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Siberia, the wandering northern terrane, and its changing geography through the Palaeozoic

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Abstract

The old terrane of Siberia occupied a very substantial area in the centre of today's political Siberia and also adjacent areas of Mongolia, eastern Kazakhstan, and northwestern China. Siberia's location within the Early Neoproterozoic Rodinia Superterrane is contentious (since few if any reliable palaeomagnetic data exist between about 1.0 Ga and 540 Ma), but Siberia probably became independent during the breakup of Rodinia soon after 800 Ma and continued to be so until very near the end of the Palaeozoic, when it became an integral part of the Pangea Supercontinent. The boundaries of the cratonic core of the Siberian Terrane (including the Patom area) are briefly described, together with summaries of some of the geologically complex surrounding areas, and it is concluded that all of the Palaeozoic underlying the West Siberian Basin (including the Ob–Saisan Surgut area), Tomsk Terrane, Altai–Sayan Terranes (including Salair, Kuznetsk Alatau, Batenov, Kobdin and West Sayan), Ertix Terrane, Barguzin Terrane, Tuva–Mongol Terrane, Central Mongolia Terrane Assemblage, Gobi Altai and Mandalovoo Terranes, Okhotsk Terrane and much of the Verkhoyansk–Kolyma region all formed parts of peri-Siberia, and thus rotated with the main Siberian Craton as those areas were progressively accreted to the main Siberian Terrane at various times during the latest Neoproterozoic and Palaeozoic. The Ertix Terrane is a new term combining what has been termed the “Altay Terrane” or “NE Xinjiang” area of China, and the Baytag, Baaran and Bidz terranes of Mongolia. The Silurian *Tuvaella* brachiopod fauna is restricted only to today's southern parts of peri-Siberia. Thus, allowing for subsequent rotation, the fauna occurs only in the N of the Siberian Terrane, and, as well as being a helpful indicator of what marginal terranes made up peri-Siberia, is distinctive as being the only Silurian fauna known from northern higher latitudes globally. In contrast, the other terranes adjacent to peri-Siberia, the North China Terrane, the Manchurides terranes (including the Khingan–Bureya Massif area), the Gurvanshayan Terrane, the Ala Shan Terrane, the Qaidam–Qilian Terrane, the Tarim Terrane, the Junggar Terrane, the Tien Shan terranes and the various Kazakh terranes, did not become part of the Siberian Terrane assemblage until they accreted to it in the Upper Palaeozoic or later during the formation of Pangea. The Farewell Terrane of Alaska includes typical Lower and Middle Palaeozoic Siberian endemic faunas, but its Palaeozoic position is unknown.

Cambrian to Early Silurian palaeomagnetic poles from the southern and northern parts of the Siberian Craton differ, but can be matched with an Euler pole of 60°N, 120°E and a rotation angle of 13°. We link this observation with Devonian rifting in the Viljuy Basin near the centre of the craton and also postulate that this rifting rejuvenated an older Precambrian rift zone, since 1–1.1 Ga poles from southern and northern Siberia differ as much as 23° around the same Euler pole. A revised Palaeozoic apparent polar wander (APW) path is presented for the Siberian Craton in which pre-Devonian poles are corrected for Viljuy Basin rifting. There

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is also much Late Devonian tectonic activity in the Altai–Sayan area, which may be linked. The APW path implies that Siberia was located at low southerly latitudes at the dawn of the Palaeozoic and slowly drifted northward (<4 cm/yr.). A velocity burst is noted near the Ordovician–Silurian boundary (ca. 13 cm/yr between 450 and 440 Ma), whilst the Mid-Silurian and younger history is characterized by steady clockwise rotation (totalling about 75°) until the Late Permian. The Late Palaeozoic convergence history between Siberia and Baltica (Pangea) is hard to quantify from palaeomagnetic data because there are only two reliable poles (at 360 and 275 Ma) between the Early Silurian and the Permo-Triassic boundary. The Mid and Late Palaeozoic APW path for Siberia is therefore strongly interpolated and we discuss two different APW path alternatives that result in two very different convergence scenarios between Siberia and Baltica/Kazakh terranes.

There are a newly-constructed succession of palaeogeographic maps of Siberia and its nearby areas at various times from the Cambrian to the Permian as, firstly, the peri-Siberian terranes and, secondly, the remainder of the Central Asian terranes accreted to it. Prior to the Early Ordovician, Siberia was in the southern hemisphere, but after that it drifted northwards and for most of the Phanerozoic it has been one of the few larger terranes in the northern hemisphere. The Cambrian and Ordovician maps are provisional for the Altai–Sayan and Mongolian areas, whose geology is highly complex and whose detailed palaeogeography is unresolved. The terms “Altaids” and “Paleo-Asian Ocean” have been used in so many different ways by so many different authors over so many geological periods that we reject their use.

Wider issues considered include the possible links between the Cambrian Radiation (often wrongly termed “Explosion”), when metazoan animals first gained hard parts, and True Polar Wander (TPW). New Early Cambrian palaeomagnetic data from Siberia do not show rapid APW (<10 cm/yr.) or dramatic velocity changes (<4 cm/yr). It is concluded that the Cambrian Radiation occurred over a period approaching 20 Myr, and that rapid and large-scale TPW did not take place in the Cambrian. In addition, there are no traces of glaciogenic deposits in the very large area of Siberia during the Neoproterozoic, casting some doubt on the “Snowball Earth” hypothesis.

Keywords: Siberia; Altai–Sayan; Mongolia; Palaeozoic; palaeogeography; palaeomagnetism; True Polar Wander; benthic faunas; Cambrian radiation

1. Introduction

The name Siberia has two separate concepts and definitions: firstly, the geographical and political area of present-day Russia that stretches from the Ural Mountains eastwards to the Pacific Ocean; and, secondly, the independent geological terrane which existed from the Proterozoic until the Late Palaeozoic. It is the latter that we mean throughout the substance of this paper, and thus Siberia includes not only a large area within the modern Russian state but also extends into Mongolia and the northwestern part of China (Figs. 1 and 2). The Siberian Terrane does not include the NE part of modern political Siberia, the Chukhot Terrane, which was connected to Laurentia in the Palaeozoic and forms an integral part of the North American Plate today. Nor does it include the W and SW parts of modern political Siberia, which to the N consists of the West Siberian Basin, whose Mesozoic to Recent deposits mask the division between the peri-Baltica island arcs and other microterranes to its E and the western margin of peri-Siberia; and which to the S includes the northern elements of the many terranes known as the Kazakh Terrane Assemblage. The latter occupies not only the majority of the area of Kazakhstan itself, but is also situated in many countries neighbouring it.

The core area of the Siberian Terrane, which has been termed the Angara Terrane by some workers, consists largely of a Precambrian craton and it includes the separately outcropping Archaean and Early Proterozoic cores of the Anabar Massif and the Aldan Shield. These may have subsequently formed integral parts of the superterrane of Rodinia at about a billion years ago, but the location, configuration and even identity of Rodinia remains contentious. That superterrane broke up in stages from about 800 Ma, and by probably as early as 750 Ma Siberia had become an independent terrane. It remained a relatively stable craton, with undeformed Neoproterozoic (Riphean and Vendian) and Palaeozoic sediments upon it, whose individual extents depended upon the extent of flooding onto the craton at the different times, until the assembly of Pangea during the Permian.

One of the primary purposes of this paper is to examine what parts of central and northern Asia made up the Siberian Terrane; in other words, what parts of Russia, Mongolia, Kazakhstan and China now adjacent to the Siberian Craton were or were not integral parts of the amalgamated Siberian superterrane terrane, and at what time? Our other objectives are to chart the movements of Siberia progressively through its existence as an independent terrane, to present new palaeogeographical maps

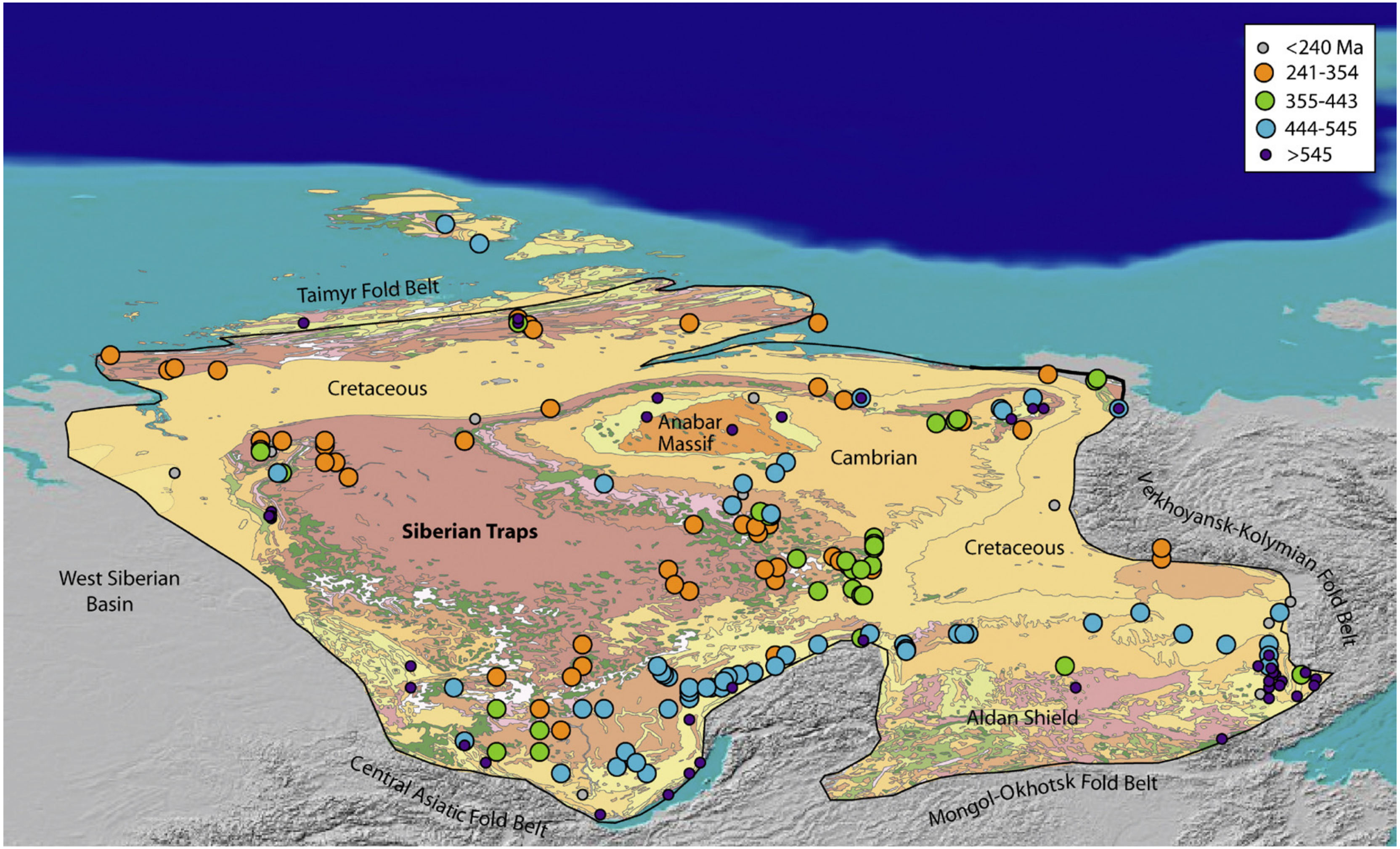


Fig. 1. Satellite bathymetry-topography map orthogonal projection on northern Eurasia (Smith and Sandwell, 1997), superimposed on which are the margins of the Siberia Craton and within which is shown the simplified outline geology. The small coloured circles indicate the sampling locations and ages of all published palaeomagnetic data from the Siberia Craton and the Taimyr region, with their colours differentiated by geological time.

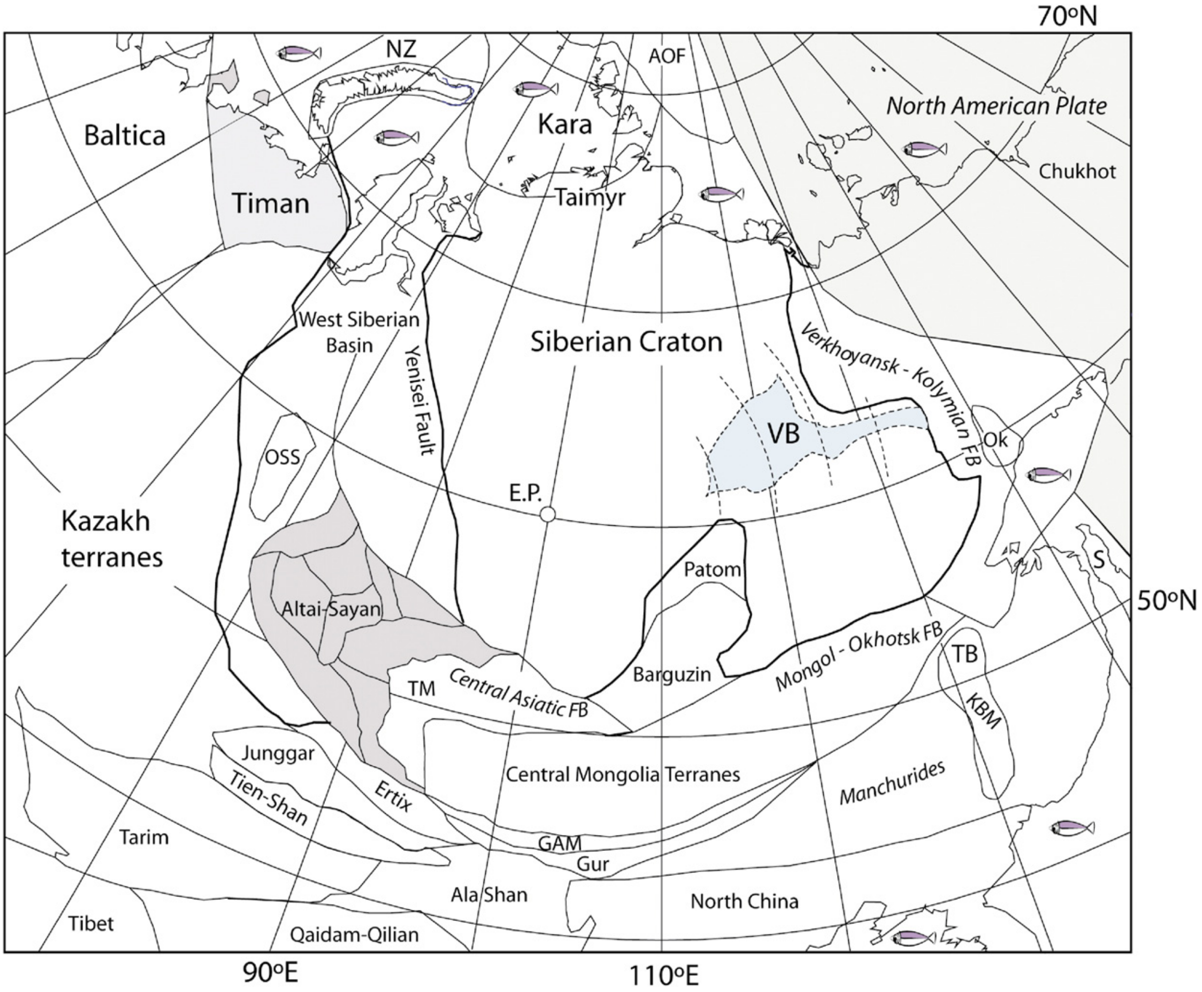


Fig. 2. A modern map showing the outlines of Siberia and the more significant adjacent terranes. Fish symbols indicate modern oceans. AOF, Arctic Ocean floor; E.P., Euler Pole; FB, fold belt; GAM, Gobi Altai and Mandalovoo Terranes; Gur, Gurvanshayan Terrane; KBM, Khingan–Bureya Massif; TB, Turan Block; NZ, Novaya Zemlya; Ok, Okhotsk Massif; OSS, Ob–Saisan–Surgut area; S, Sakhalin Island; SJ Songhuajiang Terrane; TEF, Trans–Eurasian Fault; TM, Tuva–Mongol Terrane area; VB, Viljuy Basin.

for the successive periods from the Cambrian to the Permian (Figs. 9–15) which show the distribution of land, shelf seas and the surrounding oceans for Siberia and its neighbouring terranes, and to review the successive distributions of some of its palaeobiogeographically distinctive fossil faunas and floras during the Palaeozoic. As ever, the results from palaeomagnetic studies indicate palaeolatitudes and terrane rotation but give no indications of palaeolongitude (Figs. 3–6); whereas, in contrast, the palaeontological data are less quantitative but can indicate closeness or separation from contemporary substantial neighbouring terranes such as Baltica, Gondwana and North China. Another important element of our progressive reconstructions through time is the need to recognise and conserve kinematic continuity between successive maps. Various previous papers have attempted to place Siberia's position in relation to other major terranes; for example, Torsvik et al. (1995) for the Ordovician, and Smethurst et al. (1998) and Torsvik (2003) for the Neoproterozoic and Palaeozoic, and Ziegler et al. (1997) and Shi (2006) for the Permian. However, there have been no substantial recent reviews of Siberia's history and changing geographies, in particular integrated with the changing faunas and floras, throughout its entire existence as an independent terrane. Many and various palaeogeographical reconstructions have been published, most notably by Zonenshain et al. (1990) and Sengor and Natalin (1996), to whom we pay warm tribute for their pioneering work; and also, for example, those by Didenko et al. (1994), Heubeck (2001) Buslov et al. (2004) and Yakubchuck (2004) all of which includes the terranes on today's southwestern border of Siberia. However, the tectonised areas around and inside the perimeter of what we term peri-Siberia are very far from being completely geologically unravelled and understood, and all of these palaeogeographical reconstructions, as well as our own, must be regarded as provisional.

We also discuss the suggestion that the possible cause of the Cambrian "Explosion", when fossils gained hard parts, may have been triggered by an episode of True Polar Wander, a rapid tilt of the Earth's rotation axis of up to 90°.

We commence with a review of the present-day margins of the old cratonic core of the Siberian Terrane, followed by summaries of the terranes making up the peri-Siberian area and other substantial adjacent terranes. We then present a geological history of the area between the Late Neoproterozoic and the Permian. Although not so much geological work of substance was achieved in Siberia during the nineteenth century, particularly by comparison with Europe and North America, an enormous amount of data has been amassed during the past century. Much of that stratigraphical, sedimentary and palaeontological data was gathered before knowledge and appreciation of plate tectonics, but is still entirely appropriate to use, particularly for plotting the facies and biofacies upon the large and relatively stable Siberian Craton. Siberia also possesses hydrocarbon and mineral deposits of global significance, which we do not discuss further here.

Thus we feel that this review is timely, particularly so as to focus and refine the importance of Siberia and its adjacent areas more clearly within the contexts of our previous global reviews for the Lower Palaeozoic (Cocks and Torsvik, 2002) and the Upper Palaeozoic (Torsvik and Cocks, 2004).

2. The geology of the Siberia Craton

General summaries of the geology of Russia, including Siberia, in English may be found in the substantial books by Khain (1985) and Zonenshain et al. (1990), and also in Yakubchuk and Nikishin (2005). The vast plume-generated volcanic outpourings of the 251 Ma Siberian Traps (Bowring et al., 1998) are a dominating feature, occupying about 40% of the total area of Siberia today (Fig. 1), but unfortunately thereby obscuring a substantial amount of the Palaeozoic and earlier geology. There are also very substantial amounts of Cretaceous to Recent sediments outcropping on much of the craton and surrounding areas, which are consequently also topographically relatively flat-lying, thus making investigations into the Precambrian and Palaeozoic parts of Siberia difficult and often obscure in many places. Nevertheless, there are extensive exposures in some of the incised vallies in the major rivers, and a large number of boreholes have been put down in many parts of Siberia, enabling us to build up a picture, albeit patchy, of the underlying older geology. The rocks in the centre of the Siberian Platform have been little tectonically altered during the Phanerozoic; for example, the very extensive Late Precambrian and Palaeozoic successions outcropping along the Lena River mostly have dips of less than two degrees. Because the Siberian Craton has remained a single tectonic unit largely undeformed since the Late Precambrian, the extensive and detailed facies and palaeogeographical maps created by Soviet geologists during the pre-plate tectonic days of the 1960s (summarised in Keller and Predtechensky, 1968, for the Lower Palaeozoic, and Nalivkin and Posner, 1969, for the Upper Palaeozoic) can still be used as invaluable primary sources for the understanding of the palaeoecology of that central core of the Siberian Terrane.

Some authors, for example Pavlov and Petrov (1996), have asserted that the core Siberian Craton consisted of two separate terranes with different rotation histories until the Devonian. At the northeast end of the Viljuy Basin (Zonenshain et al., 1990, p. 21), in a graben not far from the centre of Siberia (Fig. 2), geophysical evidence suggests that oceanic crust lies directly and unconformably beneath the Devonian there. There are also large quantities of Devonian volcanics both within the Siberian Craton and also in many parts of peri-Siberia which surround it, from Altai–Sayan in today's SW (Zonenshain et al., 1990, Fig. 60) to the Okhotsk Massif in the E. Thus, although an oceanic arm can certainly be inferred to have been present in the Viljui Basin prior to the latest Devonian, it seems most probable that it represented a relative brief geological episode of Red Sea type rifting and one in which ocean-floor spreading did not exist for long before the component parts of Siberia were reunited, assuming that they had ever been completely separate. Interestingly, the same Viljuy aulacogen had opened in the Riphean and then closed again before the Vendian (Zonenshain et al., 1990), indicating a fundamental tectonic weakness between the Archaean and Early Proterozoic rocks which surround the area. A review of the palaeomagnetic data (see below under Palaeomagnetic Record (Section 3), Tables 1a and 1b and Figs. 3–6) confirms that the northern and southern halves of Siberia do indeed show that they had a dissimilar drift pattern before the Devonian.

The whole of today's southern margin of the Siberian Craton is dominated by the tectonics which are often termed the Baikalides (named after Lake Baikal); however, it is unfortunate that different authors define both the Baikalides and the Baikalian Orogeny in different ways, making the literature, let alone the geology, in many cases hard to unravel and thus we do not use the term. For example, Khain uses Baikalian as an age stage lasting from the Proterozoic to the Lower Palaeozoic when describing the East European Craton of Baltica (1985, pp 51–53) but as the name of a suture when describing the Siberian Platform (1985, p. 86). Baikalian is also often and variably used to describe a chiefly Late Precambrian orogeny, e.g, by Sengor and Natalin (1996). Those Late Precambrian "Baikalian-affected" rocks are also overprinted by other Phanerozoic tectonic events, as detailed by many authors, including Didenko et al. (1994), Sengor and Natalin (1996), Heubeck (2001) and Xiao et al. (2004).

3. The palaeomagnetic record

The palaeomagnetic record for the very large area of Siberia is relatively sparse compared to that from Europe and North America; there is no reliable data between about 1 Ga (before the breakup of Rodinia) until the Ediacaran at about 600 Ma, but the Siberian platform core of the continent is well constrained from the Early Cambrian to the Early Silurian and at the Permo-Triassic boundary at about 251 Ma. Between the Early Silurian and the Permo-Triassic boundary there are only two well-documented palaeomagnetic poles (at about 360 and 275 Ma). As a consequence, modelling Siberia's Late Palaeozoic convergence history with the Kazakh Terranes and Baltica is hard to quantify, and is based on much interpolation (Tables 1a and 1b). The substantial review by Smethurst et al. (1998) included an APW path for the Siberian Platform, which, although modified here, nevertheless remains substantially correct, apart from in the Precambrian, in which radiometric ages which are now proved obsolete were assigned to the palaeomagnetic poles (cf. Pisarevsky and Natapov, 2003; Torsvik, 1995), and also in the Late Palaeozoic.

