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Chapter 5

Palaeogeographic and tectonic evolution of the Arctic region during the Palaeozoic

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Abstract: The Palaeozoic motion of the future Arctic continents is presented in the animation found in the accompanying CD-ROM. The animation shows snapshots of the motion of the tectonic blocks from 550 to 250 Ma in 3 million year steps. The locations of the blocks are controlled mainly by palaeomagnetic pole values for the blocks tied to known geological events, particularly the three main Arctic orogenies: the Scandian Caledonian which began in the Silurian, the Ellesmerian in the Late Devonian and the Uralian that began in the Late Pennsylvanian. Perhaps the most significant observation to come out of the animation is that the future Arctic continents were never very far from one another during the Palaeozoic. The maximum distance from Baltica to Laurentia may have reached 6000 km during the Middle Cambrian but the Arctic continents all surrounded the same eastern Iapetus Ocean and, by Silurian, they were quite close. Reliance on the 'Y-loop' palaeomagnetic data causes extremely rapid motion of Gondwana during the Silurian. Consequently the 'X-path' for that period is used. The palaeomagnetic poles for 422 and 406 Ma have been eliminated so that Gondwana motion is within the bounds of present day plate motion.

Supplementary material: A Quicktime™ movie of palaeogeographic and tectonic evolution of the Arctic region during the Palaeozoic is available at http://www.geolsoc.org.uk/SUP18472.

Previous work on tectonic reconstructions for the Palaeozoic continents, have either been single snapshots or at most a few time-slices. Plafker & Berg (1994) show one reconstruction for the Pacific–Arctic region for Cambrian to Late Devonian (570–360 Ma) and another for Early Mississippian to Middle Triassic (360–230 Ma). Pisarevsky *et al.* (2008) show two variants of five time-slices from 615 to 530 Ma with high v. low latitude models but only the last two time-slices, 550 and 530 Ma, can be considered in or near the Palaeozoic. Nokleberg *et al.* (2000) present three time-slices for the future NW Pacific continents, one each for Middle through Late Devonian (387–360 Ma), Mississippian (360–320 Ma) and Pennsylvanian (320–287 Ma). As part of Lawver *et al.* (2002), there is an animation for the Arctic continents but it begins at 450 Ma in the Late Ordovician, immediately prior to the collision of Baltica with Laurentia during the Scandian phase of the Caledonian Orogeny. Numerous other papers such as the one by Vernikovsky (1997) show profiles of Palaeozoic tectonic events but there are very few animations focused on the Palaeozoic Arctic continental blocks and their latitudinal motion.

The Palaeozoic tectonic evolution of the present-day Arctic continents is presented in this paper as an animation found on the CD-ROM in the pocket of the volume and in select time-slices presented in the figures. Two pre-Palaeozoic reconstructions, one at 741 Ma based on geological constraints and one at 616 Ma based on palaeomagnetic data, are included to set the stage for the Palaeozoic reconstructions. In the animation and in the figures, the tectonic blocks shown represent their present day subaerial extent, with one exception: the Chukchi Cap part of the present day Chukchi Borderland, presently submarine, is shown only in the figures as having been subaerial during the Palaeozoic because it was an important factor in the Ellesmerian Orogeny in the Canadian Arctic region during the Devonian to Early Carboniferous deformation (Embry 2009). In the animation, the deformation between rigid blocks is indicated by the closure of gaps between tectonic blocks, or by overlap if future extension is inferred, or in rare cases obduction may be implied by overlap. The animation (see Supplementary material) spans the Palaeozoic from 550 to 250 Ma at 3 million year steps. Present-day 5° grid marks are preserved on the tectonic blocks as well as obvious recent geographic landmarks such as the Great Lakes and Hudson Bay on Laurentia/North America. Such visual clues help identify irregularly shaped Palaeozoic tectonic blocks that undergo accretion through time. Obviously the recent geography and coastlines were not part of the Palaeozoic outlines.

Constraints on the relative positions of Neoproterozoic and even Palaeozoic cratons are limited. Even though palaeomagnetic measurements are quality rated (van der Voo 1993), there are still some 'good' palaeomagnetic poles that give improbable plate movements and need additional geological constraints if they are to be considered valid. Accurate dating and precise matching of contemporary geological events help put some limits on relative plate locations. Our interactive PLATES™ software allows quick animations of plate motions through time, such that overlap and other unacceptable rigid plate tectonic situations can be found and avoided. If a palaeomagnetic pole produces improbably fast plate motion as well as a departure from what is a generally smooth motion, then its exclusion is seriously considered. While the measurement of palaeomagnetic parameters and the age of the sample may be quite valid, some 'errant' palaeomagnetic data may simply be indications of local rotations of minor blocks in a suture zone or along a fault, or flattening of sediments with time. Absolute plate motion models based on palaeomagnetic poles are only as good as the data that are input and the available Palaeozoic data are still quite limited for even the major plates.

The Palaeozoic plate reconstructions shown in this paper and on the animation rely on both palaeomagnetic measurements and dated geological events. The PLATES palaeoreconstructions primarily use the Pisarevsky (2005) palaeomagnetic database to constrain relative Palaeozoic reconstructions. This database, the Global Palaeomagnetic Database – GPMDB V 4.6 of Pisarevsky (2005) can be downloaded from: http://www.ngdc.noaa.gov/geomag/paleo.shtml. Palaeomagnetically determined locations for Siberia are modified from Pisarevsky *et al.* (2008) for the late Neoproterozoic into the Early Palaeozoic but then use the palaeomagnetic poles for Siberia from Smethurst *et al.* (1998) for the later Palaeozoic. In an early version of the animation, Gondwana began rapid motion to the NE from its Late Ordovician (*c.* 454 Ma) position until Late Silurian (*c.* 422 Ma) when it abruptly reversed course and moved equally rapidly to the SW

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until the Early Devonian about 406 Ma. This so-called ‘Y-loop’ or the Y-path of Morel & Irving (1978) for the apparent polar wander (APW) path for Gondwana during the Silurian and Devonian, is discussed in some detail by Vérard *et al.* (2005). The motion of Gondwana for the ‘Y-loop’ path during the Silurian depends on palaeomagnetic poles for Africa, one at 450 Ma (van der Voo 1988), another at 448 Ma (van der Voo 1993), one for 422 Ma (van der Voo 1993) and the final one at 406 Ma for Laurentia (van der Voo 1993) tied to Gondwana. In our interactive plate reconstructions, the age of a palaeomagnetic pole is given a range of ± 5 Ma, which explains the initiation of rapid movement of Gondwana 5 Ma prior to the 448 and 450 Ma poles for Africa of van der Voo (1988, 1993). By using palaeomagnetic poles for Gondwana dated at 407 Ma (Valencio *et al.* (1980) and Rapalini & Vilas (1991) for Argentina; Hargraves *et al.* (1987) for Niger), the abrupt reversal of motion of Laurentia at 422 Ma was eliminated but not the rapid Silurian motion.

The Caledonian Orogeny resulted from the collision of Baltica with Laurentia as Baltica moved rapidly westward towards the relatively stationary Laurentia. Africa and the rest of Gondwana were not affected by the Caledonian Orogeny. An initial animation showed a close approach of the very leading edge of Gondwana to the Kazahkstan block, then an abrupt reversal in direction which was difficult to reconcile with probable and known geological events. Inclusion of the Argentinian and Niger poles mentioned above produces a smoother motion of Gondwana at the end of the Silurian and beginning of the Devonian and effectively eliminates the rapid reversal of plate motion. Plate motion velocities for the ‘Y-loop’ for Gondwana during the Silurian to Devonian are more than double the Late Cretaceous motion of India with respect to Eurasia; consequently the ‘X-path’ of Bachtadse & Briden (1991) and Vérard *et al.* (2005) is used in the animation for the period 454 Ma until 406 Ma instead of the ‘Y-loop’. In addition, the very rapid Silurian motion of Gondwana is reduced by incorporation of the ‘X-path’ instead of the ‘Y-loop’. Additional Silurian poles are needed for Gondwana to either document its rapid mid-Palaeozoic motion or to provide additional support of the ‘X-path’. Since many details about actual Arctic plate motions during the Palaeozoic remain unknown, much of the faunal, plant and conodont information for the Arctic plates produce ambiguous affinities. Consequently the precise locations through time of many of the minor blocks, particularly as to whether they were close to Siberia, Baltica, Laurentia or in-between are still uncertain.

Initial Palaeozoic palaeo-positions

During the Palaeozoic, Laurentia, Baltica and Siberia were the major future Arctic plates. As a starting point for the Palaeozoic reconstructions of these plates, Figure 5.1 shows a possible plate configuration at about 750 Ma that uses a modified Rodinia

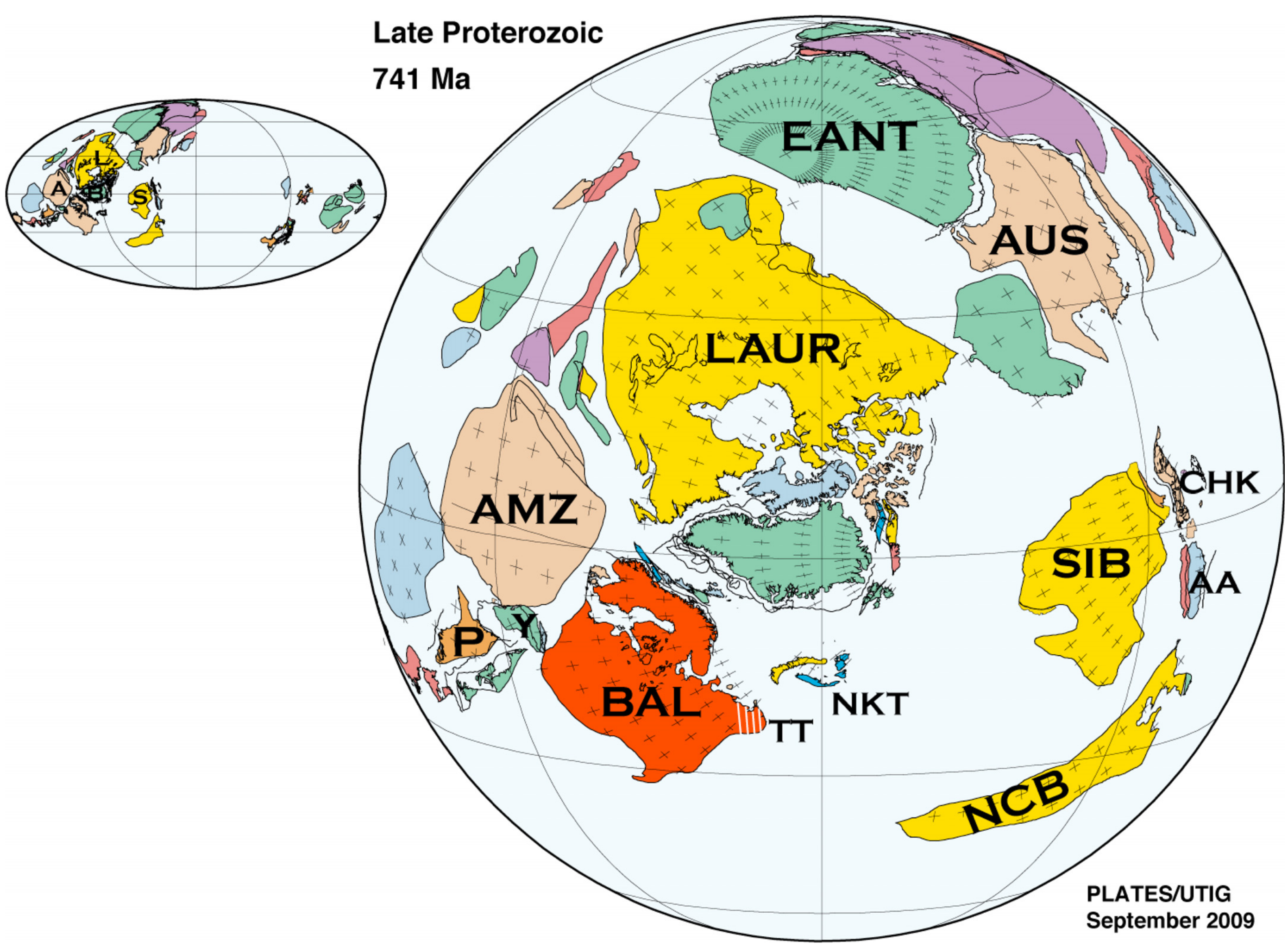

Fig. 5.1. A possible palaeoreconstruction of the Arctic blocks, Baltica, Siberia and Laurentia, at 741 Ma is shown. Rigid blocks are shown with present-day 5° tick marks and coastlines where appropriate. AA, Arctic Alaska; AMZ, Amazonia; AUS, Australia; BAL, Baltica; CHK, Chukotka; EANT, East Antarctica; LAUR, Laurentia; NCB, North China Block; SIB, Siberia. The present southern margin of Siberia is facing the future Arctic margin of Laurentia. Gladkochub *et al.* (2006) suggest that the area between Siberia and Laurentia may have been filled with micro-continents and other smaller blocks. The inset Molleweide projection of the globe shows all the continents, with the future Arctic continents identified as B, Baltica; L, Laurentia; and S, Siberia.

model of Li *et al.* (2008). Siberia is shifted from its location with respect to Laurentia so that it is similar to the one shown by Gladkochub *et al.* (2006), who place Siberia in their middle Neoproterozoic, *c.* 741 ± 4 Ma, reconstruction just off the northern margin of Laurentia, equivalent to the present-day Arctic Canada margin. Gladkochub *et al.* (2006) surmise that the Neoproterozoic location of Siberia with respect to Arctic Canada is constrained by a new age determination for the Biryusa metamorphic massif of southwestern Siberia. They relate the southwestern Siberian Biryusa dykes to the Franklinian dykes of Arctic Canada, and rule out other (Hoffman 1991; Pisarevsky & Natapov 2003; Sears & Price 2003) previously suggested Rodinian locations of Siberia. While the 741 ± 4 Ma age for the Group 1 sills of Gladkochub *et al.* (2006) is slightly older than the 723 + 4/−2 Ma age for the Franklinian event, they feel that the features are related and portray the southwestern Siberian complex as an outer limit to the eruptive Franklinian centre of Laurentia.

