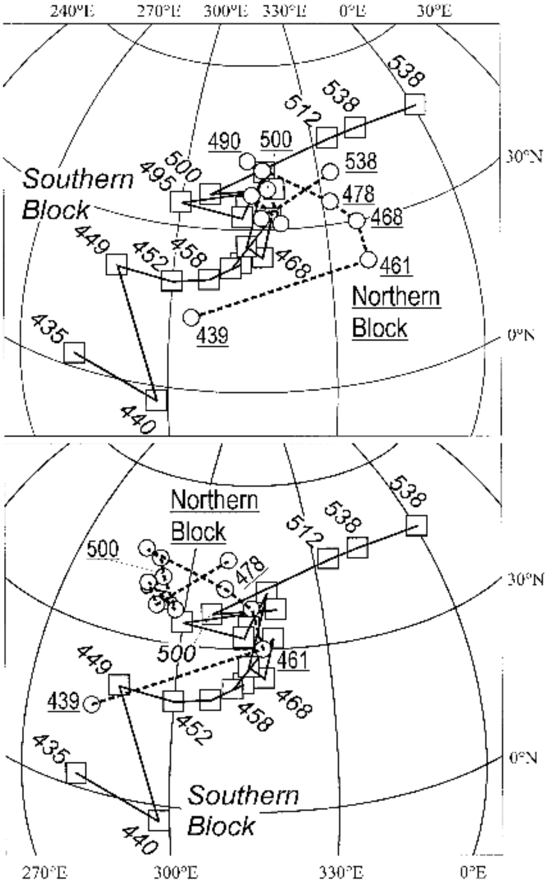


Fig. 4. South poles for the northern and southern parts of Siberia for 538 Ma through 435 Ma. (a) Circles: poles for the northern block with ages in Ma (underlined); Squares: southern poles with ages in Ma (italic). (b) As (a) with the poles for the northern block rotated 20 degrees clockwise about a pole at 60°N, 100°E ('correcting' for a Wenlock/Emsian anticlockwise rotation of the northern block relative to the southern block, Gurevich, 1984; Pavlov and Petrov, 1996).

From this we conclude that the data sets themselves are not sufficient to determine a realistic rotation pole and angle on their own, but that they support a simple geological model for pivotal opening of the Viljuy Graben and development of the Viljuy Basin, and constrain the amount of anticlockwise rotation of the northern block relative to the south of Siberia to approximately 20 degrees, confirming the earlier findings of Gurevich (1984) and Pavlov and Petrov (1996).

5. Palaeo-latitudes and orientations of Siberia

Fig. 5 shows the palaeo-latitudes and orientations of Siberia implied by the new APW path for the southern Aldanian block at times where there are data. We show the whole of Siberia positioned according to the southern data set. This is not strictly correct for the pre-Devonian positions where the present northern part of Siberia should be translated 20 degrees clockwise relative to the present southern part. Since the exact nature of this rotation is unclear and the overall effect on the palaeo-latitudinal range of Siberia is relatively small we chose to use the present outline of Siberia for all palaeo-positions.

Much of Siberia was restricted to low (< 30°) latitudes from 1100 Ma through to 435 Ma, undergo-