Our revised palaeomagnetic compilation from ca. 615 to 228 Ma is based on thirty-seven poles. Fig. 1 shows the location of all the published poles from Siberia, whereas the poles shown in Fig. 3 represent a careful selection based on the Van der Voo (1993) grading scheme ($Q \geq 3$), including twenty-three new poles (Fig. 3; Table 1a) published since the review by Smethurst et al. (1998). Due to this substantial number of new poles, we have excluded all the poles in the compilation of Smethurst et al. (1998) in which the samples had not undergone thorough stepwise

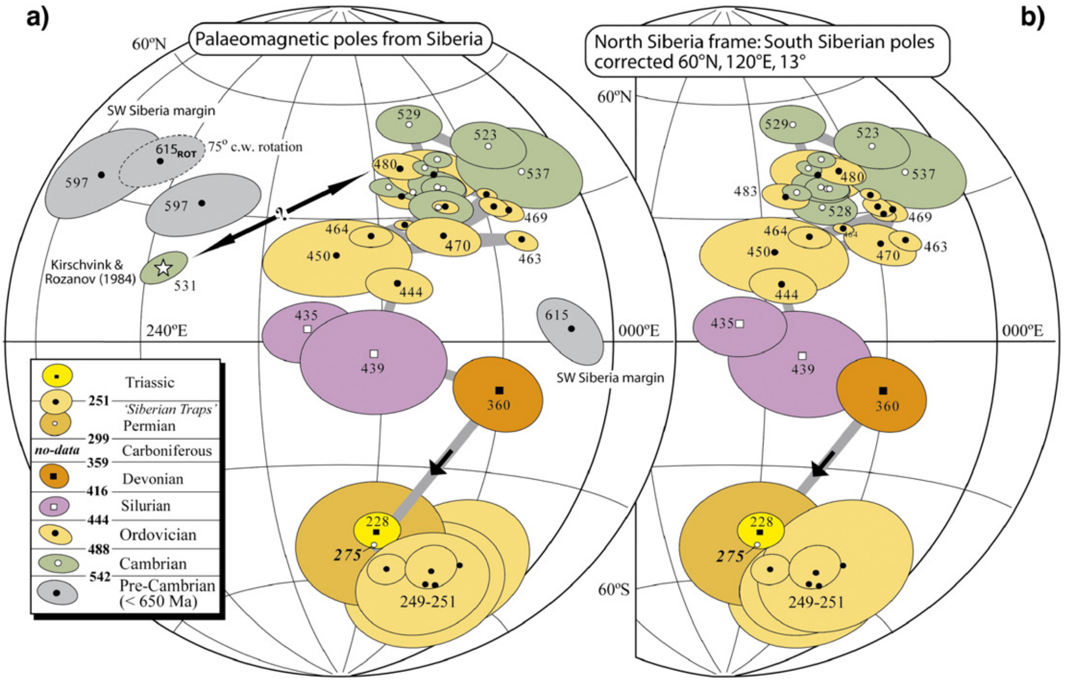


Fig. 3. (a), reliable Ediacaran to Triassic poles from Siberia with 95% confidence ovals (dp/dm). Note that the 615 Ma pole (Table 1a) can only be reconciled with the two other Ediacaran poles (597 Ma) if we impose ca. 75° rotation on their vertical axes. The ca. 531 Ma pole of Kirschvink and Rozanov (1984) is marked with a star symbol and is clearly anomalous. (b), Cambrian to Triassic poles from the Siberian Craton [as in (a)] but in which pre-Devonian poles from S Siberia have been corrected for a rotation of 13° around an Euler pole of 60°N–120°E (see text).

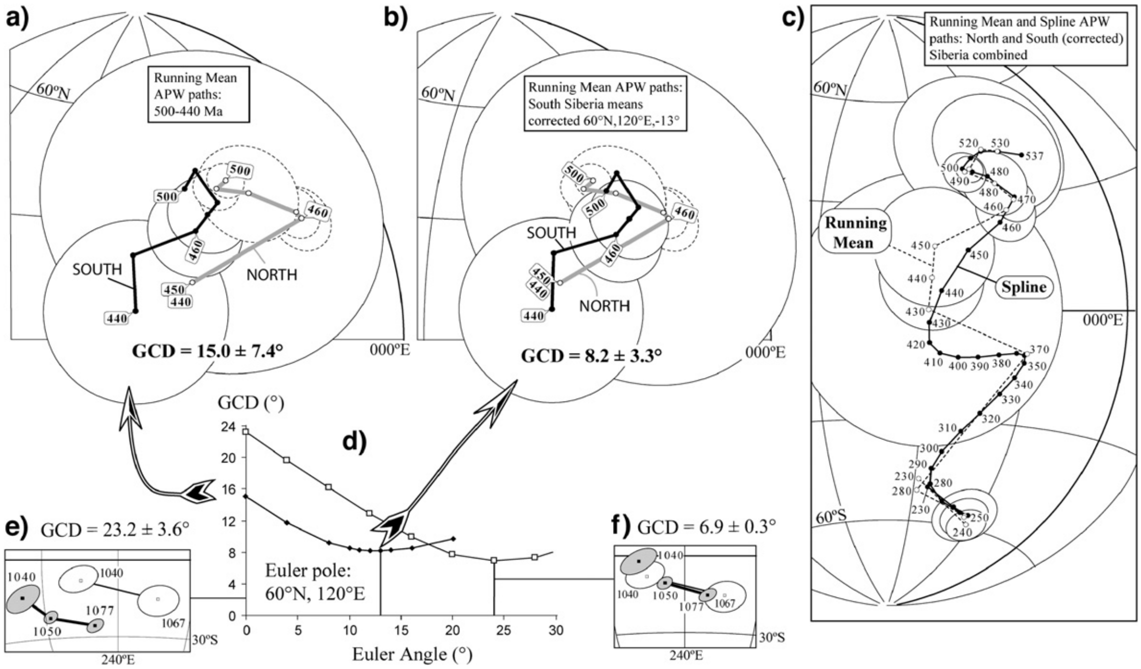


Fig. 4. (a), comparison of running mean APW paths (window-length = 20 Ma) for the northern and southern Siberian Craton (shown with A95 circles). Great-circle distance (GCD) between the two paths (500–440 Ma) averages to about 15°. (b), the same as (a), but with the southern Siberian mean poles rotated 13° around 60°N–120°E and GCD reduced to ca. 8°. (c), the final running mean APW paths (window-length = 20 Ma) and spherical spline (smoothing = 500; Q-factor weighted; see Torsvik et al., 1996 for procedure) for Siberia, combining northern and southern Siberia corrected for a 13° rotation associated with the opening of the Viljuy Basin. The APW path is based on all the poles in Fig. 3b (Table 1a). (d), change in GCD (Euler pole 60°N–120°E) as a function of rotation angle. Note that the minimum GCD for the Cambrian–Early Silurian (500–440 Ma) mean poles is 13°, whilst a larger angle (24°) is required to match ca. 1050 Ma poles for northern and southern Siberia. (e), ca. 1050 Ma poles from the southern (shaded dp/dm ovals) and northern Siberian Craton (Table 1a). GCD is ca. 23°, (f) ca. 1050 poles corrected for a 24° rotation that leans to a GCD of ca. 7°.

demagnetisation. Many of the excluded studies have since been restudied with more modern techniques and analytical procedures.

Our review focuses on the Palaeozoic history of Siberia, but we show three recently published Ediacaran poles (Fig. 3a) from SW Siberia. However, their large age uncertainties (about ±50 Ma), as well as the uncertain tectonic coherence of the collecting sites to the Siberian Craton, do not make them ideal for APW path construction. For example, it is not clear to us if the ca. 615 Ma Lena River pole of Pisarevsky et al. (2000) is based on studies of autochthonous or allochthonous sediments that were involved in the Late Precambrian–Early Palaeozoic Baikal–Patom folding along the Siberian margin (Mats et al., 2000). The Lena River pole differs considerable from the ca. 597 Ma Minya and Shaman poles (Table 1a) from the Angara part of the craton, and only a 75° clockwise rotation of the Lena River pole (Fig. 3a) could reconcile the very different poles. In any case, all these poles indicate equatorial to subtropical latitudes for southern Siberia in the Late Neoproterozoic (ca. 650–543 Ma).

Smethurst et al. (1998), based on Gurevitch (1984), Pavlov and Petrov (1996) and their own analysis, concluded that northern Siberia had rotated counter-clockwise relative to southern Siberia in Wenlock to Emsian times around an Euler pole (latitude = 60°N, longitude = 100°E and angle of −20°) located to the west of the Viljuy Basin (Fig. 2). A comparison of Cambrian to Early Silurian running mean poles from the northern (>64°N) and southern parts of the Siberian Craton demonstrate that the mean poles from northern Siberia plot systematically east of the southern Siberia poles (Fig. 4a); the angular difference varies between 6.5° and 26.8° (average 15.0 ± 7.4° for the 440 to 550 Ma interval, Fig. 4d). Using the rotation pole of Smethurst et al. (1998), we find that the southern and northern poles best match with an Euler angle of 13° (Fig. 4d) (average 8.2 ± 3.3° for the 440 to 550 Ma interval). Thus, for the Cambrian to Early Silurian we have combined the northern and corrected (60°N–120°E–13°) southern Siberian Craton poles (Fig. 3b) to produce our final overall APW path for Siberia (Fig. 4c; Table 1b). In general, the running mean and the spherical spline

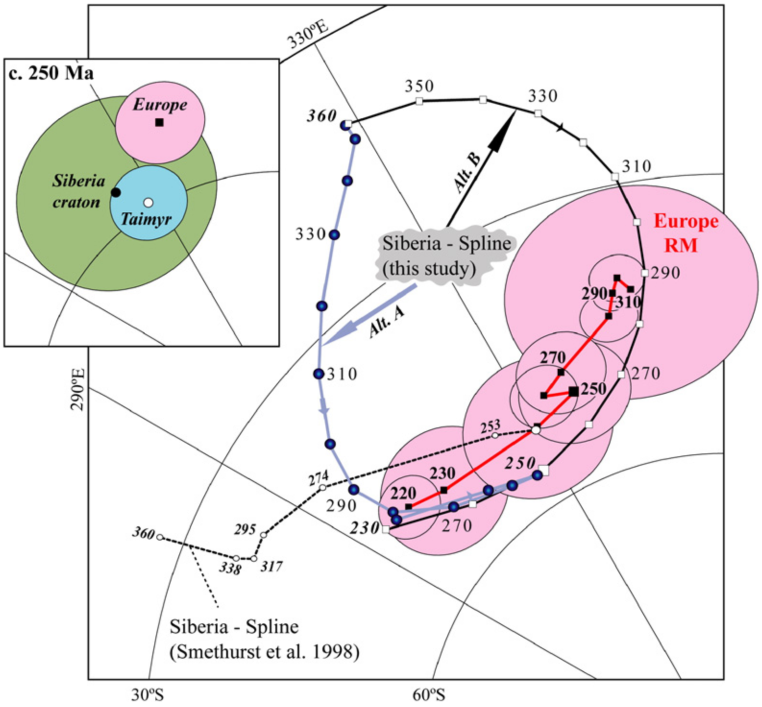


Fig. 5. Comparison of our new Siberia spline paths with that of stable Europe (incuding data from Baltica) for the 310–220 Ma range. Alternative A (Alt. A) as in Fig. 4c, whilst Alternative B (Alt. B) excludes the 275 Ma pole (Table 1a). The European APW path is a running mean path (window-length = 20 Ma) and shown with A95 confidence circles (original data listed in Torsvik et al., in press). For comparison, we also show the Siberia spline path of Smethurst et al. (1998) as a stippled line.

methods generate similar APW paths (Fig. 4c), but the spline path from this anlysis is used to generate the drift and rotation history for Siberia (Fig. 6) and all the consequent reconstructions in Figs. 9–15.

If we compare ca. 1050 Ma poles from southern and northern Siberia (Fig. 4e, f; Table 1a), the difference is substantially larger (23.2 ± 3.6°), and using the postulated Euler pole of 60°N–100°E would in fact best match these regions with an Euler angle of ca. 23°. We therefore suggest that the Devonian rifting in the Viljuy Basin rejuvenated an older but more profound Precambrian rift zone (which could possibly also have been a Precambrian suture-collision zone), thus supporting the original suggestion of Zonenshain et al. (1990).

During Cambrian times, Siberia was located in tropical latitudes and was geographically inverted compared to its present position (Fig. 6a). During the Cambrian, Siberia drifted slowly northward, but this was followed by more rapid northward drift during the Ordovician and Silurian, peaking at 13 cm/yr near the Ordovician–Silurian boundary (Fig. 6b). The Mid and Late Palaeozoic drift history and the Late Palaeozoic convergence history between Siberia and Baltica (Pangea) is difficult to quantify from palaeomagnetic data (Fig. 6), since the APW path is substantially interpolated between the Early Silurian and the Permo-Triassic boundary (Fig. 4c), because there are only two reliable poles (at 360 and 275 Ma: Fig. 3b).

We are somewhat puzzled by a recently reported 275 Ma pole (Pisarevsky et al., 2006) from Siberia, since this pole plots near Triassic poles from southern Taimyr and Europe/Baltica and its acceptance would inevitably lead to some interesting and very radical new reconstructions between Siberia and Baltica (see later). We have therefore analysed the Upper Palaeozoic drift and rotational history of Siberia with (Alternative A: Figs. 5 and 6) and without (Alternative B; Figs. 5 and 6) the 275 Ma pole. Alternative A predicts that Siberia accelerated northward (also compared with Baltica; see thick grey-shaded latitude curve in Fig. 6b) during the Carboniferous, followed by Permian clockwise rotation and southward drift towards the Permo-Triassic boundary. Conversely, Alternative B (ignoring the 275 Ma pole) shows a smoother northward movement after the Carboniferous which is comparable with the latitudinal drift history for Baltica. These differences are clearly reflected in the different APW paths shown in Fig. 5. In contrast to Alternative A (and the APW path of Smethurst

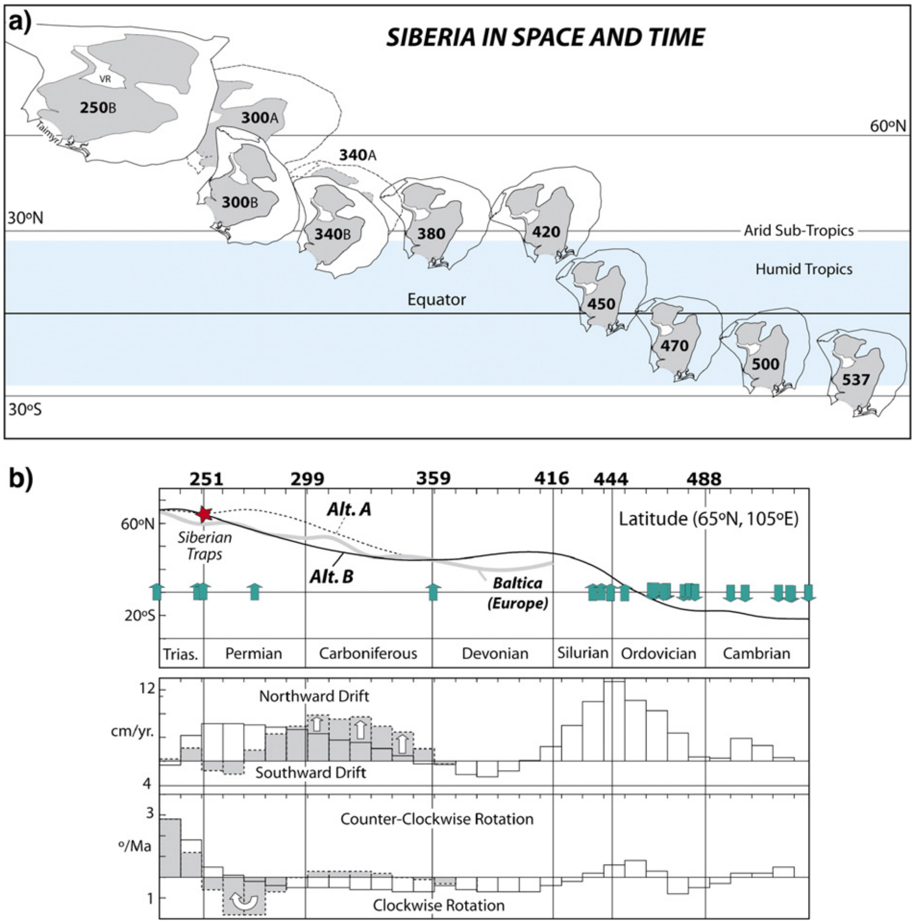


Fig. 6. (a), drift and rotation history for Siberia from 537 Ma to 250 Ma, based on the spherical spline path shown in Figs. 4c and 5 (Table 1b). Note that alternatives A and B differ substantially at 340 and 300 Ma (exclusively based on interpolation). The core Siberian Craton is shown in grey, and the peri-Siberian contiguous fold belts (which were accreted at various times) in white. (b), *upper*, the latitudinal drift for a location at 65°N and 105°E in northern Siberia based on spherical spline path (see Table 1b). Siberia is shown for both alternatives A and B. and also compared with a latitudinal curve predicted from Baltica/Europe. Green arrows show actual data coverage; *middle*, latitudinal velocities (alternative A is grey shaded), separated into northward and southward (they are minimum velocities, since the palaeolongitude is unknown); *lower*, angle of rotation of Siberia through time separated into clockwise and counterclockwise rotations. Part of the Triassic is also included.

et al., 1998), our Alternative B path 'converges' with the European APW path during the Early-Mid Permian. Alternative A would also require that the APW path would also have backtracked during its 280–250 Ma segment, since the 275 Ma pole is similar to younger Triassic poles. Thus we consider Alternative B as much the more likely.

Torsvik and Andersen (2002) noted that ca. 250 Ma poles from Siberia differ slightly from poles of similar ages from northern Europe (indicating a slightly higher latitude), but within errors they overlap at the 95% confidence level (Fig. 5 *inset* diagram). Ca. 250 Ma poles from Taimyr also statistically overlap with Siberian poles, and for that reasons are also incorporated in Table 1a and Fig. 3. However, from the geological history it is clear that there must have been younger relative movements between Siberia and Baltica (Torsvik and Andersen, 2002), but those movements were probably below the resolution power of palaeomagnetic studies (Buiter and Torsvik, 2007).

Some Russian workers, e.g. Dobretsov et al. (1995) and Yolkin et al. (2003), do not accept that Siberia underwent any significant rotation, for a variety of stated reasons; for example, they believed that the apparently warm-water reefs to be found widespread within the Altai–Sayan area (in today's S of the terrane area) in the Silurian, indicated equatorial latitudes. Nevertheless, we believe that the palaeomagnetic evidence for the inversions shown on Fig. 6 is overwhelming, and that the Altai–Sayan part of Siberia, although we estimate it to have been at from 35° to 45°N of the palaeoequator,

Table 1a
Selected palaeomagnetic poles from Siberia

Formation	Age	*Q*	α_{95}	GLat	GLon	PLat	PLon	Reference
South Taimyr Sills[a]	228	6	2.9	74.8	100.6	−47.1	301.6	W05
South Taimyr Basalts[a]	248	6	7.8	74.9	100.5	−59.3	325.8	W05
West Taimyr Siberian Traps[a]	250	7	10	72	84	−59	330	GPDB2832
Siberian Traps, Noril'sk and Abagalakh[a]	251	6	3.3	70	89	−56.2	326	G04
Siberian Traps (recalculated)[a]	251	6	9.7	66.1	111.6	−52.8	334.4	GPDB3486
Moyero River Siberian Traps related rocks[a]	251	3	2.2	68	104	−56.6	307.9	GP96
Mafic dykes South Siberia[a]	275	4	8.6	51.8	104	−50.5	301.4	P06
Data Gap (85 Ma)								
Devono–Carbon. Traps (recalculated)[a]	360	6	8.9	64.6	114.7	−11.1	329.7	GPDB3486
Data Gap (75 Ma)								
Lena River Sediments	435	3	9	60	116	3	282	MAS
Lena River Sediments	439	5	13.1	60.5	116.4	−3	298	MAS
Moyero River Sediments[a]	444	4	8	68	104	14	304	MAS
Lena River Sediments	450	4	17.3	60.5	116.4	21	289	MAS
Moyero River Sediments[a]	463	6	4	68	104	23	338	MAS
Krivaya Luka Formation	464	5	2.5	59.7	118.1	28.2	307.1	GPDB3473
Krivaya Luka Formation	464	5	5.1	59.7	118.1	25.6	297.9	GPDB3473
Lena River Sediments	468	5	3.1	59.8	118.1	32	319	MAS
Moyero River Sedimens[a]	469	5	4	68	104	30	337	MAS
Lena River Redbeds	470	4	9	60	114	25	317	MAS
Guragir Formation[a]	470	5	3.2	68	88.8	30.9	332.7	GPDB3448
Moyero River Sediments[a]	478	5	2.2	67.5	104	33.9	331.7	MAS
Surinsk Formation	480	4	5.8	58.3	109.6	42.2	308.1	GPDB3474
Moyero River Sediments[a]	483	5	9	68	104	40	318	MAS
Uigur and Nizhneiltyk Formations[a]	483	5	4.9	68	88.8	35.2	307.2	GPDB3448
Moyero River Sediments[a]	500	4	6	68	104	37	318	MAS
Kulumbinskaya Formation[a]	500	6	3	68	88.8	36.1	310.7	GPDB3192
Verkholensk Formation	501	3	4.5	58.5	109.8	37.7	304	GPDB3472
Kulumbe River Section[a]	507	7	2.3	68	88.4	41.9	315.8	GPDB3192
Khorbusuonka Amgan and Mayan Sediments[a]	507	7	2.6	71.5	124	43.7	320.5	GPDB3537
Yunkyulyabit–Yuryakh Formation[a]	507	5	4.6	70.9	122.6	36.4	319.6	GPDB3164
Erkeket Formation[a]	523	5	6.8	70.9	122.6	44.8	338.7	GPDB3164
Udzha River Sediments[a]	528	5	7	72	116	32	317	MAS
Khorbusuonka Toyonian Sediments[a]	529	5	5.1	71.5	124	53.3	315	GPDB3537
Lena River sediments, Yakutsk[b]	531	?	6.2	61	126.8	16.6	244.5	GPDB1627
Kessyusa Formation[a]	537	5	12.8	70.9	122.6	37.6	345	GPDB3164
Data gap (78 Ma)								
Minya Formation, Chaya River, South Siberia	597	4	12.7	58	110	−33.7	37.2	GPDB3421
Shaman Formation, Irkut River, South Siberia	597	5	13.8	52.1	103.8	−32	71.1	GPDB3421
Lena River red beds, Cisbaikalia, South Siberia	615	6	9.2	54	108	2.7	348.2	GPDB3301
Data gap (415 Ma)								
Kandykskaya suite combined	975	6	5.0	59.4	136.4	−3.1	176.5	GPDB3518
Ignican Formation	1012	4	26.5	58.5	135.3	−19.8	197.4	GPDB3476
Ignican Formation	1012	4	11.9	58.9	135.1	−14.7	202.9	GPDB3476
Nelkan Formation	1012	4	12.3	57.6	136.3	−14.6	219.5	GPDB3476
Nelkan Formation	1012	4	14.4	58.9	134.9	−13	217.1	GPDB3476
Milkon Formation	1025	4	7.3	58.7	134.8	−7.4	195.5	GPDB3476
Milkon Formation	1025	4	7.7	57.6	136.3	−5.2	196.7	GPDB3476
Sukhotungusinskaya and Dererevinskaya Suite[a]	1040	4	6.5	66	88.5	−7.8	225.3	GPDB3048
Kumakha Formation	1040	4	7.8	58.9	135.1	−13.9	201.2	GPDB3476
Kartochka Formation	1050	7	2.3	59	96	−22	212	GPDB3048
Linok Formation[a]	1067	6	5.5	66	88.4	−15.2	256.2	GPDB3355
Malgina Formation	1077	6	2.9	58.3	135	−25.4	230.5	GPDB3355

was warm enough to support the reef formation, like the area around Bermuda today. This is probable, since most of both the Ordovician and Silurian were times of high sea-level stands and "Greenhouse" conditions (apart from the end-Ordovician glaciation and its Early Silurian recovery), in contrast to the "Icehouse" background to the present day.

There are various papers recording Palaeozoic palaeomagnetic data from some of the peri-Siberian terranes, for example Tuva (Bachtadse et al., 2000); however, there are problems with each of those works, and we conclude that the data from the structurally unaffected Siberian Craton should take precedence over that from the tectonised peri-Siberian terranes to locate the main Siberian Terrane collage. The changing latitudinal positions through time of the various peri-Siberian terranes seem best understood through analysis of their tectonics and faunas (see Section 5 below), leading to recognition of when they accreted to Siberia.

4. The margins of the Siberian Craton

The margins of the Siberian Craton (Figs. 1 and 2) are now reviewed in order, commencing from today's northwestern corner at the N of the Ural Mountains and proceeding clockwise. However, it should be clearly stated that, unlike some other major terranes such as Laurentia and Baltica (Cocks and Torsvik, 2005), most of the margins of the Siberian Terrane are quite obscure because of the adjacent complex fold belts, the Permo-Triassic Siberian Traps (Fig. 1), the extensive overlying Mesozoic to Recent sediments, for example those in the West Siberian Basin, and the Arctic Ocean. In common with all the other ancient terranes, even when they are clearly exposed, the terrane boundaries of Siberia today are in fact delimited in many places by post-Palaeozoic tectonics which have occurred as part of, or even subsequently to, the breakup of Pangea. In addition, most of the margins of Siberia were ever-changing during the Palaeozoic due to the progressive accretion to it of the various peri-Siberian terranes described below.