If the Gladkochub *et al.* (2006) Neoproterozoic reconstruction for Siberia with respect to Laurentia is correct, then the future present-day Arctic continents were in reasonable proximity to one another even during the Late Neoproterozoic although they lay astride the equator rather than in polar latitudes. It should be noted, though, that in the Gladkochub *et al.* (2006) reconstruction, Siberia is rotated almost exactly 180° from its present orientation. As shown in Figure 5.1, it is the present-day southern edge of Siberia that is facing the future Arctic Canada margin. Arctic Alaska (AA on Fig. 5.1) and Chukotka (CHK on Fig. 5.1) are shown proximal to the 'northern-side' of Siberia, so they would have been facing away from both Laurentia and Baltica if they existed as part of a greater Siberia plate at that time. While the North Kara terrane (NKT = the northern Taimyr subterrane and Severnaya Zemlya) and Novaya Zemlya are shown near Baltica, they were not part of Baltica until the Timanide Orogen just prior to Cambrian time, about 550 Ma. There is little information as to where they or the Timan Terrane (TT) might have been with respect to Baltica during the Neoproterozoic.

Walderhaug *et al.* (2007) produced a robust palaeomagnetic pole for Baltica at 616 Ma (shown in blue in Fig. 5.2) from measurements on the Egersund dykes of southern Norway. Their result compares very closely with earlier poles for the same dykes (shown in red in Fig. 5.2) compiled in Pisarevsky *et al.* (2008), including those of Storetvedt (1966) and Poorter (1972). All three palaeomagnetic results use an age of 616 ± 3 Ma for the Egersund dykes given by Bingen *et al.* (1998). The Siberian palaeomagnetic pole (in green), used for the 616 Ma reconstruction, is at 25°N, 301°E (618–608 Ma from Metelkin *et al.* 2005).

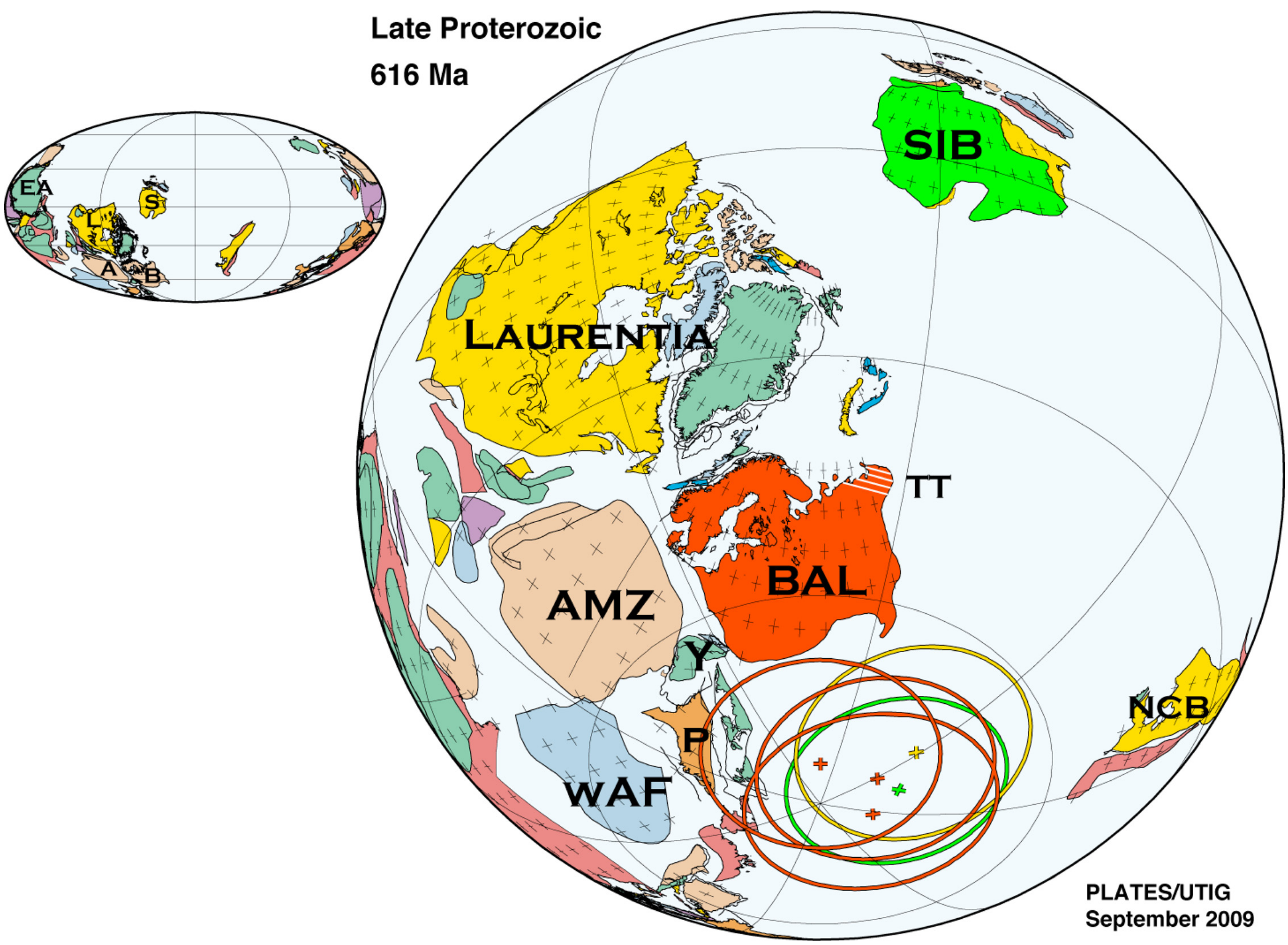

Fig. 5.2. A palaeoreconstruction for 616 Ma is shown. Fifteen degree radius circles shown for the palaeomagnetic poles for Baltica in red (Pisarevsky *et al.* 2008) and blue (Walderhaug *et al.* 2007), for Siberia in green (Metelkin *et al.* 2005), and for Laurentia in yellow (Pisarevsky *et al.* 2008). AMZ, Amazonia; BAL, Baltica; NCB, North China Block; P, Piedmont; Pya, Pearya block; SIB, Siberia; Sv, Svalbard; TT, Timan Terrane (shown striped at the NE corner of Baltica); wAF, West Africa; and Y, Yucatan. The East Iapetus Ocean has formed by the movement of Baltica and Siberia away from Laurentia. In the inset Molleweide projection of the globe, B, Baltica; L, Laurentia; and S, Siberia.

It should be noted that this pole for Siberia results in Siberia rotated approximately 180° from the orientation that Smethurst *et al.* (1998) showed for Siberia during the period 730–545 Ma. The inverted Siberia of Metelkin *et al.* (2005) and Pisarevsky *et al.* (2008) necessitates an as yet unexplained rotation of nearly 180° between 616 and 545 Ma, which defies conventional plate kinematics. The yellow circle in Figure 5.2 is the 615 Ma Laurentian palaeomagnetic pole given in table 1 of Pisarevsky *et al.* (2008) while the actual location of Laurentia differs slightly from that pole and is the Euler rotation parameter to the absolute framework from table 2 of Pisarevsky *et al.* (2008). The relation of Laurentia to Amazonia and other future South American and African blocks is similar to that shown in Pisarevsky *et al.* (2008, Fig. 5.3). The palaeolatitude of our location for Baltica is only slightly north of the one shown in Walderhaug *et al.* (2007). Figure 5.2 shows Baltica near northern South America (AMZ) and the Yucatan (Y shown in green), and near Avalonia and other smaller terranes along the margin of western Africa. Li *et al.* (2008) show a similar position of the Amazonia craton with respect to Laurentia, with Amazonia abutting the present day eastern margin of North America at 630 Ma and in their low latitude option for Laurentia in their 600 Ma reconstruction.

The future Arctic continents at 616 Ma (Fig. 5.2) were situated with the 'western' edge of Laurentia along the equator and with Siberia straddling the equator. The future Arctic margin of Siberia is rotated away from the other Arctic continents even though they are in reasonable proximity. For 616 Ma, Walderhaug *et al.* (2007) show a 1700 km separation between the Timan terranes and Baltica, and suggest a 3 cm/year approach of the Timan terranes towards Baltica with suturing occurring at *c.* 550 Ma. Their Timan terranes include the North Kara terrane (NKT) of Lorenz *et al.* (2008), Novaya Zemlya, Franz Josef Land and the Pechora Basin and the Timan Range parts of Baltica. Korago *et al.* (2004) and Pease & Scott (2009) show scattered Riphean granitoids and Riphean to Cambrian clastic metasediments as well as some Neoproterozoic granitoids on Novaya Zemlya (NZ, see Fig. 5.3 for location), but it is unclear where NZ was located with respect to Baltica prior to the Timanide Orogen, so we simply show NZ and the NKT slightly away from Baltica at 616 Ma with the Timanides (Pechora Basin and the Timan Range) of Gee *et al.* (2006) attached to Baltica but with white lines across them indicating our uncertainty. We show Novaya Zemlya and the NKT accreted to Baltica on Figure 5.3, a reconstruction at 544 Ma. Gee & Pease (2004) show additional Timanides along the eastern margin of Baltica as well as small outcrops on the southern end of Novaya Zemlya. They suggest in their paper that there are four lines of independent evidence that support the Timan terranes as simply a northerly continuation of the