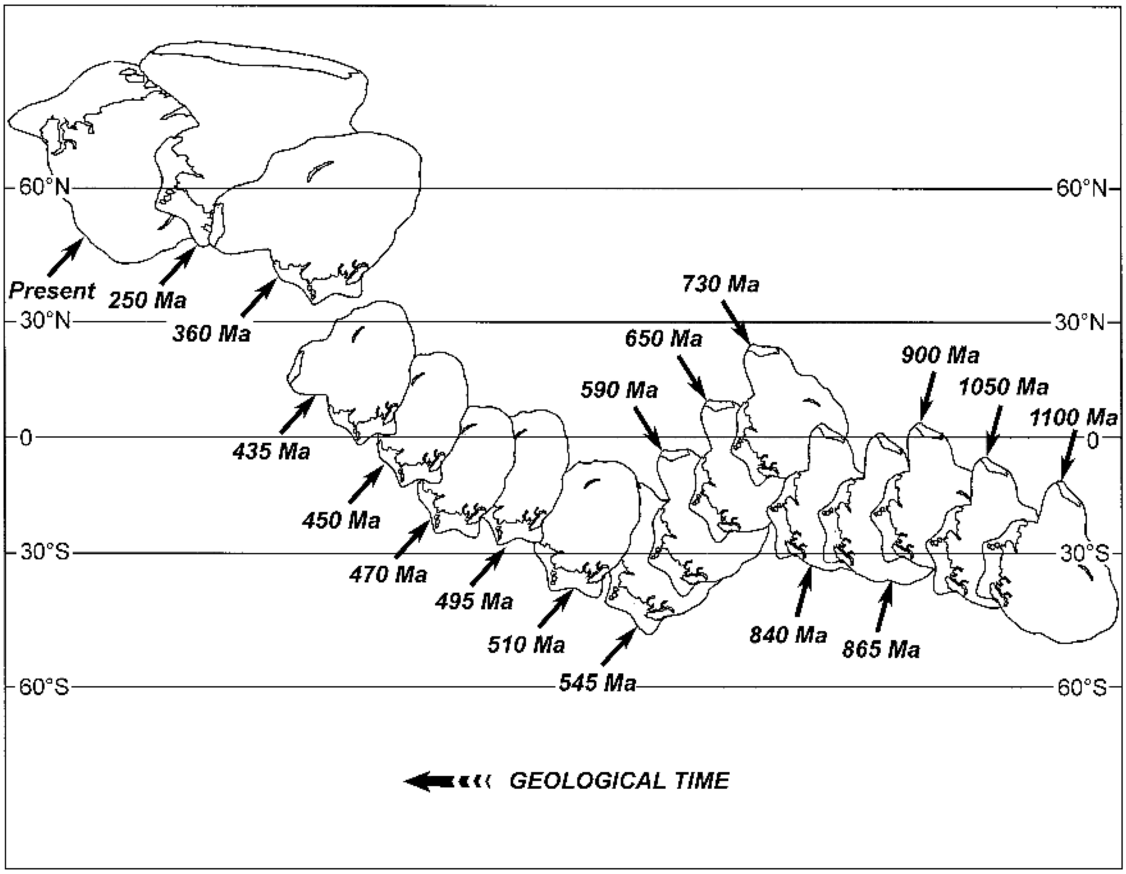


Fig. 5. Palaeo-positions for Siberia implied by the present APW path. Positions are drawn for times where there are underlying palaeomagnetic poles (Table 1). Palaeo-latitudes are indicated by horizontal lines. Time progresses from right (1100 Ma) to left (Present). The outline of Siberia is as given in Figs. 1 and 2. It should be noted that the 20 degree Wenlock/Emsian rotation of northern Siberia relative to southern Siberia (Gurevich, 1984; Pavlov and Petrov, 1996) is not indicated on the pre-Devonian outlines given that its geometry is not precisely known and that it makes little difference to the palaeo-latitudinal range of Siberia in its various positions. Rotation poles for the palaeo-positions from present Siberia (Lat., Long., Angle clockwise): *1100 Ma* = 0°N, 316°E, 112°; *1050 Ma* = 0°N, 298°E, 114°; *900 Ma* = 0°N, 289°E, 108°; *865 Ma* = 0°N, 300°E, 106°; *840 Ma* = 0°N, 294°E, 106°; *730 Ma* = 0°N, 265°E, 94°; *650 Ma* = 0°N, 267°E, 109°; *590 Ma* = 0°N, 267°E, 123°; *545 Ma* = 0°N, 264°E, 133°; *510 Ma* = 0°N, 234°E, 134°; *495 Ma* = 0°N, 218°E, 124°; *470 Ma* = 0°N, 227°E, 120°; *450 Ma* = 0°N, 213°E, 110°; *435 Ma* = 0°N, 201°E, 100°; *360 Ma* = 0°N, 21°E, −63°; *250 Ma* = 0°N, 63°E, −37°. Siberia may be freely moved longitudinally in relation to other palaeo-continents to satisfy other geological controls.

ing gradual anticlockwise rotation to end in a fully inverted position. From 435 Ma onwards Siberia moved from its equatorial and inverted position northwards, rotating clockwise into its more familiar upright position of today.

We have used the APW path for Siberia to constrain the rotation and latitudinal translation history of an arbitrary reference position on the Siberian palaeo-continent (latitude = 64°N, longitude = 66°E; Fig. 6). Latitudinal drift rates for Siberia were generally low, less than 4 cm per year, although drift maxima of 10 cm per year were reached in Cambrian, Late Ordovician and Late Devonian times. A peak clockwise rotation rate of 1 degree per million years was reached in Devonian and Carboniferous times. These rates are comparable to the rates of motion of modern continents.