In the Palaeozoic the Ural Mountains and their northward extension into Novaya Zemlya lay entirely within the Baltica Terrane and its associated peri-Baltica island arcs, as reviewed by Cocks and Torsvik (2005), although there is debate as to whether or not Novaya Zemlya formed part of a separate terrane which was thrust into the E Barents Sea during the Early Mesozoic. Proceeding eastwards from the Urals along the Arctic Ocean margin of Eurasia today, the next significant Palaeozoic surface outcrops are at the southwestern end of the Taimyr Peninsula, and these formed part of the Siberia Terrane. Because of the very substantial cover of Cretaceous to Recent rocks of the West Siberian Basin outcropping along the edge of the Kara Sea between southern Novaya Zemlya and southwestern Taimyr, the detailed margin of the Siberia Craton is poorly constrained there. However, as described below (Section 5.1) under the Ob–Saisan–Surgut area, all or most of the West Siberian Basin appears to overlie what was clearly part of the peri-Siberian Terrane in the Palaeozoic, and the area is included as part of the "Baikalide" accretionary area of Siberia in the pre-Mesozoic map of Russia by Yakubchuk and Nikishin (2005). In contrast, the position of the Siberian margin is well known within the Taimyr Peninsula. The latter has traditionally been divided into Northern, Central and Southern Taimyr, but it is now known that there is no major tectonic boundary between Central and Southern Taimyr and the two may be considered as a single unit (Torsvik and Andersen, 2002), which was an integral part of Siberia and contains Ordovician trilobite faunas endemic to Siberia. In contrast, Northern Taimyr is now known to be today's southern part of the Kara Terrane, which was independent of Siberia in the Lower Palaeozoic (Metoelkin et al., 2000; Cocks and Torsvik, 2005). The Kara Terrane accreted to the Siberian Terrane progressively from the Permian (Fig. 15) to the end of the Triassic.

The Enisei–Khatanga Trough, which is full of Mesozoic sediments and which lies at the southern end of Taimyr, extending from the Kara Sea to the Laptev Sea and thus obscuring the Palaeozoic geology between southern Taimyr and the main Siberian Craton, is therefore irrelevant in the determination of the position of today's northern sector of the Palaeozoic Siberian Terrane boundary since it overlies only Siberian Neoproterozoic and Palaeozoic rocks.

Notes to Table 1a:

Q = Van der Voo (1993) quality factor (7 is best, 1 is worst score); α_{95}=95% confidence oval; GLat/GLon = Geographic latitude/longitude; PLat/PLon = Pole latitude/longitude (listed as south poles). Reference: GPDB*3355* = Global Palaeomagnetic Data Base Reference Number (REFNO in McElhinny and Lock, 1996); W05 = Walderhaug et al. (2005); MAS = compiled and listed in Smethurst et al. (1998); G04 = Gurevitch et al. (2004); GP96 = Pavlov and Gallet (1996); P06 = Pisarevsky et al. (2006). Mean numerical ages listed for sedimentary strata follows the time-scale of Gradstein et al. (2004) and note that many ages deviates slightly from those listed in Smethurst et al. (1998).

[a] North Siberia poles.

[b] Anomalous pole in Fig. 3a and *not* used to construct APW path (Table 1b).

Table 1b
Final APW paths for Siberia (South and North Siberia combined)

Age (Ma)	Spline path				Running mean path (20 Ma window length)			
	Pole latitude	Pole longitude	Pole latitude	Pole longitude	*N*	A95	Pole latitude	Pole longitude
	Alternative A		Alternative B				Alternative A	
230	−49.4	305.5	−49.1	303.5	1	0.0	−47.1	301.6
240	−54.6	318.2	−54.5	314.8	2	4.7	−59.2	327.9
250	−56.4	326.2	−56.3	327.4	5	5.8	−57.1	325.0
260	−55.8	321.9	−54.3	337.7	4	7.9	−56.6	324.8
270	−53.2	312.4	−50.5	344.8	1	0.0	−50.5	301.4
280	−48.6	306.1	−45.6	349.0	1	0.0	−50.5	301.4
290	−43.9	305.5	−40.2	350.7				
300	−38.8	308.0	−34.6	350.8				
310	−32.8	313.1	−29.1	349.4				
320	−27.5	318.0	−24.4	347.1				
330	−21.9	323.1	−19.8	343.9				
340	−17.4	326.7	−15.9	339.8				
350	−13.6	329.1	−13.1	335.0	1	0.0	−11.1	329.7
360	−11.5	329.0	−11.4	329.3	1	0.0	−11.1	329.7
370	−11.0	326.5			1	0.0	−11.1	329.7
380	−11.6	321.5						
390	−12.4	315.4						
400	−12.5	309.8						
410	−11.4	304.6						
420	−8.7	301.6						
430	−3.2	301.5			2	38.1	0.5	301.3
440	5.5	304.9			4	14.4	9.2	302.3
450	16.4	313.0			2	16.5	17.7	303.4
460	23.5	323.6			8	8.3	26.6	326.0
470	29.9	329.7			9	5.9	29.3	329.2
480	36.1	322.8			6	8.9	34.1	324.6
490	37.8	318.1			5	5.6	37.9	315.6
500	38.9	315.0			6	3.7	38.6	317.4
510	41.7	318.9			6	3.7	38.6	317.4
520	43.4	323.2			3	22.0	43.9	323.6
530	42.5	329.5			4	16.7	42.7	329.3
537	40.5	337.4						

N = number of poles; A95 = 95% confidence circle around the mean pole. Alternative B (spline path) is equal to Alternative A from 370 Ma and older.

To the E of the Taimyr Peninsula, the terrane margin follows the Arctic Ocean (Laptev Sea) until the junction between Siberia and the Chukhot Terrane, which was a westward extension of Laurentia in the Palaeozoic and which today forms part of the North American Plate (Fig. 2). That junction lies at the northern end of the approximately N–S trending but sinuous mountains of the Verkhoyansk Fold Belt which itself extends southwards into the Kolymian Belt (see below under Peri-Siberian terranes). At a point at about 138°E and 56°N the Kolymian Fold Belt merges with the Mongol–Okhotsk Fold Belt (also known as the Tuva–Mongol Arc Massif), which lies to the SE of the old Aldan Shield, which is part of the Siberian Craton. We have included the Verkoyansk–Kolymian Fold Belt area as part of the greater Siberian Terrane in Fig. 2, although it consists largely of Mesozoic rocks.

At the most southwesterly point of the Aldan Shield, to the E and NE of Lake Baikal, there is a very marked indentation into today's southern margin of the underformed Siberian Craton, and the area to the S of the craton there is variably termed the Patom Fold Belt or Baikal–Vitim Zone (which includes the Muya Block of Zonenshain et al., 1990). According to Parfenov et al. (1995), Patom consists entirely of folded Precambrian rocks, which they divided into Riphean and pre-Riphean. The Riphean consists of terrigenous and shallow marine shelf deposits, which Zonenshain et al. interpreted as marginal deposits to the modern Siberian Craton deposits and which prograde outwards into deeper-water continental slope deposits. Parfenov et al. (1995) considered the Patom tectonics to be nappes of Permian age, which caused the margins of the craton there to be thrust onto the craton: the nappe thrusts acting along zones of Cambrian salt deposits, and thus we show the Patom area as part of the core Siberian Terrane from the beginning of the Palaeozoic (Fig. 8). However, Pisarevsky and Natapov (2003) considered that the Patom thrusting took place earlier. There is an unconformity in the Patom area between the marine Ordovician and overlying apparently terrestrial red beds, which are poorly dated but are probably Devonian. To the S of the Patom area lie the Parama, Kelyana, Maya and Barzugin terranes, which are described below under peri-Siberia (Section 5.5).

At the western end of the Patom Fold belt there lies the Central Asiatic Fold Belt (Fig. 2), which includes Lake Baikal and also includes rocks of Precambrian and Palaeozoic age, and therefore represents some of the marginal areas of the old Siberia (see below under Peri-Siberian terranes). That fold belt curves round to border the Siberian Terrane at its most southwestern point and continues on northwards. Much of the Siberian Craton margin there is delimited by the very extensive Yenesei Fault (Fig. 2), which has a major shear component. The margin continues on northwards and becomes lost under the eastern margin of the Jurassic to Recent sediment-filled West Siberian Basin, a post-Triassic graben structure which extends on up to the southern margin of the Arctic Ocean near the northern Urals. Zonenshain et al. (1990, Fig. 179) show several substantial unexposed "Precambrian" massifs concealed under the Mesozoic to recent sedimentary cover of the West Siberian Basin, but they all appear to lie to the W of the peri-Siberian area, apart from the Precambrian of the Tomsk area, which extends into the NW part of the Altai–Sayan area (see below, Section 5.2).

5. Peri-Siberian terranes

A substantial, and still not entirely resolved, series of questions is the varied extent to which Siberia was directly connected in the different parts of Palaeozoic time to the series of formerly independent terranes which form central Asia today, some of which had amalgamated to form the relatively large Kazakhstania Terrane (within the "Kazakh Terranes" area of Fig. 2) by Early Carboniferous times or before. The key problem is the extent to which areas lying today largely to the S and E of the core Siberian Craton described above (Angara) were or were not integral parts of the Siberian Terrane during Palaeozoic times; because, if they were, they must therefore have followed its progressive rotations. The terminology used for this very large area has differed, and our compromise terrane boundaries and terminology are shown in Figs. 2 and 7. The term "Central Asian Fold Belt" is often used for the area S of the Irkutsk part of the Siberian Craton, and that area also includes Tuva and Altai–Sayan (see below). Many authors, for example Sengor and Natalin (1996), used the term "Altaids" for a very extensive area of complex tectonics, but that term includes units from both what we term peri-Siberia (including the modern Altai Mountains themselves) but also the many Kazakh terranes which were tectonically and geographically independent of Siberia for much of the Late Precambrian and Palaeozoic; and thus we have not found the term useful in this analysis.

The chief areas and their constituent earlier terranes which we believe eventually made up peri-Siberia will now be reviewed in turn. However, it has been a problem for us to identify and define which of the many tectonically distinct areas actually formed independent terranes on separate plates at successive times in the Palaeozoic. The chief problems are in the Altai–Sayan area and, adjacent to the E of it, Tuva and most of Mongolia. We have constructed Fig. 8 to show how we assess the various terranes in those areas to have changed in aspect through the Palaeozoic as they gradually accreted to the modern Siberian Craton to enlarge the old Siberian Terrane.

5.1. Ob–Saisan–Surgut area

Sengor and Natalin (1996) described an Ob–Saisan–Surgut area (their Unit 19), which is only known through boreholes and geophysical surveys as an Upper Devonian to Lower Carboniferous accretionary complex unconformably followed by Middle Carboniferous clastics and coals and Upper Carboniferous terrestrial deposits all intruded by Carboniferous and Permian granites, and all today buried beneath the largely Cretaceous to Cenozoic deposits of the West Siberian Basin. However, Zonenshain et al. (1990, Fig. 179) showed a somewhat larger area, which extends further N than the Ob–Saisan–Surgat area shown on Fig. 2, which is simply labelled as "Precambrian and Palaeozoic basement", and Yakubchuk and Nikishin (2005), in their pre-Mesozoic map of Russia, included the whole of that part of the area, like Altai–Sayan, within their "Baikalide accretionary terranes and island arcs". The margins of the area can only be shown conjecturally in Figs. 2 and 7. There is no hint that the area was a separate Lower Palaeozoic terrane, and therefore we have included its known geology as part of the Siberian Terrane in our palaeogeographical maps for the Carboniferous and Permian (Figs. 8, 12, 13) and shown its palaeogeography without confident facies detail within our Cambrian to Devonian reconstructions

(Figs. 9–12), all in its current position relative to the rest of today's Siberian Craton NW of the Tomsk Terrane.

5.2. Tomsk Terrane

The town of Tomsk itself (Fig. 7) lies in the flat West Siberian Basin, but, beneath the Mesozoic to Recent deposits, Zonenshain et al. (1990) recognised what they variably termed a Tom or Tomsk Massif. This is a massif with a metamorphosed Precambrian core whose Palaeozoic cover is undocumented and which adjoins the Altai–Sayan complex to the NW. Zonenshain et al. (1990, Figs. 188–189) also showed an independent Tom (or Tomsky) Terrane in their basal (540 Ma) and uppermost (490 Ma) Cambrian palaeogeographical reconstructions to the SW of Tomsk, a terrane which they also showed (1990, Fig. 179) as extending NW under part of the West Siberian Basin. They considered this to be an independent Precambrian terrane which in the Middle Cambrian collided with the island arcs on today's SW margin of the Siberian Craton, to produce what Zonenshain et al. (1990, p. 79) described as an "accretionary mosaic" which was thrust onto the craton before the Upper Cambrian and subsequently formed an integral part of the main Siberian Terrane from the Ordovician onwards (Fig. 8). Sengor and Natalin (1996) included the area within their Salair–Kuzbas unit, and Buslov et al. (2004) within their Tom–Kolyvan Terrane.

5.3. Altai–Sayan and adjacent areas

The whole Altai–Sayan area (Fig. 2) is extremely geologically complex, and unfortunately that complexity is compounded by confusion over the various topographical and geological structural unit terminologies that have been used. In today's Russia there are two administrative areas, the first named "Altai" (or "Altay–Kray"), which is not within the mountain area, and that immediately adjacent to it in the mountainous area to the SE termed "Altay" (*Times Atlas of the World,* 2000 edition) or alternatively "Gorny–Altai" (*National Geographic Magazine,* 1993 map). However, "Gorny" simply means "mountainous" in Russian, and the two administrative areas together are far smaller than the topographical Altai Mountains, which stretch for more than 1000 km from Kazakhstan through southern Russia and into NW China and W Mongolia: indeed the two relatively close triple junctions between the four countries in the Youyi Feng Mountain (4374 m altitude) area lie within the Altai mountain range at about 88°E and 49°N. Thus we do not use the term "Gorny Altai" for any specific terrane in this paper. To confuse matters further, there is a substantial town named Altay in the Altai Mountains within NE Xinjiang Province, China, which lies in what we term the Ertix Terrane area below. The Altai Mountains lie S and W of the Sayan area and to the N of them is Salair and to the NE the Kuznetsk–Alatau area. The whole area lies to the NW of Tuva (Figs. 2 and 7). The SW of the area is bounded by the Trans-Eurasian Fault, also termed in parts the Gornostaev and Irtysh Shear Zones (Fig. 7); for example, by Sengor and Natalin (1996).

Sengor and Natalin (1996, Fig. 21.26) show more than twenty tectonically distinct areas in the Altai–Sayan area alone. However, Yolkin et al. (2003) demonstrated that the parts of the Altai–Sayan area to the W of Tuva had already formed parts of the passive margin of the main Siberian Terrane before the Silurian. Since this paper deals principally with the Phanerozoic of the area, we recognize the following tectonic units within the area, which were probably independent terranes at times in the Lower Palaeozoic and these are shown in Fig. 7. We do not show as individual terranes on our diagrams those which were accreted to each other in the Precambrian. However, we agree with Sengor and Natalin (1996, p. 534) that all the Altai–Sayan area terrane units were probably in their modern positions with respect to the Siberian Craton by the end of the Devonian. The units we use are now reviewed in turn.

5.3.1. Kuznetsk–Alatau Terrane unit

The Kuznetsk area (Fig. 7) consists of a Late Cambrian to earliest Ordovician volcanic arc, including the Kurai and Biya microterranes of Gornoi Altai, which became accreted to the main Siberian Craton in two orogenic events in the Late Tremadoc–Early Arenig and also the Early Llanvirn according to Sennikov (2003). We have followed Yolkin et al. (2003, Fig. 2) in the definition of this terrane, but it includes both the Kuznetz Alatau and the Batenevsky zones of Zonenshain et al. (1990) and the Kozhykov (26) and Kuznetsk Alatau (27) units of Sengor and Natalin (1996), which they state were united during Precambrian time. In the Lower Cambrian, volcanics were insignificant by comparison with the rest of the Altai–Sayan area, but there is a richly fossiliferous series of limestones extending through all the stages of the Lower Cambrian and the lower (Amgan) stage of the Middle Cambrian, above which are late Middle Cambrian clastics and basic volcanics below a further unconformity underlying Upper Cambrian subaerial volcanics (Astashkin et al., 1995). Above these there are Tremadoc to Early Llanvirn volcanics and clastics (Sennikov et al., 1988).

5.3.2. Salair Terrane unit (Fig. 7)

We have followed the boundaries of Sengor and Natalin (1996) for this terrane (their Unit 23), which includes both the Kuzbass area of Zonenshain et al. (1990) and part of the Kuznetsk Basin of Yolkin et al. (2003). Dobretsov et al. (2004) have described the later Neoproterozoic and Early Cambrian accretionary events in the area. There was considerable Lower Cambrian volcanism which continued on into the Late Cambrian (Astashkin et al., 1995), together with a full Cambrian sequence of fossiliferous interbedded limestones and clastics, and it is most probable that the final accretion to the Siberian Craton occurred in the Late Cambrian. Fortey and Cocks (2003, p. 291) reviewed the relatively complete (apart from the Ashgill) Ordovician and Silurian trilobite and brachiopod faunas from that terrane. Many of the faunal elements are endemic, but the lowest Ordovician endemic brachiopods *Kozuchinella* and *Akelina* are particularly distinctive, not least since the latter is the oldest known genus within its superfamily (the Plectambonitoidea), suggesting some degree of separation, perhaps distance, perhaps environmental, or more likely both, which would have allowed that biological diversification to have occurred there. However, another distinctive Early Ordovician brachiopod occurring there in quantity is *Rhyselasma*, which is elsewhere only known from the Siberian Craton (Severgina, 1984), and confirms the probable proximity to it.

5.3.3. Eastern Altai Terrane unit (Fig. 7)

This includes the Shoria Mountains and is the same as Unit 25 with the same name of Sengor and Natalin (1996). There are thick basal Cambrian oceanic volcanics and tuffs followed by Lower Cambrian carbonates below an unconformity beneath Middle Cambrian (Lower Amgan Stage) acid volcanics which are followed unconformably again by Late Cambrian clastics with trilobites (Astashkin et al., 1995). In the Ordovician, Tremadoc clastics with interbedded volcanics and tuffs are unconformably overlain by Caradoc limestones and clastics which lie unconformably beneath Lower Devonian rocks (Sennikov et al., 1988).

5.3.4. Western Altai Terrane unit

This is a new terrane term for the area shown marked as such in Fig. 7, which is a combination of the Charysh–Chuya–Barnaul (22) and the Anuy–Chuya (24) units of Sengor and Natalin (1996), and includes much of what many Russian biostratigraphers have simply termed the “Gorny Altai” area. Dobretsov et al. (2004) have summarised the Neoproterozoic to Early Cambrian accretionary events within the area. There are Lower to early Middle Cambrian (Amgan Stage) thick basic volcanics and tuffs interbedded with fossiliferous carbonates and clastics. Unconformably above these are late Middle and Upper Cambrian clastics and subsidiary carbonates with abundant trilobites and shelly fossils (Astashkin et al., 1995) which are followed by a fairly full mainly clastic Ordovician succession and a near-complete Silurian section with more carbonates: volcanics are absent from both the Ordovician and Silurian (Sennikov et al., 1988; Yolkin et al., 2003), further suggesting that the area was by then a stable part of the main Siberian Craton.

5.3.5. Rudny Altai Terrane unit

“Rudnik” means “rich in ores” in Russian, which emphasises the mineral importance of the area marked on Fig. 7. This includes the Kolyvan–Rudny Altai (20) and the Gorny Altai (21) units of Sengor and Natalin (1996) and includes the “South Altai” of some other authors. Its northern part was thrust on to the Salair area in the Permian. Over most of the area there are Vendian to Lower Cambrian ophiolites, and a variety of volcanic island arc deposits unconformably overlain by Middle Cambrian to Lower Ordovician turbidites and olistostromes in places. Silurian reef limestones and clastics outcrop over most of the area and the whole region is intruded by Ordovician and Devonian granitoids. There are also Mid Devonian and Lower Carboniferous calc-alkali volcanics. The area was finally stitched to the adjacent Kobdin area by Lower Carboniferous (Visean) island arc volcanics and later Carboniferous granites.

5.3.6. Batenov Terrane unit

The margins of this unit (Fig. 7) follow Heubeck (2001) and it includes both the Belyk (28) and Kizir–Kazyr (29) units of Sengor and Natalin (1996), who stated that they were united in the Precambrian: it is also the area termed “East Sayan” by various workers. Sengor and Natalin also noted the subduction-related volcanic activity present there in the Middle Cambrian which may have heralded their accretion to the Siberian Craton. Lying unconformably below this there is a complete Lower Cambrian sequence of carbonates which goes on up to the early Middle Cambrian (Amgan Stage), apart from in the SW of the area, where there are the deeper-water dominantly clastic rocks of the Balakhtison Formation (Astashkin et al., 1995). The Upper Cambrian may be represented by the terrestrial rocks of the Badzhey and Narva Formations.

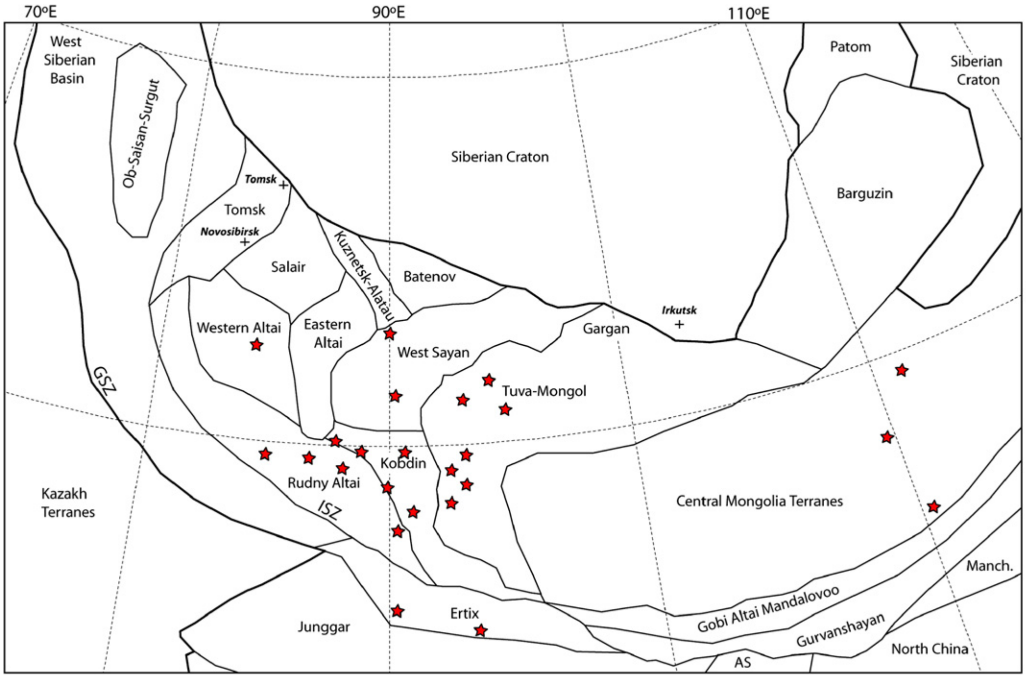


Fig. 7. Map of the SW part of the Siberian Craton and adjacent terranes in southern Siberia, Mongolia, eastern Kazakhstan and northwestern China. Note that all of the Ob–Saisan–Surgat (whose margins are shown diagramatically) and much of the Tomsk and Rudny Altai areas are today obscured by Mesozoic to Recent cover. The area between the West Siberian Basin and the Tuva Mongol terranes is generally termed Altai–Sayan (see Fig. 2). AS, Ala Shan; Manch., Manchurides; GSZ, Gornostaev Shear Zone; ISZ, Irtysh Shear Zone. Newly compiled with underlying data and boundaries integrated from many sources, including Badarch et al. (2002), Heubeck (2001), Sengor and Natalin (1996), Zonenshain et al. (1990). Stars show the distribution of the *Tuvaella* brachiopod fauna in the Silurian (data points derived from Rong and Zhang, 1982; Rozman, 1986).

There are no Ordovician or Silurian sediments known from the region, suggesting land in the area at those times.

5.3.7. West Sayan Terrane unit

For this unit (Fig. 7), we follow the boundaries of Heubeck (2001), which broadly corresponds to the “Western Sayan” of Yolkin et al. (2003): this is a combination of both the “North Sayan” (Unit 30) and “West Sayan” (Unit 39) of Sengor and Natalin (1996). There are thick Lower Cambrian oceanic volcanics, late Lower Cambrian clastics and Middle and Upper Cambrian subaerial volcanics which are unconformably overlain by the Silurian (Astashkin et al., 1995). In Western Sayan and Dzida valley (Units 30-1, 33-5, 39) the youngest rocks in the magmatic arcs and the flysch in the accretionary complexes are Ordovician–Silurian in age (Sengor and Natalin, 1996, p. 536); however, Yolkin et al. (2003, p. 307) describe extensive shallower-shelf marine invertebrates from various Llandovery and later sections in the area. Thus we agree with Yolkin et al. (2003), who considered the area as forming part of the passive margin of the main Siberian Terrane from the Silurian onwards (Fig. 8).