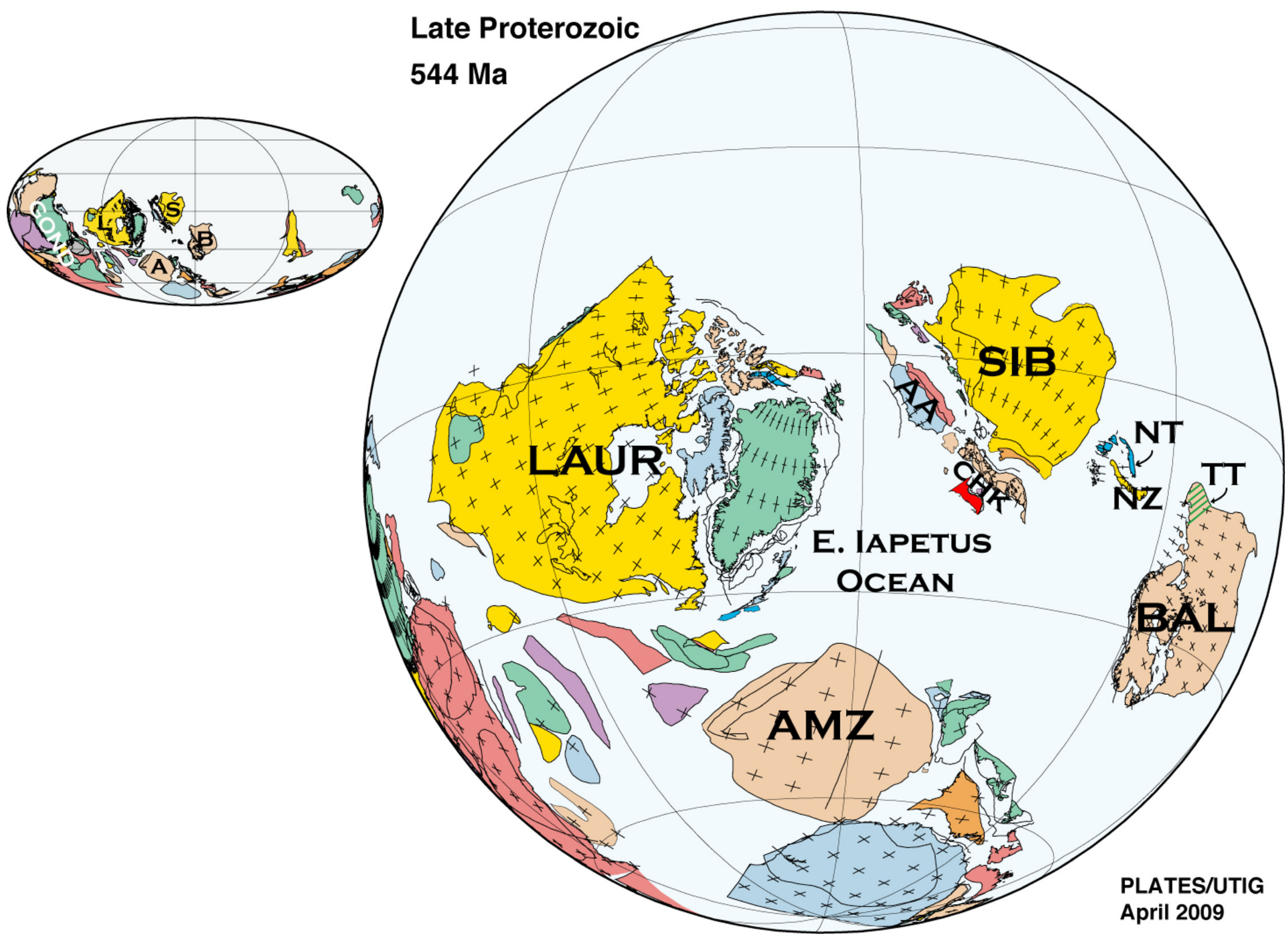

Fig. 5.3. A palaeoreconstruction for 544 Ma is shown. Siberia rotated approximately 180° counter-clockwise and then passed very close to the Arctic edge of Laurentia from 570 to 550 Ma. AA, Arctic Alaska; BAL, Baltica; CHK, Chukotka; LAUR, Laurentia; NT, Northern Taimyr Block; NZ, Novaya Zemlya; Pya, Pearya block; SIB, Siberia; Sv, Svalbard; and TT, Timan Terrane (shown striped at the NE corner of Baltica). Future Arctic terranes are in close proximity and the greater Baltica block may have been contiguous with Siberia at the beginning of the Palaeozoic. The inset Molleweide projection of the globe shows all the continents with future Arctic continents identified as B, Baltica; L, Laurentia; and S, Siberia; also identified is A, Amazonia.

Timanide domain, or at least the part that was accreted to Baltica at *c.* 550 Ma according to Gee *et al.* (2006). These lines include similar characteristic lithofacies and faunas, provenance of the sediments, age of their source rocks and the age of xenocrysts in Ordovician igneous rocks. The NE limit of Timanide folding of Pease & Scott (2009) included only the very southern end of Novaya Zemlya. By early Palaeozoic, the Timan Terrane including Novaya Zemlya had the 'unique Timanide "fingerprint" (Pease & Scott 2009)', so the Timan Terrane possibly should not be shown as part of Baltica as it is in Figure 5.2, but only after it accreted at some time later than 550 Ma. V. Pease (pers. comm.) does not think the relation of the Timan Terrane to Baltica is known precisely for this time, so we show Novaya Zemlya approaching Baltica at 544 Ma (Fig. 5.3) and attached to Baltica by the end of the Early Cambrian. Siberia moves from a position distant to Baltica at 616 Ma until it is reasonably close to Baltica at about 550 Ma, which may have been the cause of the Timanide Orogen.

Beginning of the Palaeozoic

The future Arctic terranes, the northern margin of North America with Greenland, Siberia and Baltica, are shown in a palaeoreconstruction for 544 Ma (Fig. 5.3). At the end of the Neoproterozoic, Laurentia is still near Amazonia, as it was at 616 Ma (Fig. 5.2), but has shifted slightly westward. Together they have rotated such that northwestern Laurentia is almost 20° north of the equator while at 616 Ma Laurentia was equatorial or even slightly south of the equator. Baltica has rotated 90° counter-clockwise and moved almost 30° northward. At the beginning of the Palaeozoic, the future Arctic continents were again quite close to one another with only a relatively narrow eastern Iapetus or 'Arctic' ocean between them, located between 10°S and 40°S. The outer 'Barents' shelf of Baltica was almost, or possibly, continuous with Siberia at 544 Ma.

The palaeo-positions of the major blocks shown in Figure 5.3 are nearly identical to the locations for the same blocks shown in the 'low-latitude' model of Pisarevsky *et al.* (2008) for 550 Ma. The palaeomagnetic pole used for Baltica at 550 Ma is 48°S, 25°E (data for 560.3–550 Ma from Popov *et al.* 2002, with an age for the sample from Martin *et al.* 2000). For Laurentia, the palaeomagnetic pole (23°S, 15°W) is from McCausland & Hodych (1998) with the age (555–545 Ma) from Cawood *et al.* (2001). The age and location of Siberia is from Pisarevsky *et al.* (1997, 2000). Between the late Neoproterozoic and the beginning of the Palaeozoic, Siberia appears to have rotated almost 180° counter-clockwise, if the palaeomagnetic poles listed in Pisarevsky *et al.* (2008) are used (618–606 Ma for the Biryusa dykes, Metelkin *et al.* 2005; 630–542 Ma, Pisarevsky *et al.* 2000). A pseudo pole for 570 Ma has been inserted to avoid overlap between Baltica and Laurentia but the 583 Ma pole of Meert *et al.* (1998) was not used because it produced an extraordinarily rapid motion of Baltica with respect to the other blocks. Meert *et al.* (2007) discuss the controversial Neoproterozoic palaeoposition of Baltica and conclude that the 583 Ma pole (mentioned above), their 584 Ma pole for the Fen complex in Sweden, and other Ediacaran-age palaeopoles from Baltica indicate that the Neoproterozoic–Ediacaran APW path for Baltica is poorly constrained and all conclusions (including geodynamic models) should be viewed with extreme caution pending the acquisition of new high-quality palaeomagnetic data.

The positions of Laurentia and Baltica shown by McCausland *et al.* (2007) for 550 Ma, do not match the 550 Ma reconstruction shown in the animation. In Figure 5.3 (544 Ma), our position for Siberia is between Laurentia and Baltica, whereas McCausland *et al.* (2007) do not show Siberia until their 530 Ma but it would presumably have been to the north and east of Baltica in the earliest Cambrian. They also show the Gondwanide continents in much different positions than we do. McCausland *et al.* (2007) contrast an 'inverted' with a 'rightside-up' orientation of Baltica, but the available palaeomagnetic data do not support their inverted orientation. Between 616 and 544 Ma, the southeastern corner of Baltica has moved from almost 65°S to about 10°S. By 544 Ma, both Laurentia and Siberia straddle the equator with only a relatively narrow sea between northeastern Greenland and the North Slope subterrane and Chukotka that are attached to the future northern margin of Siberia. Such a location of the North Slope subterrane with respect to Siberia (locations shown on Fig. 5.4) follows the geology for the North Slope subterrane of the Arctic Alaska block discussed in Lane (2007) and in Macdonald *et al.* (2009). It fits the Palaeozoic links based on mega-fossils as proposed by Blodgett *et al.* (2002) and also satisfies the tectonics of the future Hammond terrane (Fig. 5.4) as suggested by McClelland (2007). Siberian and northern Laurentian faunas from this period could well be very similar if the palaeogeography as derived from the palaeomagnetic data and shown in Figure 5.3 is correct. The precise locations of Arctic Alaska and Chukotka with respect to Siberia are not known for this period so we simply place them very close to Siberia and leave them in that configuration until the Devonian. Baltica is only slightly farther away from Laurentia and Siberia, although a little further south than shown by either McCausland *et al.* (2007) or by Pisarevsky *et al.* (2008), but is in a generally similar palaeo-environment. Li *et al.* (2008) show Laurentia at 550 Ma in a high latitude palaeogeographic location while it is shown here in Figure 5.3 in the 'low-latitude' position of Pisarevsky *et al.* (2008). Chukotka is shown near Siberia

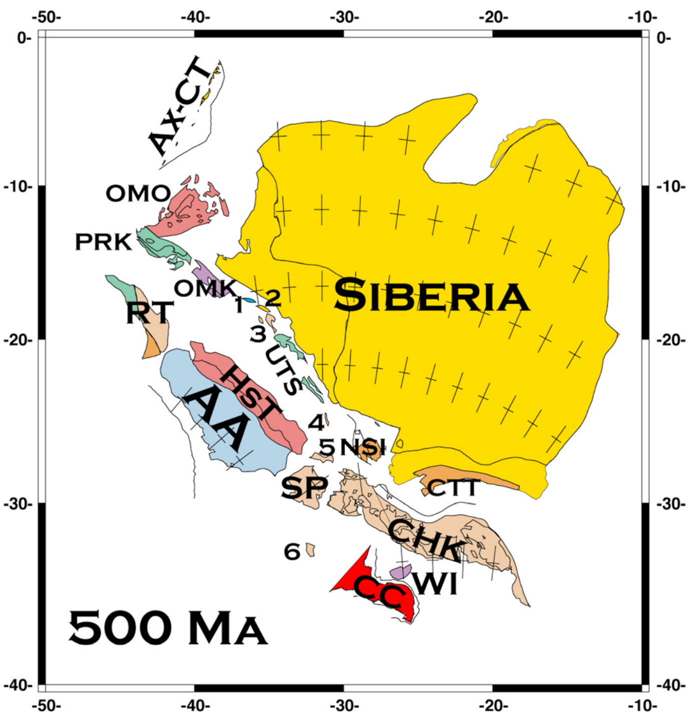

Fig. 5.4. The greater Siberian block is shown at approximately 500 Ma. AA, Arctic Alaska but until the Hammond and Endicott subterranes are accreted in the Devonian, it represents primarily the basement for the North Slope subterrane. Ax-CT, Alexander and Craig Terranes, now in SE Alaska. CC, Chukchi Cap, a continental fragment, now submarine but undoubtedly subaerial at many times in the past. CHK, Chukotka Terrane, now NE Siberia. CTT, Central Taimyr Terrane. HsT, Hammond subterrane, now part of AA but formerly separate until overthrust onto AA. NSI, New Siberian Islands. OMK, Omulevka Terrane. OMO, Omolon Terrane. PRK, Prikolyma Terrane. RT, Ruby Terrane. UTS, Ulan-Tas-Selennyakh Terrane. WI, Wrangell Island (Kos'ko *et al*. 1993). 1, Ucha Terrane (Parfenov *et al*. 1993); 2, Chemalginskiy Terrane (Parfenov *et al*. 1993); 3, Tas-Khayakhtakh Terrane (Kula-Nera of Nokleberg *et al.* 2000). 1, 2 and 3 are all minor continental shelf terranes of Siberia. 4, Kilbuck Terrane, later part of southwestern Alaska; 5, St Lawrence Island; and 6, Cape Lisburne of northwestern Alaska as part of Chukotka.

along the future Taimyr margin and in line with Arctic Alaska in Figure 5.3 and in the reconstructions for 741 and 616 Ma. Vernikovsky (1997) shows a 'Faddey' terrane that rifted from the Siberian continent sometime prior to the collision of the Kara continent at 300 Ma. While Vernikovsky (1997) indicates that the Faddey terrane subsequently re-accreted to the Siberian continent with ophiolites in the collision zone, it is possible that the rifting of the Chukotka terrane from Siberia may have been similar to that of the 'Faddey' terrane, or left it behind as a fragment that then subsequently reconnected with Siberia.