6. Siberia and Rodinia

Precambrian palaeogeographic reconstructions have received a great deal of attention following the conception by McMenamin and McMenamin (1990) of the Rodinia postulate. The Rodinia continental assembly is based mainly on an attempt to reconstruct a simple branching trace for the Grenvillian including Sveconorwegian orogenic belts of the world at approximately 1000 to 1300 Ma. Palaeomagnetic

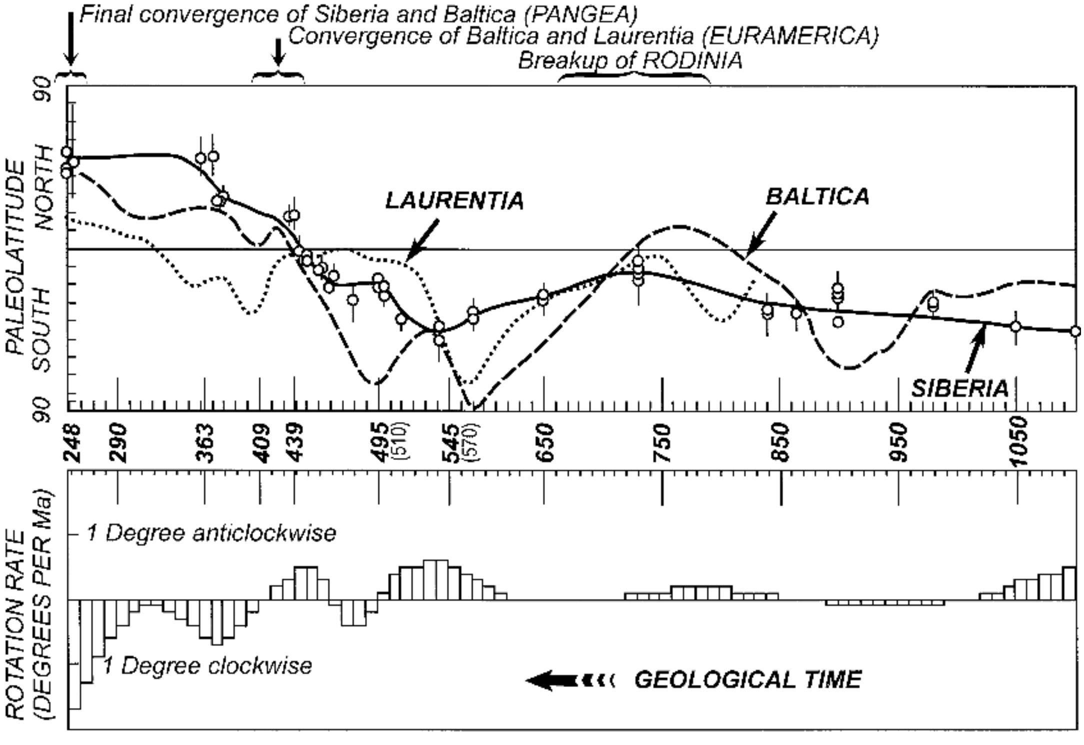


Fig. 6. Top: palaeo-latitudinal drift history of Siberia, Baltica and Laurentia for the period 1100 Ma to 250 Ma. Time progresses from right to left (ages in Ma; ages in parentheses are for the early Palaeozoic time scale of Harland et al., 1990). Palaeo-latitude passes from 90 degrees south to 90 degrees north from bottom to top. Circles indicate the constraints offered by the palaeo-poles in Table 1 on the form of the Siberian curve. The Laurentia and Baltica curves are derived from the APW paths of Torsvik et al. (1996). The drift histories for Siberia and Baltica are for a single reference location in the Urals at 64°N, 66°E. The reference location of 50°N, 270°E was chosen for Laurentia. Bottom: apparent rotation history of Siberia (at the reference location). The diagram shares its time scale with the palaeo-latitude plot above. Columns pointing up indicate the rates of anticlockwise rotation in degrees per million years. Columns pointing down indicate rates of clockwise rotation.