5.3.8. Kobdin Terrane unit

This is the same name and concept as Unit 40 of Sengor and Natalin (1996). There are Middle Cambrian to lower Ordovician turbidites unconformably overlain by Ordovician to Silurian andesites, clastics and limestones. Mid to Upper Devonian clastics and cherts to the SW may represent an accretionary complex or forearc basin fill. Final proof of stitching with the adjacent Rudny Altai Terrane (Fig. 7) is not provided until Lower Carboniferous (Visean) granites cross the suture; however, we think that it is most likely that Kobdin was united with the Eastern Altai and West Sayan Terranes to its N before the Ordovician. Dobretsov et al. (2004) have described the complex Kurai Accretionary Wedge of Lower Cambrian age in the part of the Kobdin Terrane which borders West Sayan.

5.4. Ertix Terrane area

A substantial area to the S of the Rudny Altai, Kobdin and Central Mongolian areas is newly termed the Ertix Terrane area here, and its boundaries are shown in Figs. 2 and 7. To consider it as a single unified terane unit throughout the Palaeozoic is probably simplistic. Because it straddles parts of NW China and SW Mongolia, it has been treated differently by different research teams; but, nevertheless, it seems most useful to consider it as a single unit here. The name has presented problems; in some Chinese papers, e.g. Zhou and Dean (1996) and Rong et al. (2003), part of it is termed the "Altay" or "NE Xinjiang" area, but the Altai Mountains cover a very wide area, and Xinjiang Province is itself confined to China, whereas the terrane area in question is mostly in Mongolia. In addition, the very substantial Xinjiang Province straddles several tectonic zones and Palaeozoic terranes, which makes confusing the use of that name for a single terrane. Rong et al. (2003) include the NE Xinjiang area as part of the "Southern Mobile Belt" of the Siberia Terrane, and we have included it within peri-Siberia because the characteristic Silurian peri-Siberian *Tuvaella* brachiopod fauna occurs within the terrane at Qitai and Hongliuxia, NE Xinjiang (Rong and Zhang, 1982; Rong et al., 2003, Section 4; Fig. 7 here). The terrane's southern border with the Junggar and Tien Shan Terranes is delineated by the Ertix Fault and the Hegen–Solo Obo Suture Zone, which appear to be eastern extensions of the Gornostaev Shear Zone bordering Altai–Sayan. The geology of the parts of NE Xinjiang Province which lie in this terrane is described in Zhou and Dean (1996): a thick Vendian to Middle Ordovician Habahe Group, largely flysch, is unconformably overlain by the intermediate to acid volcanics and tuffs of the Upper Ordovician Dongxileke Formation and the Silurian Kelumute Group, with intercalated limestones and clastics in the W, all unconformably overlain by the Lower Devonian. However, in the Barkol area of NE Xinjiang, Rong et al. (2003, their Section 4) described a Silurian fault-bounded sequence of interbedded clastics and carbonates of Late Wenlock and Ludlow age yielding *Tuvaella*. Deeper-water Silurian graptolite-bearing shales occur within the terrane in adjacent Mongolia. In the Mongolian sector, Badarch et al. (2002) have recognised three terrane units which we have provisionally included within the Ertix Terrane unit here (Fig. 7); they are their Unit 29, the Baytag Terrane, an island arc which only existed independently in the Devonian and Carboniferous; Unit 30, the Baaran Terrane, a backarc–forearc basin which was only an independent terrane in the Devonian; and Unit 31, the Bidz Ophiolite Terrane, which was also independent only in the Devonian. The Lower, Middle and Upper Devonian all have further acid volcanics, limestones and clastics across the whole Ertix Terrane. Unfortunately, Carboniferous (often termed "Hercynian") metamorphism is prevalent over nearly all of the terrane, making interpretation difficult; although the distortion is not so bad as to have destroyed key fossils for dating, which have been found in many of the rocks mentioned above.

5.5. Barguzin Terrane

Adjacent to the Patom zone (see above under Section 4 Margins of the Siberian Craton) to the S is the Barguzin area (Figs. 2 and 7). Barguzin was termed a "microcontinent" by Zonenshain et al. (1990), in which there are Proterozoic metamorphics and ophiolites overlain by Vendian to Cambrian sediments. Included within it are the Precambrian Parama, Kelyana and Maya massifs, which Parfenov et al. (1995) concluded represented three separate terrane areas which amalgamated before the Vendian. The massifs underlie Vendian terrigenous sediments and Cambrian carbonates which were probably erosional remnants of platform cover on the passive margin of the Siberian Craton. Berzin and Dobretsov (1994) considered that Barguzin collided with the Siberian Craton passive margin in the Patom Highlands in basal Vendian times, although shortening of the Patom Fold and Thrust belt also occurred in the Lower Devonian, implying a technically separate existence for the terrane from Siberia in the Lower Palaeozoic, which is why we show it only as a "possible" part of the Siberian Terrane in Fig. 8. Vendian to Cambrian deposits in Barguzin are interpreted as deeper-water remnants of the Siberian passive continental margin (Parfenov et al., 1995), but they are overlain by Ordovician and Silurian turbidites and Devonian marine shelf areas with fossils. Much of the area is occupied by the vast Barguzin Late Devonian granodiorite–tonalite batholith, which Zonenshain et al. (1990) interpreted as being intruded after the collisional event of the Barguzin Terrane on to the Siberian passive margin. However, the Patom thrusting is subject to published differences of opinion: it has been dated as Permian by Parfenov et al. (1995), but Pisarevsky and Natapov (2003) considered the final stages of the accretion of the Barzugin Terrane to the Siberian Craton as "latest Neoproterozoic or Early Palaeozoic" in age. How the latter authors would explain the Devonian Barzugin granite intrusions is not stated by them. We tentatively conclude that the batholith intrusion, like much of the other Late Devonian igneous activity, was most likely linked to the splitting of the Viljuy Basin aulacogen and also the rotation of the entire Siberian Terrane (see Section 13 below); perhaps because it passed over a hot spot.

5.6. Tuva–Mongol Terrane assemblage

The southern margin of peri-Siberia is an arcuate line (Figs. 2 and 7) which bisects Mongolia and lies immediately to the south of the Gobi–Altai–Mandaloovo tectonic belt which is (wrongly) termed locally as of "Caledonian" age. Much of the northern part of Mongolia and the Tuva area of Russia to its NW apparently made up what we term here the Tuva–Mongol Terranes, which includes the Eastern Sayan of Parfenov et al. (1995). The terranes in reality consisted of a series of fragments, many interrelated but others independent. Kuzmichev et al. (2005) present a summary of the Neoproterozoic segments of the area. Buchan et al. (2001) have attempted to unravel the complex geology of west-central Mongolia, in which there is a basal Ordovician (484 Ma) 300 km-long Bayankhongor Ophiolite, and where deformation was apparently continuous until post-Carboniferous times. Dobretsov et al. (2003, fig. 6) showed a useful tectonic sketch map of the area, and Salnikova et al. (2001) have identified, itemised and dated several Cambrian and earliest Ordovician (536 to 480 Ma) tectonic events, including a major thrusting event prior to 497 Ma, followed after an interval by an Mid-Ordovician (464 Ma) intrusive event in the Moren Complex. Sengor and Natalin (1996, Fig. 21.18) show what they term the Tuva–Mongol unit as extending over an area more than 2500 km wide and stretching from Tuva (94°E) to the Sea of Okhotsk (135°E). We have divided the latter into a smaller Tuva–Mongol Terrane and a larger Central Mongolia Terrane Assemblage area (see below), both of which themselves represent amalgamated areas but which were apparently accreted to the main Siberian Terrane area at different times, the Upper Ordovician and the Devonian onwards respectively. However, Upper Silurian and Lower Devonian palaeomagnetic data from the Tuva–Mongol Terrane (Bachtadse et al., 2000) show somewhat lower latitudes (ca. 10–15°) than those expected if fully amalgamated to the main Siberia Terrane by this time.

Badarch et al. (2002) have sensibly rationalised terranes and their terminology within the whole of Mongolia, and they have identified no fewer than 28 separate terranes in what we term the peri-Siberian area and a further 16 terranes outside it in the Mongolian parts of today's S of peri-Siberia. We refer the reader to their paper for the localitions of the many terranes, and include their units 1 to 7 and 10 to 16 within the Tuva–Mongol Terrane Assemblage area. They have allocated their terrane units into several categories as follows (the geological ages (in brackets) are the periods in which Badarch et al. considered the individual terranes to have had an independent existence). The terranes are: cratonal; 13, Gargan Terrane (Precambrian): metamorphic; 3, Tsagaanshiveet (Precambrian to Silurian); 5, Tseel (Precambrian to Silurian); 10, Sangelin (Precambrian to Middle Ordovician); 15, Hamardavaa (Precambrian to Upper Ordovician): island arc; 6, Lake (Vendian); 12, Darhad (Precambrian); 16, Dzida (Vendian to Upper Ordovician); backarc/forearc basins; 1, Altai (Cambrian to Upper Ordovician); 7, Agardag (Vendian to Lower Ordovician): accretionary wedge terranes; 2, Hovd (Cambrian to Silurian); 4, Turgen (Cambrian to Middle Devonian); 11, Hug (Vendian to Lower Cambrian); and ophiolitic terranes; 14, Ilchir (Vendian). They describe the history and accretion of each terrane area, and we have essentially accepted their analysis and terrane boundaries here. In their Late Precambrian reconstruction they show at least three terranes in the Tuva–Mongol area which were independent of Siberia: Tsagaanshiveet (Unit 3), Sangelin (Unit 10), and Hug/Darhal/Gargon/Ilchir (Units 11–14), and they each formed the cores of microcontinents.

The area is dominated by sedimentary melanges, including oceanic deposits. Within the Tuva–Mongolia Massif there are Precambrian rocks (the Baidrag and Bumberger complexes) of Archaean and Proterozoic age (Fig. 8). Adjacent to the massif in the western part of the area is the Tannuola island arc complex (the Eastern Tannuola Unit 38 of Sengor and Natalin, 1996), which existed only in the Cambrian and which is separated from the massif by chaotic complexes which Zonenshain et al. (1990, p. 79) interpreted as a subduction melange arising in front of the island arc when it overrode the massif. The Gargan area, in the northern part of the Tuva–Mongol area, is a Precambrian massif with a Proterozoic core, and overlying it are at least four nappes. The lowest and third nappes include Vendian to Lower Cambrian island arc sequences including ophiolites, the second one is an Ordovician to Silurian chert-carbonate sequence probably representing a continental rise, and the fourth is of Cambrian to Silurian age and represents an island arc (Zonenshain et al., 1990, pp 76, 81). Sengor and Natalin (1996) interpreted the whole Gargan area (their Unit 33) as an island arc situated offshore of the Barguzin Terrane, and on the other side of it from the Siberian Craton, during the Lower Palaeozoic.

A so-called "Salairian" Orogeny affected much of the area in the latest Cambrian at about 500 Ma, with apparently post-orogenic granites of Ordovician age and Early Ordovician ophiolites in the N of Mongolia, although the Cambrian rocks of the area are substantially deformed (Astashkin et al., 1995), and there were probably several episodes of deformation. There are substantial Neoproterozoic carbonates with stromatolites indicating low palaeolatitudes. At the western margin (the Hovd area), thick Tremadoc turbidites are followed by Late Ordovician and Silurian carbonates. There was active volcanism as well as oceanic radiolarian deposits in the Tuva basin in the Lower Ordovician, with later Mid-Ordovician shelly faunas of low diversity and with many endemic taxa in adjacent back arc basins (Tarlyk Formation). Collision between the Tuva–Mongol Terrane and the West Sayan Volcanic Arc occurred in the Mid-Llanvirn (Sennikov, 2003). Sengor and Natalin (1996, p. 532) have suggested that the Tuva–Mongol area may originally have been part of the main Siberian Craton, but became separated from it in a pre-Riphean rifting event and subsequently underwent much rotation; however, we are unable to confirm this, and it seems unlikely: in contrast, we agree with Badarch et al. (2002), who consider it to have been a terrane collage separate from Siberia in the Precambrian and Early Palaeozoic.

5.7. Central Mongolia Terrane assemblage

To the E of the Tuva–Mongol Terrane there is an extensive area (Figs. 2 and 7), which Zonenshain et al. (1990) and other authors have termed the Mongol–Okhotsk Fold Belt. There is a terminological problem in that the Mongol–Okhotsk Fold Belt runs approximately E–W along the SE margin of the Siberian Craton from Mongolia to the Sea of Okhotsk (Fig. 2) but it does not include the Okhotsk Massif itself, which we treat as a key component of the Okhotsk Terrane (see Section 5.9 below). There are several areas within that belt with Precambrian basements, which are now mentioned from W to E in turn. The Argun Massif has an Archaean metamorphosed basement unconformably overlain by Vendian to Cambrian sedimentary cover, including archaeocyathid limestones. Adjacent to the Argun Massif is the Amur Basin, with a 5–6 km thick sedimentary marine sequence of Silurian to Lower Carboniferous age which is in turn overlain by Lower Permian continental volcanic rocks.

We have again accepted the analysis of Badarch et al. (shown in their 2002, Fig. 2), who divided the Mongolian part of this collage into 14 terrane units as follows (we include their unit numbers and the dates of their existence as separate terranes). They allocated them to terrane categories as follows: cratonal terranes; 8, Zavhan (Precambrian); 17, Tarvagatay (Precambrian); 18, Baydrag (Precambrian to Ordovician); 26, Ereendavaa (Precambrian to Lower Carboniferous): metamorphic terranes; 9, Dariv (Precambrian); 21, Buteel (Precambrian): passive continental margins; 20, Zag (Cambrian to Lower Ordovician); 28, Idermeg (Precambrian to Silurian): island arc terranes; 22, Bayangol (Precambrian to Silurian); 27, Herlen (Precambrian to Lower Carboniferous): backarc/forearc basin terranes; 23, Haraa (Cambrian to Silurian): accretionary wedge terranes; 24, Adaatsag (Cambrian to Permian); 25, Dochgol (Cambrian to Triassic); and ophiolitic terranes; 19, Bayanhongor (Vendian to Lower Ordovician). Thus Badarch et al. (2002, Fig. 12) have a minimum of six Late Precambrian terranes in the Central Mongolia terrane area which were independent of Siberia as follows: Zhavhan/Darin (Units 8 and 9), Baydra (18), Tavagatay/Zag (17 and 20), Ereendavaa (26), and Idermeg (28) terranes.

Spread across the whole Tuva–Mongol and Central Mongolia terrane collages there are well-studied Cambrian sequences with typical endemic Siberian trilobite faunas (Astashkin et al., 1995). Also, as discussed below under the Silurian, it is instructive to plot the distribution of the low-diversity brachiopod-dominated *Tuvaella* fauna there (Figs. 7 and 11). Thus we can identify the central Mongolian Terrane Assemblage as having formed part of the Palaeozoic peri-Siberian collage which lay to the then N of the Siberian Craton, and which was, together with the Tuva–Mongol Terrane Assemblage, clearly adjacent to Siberia in the Silurian. In the Devonian, Hou and Boucot (1990) have defined what they termed a Balkhash–Mongolia–Okhotsk Faunal Region, in which the Emsian brachiopods which occur there, some of which are endemic and some attributable to what they term the Old World Realm, are different from those occurring in terranes which today adjoin them to the S, in particular the North China and South China Terranes.

Onshore from the Shantar Islands, in the western Sea of Okhotsk, Borukaev and Natalin (1994) have analysed the geology and mapped what they term the Mongolo–Okhotsk Suture at the southern margin of a large Mesozoic accretionary prism: we have taken that (admittedly later) suture as representing the local southern margin of Palaeozoic peri-Siberia. The suture runs to the N of the Turan and Malo–Khingan blocks, which we think are part of the Manchurides (see below). Since there is little space between the Turan Block and the main Siberian Craton, we think that the Okhotsk Terrane (Fig. 2) was probably separate from the Mongolian Terrane Assemblage in the Palaeozoic. Tomurtogoo et al. (2005) further identify and map the Mongol–Okhotsk suture from 100°E to the Sea of Okhotsk, and deduced that it closed progressively in a "scissor-like" motion from W to E from the Late Devonian to the Late Jurassic.

The Khingan–Bureya Massif (Fig. 2) consists of Archaean and Proterozoic metamorphics overlain by Vendian to Cambrian marine sediments and it underwent a substantial end-Cambrian tectonic event with nappe formation and subsequent substantial granite intrusions. It is termed the Burean–Jiamasu Palaeoplate by Li (2006). Zonenshain et al. (1990, p. 112) regarded the separate but nearby Khankai Massif as part of the same old terrane as Kingan–Bureya, which they have inferred to have split up at the same time as the intrusion of the 495 Ma post-orogenic batholiths, but we have included the Khingan–Bureya and Khankai Massifs within the Manchurides (see Section 6.2 below), and part of it appears within our end-Permian reconstruction (Fig. 15) as it approached the Siberian part of Pangea. The Silurian *Tuvaella* fauna only occurs to the W of the Khingan–Bureya–Khankai area, and its absence in that area reinforces our conclusion that the Manchurides did not form part of peri-Siberia, at least in the Lower Palaeozoic.

5.8. The Gobi Altai and Mandalovoo Terranes

Badarch et al. (2002) have defined these terranes (their Units 33 and 34), which are largely within Mongolia (Fig. 2, 7). The Gobi Altai Terrane consists of possible Cambrian metamorphics overlain by Ordovician to Silurian shallow-marine clastics and carbonates with subsidiary olistostromes, Devonian to Permo-Triassic clastics, carbonates and volcanics. Serpentinite and gabbro lenses occur within the Cambrian to Silurian rocks and there are Silurian, Devonian, Carboniferous and Permian granites. The Mandalovoo Terrane is a deformed succession of Ordovician to Carboniferous volcanic and sedimentary rocks, including *Tuvaella gigantea* in the Silurian (middle Ludlow), although Wenlock and earliest Ludlow rocks are absent (Wang et al., 2005). There are Upper Devonian (Givetian–Frasnian) pillow basalts, andesites, sandstones and cherts overlain by Lower Carboniferous sedimentary rocks (Wang et al., 2005) which are intruded by Devonian and Permian plutons. The pillow lavas indicate a subduction zone setting, and accretion occurred before the Upper Carboniferous. Badarch et al. (2002, Fig. 12) show the two terranes as having amalgamated with each other before the Devonian, and we provisionally group them together in this paper.

5.9. The Okhotsk Terrane

The Okhotsk Massif (Fig. 2) has a Precambrian core (Zonenshain et al., 1990, pp 102–3) above which are Cambrian and later sediments (Astashkin et al., 1995). Zonenshain et al. (1990, p. 139) and Pisarevsky and Natapov (2003) postulated that the Okhotsk Massif was part of an independent terrane, together with the Omolon Massif and the Levo–Oloi Block; a terrane which was situated far to the south of Siberia from the Devonian to the Triassic. Whilst that may well have been true for Omolon and Levo–Oloi, which in Triassic times are now considered to have formed part of Laurentia and for whose position Zonenshain et al. (1990) quoted some palaeomagnetic support; there is no palaeomagnetic data known to us from the Okhotsk Massif itself. The latter is today separated from Omolon and Levo–Oloi by the Verkhoyansk–Kolymian Fold belt, and we therefore feel that the Okhotsk Massif is best considered as having formed part of peri-Siberia during the Palaeozoic in a terrane setting quite separate from Omolon–Levi–Oloi (which did not accrete to Siberia until the Cretaceous). Exactly when the Okhotsk Terrane was accreted to the main Siberian Craton is not known; like the main Siberian Craton, there are widely distributed Upper Devonian volcanics there. Sengor and Natalin (1996, Fig. 21.4) showed the Okhotsk Terrane as an extension of the main Siberian Craton, and in a relatively unchanged position with respect to it, from the Early Riphean onwards into the Jurassic. S of the Okhotsk Massif, there is a full Cambrian succession in the Upper Maya River area with typical Siberian Province trilobites. In contrast, in the Gerbikan–Nelkan River sections near the SW corner of the Sea of Okhotsk, the relatively complete Cambrian succession is dominated by chert, jasper and deeper-water oceanic volcanics, although there are a few dateable archaeocyathids and trilobites in the Botomian there (Astashkin et al., 1995). In the Ordovician, Tremadoc to Llanvirn clastics, with endemic Siberian trilobites (*Nyaya*, *Plethopeltides*) and brachiopods (*Altorthis*), occur in the Okhotsk Massif, and SW of it within the same terrane in the Shevli and Uda River areas, there are Tremadoc clastics unconformably overlain by the Lower Silurian. However, in the nearby Allakh–Yain and Yudoma River areas there is a full Ordovician and Lower Silurian sequence dominated by limestones and from which volcanics are absent (Oradovskaya, 1988). Thus, although there are no palaeomagnetic data from the area, in both the Cambrian and the Ordovician there are distinctive Siberian trilobites and brachiopods present and therefore we also place the Okhotsk Terrane immediately adjacent to the Siberian Craton and identify it as an integral part of the Siberian Terrane during the Palaeozoic.

5.10. Verkhoyansk–Kolyma region

Zonenshain et al. (1990, Fig. 109) show a very large "Verkhoyansk Zone" stretching from the Laptev Sea within the Arctic Ocean to the Sea of Okhotsk in the NW Pacific Ocean, with the Okhotsk Massif at its S. That zone includes not only all of the Verkoyansk Mountains area, but curves round northeastwards into the Oldzhoi Trough: it consists of Late Palaeozoic, Triassic and Jurassic sediments. However, it is now known that the western margin of the North American Plate today cuts through the area (Fig. 2), between the Verkoyansk and the Cherskov Mountain Ranges, and with the Oldzhoi Trough on the North American side of the suture. The Verkoyansk Zone has no rocks older than Permian within it, and thus the extent to which parts of it overlies parts of the core Siberian Craton or peri-Siberian terranes is not known. We have tentatively included it within the Greater Siberian terrane area to the N of the Okhotsk Terrane in some of our diagrams (e.g. Fig. 2. Zonenshain et al. (1990, p. 121) have suggested that the Verkhoyansk sediments were deposited on the passive margin of Siberia and its succesive Pangea, and this was generally agreed by Sengor and Natalin (1996, p. 554), but they also noted the Mid to Late Devonian basalts intruded into the region in the Sette Daban area, a volcanic episode which continued sporadically on into the Lower Carboniferous. That episode may have been connected in some way to the rifting events seen in the Viljuy Basin of the craton.

An additional unresolved dispute is that, within what is today the North American Plate (Fig. 2), there lies the Omolon area. Some authors, e.g. Sengor and Natalin (1996, Fig. 21.40), have plotted the Omolon area as the NE continuation of the Verkoyansk Passive Margin of what we would term the peri-Siberian Terrane Assemblage, and a separate Omolon Terrane area is shown on the Permian reconstructions of Ziegler et al. (1997, 1998) immediately adjacent to today's NE part of the Siberian Terrane. However, in the absence of both critical palaeomagnetic and terrane-dependent faunal data from that area, we have followed the conclusions of Zonenshain et al. (1990, p. 127), who regarded Omolon as a terrane quite separate from Siberia, and thus we have only included it within our later palaeogeographical reconstructions (Figs. 14 and 15) as a distinct terrane to the then NE of Siberia. We think that it may have been closer to Laurentia than Siberia in the Lower Palaeozoic.

6. Terranes adjacent to Siberia today

Also shown on Fig. 2 are a number of other areas surrounding the peri-Siberian Terrane collage which were also formerly independent terranes. Baltica (to the W), Kara (to the N) and the North American Plate (which includes the Chukhot Peninsula of the eastern part of modern Siberia) have been mentioned above. Unfortunately, a large number of very different terrane names and divisions have been published for Central Asia over the past 15 yr, but a critical review of each one is beyond the scope of this paper, and thus those named on Fig. 2 represent a series of compromises and are not to be considered definitive. Those other terranes shown on Fig. 2 to the S and W of the Siberian Terrane are North China, the Manchurides, Gurvansayhan, Ala Shan, Qaidam–Qilian, Tarim, the Junggar Terrane (including Tien Shan), and the Kazakh terranes. Helpful summaries and definitions of many of these central Asian terranes and their Palaeozoic history are in Heubeck (2001) and Metcalfe (2002). These terranes will now be reviewed briefly, as will be the enigmatic Farewell Terrane of Alaska.

6.1. The North China Terrane

North China (or Sino–Korean) is a well-characterised and major terrane which includes most of the Korean Peninsula as well as a large area of N China itself, and we have discussed its Palaeozoic positionings elsewhere (Cocks and Torsvik, 2002; Torsvik and Cocks, 2004): much of its geology is summarised by Zhou and Dean (1996) and palaeogeography by Li (2006). North China has useful palaeomagnetic data recorded from it. The complex relationships between North China and the varied units of the Manchurides to its NE are obscure and outside the scope of this paper; however, North China did not finally accrete to Siberia until the Jurassic. Dacheng et al. (2004) have documented the accretion of the Khanka Terrane of the Manchurides to North China as occurring in the Late Permian and Early Triassic.