The details of the many Early Palaeozoic terranes that may have been part of a larger Siberia block are shown in Figure 5.4 for Late Cambrian time or about 500 Ma. Many of the terranes shown are surmised to have been outboard of the Siberian block but were transferred to Laurentia during the Ellesmerian Orogeny in the Devonian. According to Gil Mull (pers. comm.), an outboard location of the present-day northern edge of the North Slope subterrane (NSs) of Arctic Alaska (AA) solves some depositional problems for the Devonian strata found on the North Slope. Plafker & Berg (1994) show subduction along the future southern margin of the Arctic Alaska block on their figure for Cambrian to Late Devonian tectonics. If that subduction only occurred from Middle to Late Devonian then such subduction could have occurred in our scenario just prior to the suggested active Ellesmerian transfer of the Arctic Alaska block from Siberia to Laurentia. By Middle Devonian time, Plafker & Berg (1994) show a 'northern' source for North Slope deposition, as well as plutonic rocks of Early to Middle Devonian age. A northern source, as they show, now replaced by the Arctic Ocean, has always been a key component in the placement of the AA and Chukotka terranes folded against the Canadian Arctic Islands in the vicinity of the Sverdrup Basin (Embry 1988, 1991, 2009). The Chukchi Cap block which is shown in red on Figure 5.4 is presently submarine and does not show up as subaerial in the animation but would be the Crockerland that Embry has suggested for collision with the Canadian Arctic margin during the Ellesmerian Orogeny. If Arctic Alaska and Chukotka with Chukchi Cap were part of a greater Siberia block during the early Palaeozoic, as shown in Figure 5.4, then the detrital zircon geochronology, chemostratigraphic correlations and style of sedimentation cited by Macdonald *et al.* (2009) for deposition of the Katakturuk Dolomite could be satisfied since the North Slope subterrane was not part of Laurentia during the Neoproterozoic into the early Palaeozoic.

Shortly after their relatively close approach at the beginning of the Cambrian, the future Arctic continents began to drift apart. By Middle Cambrian *c.* 510 Ma, Baltica and northern Laurentia were as much as 6000 km apart with Siberia mid-way but not directly between the two. By the end of the Cambrian, there was a wide 'Iapetus Ocean' between Laurentia and Baltica that lay between 60°S and the equator with the future northern margin to the north of the equator. The southwestern margin of the open oceanic space between them was lined with terranes that would later become part of the eastern North American margin or the present-day, northwestern South American margin. As Gondwana

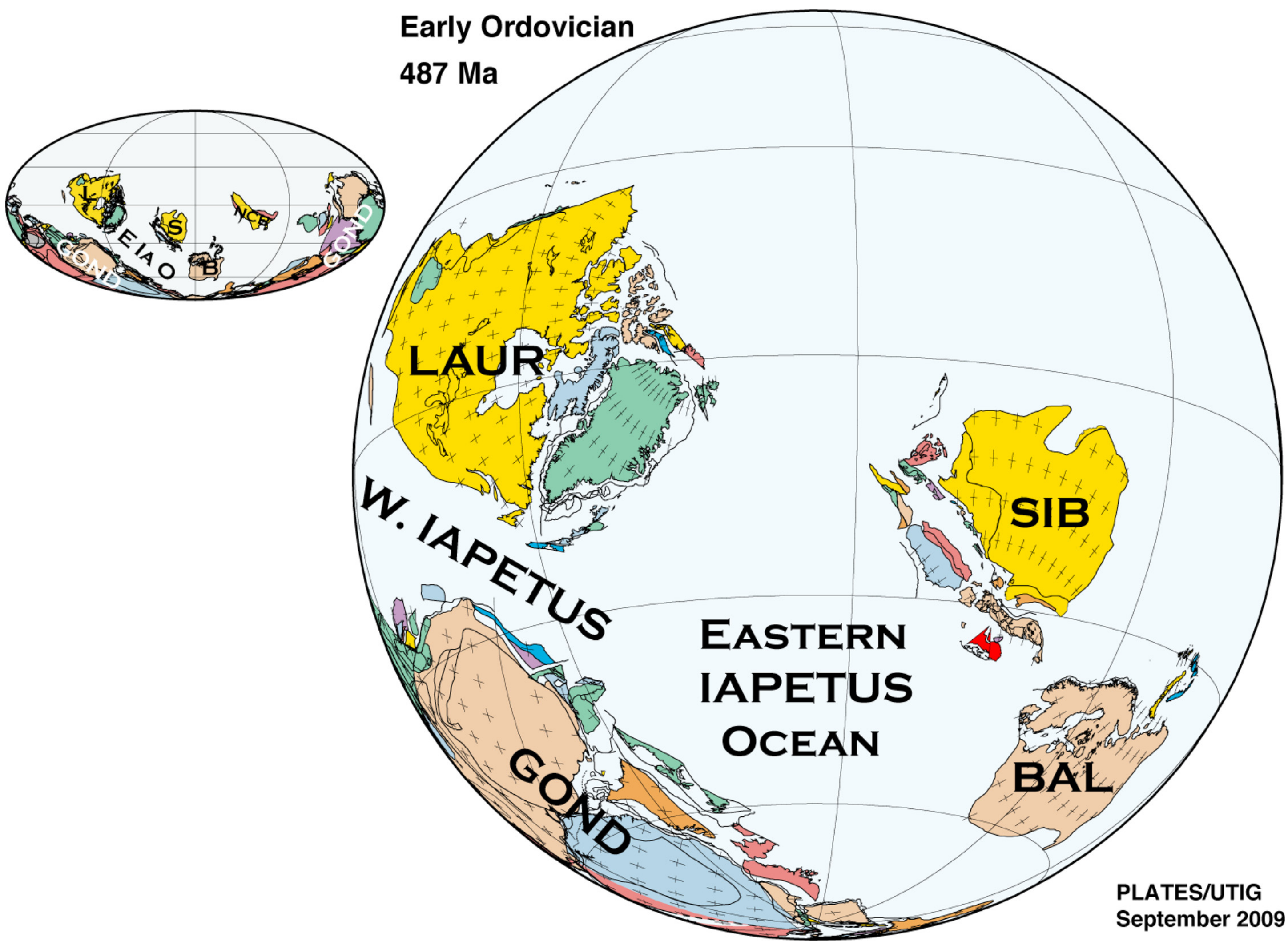

Fig. 5.5. Palaeoreconstruction for 487 Ma; the beginning of the Ordovician is shown. The eastern Iapetus Ocean has grown as Gondwana has consolidated. A western Iapetus Ocean has opened between Laurentia and Gondwana. BAL, Baltica; GOND, Gondwana; LAUR, Laurentia; SIB, Siberia. Baltica has rotated *c.* 90° clockwise and reached its southernmost Palaeozoic position. In the inset Molleweide projection of the globe, B, Baltica; E Ia O, Eastern Iapetus Ocean; L, Laurentia; and S, Siberia.

coalesced in the Early Palaeozoic, Laurentia moved only a few degrees northward from its earliest Palaeozoic position. By the Early Ordovician (487 Ma), shown in Figure 5.5, the eastern Iapetus Ocean was close to its greatest extent and Siberia was perhaps at its southernmost latitude for the Palaeozoic while Laurentia straddled the equator. Baltica had rotated about 90° clockwise from its beginning Palaeozoic position and had changed its direction of motion from southward to northward although the available palaeomagnetic poles do not precisely constrain its location with respect to the other continental blocks. Between 487 and 469 Ma, Baltica may have passed very close to Siberia, but as shown in the animation, collision could be avoided, even for the northern outliers of the greater Baltica block. The inset Mollweide projection of the world for 490 Ma (Fig. 5.5) shows the extent of Gondwana as well as the relation of the three Arctic blocks, Laurentia, Siberia and Baltica to Gondwana and to the North China Block. As depicted, the four non-Gondwanide terranes were adrift in a single, large ocean.

Late Ordovician (450 Ma) to Early Devonian (400 Ma)

Near the end of the Middle Ordovician, Baltica undergoes a rapid increase in velocity and begins its movement towards Laurentia, leading to the Caledonian Orogeny. At the same time, Siberia was moving westward, possibly with Baltica. At about 450 Ma, Laurentia spanned a latitudinal zone that stretched from 10°S to *c.* 35°N and began a relatively slow drift southward. By the end of the Ordovician (444 Ma), the Iapetus Ocean between Laurentia and Baltica was closing with a rapid westward motion of Baltica. The complete closure of the Iapetus Ocean produced the Caledonian deformation shown in Figure 5.6 (436 Ma) along Greenland and Scandinavia, as indicated by the double-dashed lines, principally between eastern Greenland and western Baltica (BAL). In the animation, even though Siberia seems to be moving westward with Baltica, it was apparently not involved in the Caledonian Orogeny and continued on a westward trajectory until Middle Devonian time. Observed Caledonian deformation in the Barents Sea region branches into an eastern and western system (Gudlaugsson *et al.* 1998). By the end of the Silurian (416 Ma), the Caledonian Orogeny was finished, with Baltica welded to Laurentia and Pearya coalesced with northern Ellesmere Island. Pearya is perhaps the furthest 'northwest' evidence of Caledonide deformation (Trettin 1991*a*). At the time of the formation of Laurussia, the combination of Laurentia and Baltica, it was equatorial, with the combined blocks straddling the equator and extending about 20° into the northern and southern hemispheres. After collision, Laurussia continued to move slowly southward, reaching its farthest south position at 406 Ma with the future east coast of North America at almost 50°S. At 406 Ma, Laurussia changed its

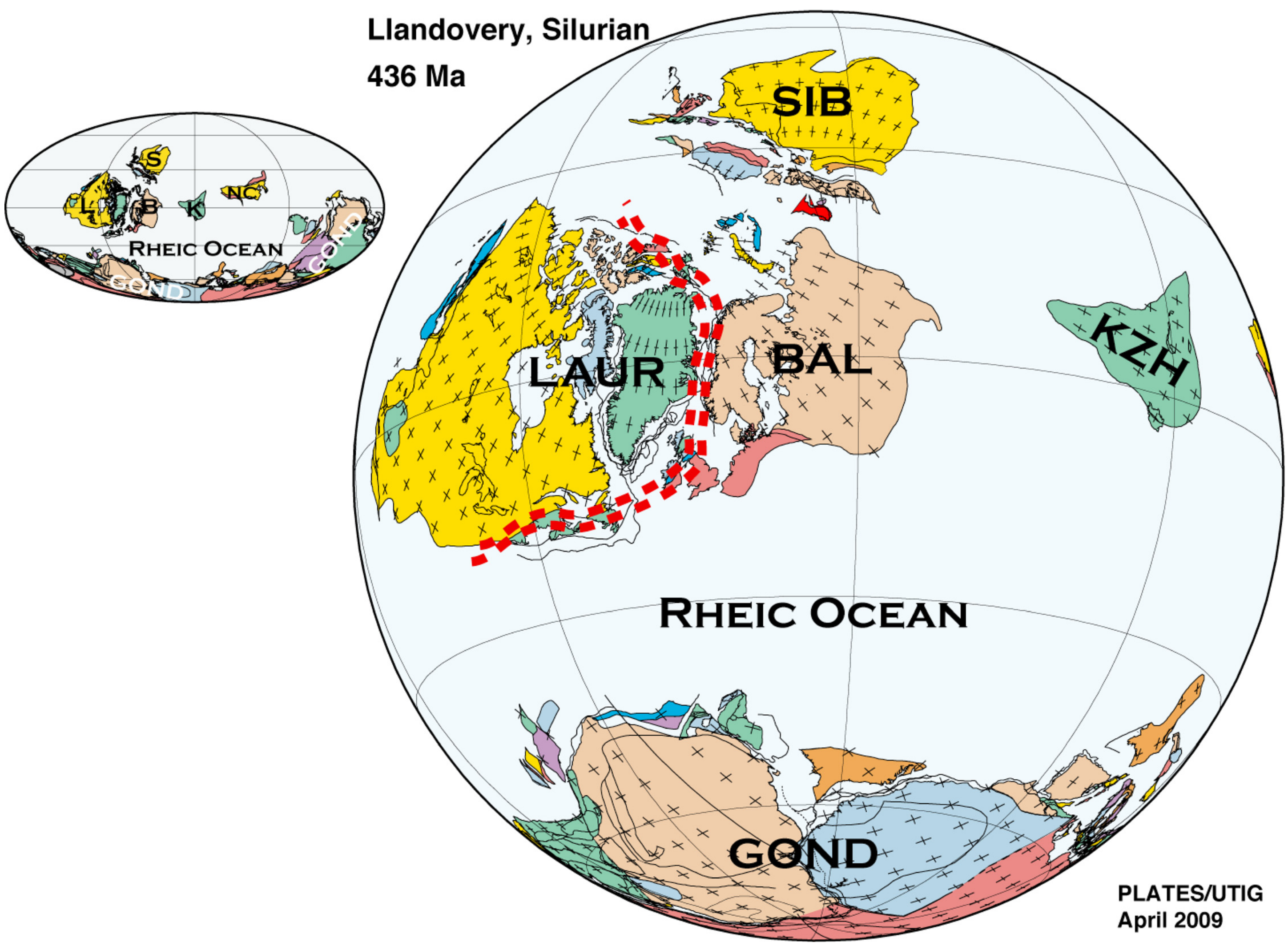

Fig. 5.6. Palaeoreconstruction for 436 Ma at the beginning of the Caledonian Orogeny is shown. The Iapetus Ocean closed as Baltica collided with Laurentia to form Laurussia. The double-dashed red line follows the Caledonian Orogen although, as shown, it follows the western branch in the Barents Sea/Shelf region. BAL, Baltica; GOND, Gondwana; KZH, Kazakhstan Block; LAUR, former Laurentia; SIB, Siberia. Closure of the Iapetus Ocean has resulted in the transfer of Pearya in the north to the future Ellesmere Island and Avalonia in the south to the future eastern margin of North America. Rifting of the Avalonian blocks from Gondwana has produced the Rheic Ocean as shown. In the inset Molleweide projection of the globe, B, Baltica; GOND, Gondwana; KZH, Kazakhstan; L, Laurentia; NC, North China block; and S, Siberia.

southward drift and began a rapid northward motion, probably driven by subduction beneath the Arctic terranes that lay along the then southern margin of Siberia. On the animation, the northward motion seems to accelerate and a 'back-arc' type basin develops that begins to rift the Arctic Alaska block from Siberia. Lane (2007) and Macdonald *et al.* (2009) say that the North Slope subterrane of Arctic Alaska did not accrete to NW Laurentia before the Early to Middle Devonian.