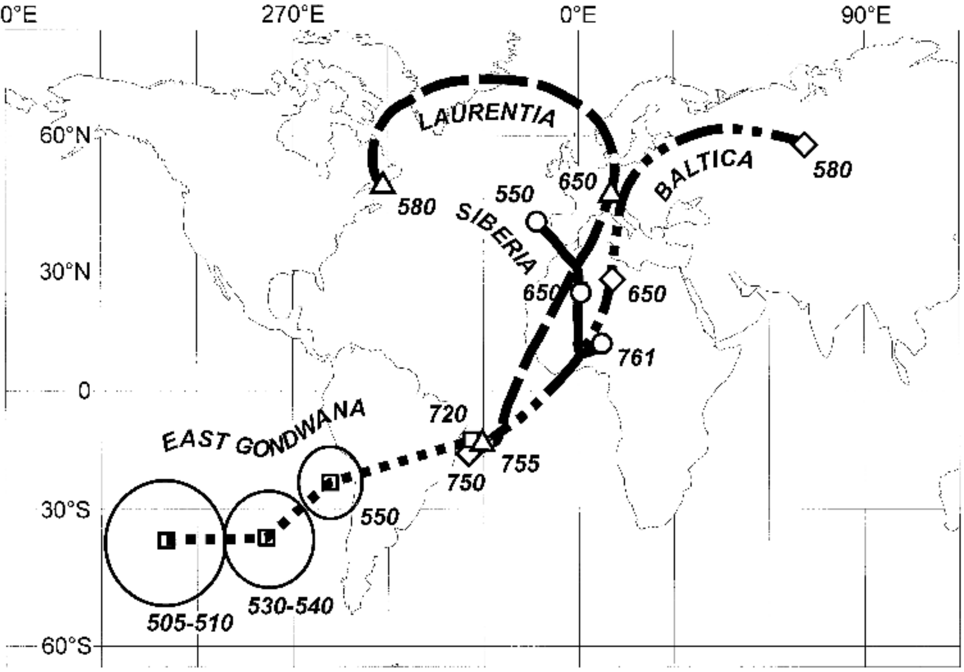


Fig. 7. APW path for Siberia (this paper) compared with APW paths for Baltica and Laurentia (Torsvik et al., 1996), and East Gondwana (Powell et al., 1993). Conforming with tradition, all paths are shown rotated into a Rodinia fit with Laurentia fixed in its present position on the globe as follows: *Laurentia*: no rotation; *Siberia*: rotated about Lat. 29.3°N, Long. 341.2°E, angle 19.6° into its Dalziel (1992) fit; *Baltica*: rotated about Lat. 72.0°N, Long. 043.0°E, angle −50.0° into its Torsvik et al. (1996) fit; *East Gondwana*: originally quoted in Indian co-ordinates by Powell et al. (1993) now rotated about Lat. 53.1°N, Long. 145.1°E, angle 167.9° into the Rodinia fit of Dalziel (1992).

data from Laurentia, Baltica and East Gondwana (Fig. 7) are compatible with the Rodinia reconstruction shown in Fig. 8 (redrawn from Torsvik et al., 1996) which deviates little from the model of Dalziel (1992). The positions of other palaeo-continents in the assembly are less certain. According to Hoffman (1991) and Dalziel (1992) the Siberian palaeo-continent might be placed to the north of Greenland with its northern shoreline facing south (Siberia A in Fig. 8); its inverted orientation broadly consistent with the palaeomagnetic data, but not its latitudinal position. Pelechaty (1996) is also in favour of an inverted position for Siberia north of Laurentia. Pelechaty bases his conclusion on a similarity in the tectonic histories of the Early Palaeozoic Franklin basin in northern Canada and Greenland and the Early Cambrian basins in northern Siberia. Condie and Rosen (1994) suggest a similar position for Siberia in relation to Laurentia but on geological grounds place the northern shore of Siberia facing east. They correlate the Akitkan fold belt of Siberia with the Thelon magmatic zone in Canada (zircon ages 1.9 to 2.0 Ga). They also note similarities between the Archean Slave province in Canada and the Aldan massif in Siberia (zircon ages > 3.5 to 2.6 Ga), and furthermore suggest, albeit tentatively, that the Angara belt might be part of the approximately 1 Ga Grenville orogen.

Rift-related rocks can be found which support both the south-facing and east-facing Siberia models. The south-facing Siberia model is supported by stratigraphic evidence for Early Cambrian rifting in Canada and northern Siberia (Pelechaty, 1996 and references therein). The east-facing model is supported by a possible correlation between the Franklin diabase dyke swarm in Canada at approximately 720 Ma and the diabase dykes in southeast Siberia at approximately 730 Ma (Condie and Rosen, 1994;