6.2. The Manchurides terranes

The Manchurides shown on Fig. 2 are a heterogeneous mixture of areas whose tectonic relationships and individual geological histories are poorly constrained. They lie to the NE of the North China Terrane; however, a large part of the area between it and the Mongol–Okhotsk area of peri-Siberia is obscured by Mesozoic volcanic and Mesozoic to Cenozoic sediments (Zonenshain et al., 1990, Fig. 85). Sengor and Natalin (1996) termed these terranes the Manchurides, which they described as consisting of six units which are (from W to E) the Liuyuan, Hanshan, Bayan Obo–Linxi, Jiamusi, Lesser Hinggan, and Turin units. However, Zonenshain et al. (1990. Fig. 90) presented a very different geology in the same area, with an Inner Mongolian Zone to the W, a Kirin Zone to the E, and beyond them the Sikhote–Alin Belt, the latter an area which Sengor and Natalin (1996) place in their "Circum-Pacific Belt". Between the Kirin and Sikhote–Alin areas, Zonenshain et al. (1990) show on their maps a substantial Precambrian block, the Khankai (or Khanka or Xingkai of other authors) Massif, which also has some Cambrian within it (Astashkin et al., 1995). Zonenshain et al. (1990) also show another large Precambrian area, the Khingan–Bureya Massif (Fig. 2), otherwise termed the Burean–Jiamsu Palaeoplate by Li (2006), which we have placed just outside the Mongol–Okhotsk area of Peri–Siberia in the Late Palaeozoic (see Section 5.7 above). However, Ren et al. (1999) recognised a large Songhuajiang Terrane and Bureya–Tiamusi, as well as the adjacent Khankai Massif, as substantial independent units. The geology and histories of all these blocks, which straddle the Sino–Russian border, are poorly resolved and we have omitted them from our subsequent discussions and reconstructions, apart from the Khingan–Bureya Massif, which we schematically depict not far from the Siberian part of Pangea in our latest Permian palaeogeography (Fig. 15). In addition, Ye et al. (1994) have recognised and named three separate teranes in the area, the Erguna–Xingan, Songnen and Jiamusi terranes, of which they consider the Erguna–Xingan Terrane as of possible Siberian affinity, but without quoting faunal or other evidence to support that assertion, and thus we do not consider it further here. Sengor and Natalin (1996, p. 526) regarded the terranes in the whole area as consisting largely of displaced fragments of the Palaeozic northern active margin of North China, and we tentatively share that conclusion. Few terrane-diagnostic fossils are known from the area, since many of the Proterozoic and Palaeozoic rocks of the region are metamorphosed, but Manankov et al. (2006) were able to distinguish a different marine faunal province in the Permian of the Manchurides from that in peri-Siberia. Li (2006) provides distribution maps of ophiolite belts and other probable suture zones within the area, and also presents Early and Late Permian reconstructions of the region.

6.3. The Gurvansayhan Terrane

Badarch et al. (2002) have defined and described this terrane (their Unit 35), which occupies a broad belt largely within Mongolia (Figs. 2 and 7). The terrane appears to represent one or more island arcs, which commence with a Late Cambrian ophiolite, above which there are a great variety of rocks including Ordovician to Silurian greenschist facies, Upper Silurian to Lower Devonian radiolarian cherts and tholeiitic pillow basalts, and Middle Devonian to Lower Carboniferous volcaniclastic rocks (including Frasnian cherts). The structure is complex, with many imbricate thrust sheets, and it appears to have accreted to its adjacent terranes in the Upper Carboniferous.

6.4. The Ala Shan Terrane

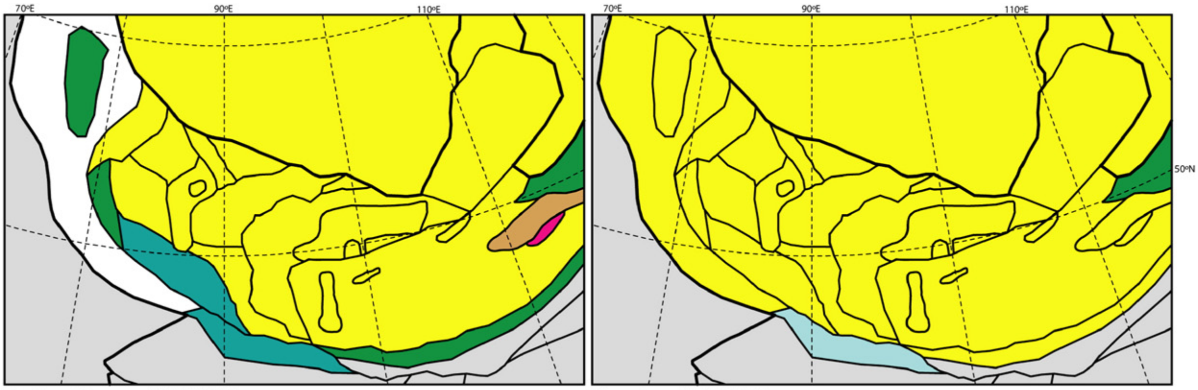
The relationships and identity of the Ala Shan Terrane, sometimes termed Badainjaria (e.g. by Rong et al., 2003) or Ordos Terrane (e.g. by Ziegler et al., 1997), are interpreted very differently by different authors, but the Ordos Basin is included within the area. Pre-Devonian rocks are poorly exposed in the terrane, but there is no record of the distinctive Silurian peri-Siberian *Tuvaella* fauna and thus we consider the terrane as probably not having formed part of the immediate Siberian Terrane collage in the Early or Middle Palaeozoic. Ala Shan and Qaidam are shown as separate plates by various authors, e.g. Metcalfe (2002), but combined within a so-called Qilian–Quaidam Plate by others, e.g. Zhou et al. (1996), and some other previous workers have even included the terrane within North China; however, we have somewhat arbitrarily decided to follow Metcalfe (2002).

6.5. The Qaidam–Qilian Terranes

We include here the adjacent Qilian area to the NE, which some workers regard as tectonically separate; however, the combined areas are often termed the Qilian–Qaidam Terrane. Once again, its geology is authoritatively summarised in Zhou and Dean (1996). Heubeck (2001) shows Qaidam–Qilian, Tarim and Ala Shan as having amalgamated before the Middle Devonian, but this is debatable (see above).

6.6. The Tarim Terrane

Much is known about Tarim, and most authors are agreed on its area and tectonic margins (Fig. 2), although a minority divide the terrane and identify Northern Tarim as a terrane independent of Southern Tarim in their early history; however, we treat is as one here. There are Precambrian cores to the terrane in the Aksu area (Kalpin Block) in NW Tarim and in the Kuruktag (or Kuruk Tagh) area in NE Tarim (Zhou et al., 2001). Over much of the terrane there were marine deposits from Vendian to Lower Silurian times, and those deposits are followed unconformably by non-



Carboniferous (340 Ma)

Permian (280 Ma)

Silurian (420 Ma)

Devonian (380 Ma)

Cambrian (510 Ma)

Ordovician (470 Ma)

LEGEND

🟨 Siberian Terrane	🟨 Probable Siberian Terrane	🟫 Other Precambrian Massifs
🟥 Island Arcs	🟦 Mixture of Island Arcs and Accretionary wedges	🟩 Accretionary wedges
☐ No data	🟦 Possible accreted areas	⬜ Non-Siberian Terranes

Fig. 8. The area from the southern West Siberian Basin to E of the Barguzin Terrane, and including the Altai–Sayan, Tuva–Mongol and much of the Central Mongolia Terrane Assemblage area (names of the individual units are shown in Figs. 2 and 7). The six maps show the terrane units in different colours reflecting their dominant aspect during each period, and also show how the central Siberian Terrane increased by accretion. The Barguzin Terrane did not completely accrete to the Siberian Craton until the Late Devonian, but may have formed part of it in the Proterozoic (see text). The generalised outlines of the Precambrian massifs (chiefly in Tuva–Mongolia and Central Mongolia), which did not form part of Siberia in the Precambrian, are modified from various authors.

marine Devonian to Permian successions in many places: the geology of the NW Tarim Basin was described by Carroll et al. (2001). There are some useful Palaeozoic palaeomagnetic data for the terrane, summarised in Cocks and Torsvik (2002) and Torsvik and Cocks (2004). Zhou et al. (1998) have described an Ordovician trilobite fauna from the NW Tarim Basin, and concluded that more than 80% of the 16 species are essentially the same as coeval forms from the South China Plate, and therefore that those two terranes cannot then have been far apart. Heubeck (2001) showed Tarim as having amalgamated with the Qaidam–Qilian and Ala Shan terranes before the Middle Devonian, but that is contentious, and the latter two terranes do not appear with Tarim in our Carboniferous and earliest Permian reconstructions (Figs. 13 and 14). The Tarim–Junggar–Tien Shan aggregated terranes did not combine with the large Siberian Terrane until the Early Permian.

6.7. The Junggar Terrane

The Junggar Desert lies between the Altai Mountains to its N and the Tien Shan Mountains to its S. The geological history of Junggar in the Palaeozoic was outlined by Zhou et al. (1996). It is divided from the Altai part of the Siberian Terrane collage by the Trans-Eurasian Fault, locally termed the Irtysh Shear Zone (Fig. 7) and the Hoxtolgay–Karamaili Fault Zone. The absence of the Late Silurian *Tuvaella* brachiopod fauna from Junggar (Rong and Zhang, 1982, p. 134; Rozman, 1986) suggests that it was not attached to, and probably situated to the then S of, the Siberian Terrane. Tarim, Central Tien Shan and the Junggar Terrane had all amalgamated by at least the latest Carboniferous (Zhou et al., 2001). Junggar is sometimes represented as a separate terrane (e.g. Heubeck, 2001), but other workers portray it simply as an eastern extension of the Kazakh terranes, and it probably extends eastwards into Mongolia in what some authors term the Gobi–Tienshan Belt. Buckman and Aitchison (2004) recognized nine separate Cambrian to Carboniferous terranes in the Junggar area and outlined their tectonic evolution. The Tangbale and Kakesayi terranes merged in the Mid-Ordovician, and with the Laba Terrane in the Silurian, all to form the Ebinur Terrane, and that composite terrane accreted to the Mayila Terrane in the Devonian. The Toli and Kulumudi terranes merged in the Devonian and with the Karamay and Sartuohai terranes in the Carboniferous, and the whole Junggar Terrane was unified by the latest Carboniferous. We include Junggar, combined with Tarim and Tien Shan, in our Carboniferous and Permian reconstructions (Figs. 13–15). The Junggar–Balkash Fold Belt, whose Late Palaeozoic geodynamics were considered by Van der Voo et al. (2006), lies largely to the W of the Junggar Terrane area that we show in Fig. 2.

6.8. The Tien Shan Terranes

The Tien Shan (or Tian Shan) Mountains stretch for more than 2000 km from their SW, where they pass N of the Pamirs in Tajikistan, through Kyrgyzstan, Kazakhstan and on in to China. The SW Tien Shan Terrane forms a separate small terrane near the Fergana Basin to the W of Tarim, and, since it is therefore one of the many "Kazakh" Terranes, will not be considered further here. However, the area that forms the southern margin of the Junggar area is often divided into North, Central and South Tien Shan and appears to represent three different terranes at various geological times, North Tien Shan, Central Tien Shan (termed the Turian Terrane by some authors) and the South Tien Shan Terrane. They may largely be regarded as part of the Kazakh Terrane Assemblage to their W. Central Tien Shan has a Precambrian core area and volcanoes were active along its northern margin from the Devonian to the Late Carboniferous amidst Lower to Mid Carboniferous marine carbonates. It appears to have merged with Tarim before the Mid-Carboniferous (Zhou et al., 2001, p. 45) and North Tien Shan by the Late Carboniferous. The western part of northern Tien Shan (between 72° and 74°) has Upper Cambrian to Lower Ordovician (Arenig) island arc complexes unconformably overlying some Precambrian basement, and these were followed by more Arenig to Caradoc island arc volcanics in the N and clastic sediments in the S, ending with Late Ordovician redbeds. These were all cut by Late Ordovician to Silurian granites, which are in turn overlain firstly by Middle to Upper Devonian acid volcanics and secondly by Lower Carboniferous redbeds, Upper Carboniferous marine clastics and Permian volcanics, all subsequently intruded by Late Permian granites (Bazhenov et al., 2003). The term "North Tien Shan" has been used for different geographical and tectonic entities by Russian and Chinese research teams; however, further discussion of these complex areas is outside the scope of this paper.

6.9. The Kazakh Terranes

The area shown as the "Kazakh terranes" on Figs. 2 and 7 is extremely geologically complex, and the situation is not helped by the huge extent of the

Mesozoic and Tertiary cover which is at the surface of the northern part of that enormous and topographically flat area between the northern Urals and the western part of the Siberian Craton. Sengor and Natalin (1996) defined 44 tectonic units in what they term the Altaids of Kazakhstan and adjacent countries, and postulated them as distinctive and mostly separate from each other in the Lower Palaeozoic and progressively accreting with each other to form the progressively larger terrane often termed Kazakhstania during the Upper Palaeozoic. Heubeck (2001) presented substantially different Devonian to Permian reconstructions for the area. Some of these Kazakh elements are schematically shown within our latest Palaeozoic reconstructions (Figs. 13–15), but a general review of all of the Kazakh terranes is outside the scope of this paper. The Yerementau Terrane, the Chingiz–Tarbagatai Terrane, and the Alakol Terrane are the terranes lying immediately to the W of the Siberian Terrane collage, but were separate from it, as can be seen by analysis of the Ordovician faunas (Fortey and Cocks, 2003). The main mass of Kazakhstania was quite separate from the enlarged Siberian Terrane until it accreted to it progressively during the Permian (Figs. 14 and 15) during the formation of Pangea.

6.10. The Farewell Terrane

This interesting terrane, today in southwestern Alaska and far to the E of Figs. 1 and 2, is mentioned here because it contains faunas which are undoubtedly otherwise only known as endemic from Siberia. Blodgett et al. (2002) have documented, for example, monorakid trilobites from the Early Ordovician, Late Silurian sponges, and brachiopods from the Devonian (Emsian), all of Siberian aspect. Where the Farewell Terrane was situated in Palaeozoic times is quite unknown, there are no palaeomagnetic data published from it, and it is not shown on our reconstructions; however, it seems very probable that it was near Siberia in the Lower and Middle Palaeozoic or might perhaps have even formed part of the Siberian Terrane itself.

7. The geographical evolution of Siberia and its neighbours

The remainder of this paper is a summary of the history of the area. We present this review with much hesitation for two reasons. Firstly, although the Siberian Craton itself is relatively untectonised since the Proterozoic, the areas surrounding it are either much obscured by Mesozoic to Recent sediments (the West Siberian Basin and the Verkhoyansk–Kolymar area) or consist of so many independent Late Precambrian and/or Lower Palaeozoic terranes that the relative positions and geography of each of these relatively small terranes are very uncertain before the progressive accretion of Pangea from the Upper Carboniferous onwards. Secondly, the palaeomagnetic data is not very strong between the Late Devonian and the Late Permian.

Thus we are only able to present reasonably confident facies maps for the whole terrane assemblage area from the Late Silurian onwards. However, we do include here tentative palaeogeographical maps for the Late Cambrian (Fig. 9) and the Middle Ordovician (Fig. 10), which, whilst reliable for the craton area, can only be regarded as provisional for most of the peri-Siberian regions. To illustrate the problem of numerous small terranes, Fig. 8 shows the area which includes Altai–Sayan, Tuva and Mongolia with today's geography and terrane boundaries (the latter taken from Fig. 7). The terranes are coloured to show the successive development and accretion of each terrane area to the main Siberian Terrane from the Cambrian to the Permian. Objective reconstructions of, for example, the numerous successive island arc areas are clearly impossible to make; not only because of the contemporary changing tectonic developments within each area, but also because the tectonic boundaries of each of the many terrane areas today do not reflect the original Lower Palaeozoic limits of the terranes. Thus to portray the true geographical scenario for, for example, the Cambrian is not yet within our grasp. Many previous authors, chiefly Zonenshain et al. (1990), Sengor and Natalin (1996) and Badarch et al. (2002), but many more, some of which we cite, have attempted such palaeogeographical reconstructions for the Neoproterozoic and Lower Palaeozoic, and we agree that some aspects of their maps may bear some relationship to reality, but we feel that the uncertainties are so great that we can only provide provisional new maps for the periods before the Devonian. In the following sections we now review Siberia's history since its birth, but we include only a brief section on the Precambrian history of the terrane assemblage.

8. Precambrian prelude

The core of Siberia includes Archaean and older Proterozoic rocks of the Anabar Massif to the north-centre and the Aldan Shield and its westward extension into the Central Asiatic Fold Belt (including the Lake Baikal region, East Sayan and the Enisei Range) to the S of the terrane. The Archaean of the Aldan Shield includes rocks which have been isotopically dated as older than 3.6 Ga, and there are substantial greenstone belts within the shield representing suturing between originally different crustal blocks (Zonenshain et al., 1990, and references therein). These differing earlier Precambrian terranes which make up the Siberian Craton are beyond the scope of this paper, but they came together well before probably forming an integral part of the supercontinent of Rodinia, which assembled at between 1.2 and 1.0 Ga. Most published reconstructions show a united Siberia as forming the eastern margin of Rodinia, outboard of Baltica, but in truth the detailed positioning of Siberia within Rodinia is poorly constrained and thus very controversial. The correct interrelationships between, and the various successive global positions of, these diverse terranes prior to the assembly of Rodinia are quite unknown. There are no obvious 1.3 to 1.0 Ga mobile belts within Siberia, such as the ones present on other terranes (e.g. the Grenvillian–Sveconorwegian–Kibaran belts of Laurentia, Baltica and the African part of Gondwana) which have been used to link the various constituent parts of Rodinia to each other, as shown by Torsvik (2003).

Khain et al. (2002) have documented a 1.02 Ga ophiolite within the Dunzhugur Complex, which forms part of the Central Asian Fold Belt in Eastern Sayan, and they concluded that today's southern margin of the Siberia Terrane must have been established as a margin facing an open ocean before 1.0 Ga. They termed that ocean the Palaeo-Asian Ocean; however, we feel that the world-wide dispositions of the major terranes, let alone the oceans surrounding them, in the Precambrian before the assembly of Rodinia is so uncertain that we do not identify and name any specific oceans before that superterrane existed. In any case, the term Paleoasian (or Palaeo-Asian) Ocean has also been used in various different senses in Neoproterozoic (Khain et al., 2003) and Lower Palaeozoic reconstructions (e.g. Yue et al., 2001, Fig. 9; Dobretsov et al., 2003, Fig. 10), and Upper Palaeozoic (e.g. Li, 2006), and thus we do not use it in this paper.

The Rodinia superterrane broke up after 800 Ma (Torsvik, 2003). Sears and Price (2003) concluded that the northeastern margin of Siberia did not become completely detached from the southwestern part of Laurentia until the latest Neoproterozoic or even the earliest Cambrian, but we reject this (see Cambrian below): it is clear from the divergent palaeomagnetic data that Siberia was independent from Laurentia and Baltica during the Ediacaran. We also note that Pisarevsky and Natapov (2003), after a substantial analysis of the Riphean and other Proterozoic margins of Siberia, concluded that it was not immediately adjacent to Laurentia during the period of Rodinia, or indeed any other known terrane at that time. We show in Fig. 6 the changing palaeolatitudes of the terrane from ca. 540 Ma and onwards. Siberia was located at low southerly latitudes during the Cambrian, but it is clear from the very few reliable Late Precambrian poles (Table 1a; Fig. 3a) that Siberia was also located in equatorial/subtropical latitudes during the preceding Ediacaran times. Of course, during the Late Neoproterozoic there are no faunal data through which its closeness or otherwise to other terranes may be deduced, and neither is there any way of estimating its palaeolongitudinal separations from the other terranes through the palaeomagnetic results, not least since there are no useful palaeomagnetic data for Siberia until 615 Ma. However, there seems no evidence of tectonics which would indicate further accretion of major terranes to Siberia before the latest Palaeozoic progressive formation of Pangea. Siberia's position largely to the S of the Palaeoequator in the Neoproterozoic, Cambrian and Early Ordovician is in marked contrast to the rest of the Phanerozoic, when it lay in the northern hemisphere.

Khudoley et al. (2001) have reviewed the sedimentary evolution of the classic Riphean and Vendian basins of the south-eastern Siberian Craton, which vary between 12 and 14 km in thickness. The relatively flat-lying Vendian deposits are up to 1500 m thick and the underlying Riphean forms the bulk of the strata. Both consist of a variety of carbonates and relatively fine-grained clastic rocks. There are six major groups, five in the Riphean and one in the Vendian, between which are low-angle regional unconformities. All were deposited under terrestrial through tidal and subtidal to shallow-marine conditions, apart from the Late Riphean Uy Group, which, in its middle part only, contains deeper-water greywacke turbidites. The study area was to the SE of the Aldan Shield, from which most of the terrigenous material was apparently derived, and the beds continue eastwards within the adjacent Verkhoyansk thrust and fold belt. It is notable that the geochemical provenance studies demonstrate that nearly all of these Late Precambrian sediments were derived from rocks of post-Archaean age. Khudoley et al. (2001) suggest that this Riphean–Vendian sedimentary basin was initiated by rifting that subsequently failed, allowing the development of a long-lived intracratonic sedimentary basin. Pelechaty (1998) attempted an integrated global correlation for the Vendian, based on δ13C variations in the Siberian successions, and recognized three major depositional sequences there. Pisarevsky and Natapov (2003), after a survey of the various Riphean successions around the entire terrane, also concluded that all of Siberia's margins were passive at that time.

It is also very noticeable that there are no known glaciogenic rocks in either the Riphean or the Vendian (Ediacaran) of Siberia. Thus the concept of any "Snowball Earth" for the Late Precambrian is difficult to support on a global scale, since Siberia was one of the most extensive terranes in those times. Siberia was also on or near the palaeoequator for much of the time, and would thus be in an ideal position as a test case to prove the presence or absence of very widespread glaciation.

Siberia, amongst other terranes, is also famous for the very extensive development of stromatolite bioherms. Petrov and Semikhatov (2001) have described one such bioherm complex of Riphean age within the Turukhansk Uplift of the southwestern Siberian Craton which extends to nearly a kilometre in thickness. Like modern coral reefs, such bioherms apparently thrived in a range of depth environments varying from subtidal to deeper-water, and the largest individual structure which Petrov and Semikhatov describe had lateral dimensions of nearly 25 km by 10 km and with a thickness estimated at 550 m, a bulk which compares with many of the largest reefs today. Such obviously warm-water organisms as those stromatolites indicate without doubt that Siberia's position was close to equatorial, thus confirming the conclusions derived from entirely different palaeomagnetic data.

9. Cambrian

Siberia was S of the palaeoequator during all of the Cambrian, but at relatively low tropical palaeolatitudes (Fig. 6). The concomitant warmth certainly encouraged biological speciation (see below), and the Cambrian of the Siberian Craton is famous for the variety and preservation of its fossils, in particular the small forms of uncertain biological affinity at and above the very base of the Cambrian. A striking feature too is the number of archaeocyathan reefs upon and around the Siberian Platform; for example, those which are well developed in the Olenek Peninsula which is part of today's Anabar Massif, and are there of Lower Cambrian (Atdabanian) age (Kaufman et al., 1996). Many of the palaeogeographical features shown on Fig. 9 are modified from Keller and Predtechensky (1968), and the areas of submerged shelf were very extensive, particularly in today's northern part of the craton; for example, there was no known large land area in the Anabar part of the craton. Nevertheless, there seems to have been a substantial continental landmass in the then N of the terrane, and it seems probable that the adjacent Altai–Sayan and Mongolian peri-Siberian terrane components would have had substantial areas of mountain and highland, particularly in the tectonically active areas.

Astashkin et al. (1991) described the Cambrian on the Siberian Platform and it is very noticeable that there are two broad facies divisions. To the W, the so-called Turukhansk–Irkutsk–Olekma Facies Region consists largely of dolomites with interbedded anhydrites, and only occasional limestone beds with sparse and endemic trilobites and algal biostromes and also rocks of terrigenous origin. In contrast, to the E the Yudoma–Olenek Facies Region consists largely of open-marine limestones and marls, with occasional deeper-water origin bituminous shale. The total stratigraphical Cambrian thicknesses of the two extensive areas is about the same in the two areas at between 1500 and 2000 m: whether that is coincidence or caused by terrane-wide (or perhaps even global) sea level changes is uncertain.