By 400 Ma, the future Arctic continents begin a mostly northward migration. Consequently the viewpoint used in the accompanying animation (see CD-ROM in pocket) shifts between 403 Ma (Fig. 5.7a) and 400 Ma (Fig. 5.7b). During the Early Devonian, when Laurussia reached its southernmost position, the Rheic Ocean first narrowed then widened again, until it closed during the Appalachian Orogeny in the Carboniferous. By 400 Ma, all of the future Arctic continents were at least partially in the northern hemisphere although the southern tip of Greenland did not clear the equator until Middle Pennsylvanian, about 311 Ma.

Middle Devonian (397 Ma) to Late Devonian (360 Ma)

To the SE of Laurussia, the Rheic Ocean began to close during the Middle and Late Devonian. During the same time, there is a sudden change to relatively rapid northward motion of Laurussia and the initiation of a slight southward motion of Siberia. At about 406 Ma, Siberia, with Arctic Alaska and Chukotka attached, was at its northernmost latitude for its middle Palaeozoic path and was almost 3000 km away from the future Canadian Arctic margin. The Late Devonian to Carboniferous Ellesmerian Orogeny resulted from either collision of some plate, most probably Siberia (SIB), with the northern margin of Laurussia (Lawver *et al.* 2002) or flat slab subduction along that margin. Between Early Devonian and Middle Devonian, in perhaps only 15–20 million years, Siberia went from 3000 km distant from Laurentia to within striking distance at about 390 Ma, coincident with the timing of the Ellesmerian Orogeny (Trettin 1991*b*, Klaper 1992). This close approach is shown in Figure 5.8 for 388 Ma. Klaper (1992) attributed the extensive compressional deformation found on Ellesmere Island to the collison of the Siberian plate with the northern margin of Laurussia and put the timing of collision at Middle to Late Devonian. In Figure 5.8, the Siberian plate itself is still some distance from Ellesmere Island but Chukotka with the Chukchi Cap would have been between Siberia and the future Arctic margin of North America. Chukotka and, in particular, a subaerial Chukchi Cap may have been the hypothesized 'Crockerland' of Embry (1992, 2009) that he requires for a sediment source for deposition in the Sverdrup Basin of Arctic Canada.

Work by Anderson (1991) and Mull & Anderson (1991) suggests that deformation in at least parts of the North Slope subterrane must have occurred no later than the middle of the Middle

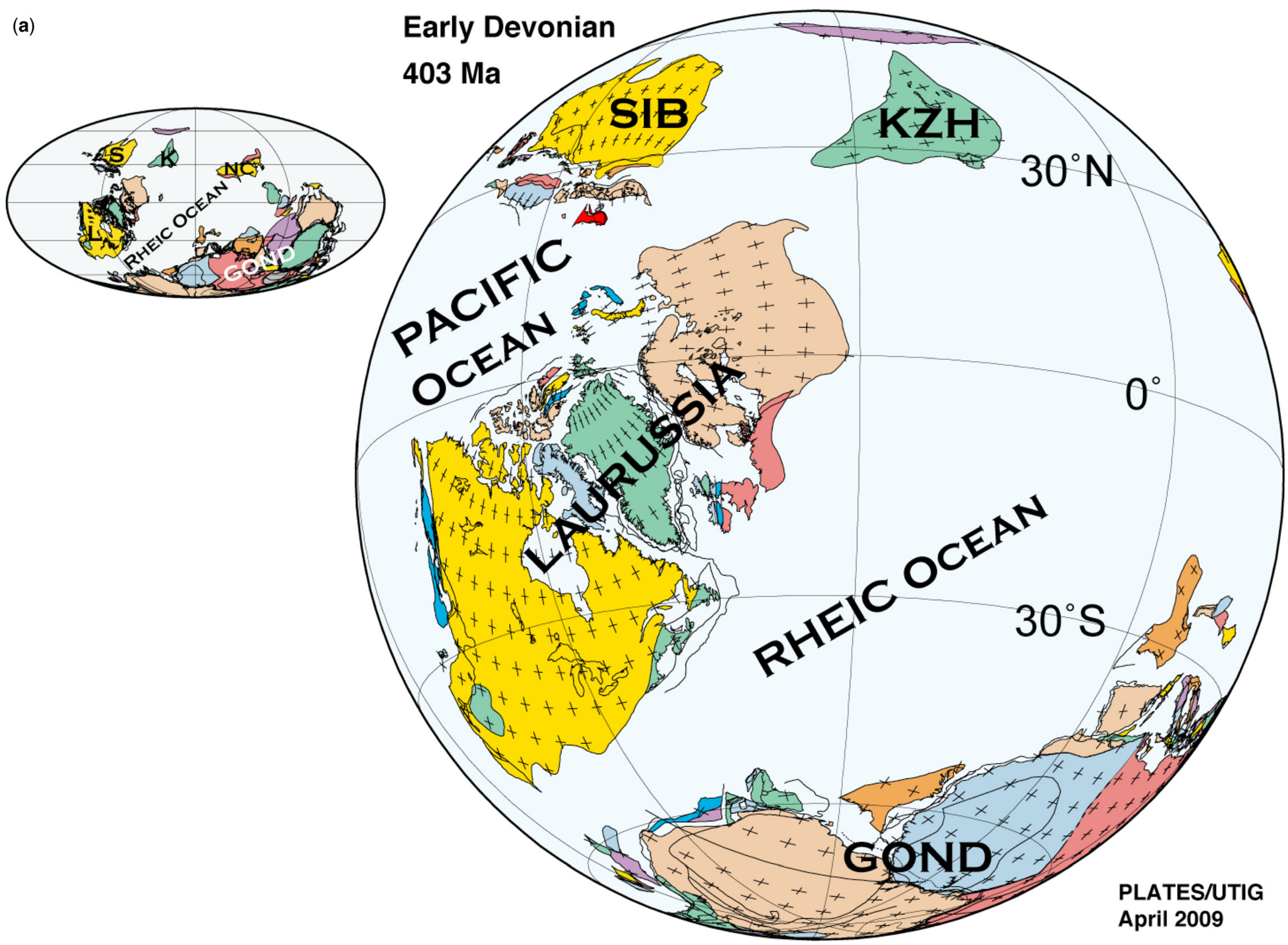

Fig. 5.7. In order for the Arctic blocks to be kept within the view frame of the animation, the centre point is moved from 15°S, 50°W for the frames from 550 to 403 Ma (**a**) to 30°S, 60°W for the frames 400 Ma (**b**) to 250 Ma. KZH, Kazakhstan; MNG, Mongolia; NP, North Pole; PAO, PalaeoAsian Ocean; SIB, Siberia; UrO, Uralian Ocean. In the inset Molleweide projection of the globe, GOND, Gondwana; KZH, Kazakhstan; L, Laurussia; NC, North China block; and S, Siberia.

Devonian since they found flat-lying Middle and Late Devonian sediments that were not deformed by the Ellesmerian Orogeny, only by the much later Brookian Orogeny. During the Early to Middle Devonian, Arctic Alaska had to have moved away from Siberia to be in position to collide with North America as part of the Ellesmerian Orogeny. The Hammond subterrane of Arctic Alaska was overthrust onto the North Slope subterrane as part of the orogeny. If the collision of Arctic Alaska with Laurentia did not produce Ellesmerian deformation in Arctic Alaska after Middle Devonian (Anderson 1991), deformation did continue in the Canadian Arctic Islands 'to the east' where Crockerland (Embry 2009), actually the Chukchi Borderland, acted as the northern source for Sverdrup Basin sediments. The eastern deformation may have continued until the end of the Devonian (Trettin 1991*b*). According to Embry (1991), a key tectonic event in the Canadian Arctic Islands occurred when foreland basin subsidence started in earnest during the very early middle Devonian, although in the animation it appears more likely to have started towards the end of the Middle Devonian. Another major tectonic event as evidenced by a widespread unconformity occurred near the Middle to Late Devonian boundary when subsidence in the foreland accelerated rapidly (3000 m of Early–Middle Frasnian strata on southern Ellesmere) and the composition of the molasse changed with more rock fragments and chert as opposed to the earlier, mainly quartzose (A. F. Embry, pers. comm.) sediment. The final Ellesmerian Orogeny caused a widespread unconformity in the late Frasnian, and produced folding and uplift near the Devonian to Mississippian boundary.

Evidence for the proximity of the North Slope subterrane of Arctic Alaska with the Canadian Arctic Islands comes from many sources. Miller *et al.* (2006) found detrital zircons in the Triassic Ivishak formation of the Sadlerochit Mountains of the North Slope and in the Pat Bay formation of the Sverdrup Basin to be dominated by latest Precambrian to Cambrian zircons, 600–500 and 490–445 Ma, while both Permo-Carboniferous and Permo-Triassic zircons were absent from the two sites. Embry (1990) shows a nearly identical correlation between the Lower Triassic to Middle Jurassic subsurface strata from the North Slope subterrane (South Meade No. 1 well) and southwestern Sverdrup Basin (Sandy Point L-46 well on Victoria Island). Both lines of evidence suggest that the North Slope subterrane was part of Laurentia, adjacent to the Canadian Arctic Islands, from at least Lower Triassic through the Jurassic. The most likely pre-Triassic time for the North Slope and Chukotka to have been transferred from Siberia to Laurentia or Laurussia was during the Ellesmerian Orogeny or Middle to Late Devonian, 395–360 Ma. Whether the two terranes were part of Laurentia as shown prior to the Middle Devonian Ellesmerian Orogeny is not certain but unlikely given the evidence presented by Lane (2007), McClelland (2007) and Macdonald *et al.* (2009), who all argue that they could not have been part of Laurentia prior to Middle Devonian. The close approach of Siberia to Laurentia during the Middle Devonian is also the most likely time that the transfer of Arctic Alaska and Chukotka might have taken place.

While there is reasonable evidence for a close approach of Siberia with Laurussia during the Middle Devonian, there is not