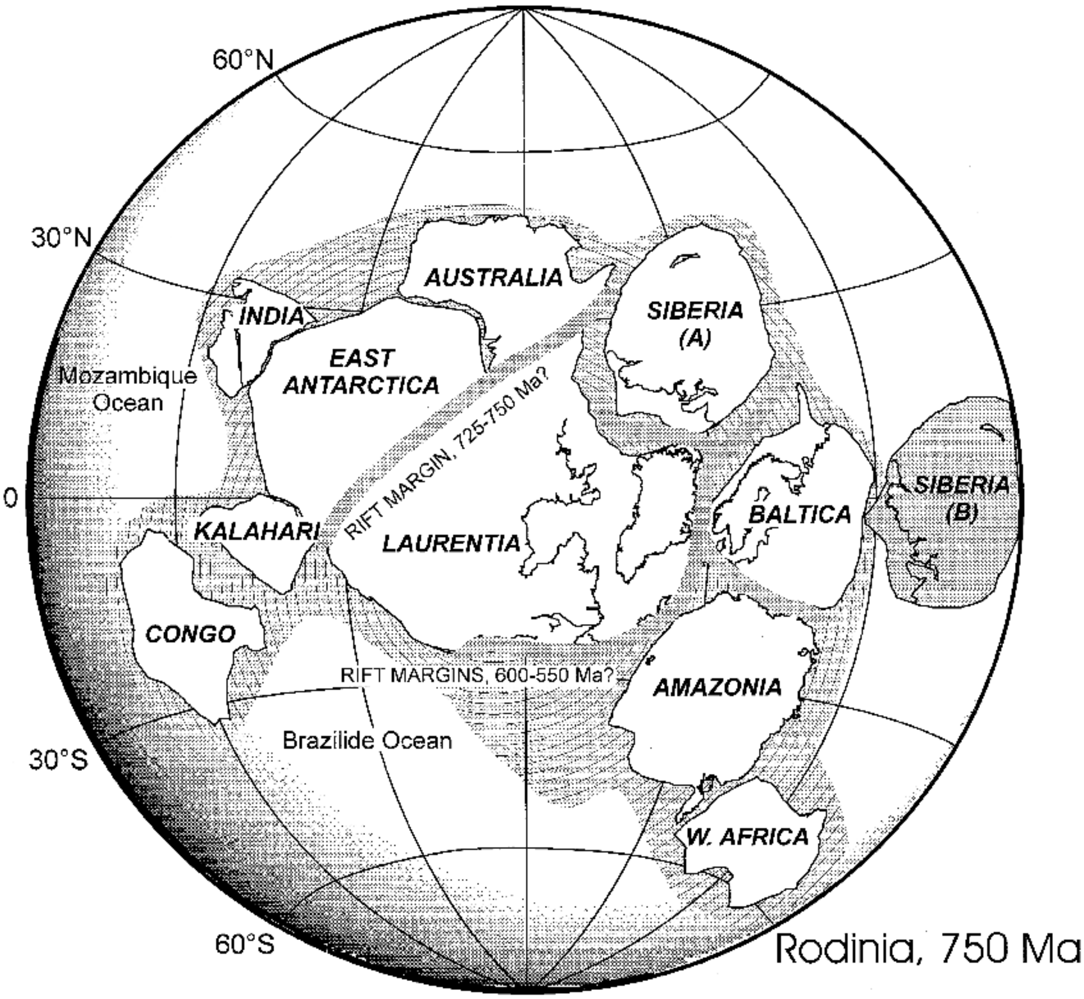


Fig. 8. Rodinia of 750 Ma modified from Dalziel (1992) and Torsvik et al. (1996). The positions of Baltica, Laurentia and East Gondwana are partially controlled by palaeomagnetic data (Fig. 7). *Siberia A* is what has become a traditional position for Siberia in Rodinia reconstructions, based largely on the correlation of geological features, many of which are older than 750 Ma (and may not constrain this reconstruction). *Siberia B* is in the latitudinal position and orientation implied by the new APW path. To avoid overlap it is placed east of Baltica. To satisfy the data it could just as well be placed in the Mozambique Ocean.

Siberian poles: Kandykskaya intrusions pole numbers 36, 37 and 40 to 46, Table 1). Both interpretations would put Siberia adjacent to Laurentia at the time of our palaeogeographic reconstruction (750 Ma, Fig. 8).

In this discussion we assume a firm palaeo-position for Rodinia (excluding Siberia) at approximately 750 Ma, controlled by palaeomagnetic data from Laurentia, Baltica and Eastern Gondwana as was done by Torsvik et al. (1996). To test the Late Proterozoic Laurentia–Siberia connection we use the new palaeomagnetic data compilation for Siberia in Table 1. Reliable palaeomagnetic data are available for Siberia at approximately 730 Ma (the rift-related rocks from southeast Siberia). The palaeomagnetic data imply a partially inverted position for Siberia at this time with the arctic coast of Siberia facing southwest (Fig. 5, palaeo-positions 730 Ma and 840 Ma). Given the angular uncertainty in the palaeomagnetic data, this falls in line with the palaeo-orientation for Siberia of Dalziel, Hoffman, Pelechaty and others. (Pelechaty, 1996 noted that the south-facing model does not preclude the linkages of orogenic belts proposed by Condie and Rosen, 1994.)