Astashkin et al. (1995) and Dobretsov et al. (2003) described the Cambrian in the fold belts surrounding the Siberian Craton, including those in Mongolia. There was very substantial volcanism from 550 to 520 Ma in the Altai–Sayan fold belts in the latest Neoproterozoic, Lower Cambrian (Tommotian, Atdabanian, Botomian and Toyonian Stages) and Middle Cambrian (Amgan and Mayan Stages), with the thickest arc volcanic material in Tuva, West Sayan and Salair and thick basalts and tuffs in the Altai and Shoria Mountains, but in the Late Cambrian this volcanism was restricted to selected areas (Salair and Kuznetz Alatau). Every group of authors who have presented palaeogeographical reconstructions for the Lower Cambrian (e.g. Zonenshain et al., 1990; Dobretsov et al., 1995; Sengor and Natalin, 1996) have come up with very different models, particularly for the Altai–Sayan terranes. All are agreed that there were accretionary complexes, ophiolites, island arcs and other indicators of extreme tectonic activity from Vendian to Middle Cambrian times, and we make no pretence that that part of peri-Siberia shown on our Upper Cambrian reconstruction (Fig. 9) is anything more than guesswork in the light of both the data known to us and the previous reconstructions available. We do however stress that that Altai–Sayan area was in the Cambrian N of the Siberian Terrane area since (a) the Siberian Craton was undoubtedly inverted by comparison to the present day, and (b) the Altai–Sayan area was accreted to the craton before the Devonian whilst the craton was still inverted.

Sengor and Natalin (1996) reconstructed their Lower Palaeozoic Altaid terranes as constituents of two enormous island arcs, which they termed the Kipchak Arc, which they believed to have stretched between

Baltica and Siberia, and the Tuva–Mongol Arc, which they placed NW of the main Siberian Craton in the Palaeozoic. The term “Kipchak Arc” has also been used by some other authors, for example Yakubchuk et al. (2001). However, analysis of the biological relationships and endemicity of the Ordovician benthic faunas from four of the more substantial Altaid areas (Altai–Sayan, Chingiz, Chu–Ili and Tien Shan) by Fortey and Cocks (2003), suggested that at least three of the four must have formed parts of the complex peri-Gondwanan collage during the Lower Palaeozoic rather than integral parts of either peri-Siberia or Baltica, and only Altai–Sayan (which we now realise was more than a single terrane in the Lower Palaeozoic) shows substantial Siberian elements in its benthic fauna (see below), and can thus be deduced to have formed part of peri-Siberia. Therefore the Kipchak Arc is not mentioned further here.

There was open ocean between the Tuva–Mongol Terrane collage and the Siberian Craton in the Cambrian: however, we agree with Kravchinsky et al. (2001) that the distance between the two was not very great. Thick Lower Cambrian ocean volcanics with some interbedded Lower to early Middle Cambrian (Amgan Stage) fossiliferous clastics and carbonates lie unconformably under the Silurian in the centre and W of Tuva: only in the NE of Tuva (Kidrik River) is there a full Cambrian sequence which is unconformably overlain by the Upper Ordovician (Astashkin et al., 1995). In the Mongolian sector (Kasagt–Khairkan Ridge, S Khubsugul Lake area), the Lower Cambrian is relatively complete, with many archaeocyathans and small endemic Siberian shelly fossils in the Tommotian, Atdabanian and Botomian all well represented, but there are no basic volcanics. Those carbonates persisted until the early Middle Cambrian (Amgan Stage) and there are a few interbedded acid volcanics in the Khubsugul area only. The Late Middle Cambrian and the Upper Cambrian are represented only by thick and poorly fossiliferous molasse deposits which are unconformably overlain by Lower Permian rocks (Astashkin et al., 1995). Comparably, various units of the Central Mongolian Terrane Assemblage have Siberian faunas, and, once again, cannot have been far separated from the main terrane, even though our palaeogeographical reconstruction (Fig. 9) can only be described as tentative for those areas.

The Middle and Upper Cambrian shelly faunas, in particular the brachiopods, have more in common with those of North America (Laurentia) than with Baltica or Gondwana, but that was just as probably due to their comparable equatorial palaeolatitudes at the time as to their possible proximity to each other, and the communities are not as diverse and the fossiliferous beds with the remains of dead benthos are not as abundant in Siberia as would normally be expected at those low palaeolatitudes. For many years it has proved difficult to correlate the successive and well-defined Siberian Platform trilobite faunal zones (Pegel, 2000) with those from elsewhere, and a distinctive Siberian Province was defined by Shergold (1988) for the region. There are certainly many endemic trilobites on the inner shelves throughout successive Cambrian periods; however, on the deeper shelves there are some genera, for example *Kootenia*, *Erbiella*, *Paradoxides* and *Hebediscus*, which have some relationships to those from western Gondwana (e.g. Morocco and southern Britain), and these links have been substantiated through the numerical analyses by Lieberman (2003). Alvaro et al. (2003, Figs. 5 and 7) have listed 8 and 27 trilobite genera which occur in both Siberia and Gondwana in the Lower and Middle Cambrian respectively.

The reasons for the endemicity are varied, but probably include at least some taxonomic artefacts (the erection of genera which truly also occur in other terranes but are called by other names there), partly the geographical isolation of Siberia, and partly because Siberia and some other large terranes (including Baltica) were covered by relatively anoxic ocean floors supporting the olenellid trilobite fauna but not much else. However, by the Upper Cambrian there were at least some trilobite faunal links with other areas: Rushton et al. (2002) identified trilobites from Severnaya Zemlya, then in the Kara Terrane, which for the first time provided faunal correlation at that age level between Siberia, Kara and Baltica.

Sears and Price (2003) have postulated that today’s northern Siberia was adjacent to today’s western United States, then part of Laurentia, based on a variety of tectonic arguments from the Precambrian and also the distribution of olenellid trilobites in the Early Cambrian. It is true that Siberia and Laurentia share four olenellid genera in the Lower Cambrian Atdabanian, but in the succeeding Botomian the trilobite faunas are very different (Briggs and Fortey, 1992), and it is unwise to base terrane affiliations solely on the four Atdabanian occurrences.

10. True Polar Wander and the Cambrian faunal “Explosion”

The base of the Cambrian (which is also the base of the Phanerozoic) is famed for the apparently relatively sudden appearance for the first time of metazoan animals with hard parts, discrimination between which enabled nineteenth-century biostratigraphers to develop faunal correlations for rocks in the oldest parts of the Phanerozoic. Much has been written on this Cambrian Radiation (for example, the various contributions in the book edited by Lipps and Signor, 1992) and the possible reasons why such varied phyla changed their morphologies so basically, and the subject is still one of much controversy. However, it is quite wrong to subscribe to the widely-held popular belief that the Cambrian Radiation was an "explosion"— it was by no means an instanteous event even by geological perceptions, but a process that went on for more than 15 Myr after the start of the Cambrian and probably preceded it as well. In fact the radiation did not even peak until about the Tommotian–Atdabanian boundary at some time after 535 Ma; more than 7 Myr later than the Precambrian–Cambrian boundary. In addition, it is now accepted by most palaeontologists, in arguments summarised by Fortey (2001), that there must have a been an additional substantial period, perhaps even longer than a hundred million years, within latest Precambrian time, when the various animal groups were radiating into recognisable post-Precambrian morphologies prior to their acquistion of hard parts, including shells, at various times peaking in the Lower Cambrian.

A completely different controversy, which has generated comparable heat within the palaeomagnetic community, is whether or not the Earth's rotation axis tilted by up to 90° (True Polar Wander) during the Cambrian at about 531 Ma (Kirschvink et al., 1997). Their model was chiefly based on an anomalous pole from the southern Siberian Craton (the 531 Ma pole marked with a star in Fig. 3b) that does not match contemporaneous nor younger poles from Siberia (Torsvik et al., 1998). Newly reported poles from Siberia, and covering the very same time interval (Table 1a), do not substantiate this anomalous pole. If the Lena River 531 Ma pole (Table 1a, Fig. 3a) pole is correct, then that would imply two phases of rapid TPW, since poles older and younger than ca. 531 Ma are largely similar to each other; and that seems extremely unlikely. Dependent of the pole of rotation, 90° of TPW would have led to very noticeable changes in sedimentary facies due to the extreme latitudinal changes over that short time period. In the case of Siberia, the pole of rotation is located near the equator in both scenarios (with or without TPW) and thus the sedimentary regime there might not have been much affected. However, the extensive palaeomagnetic data from Gondwana, Laurentia and Baltica show neither evidence for any rapid and large-scale TPW or any sedimentological changes which would be expected at the higher palaeolatitudes where they would have been at that time (Torsvik et al., 1998). The Siberian data themselves define a smooth and gentle APW path during the Cambrian (Fig. 4c). Therefore there are no continents which show any convincing evidence for Cambrian TPW, and we therefore reject this proposition for that time period, as did Meert and Lieberman (2004), following global analysis of Cambrian palaeomagnetic data and trilobite faunas.

11. Ordovician

During the Ordovician, Siberia drifted over the Palaeoequator from S to N (Fig. 6). Its palaeolatitudinal drift rate was rather high, particularly at the end of the Ordovician: from the Caradoc until the present day Siberia has remained N of the equator. We present a map (Fig. 10) at about 470 Ma, at approximately the boundary between the Llanvirn and Darriwilian Stages. Many of the facies details on the craton are derived from Keller and Predtechensky (1968). In contrast to the preceding Late Cambrian (Fig. 9), there appears to have been a substantial land area over the Anabar Massif in the then SW of the terrane, but, nevertheless, a very large proportion of the craton was flooded, with warm shallow epeiric seas. Orogeny was active in the Altai–Sayan area throughout the whole Ordovician, in which many of the previous terrane units and island arcs were in the process of accretion to the main Siberian Craton area, and there were undoubted areas of high mountains over much of then N of the main terrane area along its active margin. The Mongol–Okhotsk Ocean still divided the enlarged Siberian Terrane from the various components of the Central Mongolian Terrane Assemblage, to the N of which there were active island arcs.

In the Early Ordovician in particular, Siberia is known for its endemic faunas; for example, the trilobite family Monorakidae is not only confined to Siberia but its relationships with the other families within the Order Phacopida are enigmatic: Fortey and Cocks (2003) reviewed some of the many terrane-diagnostic benthic faunas recorded from Siberia. Considering its palaeolatitude, the articulated brachiopods of the Siberian Ordovician, as described by Nikiforova and Andreeva (1961), Severgina (1984), and Yadrenkina in many papers (e.g. Yadrenkina, 1974, and in Kanygin et al., 1988), have a very low diversity, with only five cosmopolitan genera, *Apheoorthis*, *Archaeorthis*, *Finkelnbergia*, *Nanorthis* and *Tetralobula*, as well as the endemic *Eosyntrophopsis*, from the whole of the Tremadoc (successively the Mansi, Lopar and Nyaya Horizons). Of these, only *Finkelnbergia* and *Nanorthis* carry on up in

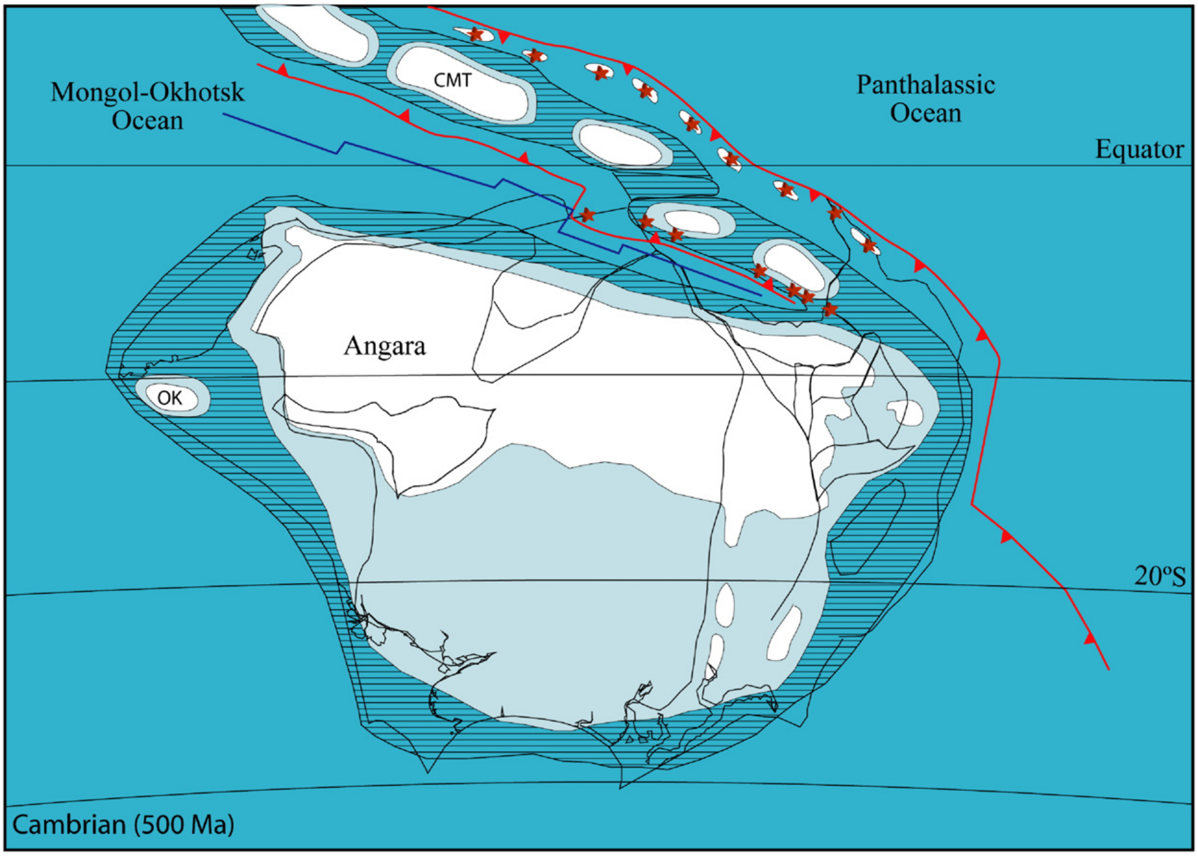


Fig. 9. Palaeogeographic map of the Siberian Terrane and its adjacent areas for the Late Cambrian, at about 500 Ma. Data in the Siberian Craton area are well-founded, but the reconstructions in the peri-Siberian area much less reliable, particularly in the Central Mongolia Terrane Assemblage area to the then N of the map. CMT, Central Mongolia Terrane Assemblage; OK, Okhotsk Massif. White, land; light blue, shallow shelf; horizontal shading, deep shelf; dark blue, ocean; red stars, volcanoes, red lines, subduction zones; blue lines, spreading ridges.

to the Arenig (Ugor and Kimai Horizons) to be joined there only by the cosmopolitan *Syntrophopsis* and also *Rhyselasma*, another endemic genus. Thus, far fewer benthic genera are present in Siberia than would be predicted from its tropical palaeolatitudes, which underlines its relative isolation from the other large contemporary terranes.

The Tremadoc and Arenig were clearly times of substantial tectonic activity on or near today's southern margin of Siberia. Sennikov (2003) has demonstrated a series of events which may or may not have been directly linked to each other along that margin of the craton, which was itself apparently passive at the time. The combined Salair–Kuznetsky Basin was deposited in a marginal sea, with maximum deposition rates near the Tremadoc–Arenig boundary, and that was followed in the Arenig by the transition from an active to a passive margin in that (today's southwestern) part of the Siberian Terrane (Sennikov, 2003). Collision between the Tuva–Mongolian Terrane and the West Sayan volcanic arc occurred in the Mid-Llanvirn, an event accompanied by the deposition of the substantial olistostromes of the Manchurek Formation in the area (Sennikov, 2003) and the intrusion of granites (Dobretsov et al., 2003). However, the unusual number of endemic trilobite and brachiopod genera present in the Ordovician and Early Silurian of the Tuva area, for example the brachiopods documented by Kulkov et al. (1985), must indicate either geographical or climatic differences between it and the surrounding areas. Further eastwards along the margin, it is uncertain whether or not the Patom and Barguzin areas still formed an independent terrane: there are few faunal data from them. The end-Cambrian to Early Ordovician events in the Mongol–Okhotsk area were probably independent of the events in the Altai–Sayan area.

In the following Darriwilian, the diversity on the craton (the Vikhorev, Mukta, Volgin and Kudri–Kiren Horizons), did increase from its Early Ordovician low, presumably reflecting both a decrease in Siberian terrane isolation but also the increase in genera seen in the global Ordovician brachiopod radiation (Harper et al., 2004). Thus, in the Volgin Horizon for example, there are 15 brachiopod genera recorded, of which only one, *Evenkina*, is endemic. In the Late Ordovician (the Caradoc age Chertov, Baksan and lower Dolbor Horizons), whose brachiopods were described by Rozman (1973) and Rozman et al. (1979) as well as by the other authors named above, there are slightly more varied brachiopod faunas, with the strophomenoid *Maakina* and the orthide *Evenkorthis* as the only endemics. However, the most common and dominant beds are full of abundant but low-diversity rhynchonelloid brachiopods (such as *Lepidocycloides*, *Evenkorhynchia* and *Rostricellula*) apparently indicating the preservation of only relatively shallower-water faunas over most of the Siberian craton. Not all of the latest Ordovician has been identified in Siberia; the upper part of the Dolbor and Nirundian Horizons are Pusgillian, and the Ketski and Burian Horizons and the faunas from the Korotkinskaya Formation of Taimyr described by Cocks and Modzalevskaya (1997) represent the Middle Ashgill Boda Event of global warming (Fortey and Cocks, 2005): however, rocks representing the latest two Ashgill stages, the Rawtheyan and Hirnantian, appear to be absent. Indeed, apart from Taimyr, the only outcrops of the Burian horizon are in the SW of the platform, in the Podkamennaya–Tunguska river area (Moskalenko, 1983). The huge carbonate platform of the Mid-Ashgill extended southwestwards into the Salair and Gorny Altai areas (the Orlov and Veber formations), with the development of many bioherms there (Sennikov, 2003). Whether the paraconformity between the latest Ordovician and the earliest Silurian was caused by the eustatic sea-level fall which accompanied the Hirnantian global glaciation event, or by one or more additional tectonic factors, is unknown. In any case, there seems to be no direct evidence in Siberia for the latest Ordovician Hirnantian glaciation event.

Interestingly, in the later Ordovician, the Caradoc, some of the shallower-water benthic trilobites, specifically *Prionocheilus*, *Neseuretinus*, *Vietnamia* and *Calymenia*, suggest that at least some faunal communication existed between Altai–Sayan and the peri-Gondwanan terranes such as South China (Fortey and Cocks, 2003); although from both the palaeomagnetic and most of the palaeontological data, it seems unlikely that the two areas were very close to each other.

Thus it is clear that the diversity of the benthic faunas was in general not as great as in the other major terranes round the world in the Ordovician: that must have been more likely due to the relative isolation of Siberia rather than to the differing palaeolatitudes of most of the terrane, which were not so high that low diversity faunas would be expected. However, as the Ordovician progressed, Siberia apparently became closer to Baltica and there was thus a steadily developing faunal interchange. Indeed, by latest Ordovician (Ashgill) times the elements of faunal similarity between the brachiopods of the Taimyr Peninsula of Siberia (Cocks and Modzalevskaya, 1997) and the Boda Limestone of Sweden in Baltica led to the false supposition that Taimyr may even have formed part of Baltica (Cocks and Fortey, 1998).

Zhan and Cocks (1998) analysed various Mid-Ashgill brachiopod faunas, with those described from Gorny Altai by Kulkov and Severgina (1989) and Taimyr by Cocks and Modzalevskaya (1997) from Siberia. They found only 19% similarity between the two, which were on opposite sides of the palaeocontinent: that is in contrast to a 30% similarity between Taimyr and South China, 29% between Gorny Altai and the Chu Ili Terrane, now within Kazakhstan but then independent, and 27% between Gorny Altai and the South China Terrane. Those figures all indicate a fair degree of separation and consequent endemism between the quoted areas, a result also supported by separate analyses of both trilobites and corals from the same localities. However, all those were more similar to each other than comparable age peri-Gondwanan marine shelly faunas from New South Wales, Australia, despite the fact that they were also living in tropical palaeolatitudes comparable to Siberia.

12. Silurian

We present a new map (Fig. 11) for the Upper Silurian, at about 420 Ma. As can be seen from Fig. 6b and by comparing the palaeolatitudes of Fig. 10 with those in Fig. 11, the northward movement of both Siberia and peri-Siberia continued apace during the whole of the Late Cambrian, Ordovician and Silurian, and the southern margin of the terrane (today's northern margin) became clear of the palaeoequator at some time close to the Ordovician–Silurian boundary at 443 Ma. The centre and SE of the craton again appears to be have been largely flooded by epeiric seas, but it seems probable that the continental land area was larger than earlier on in the Lower Palaeozoic (see below). For most of the Silurian onwards into the Late Palaeozoic, Siberia (including peri-Siberia) was the only large terrane to be situated entirely within the northern hemisphere, forming one of the margins of the immense Panthalassic Ocean.

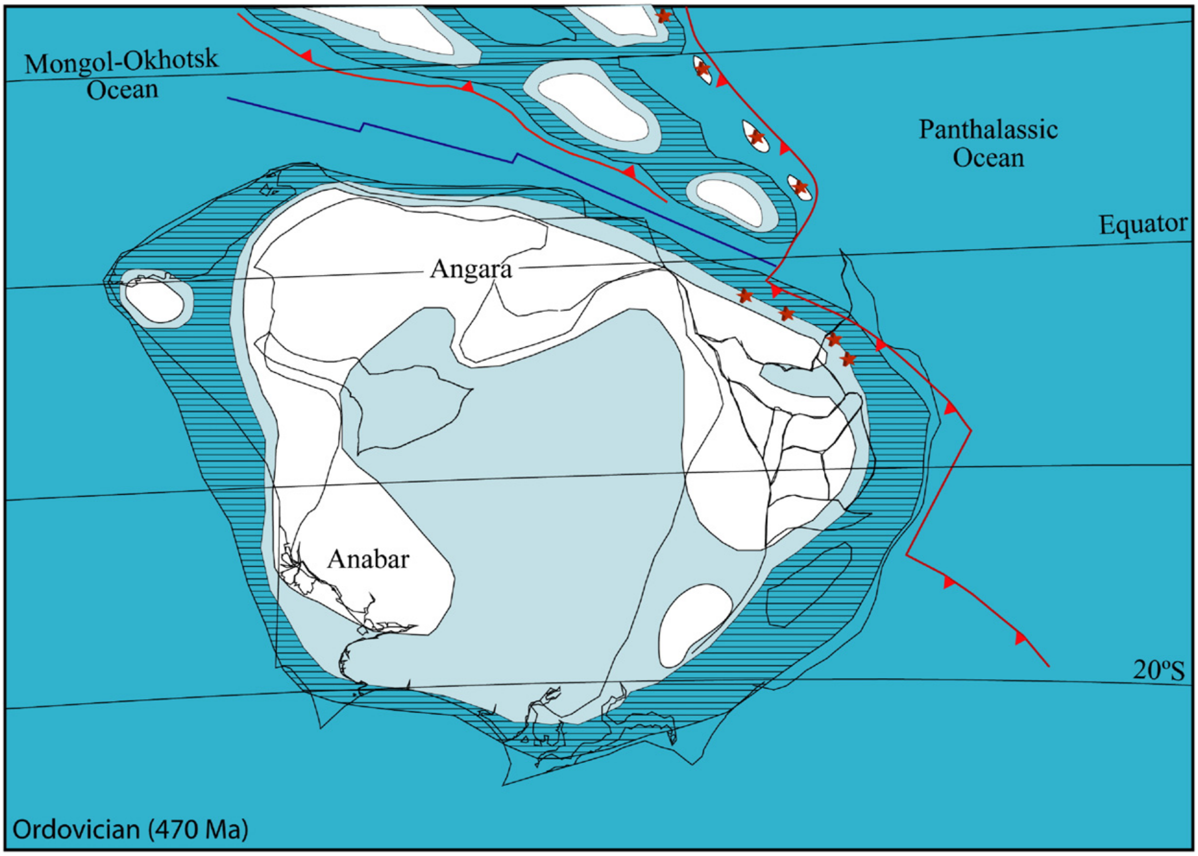


Fig. 10. Palaeogeographic map of the Siberian Terrane and adjacent area during the Middle Ordovician, at about 470 Ma. Siberia has moved northwards, so that it straddles the Equator, and much less of the craton was flooded than in Late Cambrian times. The reliability for the Central Mongolia Terrane Assemblage to the N of the map is still poor, and the area is depicted schematically. Symbols as in Fig. 9.