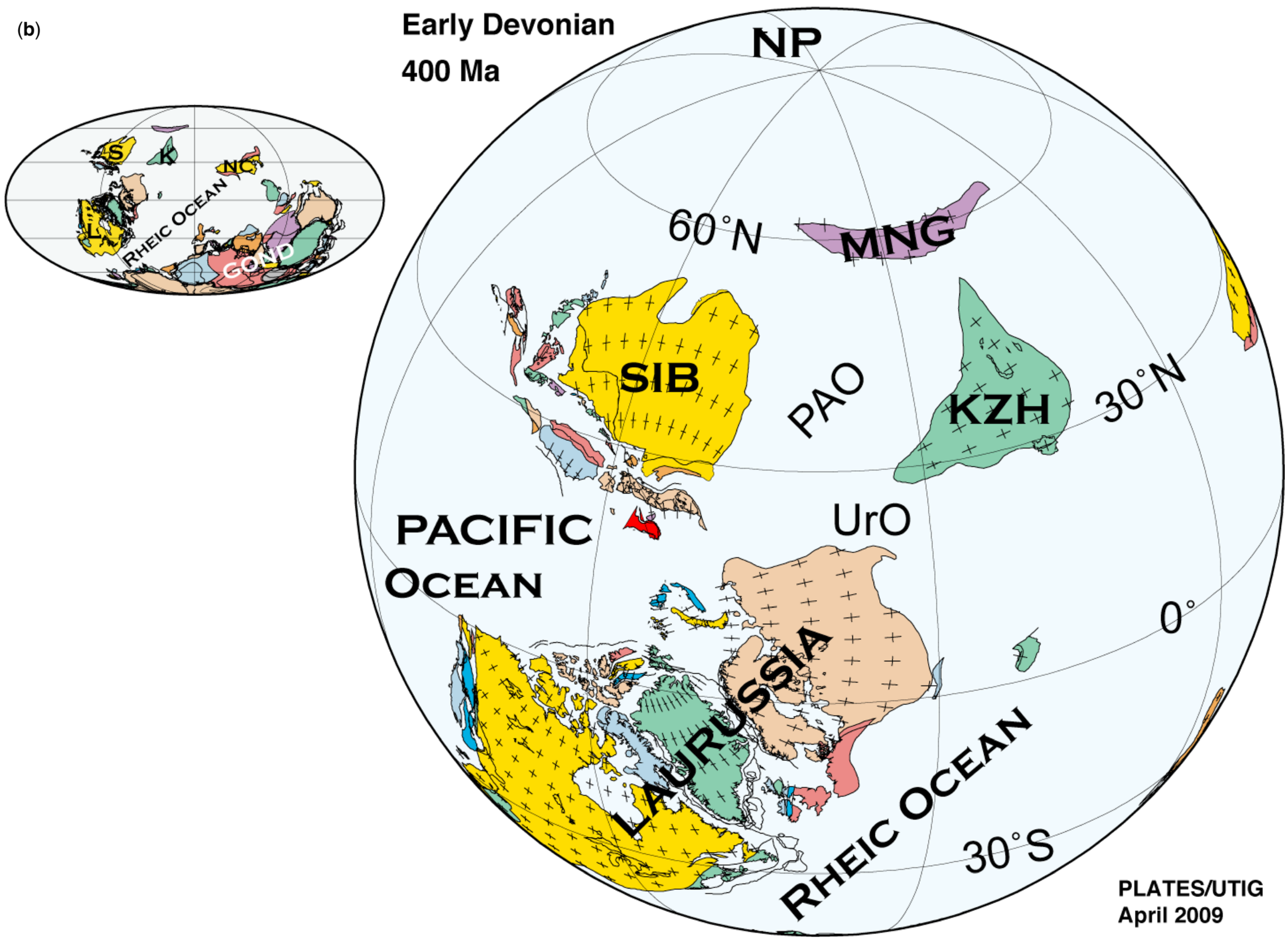

Fig. 5.7. *Continued.*

a great deal of evidence to support when Siberia may have rifted from such a collisional position, to eventually coalesce with the northern Taimyr block at about 300 Ma (Vernikovsky 1997). Embry (1988) suggests that the Ellesmerian Orogeny tapered off by the end of the Devonian, so in Figure 5.9 (364 Ma), Siberia is shown drifting away from Laurussia. Evidence for the formation of a Late Devonian, large igneous province (LIP) in the Vilyuy basin region of Siberia is summarized by Kravchinsky *et al.* (2002), although 700 km long magmatic dykes in the Vilyuy basin region were discussed by Parfenov (1997) and their emplacement as possible evidence of a mantle plume was suggested by Lawver *et al.* (2002) and Courtillot & Renne (2003). Sengör & Natal'in (1996) suggested that a Vilyuy rift basin opened during the Late Devonian (360 Ma). The ages for the magmatic samples for the Vilyuy Basin (Smethurst *et al.* 1998) range from 377 Ma for the Ygyattin basalts, to 374 Ma for the Ygyalta volcanics and intrusives and 360 Ma for the Ygyattin dolerites. Kravchinsky *et al.* (2002) sampled a much larger number of sites than just the ones Smethurst *et al.* (1998) report on, but conclude that they cannot define the age range of their palaeomagnetic samples to better than 377–350 Ma or Frasnian (Late Devonian) to Early Mississippian. The probable mantle plume would have produced the necessary force to rift the Verkhoyansk region of the present-day eastern Siberian craton away from the craton itself, leaving 'Devonian oceanic crust' at the intersection of the Vilyuy and the Ygyalla grabens, as shown by Smethurst *et al.* (1998). We infer that the plume also opened the Oimyakon Basin (OB on Fig. 5.10) on the west side of the Devonian Siberia and imparted an eastward motion to Siberia. According to Nokleberg *et al.* (2000), Middle to Late Devonian volcanic rocks are found on both the Omulevka and the Omolon blocks (Parfenov & Natal'in 1986) (Fig. 5.4), which were separated from Siberia by opening of the Oimyakon Sea.

Middle Mississippian (345 Ma) to Late Pennsylvanian (300 Ma)

During the Middle Mississippian, the future Arctic blocks as well as Gondwana begin relatively rapid motion to the east. Slightly faster eastward motion of Siberia eventually moved it into position to later collide with Baltica, with direct collision between the present day northern and central Taimyr blocks at about 300 Ma (Vernikovsky 1997). At the end of the Devonian, an elongate, continental sliver with strong lithologic affinities to cratonic North America, the Yukon Composite Terrane (Silberling *et al.* 1994), rifted from Laurussia (Templeman-Kluit 1979) and left an ocean basin between it and the North American craton (Monger & Berg 1987; Plafker & Berg 1994). The marginal sea was initially called the Anvil Ocean by Templeman-Kluit (1979) but was later named the Cache Creek Sea by Monger & Berg (1987) and

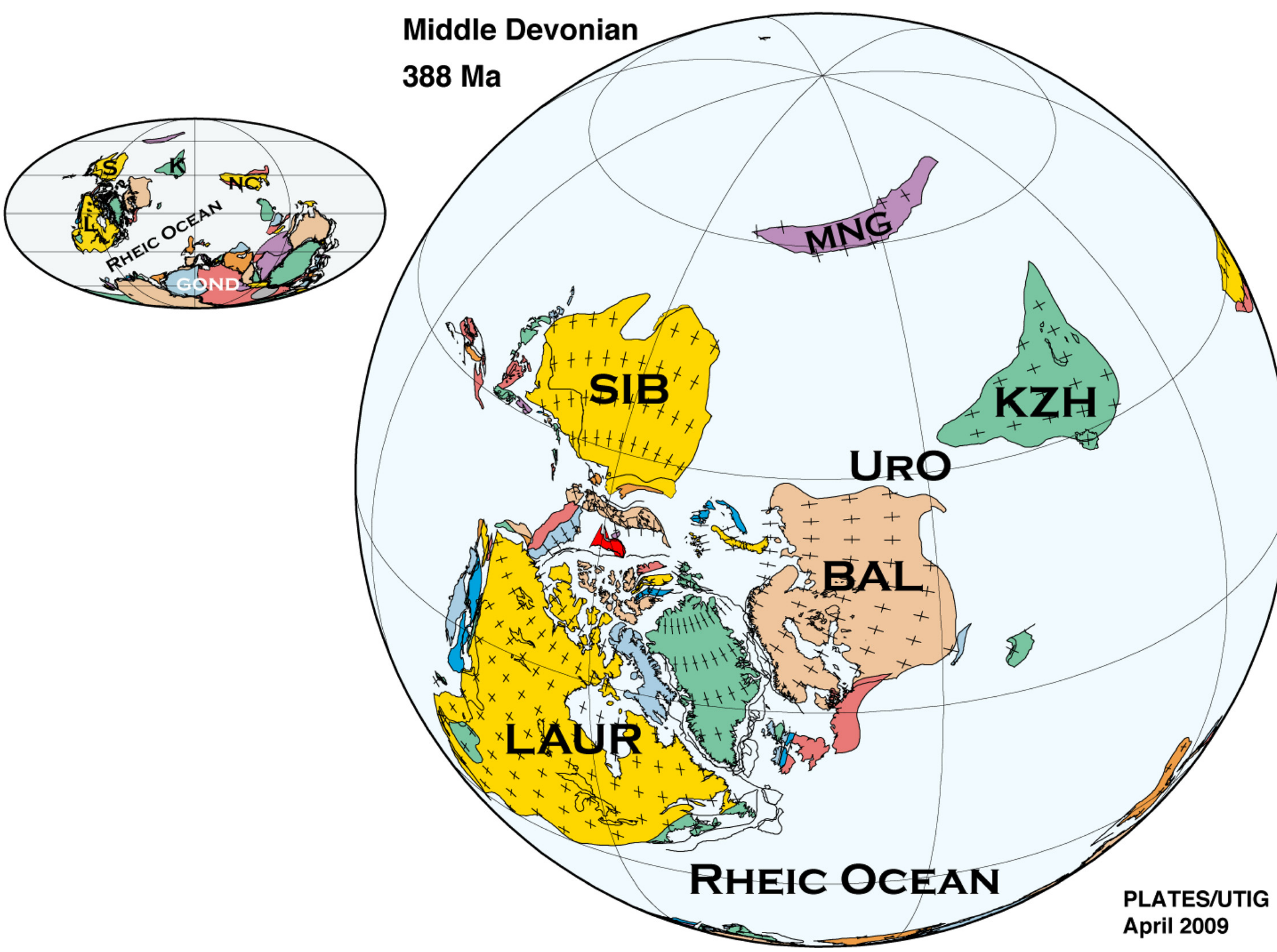

Fig. 5.8. A palaeoreconstruction for the Middle Devonian, 388 Ma is shown. Siberia with Arctic Alaska and Chukotka has collided with the future Arctic margin of North America. The Arctic Alaska block and Chukotka with the Chukchi Cap are transferred to North America as part of the Ellesmerian Orogeny. Siberia then rifts away from Laurussia at the end of the Devonian. BAL, Baltica; KZH, Kazakhstan; MNG, Mongolia; SIB, Siberia; UrO, Uralian Ocean. In the inset Molleweide projection of the globe, GOND, Gondwana; KZH, Kazakhstan; L, Laurussia; NC, North China block; and S, Siberia.

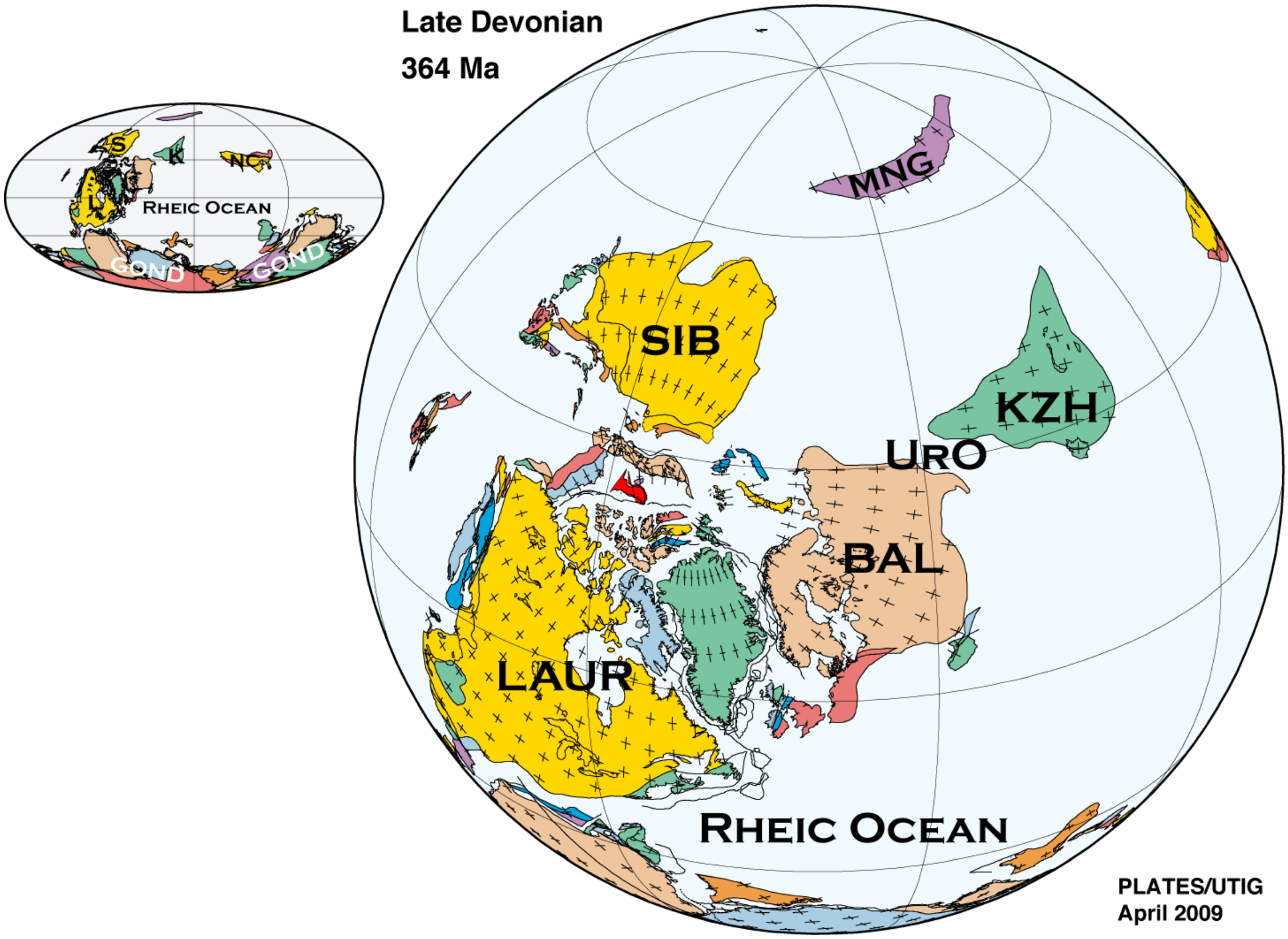

Fig. 5.9. A palaeoreconstruction for the Late Devonian, 364 Ma is shown. Siberia with Arctic Alaska and Chukotka is left as part of the future Arctic margin of North America as Siberia drifts away. BAL, Baltica subset of Laurussia; KZH, Kazakhstan; LAUR, Laurentia subset of Laurussia; MNG, Mongolia; SIB, Siberia; UrO, Uralian Ocean. In the inset Molleweide projection of the globe, GOND, Gondwana; KZH, Kazakhstan; L, Laurussia; NC, North China block; and S, Siberia.