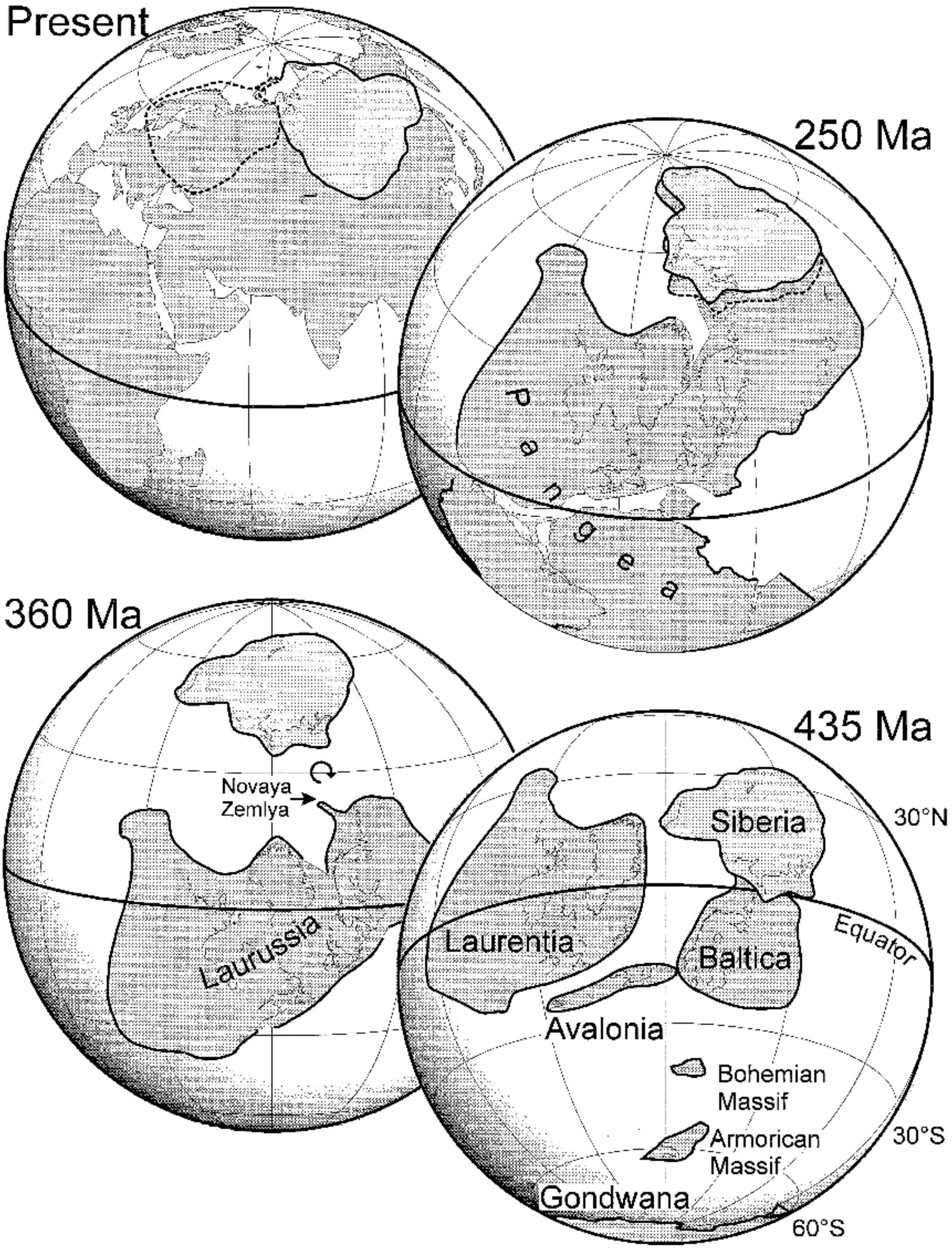
The palaeomagnetic data for Siberia suggest that Siberia occupied palaeo-latitudes between 15°S and 20°N (Fig. 5). In the Rodinia reconstruction of Fig. 8 this latitudinal belt is occupied by Laurentia, Baltica and East Antarctica. Therefore, if the position of Rodinia (excluding Siberia) is correct, and the Siberian data set is taken at face value, the Laurentia–Siberia connection is broken for 750 Ma. We indicate the palaeomagnetically controlled position of Siberia in Fig. 8 as *Siberia B*. We are restricted to placing *Siberia B* either *east* of Baltica or *west* of East Antarctica and Congo to avoid overlap. These alternative positions do not preclude an earlier Siberia–Laurentia connection, but breaking that connection and separating the continents by 750 Ma conflicts with the correlation by Pelechaty (1996) of the early Palaeozoic basins in Canada and northern Siberia.