Tesakov et al. (2003) have noted how widespread red gypsiferous marls and gypsum beds are to be found over much of the terrane area in Silurian rocks, confirming the palaeomagnetic data indicating movement of the terrane into more temperate palaeolatitudes, and also reflecting the shift to more arid climates. For that reason Siberia (including peri-Siberia) is the only terrane on which has been found the distinctive *Tuvaella* fauna, a relatively low-diversity (and thereby by inference colder-water) shallow-water benthic fauna dominated by its eponymous brachiopod *Tuvaella*, but with other associated endemic brachiopods, such as *Tannuspirifer*. This was a particularly distinctive fauna, since for most of Silurian time the benthic shallower-water faunas in all the major terranes round the world were relatively cosmopolitan, and, apart from some relatively minor faunal variations elsewhere, only the *Tuvaella* fauna in the northern hemisphere and the *Clarkeia* fauna in the southern high palaeolatitudes stand out substantially from the rest (Cocks and Scotese, 1991; Rong et al., 1995). There are four species of *Tuvaella*, of which *T. gigantea* and *T. rackovskii* are the most abundant. Because Siberia was the only known entirely northern hemisphere terrane of substance at that time, the *Tuvaella* fauna is the only Silurian northern hemisphere higher-latitude fauna preserved today. The *Tuvaella* fauna occurs (Rong and Zhang, 1982; Rozman, 1986) in Russia (Altai–Sayan, Tuva, Amur, Nora River), many parts of northern and central (but not southernmost) Mongolia, and northwestern parts of China (Xinjiang, Heilongjiang and Inner Mongolia Provinces). The *Tuvaella* fauna, with some minor variation, lasted for a considerable period, from the Mid-Llandovery until the Mid-Ludlow (Rozman, 1986).

It is noticeable that the distribution of the *Tuvaella* fauna within peri-Siberia (Fig. 7) shows it to have been confined to today's southern parts of the terrane collage, which were of course its highest-latitude parts in the

Silurian (Fig. 11), thus providing independent faunal confirmation of the subsequent large rotation of the terrane since Silurian times shown by the palaeomagnetic results (Torsvik et al., 1995; Smethurst et al., 1998) and our new APW path (Figs. 3–6). It is also very noticeable that the *Tuvaella* fauna occurs today (we have plotted our data points on Fig. 7 from Rong and Zhang, 1982; Rozman, 1986; Rong et al., 1995) both in areas of the terrane which had previously accreted to the Siberian Craton in pre-Silurian times, such as Western Altai, and also in many areas which were not part of the core Siberian Craton in the Silurian. It can therefore be deduced that all of the Altai–Sayan area, the Mongolian Terrane collage, the Ertix Terrane, the Mandalovoo Terrane and the Tuva–Mongol Fold Belt were part of the peri-Siberian terrane collage which lay to the then N of core Siberia, and that those regions must therefore have been an integral part of the collage before the Silurian. This is all despite the fact that there was the substantial Mongol–Okhotsk Ocean dividing the Siberian Terrane from the Central Mongolian Terrane Assemblage. The then northerly margins of both the Siberian Terrane and the Central Mongolian Terrane Assemblage were both very active, and it is reasonable to postulate relatively high and mountainous lands within the Angara area of the craton. There is also clear evidence of land to the then W and S of the main craton area in the Anabar Massif area. Our reconstruction (Fig. 11), following Keller and Predtechensky (1968) and Tesakov et al. (2003) for the facies on the craton, shows continuous continental land area between the Anabar and Angara Massif areas, and this seems the most likely, although the large inland shelf sea might have transgressed and extended further westwards at some times during the Silurian.

In contrast to the presence of the *Tuvaella* fauna in today's southern Siberia, in the then more southerly part of the terrane (today's N) the Silurian rocks have yielded numerous and diverse brachiopods and other benthic fauna, a large proportion of which were cosmopolitan; for example, those described by Kulkov and Dubatolov (1990) from the SE part of the Siberian Craton, and others by Lopushinskaya (1976; and revised lists by her in Yolkin et al., 2003) from northern Siberia. In contrast to the underlying Ordovician, the Silurian faunas include those representing mid to deeper-shelf communities as well as shallower-water ones, indicating that the seas covering much of the craton were of fair depth in many places. Some authors have claimed that the *Tuvaella* fauna was geographically quite separate from the more cosmopolitan Silurian faunas occurring in much of Siberia, but Rozman (1986) has described some Mongolian localities in which *Tuvaella* assemblages are interbedded with more cosmopolitan brachiopod faunas. In addition, Rozman and Rong (1993) have described some middle Llandovery brachiopod faunas from the peri-Siberian part of southern Mongolia which include the endemic genera *Templeella* and *Mongolostrophia* from deeper-water (Benthic Assemblages 4 and 5). Such endemics are unusual for the Silurian and reinforce the conclusion that the Siberian Terrane as relatively isolated. In an analysis of Lower Silurian fish faunas, Žigaitė and Blieck (2006) demonstrated that there were two separate biogeographical provinces in the Early and Middle Llandovery, termed "Tuva" (corresponding to the *Tuvaella* Brachiopod fauna outcrop in Fig. 7) and "Siberia" (in today's northern part of the Siberian Terrane). However, by Late Llandovery and Wenlock times, these provincial distinctions had disappeared.

Johnson et al. (1997) documented some of the shallower-water sedimentary facies and biofacies for the Lower Silurian of Siberia, and the transgressions and regressions, and correlated local highstands with contemporary eustatic events in Laurentia, Baltica and Avalonia, reinforcing the relative paucity of tectonic events within the Siberian Terrane at that time. We have largely followed the palaeogeography shown by Nikiforova and Obut (1965), Rozman (1986) and Tesakov et al. (2003), which cover the Silurian deposits of the whole of the former Siberian Craton, and Yolkin et al. (2003) for the SW of the Siberian Craton and the adjacent Altai–Sayan folded area. The Altai–Sayan region was then part of the Siberian passive margin, with large-scale carbonate buildups forming barrier reefs on the outer shelf, which included a 600 km long, 10–50 km wide reef belt of Late Llandovery to Late Wenlock age in the Salair and Western Altai regions (Fig. 7). These reefs lie above Early Llandovery graptolitic shales reflecting both cooler global temperatures and higher sea levels. There were extensive shallow-water siliciclastics deposited in the Tuva–Mongol area (Yolkin et al., 2003), presumably also at least partly reflecting the lower average temperatures in that then most northerly part of the Siberian Terrane collage.

13. Devonian

During the Devonian, Siberia remained entirely to the N of the Palaeoequator, straddling the 30°N palaeolatitude (Torsvik and Cocks, 2004; Fig. 6 here), and its palaeolatitudinal position did not change much between the end of the Silurian and the Early Carboniferous.

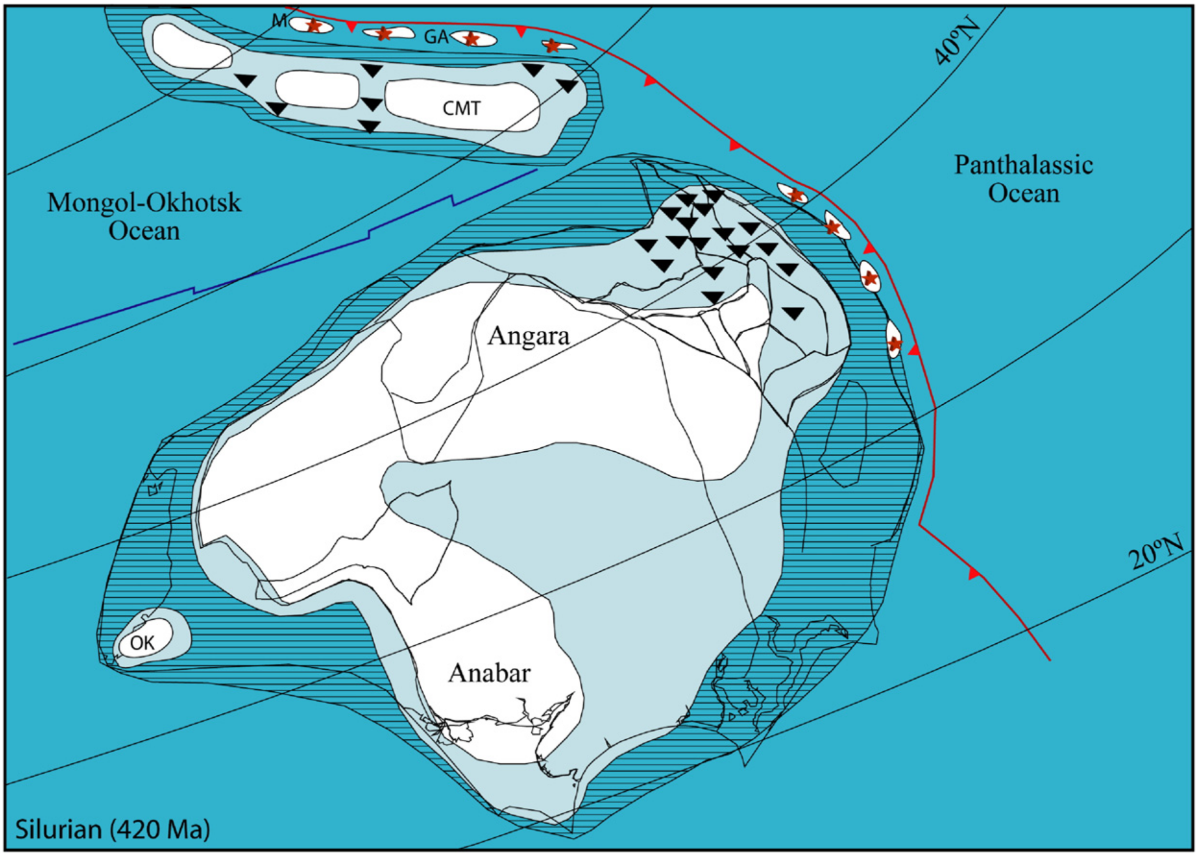


Fig. 11. Palaeogeographic map of the Siberian Terrane and adjacent area during the Upper Silurian (Ludlow), at about 420 Ma. Inverted triangles show the distribution of the *Tuvaella* fauna, with individual localities transferred from Fig. 7, and demonstrate that it was established both round the margins of the central craton and also in the Central Mongolian Terrane Assemblage (CMT) area to the then N of the main Siberian Terrane. GA, Gobi–Altai; M, Mandalovoo Terrane; OK, Okhotsk Massif. Other symbols as in Fig. 9.

In the Late Silurian and Early Devonian, there was maximum marine regression on the craton; however, there was a major transgression eastwards in the Altai–Sayan region during Lower Devonian times (Yolkin et al., 2003). Nevertheless, most of the terrane seems to have continued relatively tectonically quietly on from the Silurian during that earlier part of the Devonian. There were also tectonically quieter areas at times in the western part of the Altai–Sayan area, allowing, for example, substantial reefs to develop, including the massive accumulation of the thick-shelled strophomenoid brachiopod *Megastrophia uralensis* which aggregated in the Emsian of Salair (Gratsianova et al., 1993). We present a new palaeogeographical map (Fig. 12) for the Middle Devonian, at about 380 Ma, at around Eifelian–Givetian boundary time, many of whose facies boundaries on the main Siberian Craton have been derived from Nalivkin and Posner (1969). The accretion of the various Altai–Sayan and Tuva–Mongol terranes and island arcs to the main craton was complete by that time, and the Central Mongolian Terrane Assemblage was continuing its accretionary process to the main Siberian Terrane as the eastern arm of the Mongol–Okhotsk Ocean closed. However, the margin was still very active along the NE part of the terrane (the Altai–Sayan area), and, in addition to that, the northern margins of the Central Mongolian Terrane Assemblage were also very active, including the Mandalovoo Island Arc.

However, from the Middle Devonian onwards there was significant rifting and magmatism, particularly in today's E of the Craton area, the main rift system being in the Viljuy Basin (Fig. 2). The rifting started with flood basalt magmatism and basalt igneous dyke swarms. The second and largest phase of tectonic activity ran from the Late Devonian and continued on into the Lower Carboniferous (Tournaisian), but had ceased before the Visean (see Section 14). Numerous diamondiferous

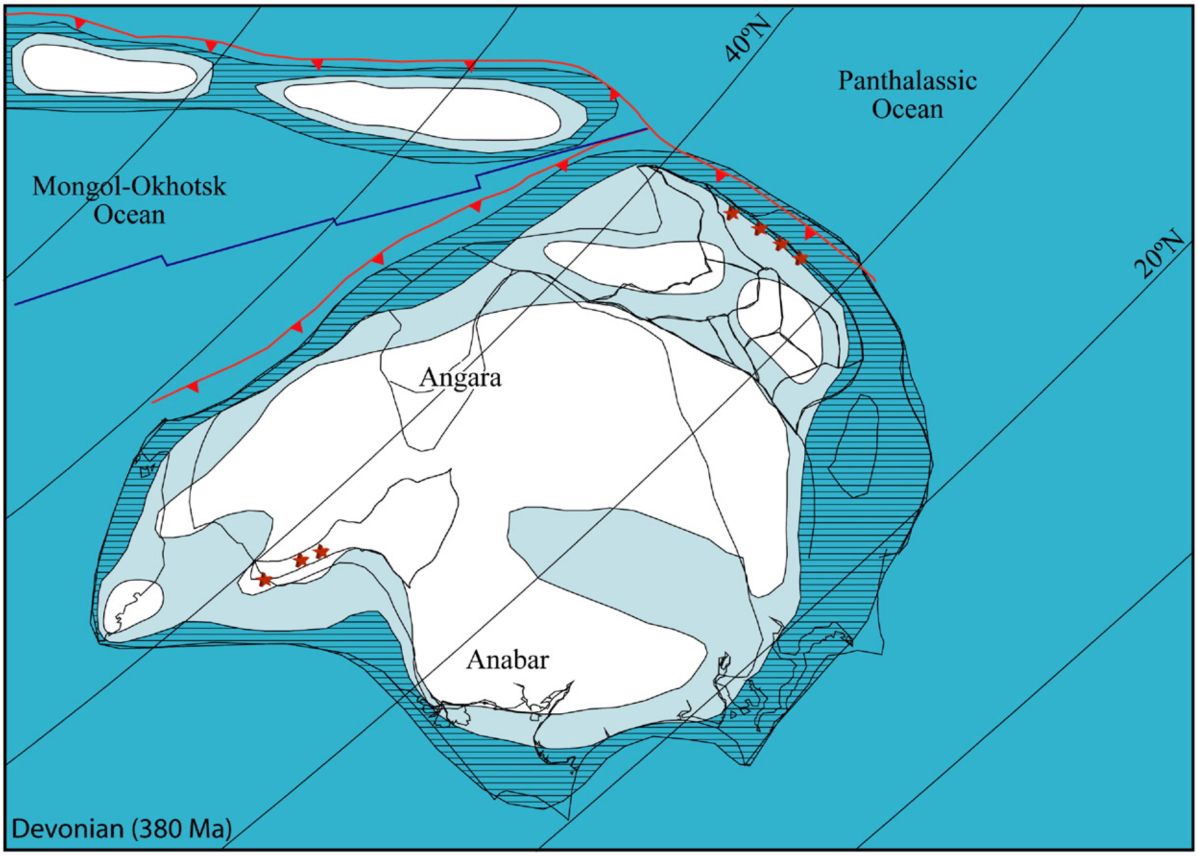


Fig. 12. Palaeogeographic map of the Siberian Terrane and adjacent areas during the Middle Devonian, at about 380 Ma (Eifelian–Givetian boundary time). All of the Altai–Sayan terranes and island arcs had completed their accretion to the main Siberian Craton by this time, and the Central Mongolian Terranes were in the process of accretion. There was significant volcanism over large areas. Symbols as in Fig. 9.

kimberlites were emplaced into Archaean nuclei within the craton, reflecting the impact of Middle to Late Devonian plume events (Yakubchuk et al., 2001). In addition, Middle to Late Devonian rifts also formed in the Tunguska Basin, and also along today's northern margin of the craton and Buslov et al. (2004) have documented very substantial strike-slip faulting in the Altai–Sayan area, which was at its maximum in Late Devonian times.

Zonenshain et al. (1990, p. 25) suggested that the cause of the exceptional tectonism was the passage by Siberia over a hot spot, which must have been of great magnitude to so much affect a terrane of Siberia's size; and either that conclusion, or perhaps the passage of Siberia over an oceanic triple junction, seems the most likely. It is certain that, apart from the accretion of the largest parts of the Central Mongolian Terrane Assemblage during the Devonian, there were no major continent–continent collisions which could explain the extensive magmatism present over so many parts of Siberia.

Zonenshain et al. (1990, p. 217) also emphasized that intraplate magmatism was widespread in the Early to Middle Devonian in southern Siberia, where large basaltic and alkaline volcanic fields formed in the Minusinsk, Tuva, Rybinsk and other depressions of the Altai–Sayan region (Zonenshain et al., 1990, Fig. 60). Yolkin et al. (2003, and references therein) illustrated how, in the western Altai–Sayan area, the volcanic activity started in the Early Devonian (Emsian), peaked in the Middle Devonian (Early Givetian) and carried on into the Late Givetian in the SW part of the area. Subaerial volcanics were also extensive in the Altai–Sayan region in the Late Devonian (Zonenshain et al., 1990, Fig. 62). There was also considerable Devonian igneous activity in the Okhotsk Massif, much of Mongolia, and elsewhere in peri-Siberia: that in the Mandalovoo Terrane, Mongolia, at today's southern margin of peri-Siberia, including Late Devonian pillow basalts and andesites. In the Tuva–Mongol and Central Mongolia Terrane assemblages,

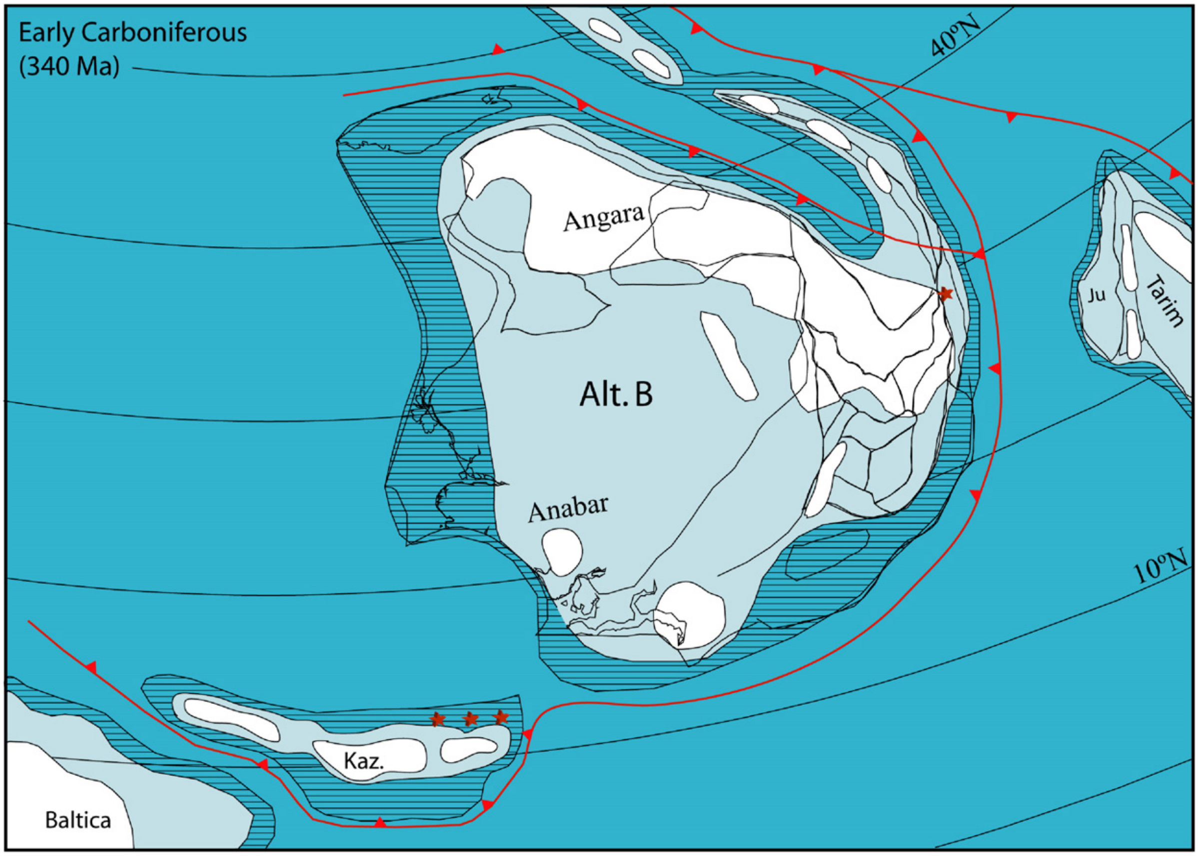


Fig. 13. Palaeogeographic map of the Siberian Terrane and adjacent areas in the Lower Carboniferous (Early Visean), at about 340 Ma. Baltica positioned according to a 340 Ma mean pole of 19.1°S, 335.2°E (A95 = 11.4°, *N* = 5 poles; from Torsvik and Cocks, 2005, Table 1a,b). Siberia according to 340 Ma pole in Table 1b (Alternative B), and Tarim according to an interpolated 340 Ma south pole of 19.8°S and 341.5°E (based on Torsvik and Cocks, 2004). Ju, Junggar; Kaz, Kazakh Terrane Assemblage. Symbols as in Fig. 9.

a high proportion of the contained terranes have Devonian volcanics, in contrast to those Mongolian terranes to today's S of peri-Siberia, in which the volcanic activity is of a much wider variety of geological ages. Many granitoid batholiths were also intruded, the most spectacular of which is the immense Barzugin granodiorite–tonalite, which today occupies a high proportion of the space of the Barzugin Terrane.

Alekseeva et al. (2001) have revised the Lower and Middle Devonian brachiopods from central Mongolia, and further documented some of the results of Hou and Boucot (1990) and Boucot and Blodgett (2001), who distinguished and defined the "Balkhash–Mongolia–Okhotsk" as a distinct assemblage within their Old World Realm. The distinctive endemic brachiopods from that region included *Khangaestrophia*, *Xingjianospirifer* and what has been termed "*Paraspirifer*" by Hou and Boucot (but which differs from that European genus).

14. Carboniferous

During the Carboniferous, Siberia still remained as a discrete major entity in temperate to intermediate northern palaeolatitudes, but it must be emphasised that the period has no direct palaeomagnetic control. Much of the Carboniferous stratigraphy of the area was summarised by Wagner et al. (1996). In the Lower Carboniferous the Verkoyansk branch of the Devonian rift system was transformed into the passive margin of the oceanic basin in today's E of the terrane. The Mongol–Okhotsk Ocean was progressively closing from W to E along the Mongol–Okhotsk suture (Badarch et al., 2002), and the substantial Adaatsag Ophiolite (in Russia near the Mongolia–China border) was intruded within the suture zone in the earliest Carboniferous (Tomurtogoo et al., 2005).