Plafker & Berg (1994), but now seems to be referred to as the Slide Mountain Ocean (SMO on Fig. 5.10) by Nokleberg *et al.* (2000) and Colpron & Nelson (2009). M. Colpron (pers. comm., 2009) assigned the Cache Creek name to a basin outboard of where the Slide Mountain Ocean existed. The mainly crystalline basement rocks of this terrane are overlain by Upper Triassic to Middle Jurassic marine clastic and volcanic and carbonate arc rocks and are intruded by comagmatic igneous rocks of the Stikine terrane. Plafker & Berg (1994) dated the Slide Mountain Ocean from at least Early Mississippian to Middle (?) Jurassic age, and wrote that it formed behind a Late Devonian to Early Mississippian magmatic belt. In Figure 5.10 (Middle Mississippian, 337 Ma), the Oimyakon Basin has opened on the western margin of Siberia and the Slide Mountain Ocean is shown off the western margin of Laurussia.

End Carboniferous

Numerous palaeomagnetic pole determinations were used for reconstructions at 300 and 295 Ma. Reliable palaeomagnetic poles for 300 Ma (S. A. Pisarevsky pers. comm., 2007) include ones for Africa, Australia, Baltica, the Congo Craton, India, the North China block, NW Africa and South America. For 295 Ma, van der Voo (1993) published poles for Africa, Australia, Baltica, India, North America, South America and the South China block. These poles with their 95% confidence circle and attached continental blocks can be grouped reasonably well about the North Pole so the fit of the continental blocks at about 300 Ma is considered to be well constrained. On the accompanying animation, the rapid motion of the future Pangea pieces that sped up at 337 Ma (Fig. 5.10) seems to slow decidedly at 306 Ma with the closure of the Rheic Ocean and the final amalgamation of Pangea. Hatcher (2007) describes the Alleghanian Orogeny (335–265 Ma) as diachronous and that it started with early dextral strike-slip faulting throughout the orogeny followed by metamorphism at 325 Ma in the southern and central Appalachians.

As mentioned before, in the animation and in the figures, tectonic blocks are depicted with their present day extent with future closure and possible deformation implied by gaps between pieces. Occasionally, overlap of blocks is shown if future extension is implied. While all of the future Pangean continents are moving eastward beginning at 337 Ma, Laurussia is moving more rapidly eastward than Gondwana to the south. The relative motion between the two major continents would produce the dextral strike-slip faulting as Hatcher (2007) describes. He states that the Alleghanian Orogeny (Hatcher *et al*. 1990) resulted in the uplift of the Appalachian range which in turn produced the large, Late Mississippian to Early Permian delta complex that

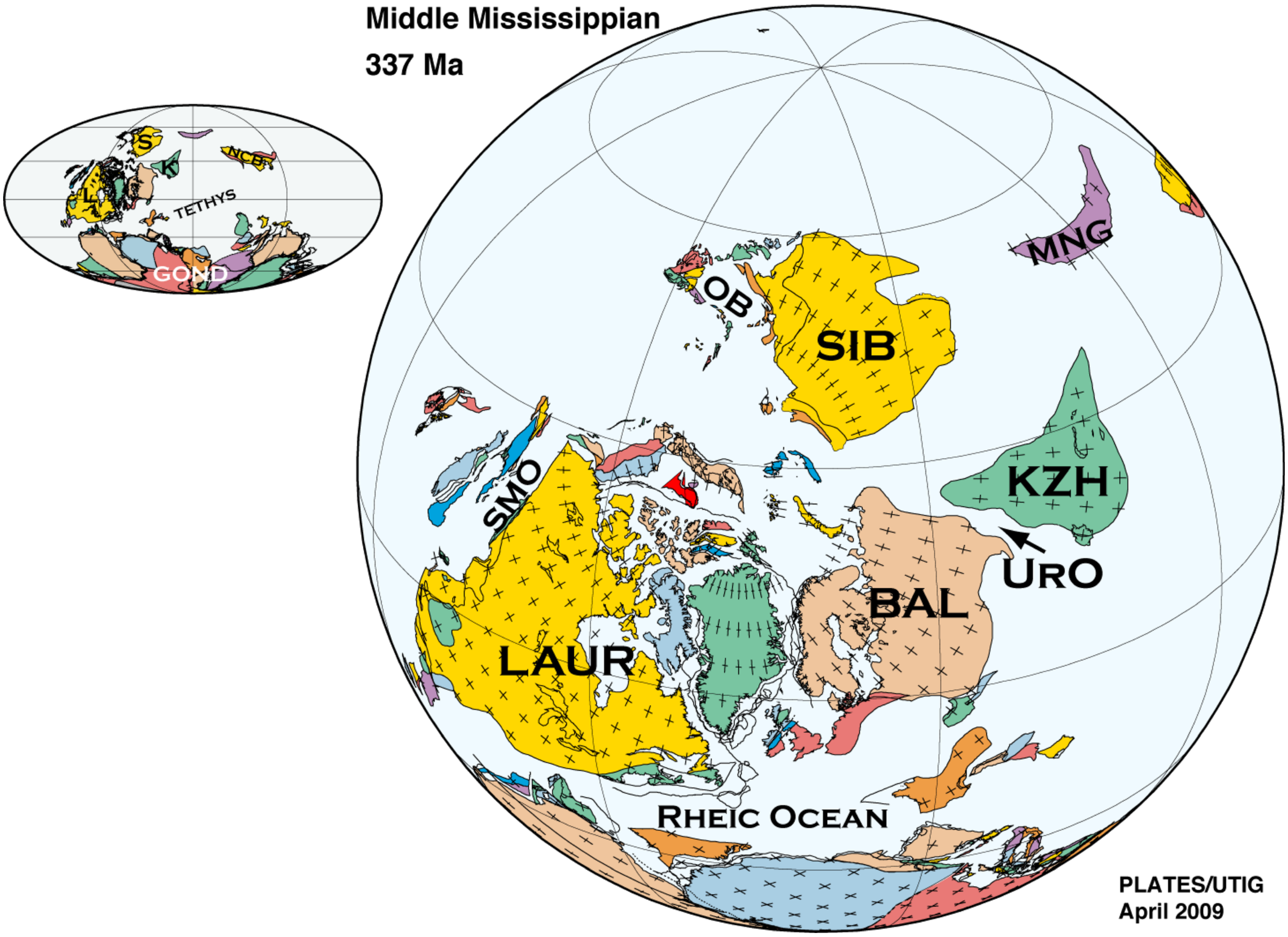

Fig. 5.10. A palaeoreconstruction for the Middle Mississippian, 337 Ma is shown. The Slide Mountain Ocean has opened along the western margin of North America. Siberia and Kazakhstan are about to coalesce with Laurussia to form Pangea. BAL, Baltica subset of Laurussia; SMO, Slide Mountain Ocean; KZH, Kazakhstan; LAUR, Laurentia subset of Laurussia; MNG, Mongolia; OB, Oimyakon Basin; SIB, Siberia; UrO, Uralian Ocean. In the inset Molleweide projection of the globe, GOND, Gondwana; KZH, Kazakhstan; L, Laurussia; NCB, North China block; and S, Siberia.

stretched from the Appalachians into the Midwest. Keller & Hatcher (1999) discuss the Appalachian (now Alleghanian)–Ouachita Orogeny that occurred nearly simultaneously with the final closure of the Rheic Ocean. Deformation along the orogen varied considerably in extent and timing. In the Ouachita region to the SW, the Late Proterozoic continental margin is preserved whereas crustal-scale deformation is most intense in the northern Appalachians. They found that the thrust-related transport distance in the Blue Ridge–Piedmont area is at least 200 km. That could explain the obvious gap between North America and the Piedmont region of southeastern North America shown in Figure 5.11 for 310 Ma just prior to closure.

From the animation for the period 340–300 Ma, it is clear that the rapid reduction in 'eastward' motion of the pieces of Pangea may have resulted from Laurussia colliding with Iberia as part of Gondwana, thrusting along the Piedmont region and/or collision between the Uralian edge of Baltica and Kazakhstan. The Uralian Ocean closed with the collision of the Kazakhstan block with Baltica (as part of Laurussia) during the Early Pennsylvanian (Bashkirian, 318.1–311.7 Ma) according to Puchkov (2002). Artyushkov *et al.* (2000) had closure of a separate Kazakhstan ocean basin, with collision between the Kazakhstan continent with an East Uralian microcontinent, beginning in the Late Visean (*c.* 330 Ma) and a final closure and amalgamation of Eurasia by Late Moscovian (*c.* 305 Ma), reasonably coincident with the timing given by Hatcher (2007) for the Alleghanian Orogeny. As far as the future Arctic continents are concerned, the collision between the northern and central terranes of the Taimyr Peninsula may have been the final segment of the 'greater' Alleghanian–Ouchita to Uralian orogenies. Within the Neoproterozoic and Cambrian rocks of the NKT are a number of Palaeozoic intrusives (Korago *et al.* 1989; Gee *et al.* 2006; Lorenz *et al.* 2008) that suggest that subduction was inboard or to the NW in present day coordinates as the NKT collided with central and southern Taimyr probably in the Early Permian. Such timing as given by Gee *et al.* (2006) fits with the ages they show in their Figure 5.4 for the intrusives (343 ± 4, 306 ± 2 Ma from Vernikovskaya *et al.* (1995); 304 ± 5 Ma from Pease (2001); and 264 ± 8 Ma from Vernikovsky *et al.* (1998)).

Permian (299–250 Ma)

At the very end of the Carboniferous, with the final closure of the Rheic Ocean, the assembled Pangea began a slow northward drift as seen in the animation. By the beginning of the Permian, most of the future continental margin of the Arctic Ocean was above 30°N with even the southern tip of Greenland, finally north of the equator. The northward drift during the Permian brought the Arctic continents to roughly 40–45°N with the eastern end of