Delving deeper into the problem of the integrity of Rodinia, we compared segments of the Siberia, Baltica, Laurentia and Eastern Gondwana APW paths for some of 'Rodinia times' to test for a common pattern or movements between them (Fig. 7; from 650 to 760 Ma—the duration restricted by the availability of reliable data). We used our present Siberia path and the Laurentia, Baltica and East Gondwana paths of Torsvik et al. (1996). Torsvik et al. (1996) remarked on a similarity in shape between the Laurentia and Baltica paths between 750 and 600 Ma. Fig. 7 shows the three paths rotated into their best fit positions (see figure caption for details). It is clearly impossible to fit the short 600 to 750 Ma segment of the Siberian path to the others, implying that Siberia might not have been part of Rodinia for any significant part of the history of the supercontinent. This interpretation is as yet tentative because the correlation made between APW paths for Laurentia, Baltica and East Gondwana would benefit from a firmer foundation in reliable data, and because the Late Proterozoic segment of the Siberian APW path, although punctuated by modern data, has breaks lasting up to 100 Ma.

7. The final convergence of Siberia and Baltica

The incomplete Siberian data set provides only three 'snap shots' of the final convergence of Siberia and Baltica (435 Ma, 360 Ma and 250 Ma: Fig. 9). Siberia appeared to rotate rapidly towards the end of the Palaeozoic (1.5–2.0 degrees per Ma, Fig. 6). It should be noted, however, that estimates of rotation rate derived from observed changes in palaeo-field azimuth tend to increase as continents move into high latitudes, simply because of the geometry of the geomagnetic field. Fig. 6, therefore, shows an over estimate of the rate of rotation of Siberia late in the Palaeozoic. The convergence of Siberia and Baltica at this time is most readily described by a simple rotation about a pole situated in the vicinity of Novaya Zemlya (Fig. 9, 360 Ma). We indicate starting positions for the two continents in Fig. 9 (435 Ma). Siberia is positioned according to the new data compilation, the other continents are positioned latitudinally according to various published palaeomagnetic data sets following the review of Torsvik et al. (1996). Baltica was oriented approximately as it is today, but with its northern margin along the palaeo-equator. Siberia, however, was almost exactly inverted in relation to its present position, with its (present) northern margin facing south on the palaeo-equator. We have placed Siberia (longitudinally) north of Baltica. This causes some overlap between the two, however uncertainty in the palaeolatitude of Siberia at this time might reach ±15°. We chose this longitudinal position because (1) a volcanic arc in northern Siberia has been proposed as the source of some Late Ordovician sediments in the Southern Uplands of Britain (McKerrow et al., 1991) and (2) a connection has been proposed between clasts in Middle to Upper Ordovician conglomerates of northern Norway and Cambro–Ordovician plutonic rocks of Taimyr (Torsvik et al., 1995).

Between 435 Ma and 360 Ma Baltica became part of Laurussia (Euramerica), drifting into low northerly latitudes. Siberia also traversed northward with little change in its orientation (Fig. 9, 360 Ma). In the period 360 Ma to 250 Ma, not punctuated by palaeo-


Present
250 Ma
Pangea
360 Ma
Novaya
Zemlya
Laurussia
435 Ma
Siberia
30°N
Laurentia
Baltica
Equator
Avalonia
Bohemian
Massif
Armorican
Massif
30°S
Gondwana
60°S

magnetic data for Siberia, Siberia remained in the same latitudinal belt but rotated clockwise to merge with a northerly-moving Baltica such that both Baltica and Siberia were incorporated into Pangea by 250 Ma.

8. Common features in the motions of Siberia and Baltica through 800 Ma.

We converted APW paths for Siberia, Baltica and Laurentia into palaeo-latitudinal drift and apparent rotation histories for the respective continents (Fig. 6). Clearly relative motions are indicated between the three continents, although it is notable that there are some long time-period motions common to all three continents.

(1) Siberia and Baltica slowly traverse from southerly palaeo-latitudes into equatorial positions in the 350 Ma between 1100 Ma and 750 Ma.

(2) From 750 Ma to 530/590 Ma Siberia, Baltica and Laurentia drift from equatorial positions into intermediate and high southerly palaeo-latitudes.

(3) From 530/590 Ma onwards all three continents drift northwards to end in northerly latitudes.

This gross correspondence in sense and timing of latitudinal drift persists for 800 Ma despite the formation and break-up of Rodinia, Pangea and Euramerica (Fig. 6). This suggests to us that plate-tectonic systems coexisted with different geographic ranges and different life-spans. Evidently the three continents were periodically separated by oceanic tracts with spreading ridges and subduction zones, explaining the differences in detail in their motions. The large-scale similarity in their motion points to a larger scale, longer-lived plate tectonic system translating them first north (Laurentia?), south and then north again.

Van der Voo (1994) proposed true polar wander as a possible explanation for similarities in the shapes of polar wander paths for the Late Ordovician–Late Devonian interval for Laurentia, Baltica and Gondwana. True polar wander cannot be completely ruled out as an explanation for the similarity in movement of Siberia, Baltica and Laurentia over long time, however, we prefer the more conservative multi-scale plate-tectonic explanation.