We present two maps, the first (Fig. 13) for the Lower Carboniferous (the Early Visean) at about 340 Ma, and

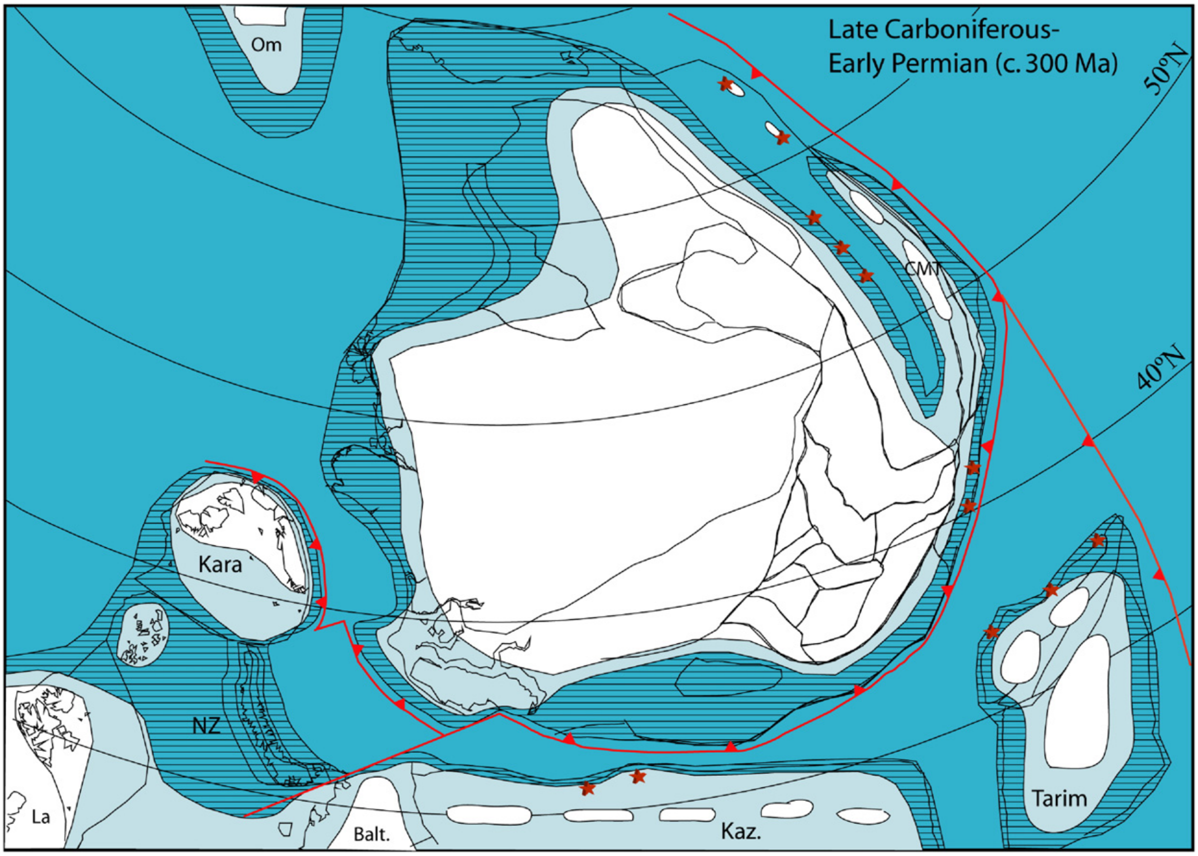


Fig. 14. Palaeogeographic map of the Siberian and adjacent terranes at Carboniferous–Permian boundary time, at about 300 Ma. Baltica is positioned according to a 300 Ma mean southpole of 40.3°S, 347.3°E (A95 = 2.5°; N = 21 poles; raw poles listed in Torsvik et al., in press). Kazakhstan Terranes are sutured to Baltica along the Urals; Svalbard is connected to Baltica and the postion of the Kara Terrane and Novaya Zemlya is explained in Fig. 15 caption. Tarim is positioned according to a mean south pole of 49.4°S, 354.6°E (A95 = 18.2°, N = 2 poles; see Torsvik and Cocks, 2004 for data compilation). Siberia's position is not located according to the 300 Ma pole in Table 1b (see also Fig. 6), since this pole would put Siberia in too low latitudes and partly on top of Kazakhstan. We opted to use the 280 Ma pole in Table 1b (Alternative B), since the Carboniferous section is entirely interpolated and the definition of the path is probably better than the actual timing along the path. Balt., Baltica; CMT, Central Mongolia Terrane Assemblage; Kaz, Kazakh Terrane Assemblage; La, Laurentia; NZ, Novaya Zemlya, Om, Omolon Terrane. Symbols as in Fig. 9.

the second (Fig. 14) at about 300 Ma, the very latest Carboniferous (the Carboniferous–Permian boundary is dated at 299 Ma). Our reconstructions for Siberia follow the Alternative B APW path shown in Fig. 5 (Table 1b). The Alternative A path (which includes the new 275 Ma pole) would position Siberia at about 700 km more to the N (see also Fig. 6b). We cannot finally discriminate between the two alternatives at 340 Ma, but at 300 Ma the difference in latitude would be about 2200 km and demands a huge ocean between Siberia and the combined Baltica/Kazakh terranes; we find this somewhat unlikely and therefore opt for Alternative B. Note however, that both alternatives are based on linear interpolation, thus allowing a vast degree of freedom in the palaeomagnetic positioning of Siberia during the Carboniferous.

Many of the facies details are taken from Nalivkin and Posner (1969) as well as from Meyen et al. and Durante et al. (both in Wagner et al., 1996). In the Altai–Sayan area there are only non-marine deposits from the Middle Carboniferous onwards (Yolkin et al., 2003). The major part of the Siberian Craton was still flooded for most of the period. However, there was one large continental land area in the then N of the terrane, as well as a variety of smaller, but still sizeable, islands elsewhere on the craton. The Yenesei Fault (Fig. 2) marks the eastern limit of Late Palaeozoic deformation (Yakubchuk and Nikishin, 2005), although basalt continued to be extruded in that area until Early Triassic times.

On the SW part of the Siberian Platform, the Upper Carboniferous Listvyazhninskaya Formation consists of

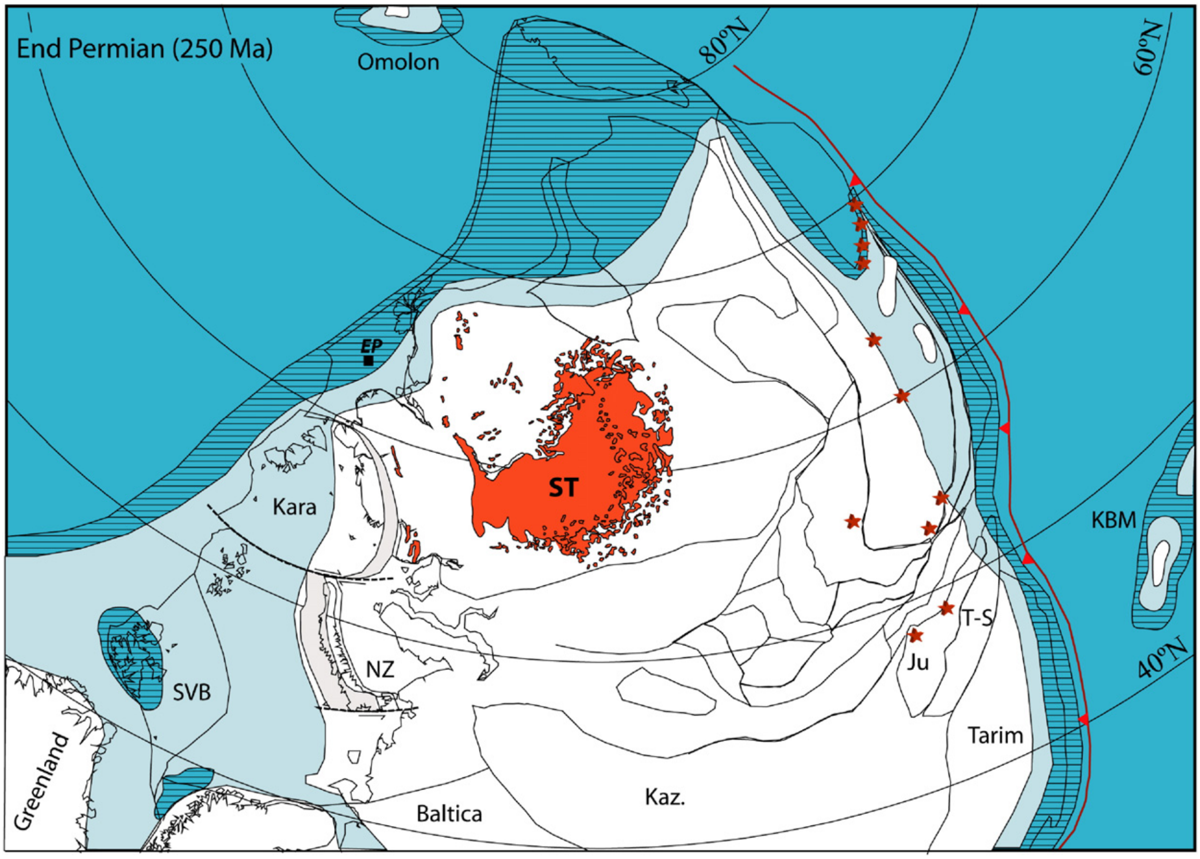


Fig. 15. Palaeogeographic map of the Siberian part of the Pangea Superterrane at the very end of the Permian, at about 250 Ma, also showing the distribution of the Siberian Traps. This reconstruction is based on an average of European and Siberian palaeomagnetic poles (250±10 Ma; mean south pole: 52.4°S, 333.8°E, A95=3.5°, N=17 poles; Torsvik et al., in press, and this paper) on the assumption that Siberia, within palaeomagnetic resolution, was sutured to Europe at this time, and therefore differs from that of Torsvik and Andersen (2002). However, in order to explain the Early Mesozoic Taymyr foldbelt and westerly thrusting of Novaya Zemlya into the Eastern Barents Sea (shown as shaded areas) younger movements are required between Baltica and Siberia, probably in the order of 100–200 km (Buiter and Torsvik, 2007). Ju, Junggar; KBM, Kingan–Bureya Massif; NZ, Novaya Zemlya; ST, Siberian Traps; SVB, Svalbard; T-S, Tien Shan. Symbols as in Fig. 9.

350 m of mainly terrestrial siliciclastics with plant remains as well as fresh-and brackish-water invertebrates. The plants include *Koretrophyllites*, *Paracalamites*, *Angaropteridium* and *Angaridium* (Rotai, 1975), which are largely endemic to the region and typical of the Angaran Province, whose plants are summarised and compared with other contemporary floral provinces by Meyen (1987). There are no plant species at all in common between the Angaran and Equatorial floras, and that endemism was well established by as early as Tournaisian times: the floral biozones in Siberia cannot yet be correlated accurately with the marine ammonoid zones used in the rest of Russia (Meyen et al. in Wagner et al., 1996). The boundary between the Angaran and Cathaysian floras within Mongolia and China in the Upper Carboniferous (Yue et al., 2001) is clearly marked by the Hongshishan Suture to the W (from 95° to 105°E) and the Hengenshan Suture to the E (from 105° to 130°E): there is no doubt that the two areas and the floral realms were widely separated from each other at those times, and both the North China and South China terranes were well distant from Siberia (Torsvik and Cocks, 2004, Figs. 7–9).

Also shown within the area of Figs. 13 and 14, apart from Siberia, are the Baltica, Kazakhstan and Tarim terranes. Baltica in fact formed the then northern sector of the supercontinent of Laurussia (Torsvik and Cocks, 2004), and only a small part of it is seen in our figures: the palaeogeography is taken from Nikishin et al. (1996) and Stemmerik and Worsley (2005). During the Carboniferous many of the terranes which were constituent parts of the adjacent Kazakhstania accreted to substantially enlarge its size, and that combined collage became progressively closer to Siberia, but because of the very variable published views on its accretion, and even indeed its identity, it is only shown schematically on our figures. The Tarim Terrane was also near Siberia, and a substantial amount of data on that terrane may be found in the review edited by Zhou and Chen (1992): the deposition of marine carbonates persisted along the NW margin of Tarim until the latest Carboniferous or Early Permian (Zhou et al., 2001). Ocean floor between the Junggar and Tarim terranes had progressively subducted under Junggar (including Central and North Tien Shan), mostly during Moscovian time, and the two were united by the latest Carboniferous. Dumitru and Hendrix (2001) asserted that those combined Junggar and Tarim terranes were also united to Qaidam–Qilian and Ala Shan, but other published opinions differ, and thus detailed discussion of those areas is outside the scope of this paper.

15. Permian

At around 250 Ma there are many high-quality palaeomagnetic data (e.g. from the latest Permian 251 Ma Siberian Traps shown on Fig. 15). We present two maps, one (Fig. 14) for 300 Ma, at about Carboniferous–Permian boundary time (which is also discussed in Section 14 above), and the second (Fig. 15) for the end Permian at about 250 Ma, by which latter time the former Siberian Terrane had become an integral part of Pangea. Torsvik and Cocks (2004) have reviewed the competing geometries through which Pangea assembled, and concluded that the so-called Pangea A configuration is the only one which can reconcile the conflicting geological and palaeomagnetic evidence available, and that is the reconstruction forming the basis for Fig. 15 here. Much of the rest of Pangea had already assembled before the end of the Carboniferous, in particular the Kazakhstania Terrane had joined Laurussia in the Uralian Orogeny between 315 and 290 Ma (Mid Carboniferous to earliest Permian). However, Siberia may not have become an integral part of Pangea until the Mid-Permian (see next section), after which the continental area stretching from Siberia to eastern Europe is often termed Angaraland (e.g. Mayen in Wagner et al., 1996). A.M. Ziegler and his colleagues, for example Ziegler et al. (1997, 1998), have published a detailed series of Permian facies and biofacies maps from which we have drawn heavily to construct Figs. 14 and 15. The two periods which they plot in most detail are the Lower Permian Sakmarian (about 290 Ma) and the Middle Permian Wordian (268–266 Ma), and they have identified Siberia as the chief constituent of the North Temperate climatic zone, in which substantial coals were deposited, particularly in the Tunguska and Kuznetsk basins. In particular, Rees et al. (2002) showed that in the Sakmarian the Angara Floral Province (which was chiefly situated in Siberia) was not so well developed as it was in the Wordian, when the Angaran flora, dominated by Cordaite and Sphenophyte genera, not only had the highest number of plant genera on the planet but was also clearly differentiated in composition from the Cathaysian, Gondwanan and other floras. Shi (2006) identified a single Middle Permian "Verkolyma Province", based on brachiopods, which included the todays's American Plate areas of Kolyma and Omolon as well as parts of eastern peri-Siberia, in contrast to a "Panthalassic Province" in far eastern Siberia (Sikote–Alin Fold Belt and Ekonay Terrane) and parts of Japan and NE China, and also to a transitional "Sino–Mongolian–Japanese Province" occupying most of the Manchurides area and the North China Terrane. He documented that the Sino–Mongolian–Japanese Province displayed intermediate faunas between the Verkolyma Province of Siberia and the more traditional concept of the Cathaysian Province in and near the South China Terrane area. Manankov et al. (2006) also confirmed that the Manchurides supported a different palaeobiogeographical marine province from peri-Siberia at that time.

The Tunguska Basin, which covers a large part of the W of the Siberian Craton, developed during the period, and it was there that the enormous flood basalts of the Siberian Traps were erupted at the very end of the Permian at 251 Ma (Bowring et al., 1998), no doubt caused by the sudden upward movement of a plume from the deep mantle.

Terranes also shown on Figs. 14 and 15 which were separate from Siberia include Baltica, Laurentia, Kara, Tarim, Kazakhstan, and what is labelled on Fig. 15 as the Khingan–Bureya Massif. Li (2006) presented Early and Late Permian reconstructions of the area as it developed, and which show the various blocks between peri-Siberia and North China as far less integrated within the Pangea Superterrane than in our reconstructions. However, the key constraining factors to definitive palaeogeographical maps, such as good palaeomagnetic and faunal data, are not sufficient to provide a definitive palaeogeography.

Baltica and Laurentia (of which only Greenland appears on Fig. 15) were in fact parts of Laurussia prior to its amalgamation within Pangea, and include Franz Josef Land, today in the Barents Sea, whose geology is described by Dibner (1998), as well as the mainland parts of Baltica, whose Carboniferous and Permian palaeogeography we have taken from Nikishin et al. (1996). Kara, now in political Siberia (Fig. 2), was an independent terrane not far from Baltica during much of the Lower Palaeozoic and Devonian (Cocks and Torsvik, 2005) and both terranes approached Siberia progressively during the Carboniferous. Tarim, discussed above under the Carboniferous, became welded to Siberia during the Mid Permian. Kazakhstan is only shown schematically in both Figs. 13 and 14. It was originally composed of many terranes, and its detailed terrane accretion and progressive palaeogeographies during the Palaeozoic are extremely contentious and outside the scope of this paper. Siberia appears to have started to collide with the Kazakhstania Terrane Assemblage during the Early Permian. There was cessation of marine sedimentation and andesite volcanism at that time, as well as the initiation of the Permian Zaisan Mountains to the W of the Siberian Craton according to Ziegler et al. (1997). The Khingan–Bureya Massif, whose modern locality is shown on Fig. 2, is part of the complex Manchurides Terrane Collage, whose geology and history were discussed by Sengor and Natalin (1996), and part of it is also shown schematically on Fig. 15. Shi (2006, Fig. 5) has yet another reconstruction for the Middle Permian, in which Siberia is attached to Kazakhstania and stretching beyond the latter there is a long string of many terranes, including Tarim, most of the Manchurides, and North China.

16. Mesozoic to recent postscript

A comparison of palaeomagnetic data from Baltica and the Siberian Traps, coupled with structural information from the Taimyr Peninsula, led Torsvik and Andersen (2002) to suggest that there were adjustments in the Siberia–Kazakhstan–Baltica configuration during the Late Triassic (see also Otto and Bailey, 1995; Inger et al., 1999). Combined with the observation that the Siberian APW path of Smethurst et al. (1998) showed no similarities with that of Baltica (Fig. 5) during the Permo-Carboniferous, Torsvik and Andersen (2002) and Torsvik (2003) were impelled to argue that Siberia only joined Pangea in the Early Mesozoic, and therefore after Siberian Trap magmatism at 251 Ma. The revised (but heavily interpolated) Alternative A path for Siberia (based on a new 275 Ma pole; Tables 1a and 1b) shows that Siberia would have had a totally different drift history from Baltica during the Permian and would have been positioned more than 2000 km N of Baltica in Mid-Permian times. However, the consequent necessity for a large Permian ocean between Siberia and the Baltica/Kazakh terranes conflicts with most recent palaeogeographical reconstructions (e.g. by Van der Voo et al., 2006), in which Siberia is placed adjacent to Baltica and in which Late Palaeozoic–Early Mesozoic transpressional convergence with Baltica led to considerable rotations within the intervening Kazakh terranes. Our Alternative B APW path implies closer proximity with Baltica during Permian times (Fig. 5) and agrees with the palaeogeographical reconstructions: thus we consider it the most likely.

Strictly interpreted, the ca. 250 Ma mean poles from Siberia and Baltica (Europe) show that Siberia was located a few hundred kms N of Baltica, but they are not statistically different at the 95% confidence level (Fig. 5 inset), and the younger Triassic APW segment (although with slightly different timing but only one available Siberia pole) shows gross similarities. We therefore consider that Siberia (within palaeomagnetic resolution power) was essentially sutured to Kazakhstan–Baltica by the Mid-Triassic, although substantial adjustments (100–200 km) are needed to explain the Late Triassic Taimyr fold and thrust belt and the contemporaneous shortening and westward thrusting of Novaya Zemlya (Buiter and Torsvik, 2007).

Once Pangea had assembled to incorporate Siberia in the latest Palaeozoic, the latter can no longer be considered as a separate terrane, and it has remained fused with Baltica to its W, the complex Kazakh Terranes area to its W and SW, and Baltica, Timan and Kara to its N and NW until the present day. The simplest terminology to use for the combined continent is Pangea, with Laurussia (North America and northern European) and most of Asia (including Siberia) as parts of Pangea. As can be seen from Fig. 6, Siberia rotated counterclockwise in the Triassic, presumably in the process of tectonic adjustment to the rest of Pangea. Both Siberia and Baltica (northern Europe) rotated relative to Laurentia during the Triassic; this strong counterclockwise rotation persisted until the Late Triassic–Early Jurassic, when the bulk of tectonic deformation had finished in the Arctic regions (including Taimyr).

It was not until the very end of the Jurassic that the Siberian part of Laurussia collided with the North China–South China–Annamia (Indochina) continent which had itself amalgamated in stages in the Late Palaeozoic and earlier Mesozoic, and which until then had not formed part of Pangea (Metcalfe, 2002, and references therein). From the time of the opening of the North Atlantic in the Early Tertiary, the continent (including Siberia) is termed Eurasia. The Siberian Craton part of Eurasia seems to be the most southerly part of central Asia to have been left relatively untectonised by the Himalayan Orogeny, although the latter was probably the cause of the 1.5 km uplift present over much of the political Siberia today. Thus today the old Siberian Terrane part of Eurasia has a modern continent–ocean boundary only to its N, where it is contiguous with the Arctic Ocean, although its margin to the E of the Verkoyansk–Kolymian Fold Belt marks the junction of the Eurasian and North American plates (Fig. 2). However, the former Siberian Terrane is still a very significant part of the total land area of Eurasia.

17. Discussion and conclusions

Siberia was a substantial and independent terrane collage from the Neoproterozoic at about 800 Ma until close to Permian–Triassic boundary time at 250 Ma. During that time the Siberian Craton remained part of a single terrane, despite the probable presence in the Devonian of Red Sea type rifting in the Viljuy Basin. Much of the old terrane area is now masked by substantial Mesozoic and Cenozoic sediments, as well as by the very extensive Siberian Traps, a massive volcanic outpouring which occurred, presumably because of Siberia's passage over a plume, at the very end of the Permian. We have reviewed Siberia's successive global positions during this nearly five hundred million year period, and conclude that it was an exceptionally interesting and significant terrane in many ways, not least because it was the only large terrane in the northern hemisphere for much of the long time since the Ordovician. Because so many authors have used the term "Paleo-Asian Ocean" for so many different oceanic concepts surrounding Siberia and peri-Siberia for such a variety of geological times, we reject the term.

The comparative isolation and relatively higher latitudes of Siberia also meant that the area was colonised throughout the Palaeozoic by marine benthic faunas and in the later Palaeozoic by both marine and land floras and faunas which are not found elsewhere on Earth, and these biota were often sufficiently distinctive to form the basis of faunal provinces at various times. Particularly striking amongst these are the Siberian trilobite Province in the Cambrian, and a comparable one (with the Siberian-restricted trilobite family Monorakidae and other features) in the Ordovician, the *Tuvaella* brachiopod fauna in the Silurian, and the Angaran floral Province in the Carboniferous and Permian.

We have constructed a revised palaeomagnetic APW path based on data published since the landmark paper by Smethurst et al. (1998). We have also constructed a series of new palaeogeographical maps (Figs. 9–15) from the Late Cambrian (500 Ma) to the latest Permian (250 Ma) showing the distributions of land, shallow shelves, deep shelves and oceans, as well as the positions of volcanoes, in Siberia and the terranes near it at the different times. We also show some postulated oceanic subduction zones and spreading ridges, although we are fully aware that their realities have very variable degrees of confidence. In particular, the Cambrian and Ordovician reconstructions (Figs. 9 and 10), although reliable for the facies distributions shown on the Siberian Craton and other features, are much more speculative than the later ones in their depictions of the tectonic arrangements of the various peri-Siberian areas as they progressively accreted to the main terrane.

From the intrusion of diamondiferous kimberlites in the Altai–Sayan area, it can also be postulated that Siberia's passage over a hot spot occurred in the Late Devonian, and we suspect that the very extensive Upper Devonian igneous activity which can be seen in many parts of both the Siberian Craton and also peri-Siberia, which includes much volcanism and the intrusion of the immense Barguzin Batholith, as well as many other igneous intrusions, may in all probability have also formed parts of the same event. To what extent these events were directly linked to the Viljuy Basin Red Sea type rifting, which also occurred in the Devonian, is not proved: although there was substantial magmatic activity in the Viljuy area, there was far more in other parts of the terrane (see Section 13 above), much of which had already commenced by Middle Devonian time. Through revised palaeomagnetic APW analysis, we have a period of substantial rotation in the Early Triassic, after the end of our period for detailed consideration, when Siberia had become a part of Pangea but before the tectonic complications of that union had become fully resolved.

Some authors, for example, McKerrow et al. (1991) and Torsvik et al. (1996) have postulated that Siberia lay adjacent to Baltica and Laurentia for much of the Lower Palaeozoic: this was partly because the large sedimentary sequence in the Southern Uplands of Scotland (part of Laurentia) was deduced to have been derived from Siberia during the Late Ordovician and Early Silurian. However, that scenario now seems unlikely, and it seems more probable that those Southern Uplands sediments were derived from further alongshore, or immediately offshore, of some other part of Laurentia, and that Siberia was some way away from Laurentia at that time (Figs. 10 and 11).

A primary question that we have attempted to answer is, presuming that the palaeomagnetic data indicating that Siberia was inverted in relation to its present-day orientation for most of the Palaeozoic is correct, which of the smaller tectonic units surrounding Siberia today were or were not part of the Siberian Terrane in the Lower and Middle Palaeozoic, and thus must have rotated with it? Because of the very varied terrane identifications and terminologies used by so many authors, we have attempted to define and characterise the terrane terms used here, and have coined the new term "Ertix Terrane", as well as redefining various others. We have defined what we term peri-Siberia as consisting of the Ob–Saisan–Surgut Terranes, Tomsk Terrane, the Altai–Sayan area (including the Salair, Kuznetsk Alatau, Batenov, Kobdin, and West Sayan Terranes), the Ertix Terrane, the Barguzin Terrane, the Tuva–Mongol Terranes, the Central Mongolian Terrane Assemblage, the Gobi Altai and Mandalovoo Terranes, the Okhotsk Terrane, and much of the Verkhoyansk–Kolyma regions. We conclude that peri-Siberia formed integral parts of the pre-Pangea Siberian Terrane, and were progressively accreted to the old Siberian Craton terrane in turn during the Palaeozoic (Fig. 8). That conclusion was reached from several criteria, one of the most important of which was the distribution of the distinctive Silurian *Tuvaella* brachiopod fauna, which was clearly a temperature-dependent higher-latitude benthic fauna, and which is confined today to the S of both the Siberia Terrane and also to many of the peri-Siberian terrane areas listed above (Figs. 7 and 11), as well as to some of the Mongolian terranes which had not yet accreted to Siberia by the Silurian. The other terranes surrounding Siberia today were accreted to it in the Carboniferous and Permian, by which time most of the Palaeozoic rotation of Siberia was over; although, of course, there was much more subsequent rotation both during tectonic adjustment of Siberia's accretion to Pangea during the Triassic and also after the break-up of Pangea in the later Mesozoic.

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