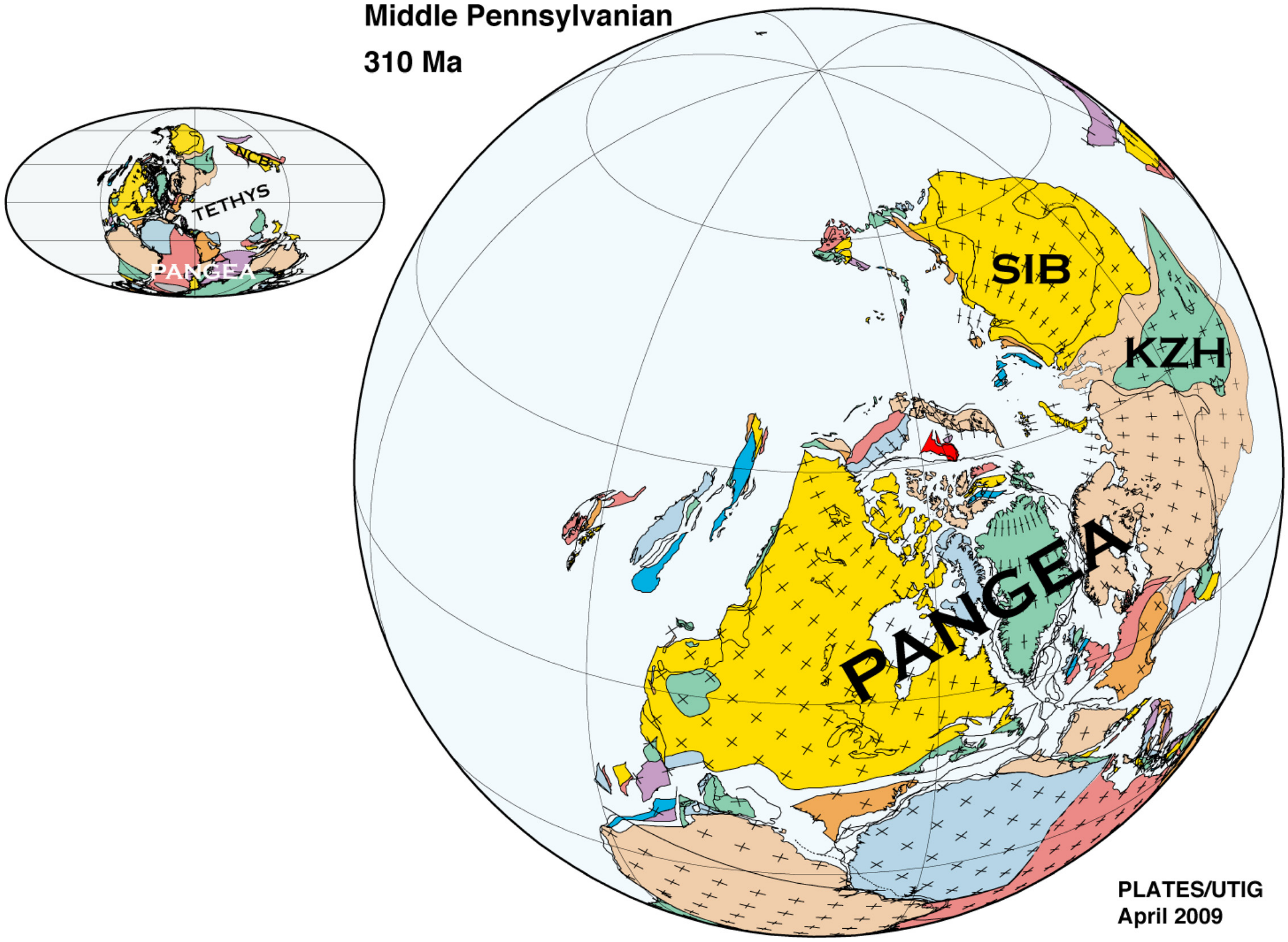

Fig. 5.11. A palaeoreconstruction for the Middle Pennsylvanian, 310 Ma is shown. The Uralian Ocean has closed by 315 M. The Rheic Ocean is essentially closed between North America and the Piedmont region. The mostly translational motion of Laurussia with Gondwana may have been stopped by collision is the vicinity of the northern Appalachians and Iberia. KZH, Kazakhstan; SIB, Siberia. In the inset Molleweide projection of the globe, NCB, North China block.

Eurasia approaching the North Pole. Tectonic activity seemed mostly confined to the probable beginning of a slow closure of the Slide Mountain Ocean along the western margin of Pangea. According to Mortensen (1992), subduction had started beneath the outboard margin of the Yukon composite terrane in the Late Devonian and continued until the Early Mississippian, but its polarity reversed by mid-Permian time. Such a scenario agrees with Tempelman-Kluit's (1979) belief that his Anvil Ocean initiated as a back arc basin. If there was a mid-Permian reversal of subduction direction then the Slide Mountain Ocean had to have been sufficiently wide, and the subduction sufficiently long-lived, to generate a westward-subducted slab that imprinted the geological record of the Yukon composite terrane and allowed the Yukon Composite terrane to eventually be obducted onto the North American craton, possibly as late as Middle Jurassic time. This is supported by the work of Gordey *et al.* (1987), who suggested that by mid-Mississippian time the Slide Mountain Ocean had become sufficiently deep and wide that clastic sediment from the rifted Yukon composite terrane no longer reached the margin of the North American craton. In Figure 5.11 (310 Ma) the Slide Mountain Ocean is shown with a width of 1000–1200 km based on an analogy with the Cenozoic South China Sea, where Palawan, Reed Bank and other blocks were rifted from the South China block margin and transported *c.*1200 km southward from the Eocene until spreading stopped in the Miocene (Lee & Lawver 1995) and will eventually be re-attached to the South China margin if Australia continues its present northward track.

By the end of the Permian at 251 Ma, shown in Figure 5.12 (250 Ma), Pangea was assembled. The Triassic rifting that would begin the breakup of Pangea had not begun but the Slide Mountain Ocean must have been closing if the age of volcanics on the Yukon composite terrane are a guide to subduction and island arc volcanism (Mortensen 1992; Plafker & Berg 1994).

Conclusions

In many ways, the 'Arctic' continents may have been close to each other since prior to the beginning of the Palaeozoic. If the Gladkochub *et al.* (2006) reconstruction for the Neoproterozoic is correct, at least Siberia and Laurentia have been relatively close since perhaps the early Neoproterozoic. They suggest, though, that the gap between Siberia and Laurentia at *c.* 750 Ma was filled with micro-continents. They go on to suggest that, based on the APW of the Mesoproterozoic to Early Neoproterozoic palaeomagnetic poles for Siberia and Laurentia, the two continents may have also been very close for the period from *c.* 1100 to *c.* 980 Ma.

For the Late Neoproterozoic, Walderhaug *et al.* (2007) provide a robust palaeomagnetic pole for Baltica that agrees quite well with earlier poles by Storetvedt (1966) and Poorter (1972). Combining

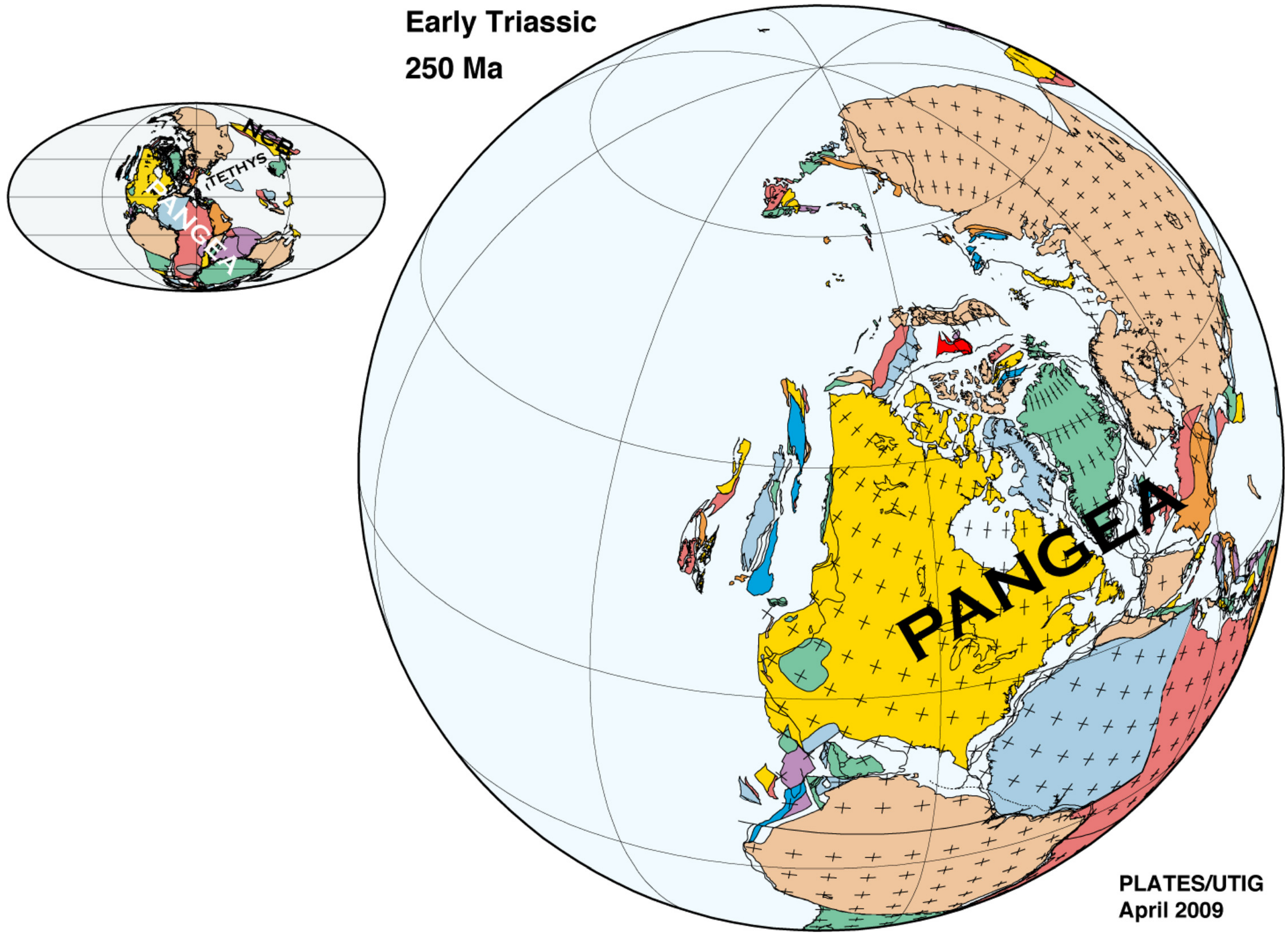

Fig. 5.12. A palaeoreconstruction for the end of the Palaeozoic at 250 Ma is shown. Pangea is shown as a tight-fit collection of continental blocks with only a small Slide Mountain Ocean still extant off what will later be western North America. The Chukchi Borderland (shown in red) is part of the northern margin of Laurentia, shedding sediments into the Sverdrup Basin. In the inset Molleweide projection of the globe, NCB, North China block.

those three poles with similar aged poles for Laurentia and for Siberia produced the Late Neoproterozoic reconstruction shown in Figure 5.2 for 616 Ma, which is very similar to the ones by Pisarevsky *et al.* (2008) and Walderhaug *et al.* (2007) but include the other Arctic blocks. All of the future Arctic continents would have been close to one another bordering a small but southern ocean. Siberia may have been rotated by 180° from Baltica and Laurentia and, if Arctic Alaska and Chukotka were attached to the present northern margin of Siberia, they would have been distant from both Laurentia and Baltica.

By the start of the Palaeozoic (Fig. 5.3, 544 Ma), if Siberia had been rotated 180° away from the other Arctic blocks in the Neoproterozoic, it was now oriented in its future orientation and Arctic Alaska and Chukotka would have been reasonably proximal to both Baltica and Laurentia as well as Amazonia. If the Timan Terranes had accreted to Baltica by this time or were still some distance away, the large present-day Barents Shelf would have been nearly continuous with the Siberian margin. Based on the palaeoreconstructions of Dalziel (1997, 2010), Gondwana had not yet amalgamated and Laurentia was further to the ‘south’ of the future South America than depicted in many other reconstructions for this time (Pisarevsky *et al.* 2008). By the Early Ordovician (Fig. 5.5, 487 Ma), Baltica was again in a far southern position, although perhaps not quite as far south as in the Early Cambrian as shown on the animation. Baltica was perhaps at its most distant position from Laurentia. By the end of the Middle Ordovician (460 Ma) Avalonia had rifted from Gondwana. Rapid subduction began and Avalonia with Baltica and Siberia moved rapidly westward. Avalonia and Baltica, with Pearya and Svalbard attached, collided with Laurentia in the Caledonian Orogeny (Embry 1989). The extent of the Caledonian Orogeny is shown in Figure 5.6 for the Early Silurian (436 Ma).

The X-path motion for the Silurian (Vérard *et al.* 2005) is used in the animation rather than the Y-loop. This choice eliminates the rapid motion of Gondwana that must be presumed to have begun in the Late Ordovician and continued eastward until a reversal in motion in the Late Silurian. Plate motions using the Y-loop during the Early Silurian exceed present day known maximum plate motions by almost a factor of 2. By the Early Devonian, *c.* 400 Ma, plate motions have returned to expected rates just prior to the possible collision of greater Siberia with Laurussia. This possible collision would have resulted in the transfer of Arctic Alaska and Chukotka with Chukchi Cap blocks to Laurussia along the future Canadian Arctic margin. By Late Devonian (364 Ma, Fig. 5.9), Siberia rifts from Laurussia and begins to move away, possibly as the result of the eruption of a large igneous province that formed long, linear dykes along the edges of the Vilyuy Basin (Parfenov 1997). During the Carboniferous (337 Ma, Fig. 5.10 and 310 Ma, Fig. 5.11), the Slide Mountain Ocean formed when the Yukon Composite Terrane rifted off northwestern Laurussia. The final figure for the end of the Palaeozoic shows Pangea as a whole with the Arctic continents in close proximity.

Summary

An ocean existed between the 'Arctic' continents for much of the Early Palaeozoic although it varied in size and latitude and eventually disappeared in the Middle Pennsylvanian (310 Ma, Fig. 5.11). The Arctic continents during the whole of the Palaeozoic were along the margins of a sea that at no time was greater than about 6000 km across at its widest point. Once Siberia had rotated to face the other Arctic blocks in a relationship similar to present day by the beginning of the Palaeozoic, the Arctic blocks were never far apart. The end Palaeozoic formation of the Arctic continents was replaced by a new ocean formed when the Arctic Alaska–Chukotka block rifted from Arctic Canada during the Late Jurassic or Early Cretaceous.

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