9. Conclusions

Palaeomagnetic data for the Siberian Platform have been evaluated and an APW path extending between 1100 Ma and 250 Ma produced. From this we derived the palaeo-latitudinal drift history and orientation change of Siberia through the Neoproterozoic and Palaeozoic.

A comparison of palaeomagnetic data from north and south of the Viljuy basin confirms the mid-Palaeozoic anticlockwise rotation of northern Siberia relative to southern Siberia proposed by Gurevich (1984) and Pavlov and Petrov (1996). The Viljuy basin runs approximately east–west along latitude 64°N. Geological evidence for increasing extension towards the east (Zonenshain et al., 1990 and references therein) implies a rotation pole near the western end of Viljuy (at approximately 60°N, 100°E). The palaeomagnetic data constrain the amount of relative rotation between north and south to approximately 20 degrees. APW paths based on compilations of pre-Devonian data spanning 64°N may therefore be distorted. Our polar wander path for

Fig. 9. The convergence of Siberia and Baltica from 435 Ma to 250 Ma. *435 Ma positions*: Siberia (APW path this paper); Baltica and Laurentia after Torsvik et al. (1996); Avalonia after Torsvik et al. (1993); Bohemian Massif after Tait et al. (1995); Armorican Massif after Torsvik et al. (1990); Gondwana after Van der Voo (1988). *360 Ma positions*: Siberia (APW path this paper); Laurussia = Laurentia rotated into Baltica co-ordinates using a Bullard fit (rotation 88°N, 27°E, −38°) and then the assemblage rotated into its palaeo-position using the 358 Ma pole for Baltica from the APW path of Torsvik et al. (1996). The Armorican and Bohemian massifs are accreted to the south-east facing margin of Laurussia. *250 Ma positions*: Siberia (APW path this paper); Pangea in the Lottes and Rowley (1990) fit, positioned on the globe according to the 256 Ma pole for Baltica from the APW path of Torsvik et al. (1992). The difference between the palaeomagnetically controlled position of Siberia (solid line) and the present position of Siberia in relation to palaeomagnetically controlled Baltica (dashed line) is not significant. Therefore the palaeomagnetic data indicate final closure of the intervening oceanic tract/s by 250 Ma. *Present*: the outlines of Siberia and Baltica in their present configuration.

Siberia is for the southern *Aldanian* block for pre-Devonian time and applicable to the whole of Siberia for post-Devonian time. There are as yet too few reliable data for the northern *Anabar* block to construct a separate pre-Devonian APW path.

The palaeomagnetic data indicate an inverted orientation for Siberia in 'Rodinia times' (ca. 750 Ma) in a palaeo-latitudinal belt between 15°S and 20°N. If 750 Ma Rodinia is positioned according to a combination of palaeomagnetic data from Laurentia, Baltica and East Gondwana as was done by Torsvik et al. (1996), it is not possible to fit Siberia into its more traditional position along the present northern margin of Laurentia. The palaeomagnetic data are easily satisfied by locating Siberia either on the eastern (outboard of Baltica) or the western margin of Rodinia, or separate from Rodinia altogether. The palaeomagnetic interpretation, however, breaks geological ties between Siberia and Laurentia from 750 Ma onwards. Given that the palaeomagnetic model is based on comparatively few data from Rodinia (Laurentia, Baltica and East Gondwana) and data from only two suites of rocks in Siberia, we interpret the data as a strong signal for taking a fresh look at the position of Siberia and its possible connections with other palaeo-continents.

The final convergence between Siberia and Baltica is poorly constrained by palaeomagnetic data. At 360 Ma Siberia was in an inverted position in mid-northerly latitudes, separated from Baltica to the south by an east–west oceanic tract approximately 1500 km wide. The next palaeomagnetic constraint on the position of Siberia is at 250 Ma which puts Siberia and Baltica together at the northern end of Pangea. The convergence of the two is characterised by the northerly drift of Baltica and clockwise rotation of Siberia.

Although the APW paths for Siberia, Baltica and Laurentia differ, they imply broadly similar palaeo-latitudinal drift trends for the three continents. During the time-period studied all three continents start in southerly/equatorial palaeo-latitudes, drift south, then drift north, changing drift sense at approximately the same time. We conclude that large continents, although intermittently separated by oceanic tracts, may be driven across the globe in a weak union for periods of 800 Ma or more, reflecting a large temporal and spatial scale geodynamic system which survived the construction and destruction of supercontinents. It is generally accepted that *slab-pull* and *ridge-push* are the most important plate tectonic driving forces. If the continents move in weak unison irrespective of the opening and closure of intervening oceanic tracts one might suspect an additional mantle driving mechanism contributing to the longer term continent motions.

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