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Paleogeographic reconstructions and basins development of the Arctic

Jan Golonka[a,*], Natalia Y. Bocharova[b], David Ford[c], Mary E. Edrich[d],
Jolanta Bednarczyk[e], James Wildharber[f]

[a]*Institute of Geological Sciences, Jagiellonian University, Oleandry Str. 2a, 30-063 Kraków, Poland*
[b]*Department of Computer Sciences, University of Arlington, Arlington, TX, USA*
[c]*709 Foxmoor Drive, Highland Village, TX 75077-7031, USA*
[d]*1927 Foreland Drive, Houston, TX 77077, USA*
[e]*12810 Midway Road # 2044, Dallas, TX 75244, USA*
[f]*105 Dan Moody Trail, Georgetown, TX 78628, USA*

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Abstract

Paleogeographic maps were constructed to depict the Phanerozoic plate tectonic configuration, paleoenvironment and lithofacies. These maps illustrate the geodynamic evolution of the circum-Arctic region. The relationship of the continental configuration, lithofacies, tectonics and climate from the disassembly of Rodinia to the assembly and breakup of Pangea is clearly depicted on this series of reconstructions. The distribution of lithofacies shows climatic change associated with continental assembly and disassembly as well as with the steady northward drift of the continents.

From a regional perspective the facies in basins along the circum-Arctic margin reflect various stages of geotectonic development. The assembly of continents contributed to the formation of foreland basins. The breakup of continents, especially of the Pangean supercontinent, generated basins related to rifting and passive margin development. The subduction zones are related to the back-arc basins. The inversion caused by ridge pushing played an important role in the basin evolution.

Keywords: Phanerozoic; Plate tectonics; Paleogeography; Arctic; Sea-level; Paleoclimate; Lithofacies

1. Introduction

1.1. Mapping methodology

This paper was prepared as a contribution to the 31st International Geological Congress, Rio de Janeiro, Brazil, 2000. Its objective is to review the paleogeography, paleoenvironment and lithofacies of the circum-Arctic margins during the Phanerozoic time. Data for the maps were derived from geologic reports, maps and stratigraphic columns and other paleogeographic interpretations regarding tectonics, basin formation, and deposition.

Thirty-one maps were constructed which depict the plate tectonic configuration, paleogeography and lithofacies for Phanerozoic time intervals from the Early Cambrian through the Neogene. Generally, the individual maps illustrate the conditions present during the maximum marine transgressions of higher frequency cyclicity within the Sauk, Tippecanoe, Kaskaskia, Absaroka, Zuni, and Tejas megasequences of Sloss (Golonka, 2000; Golonka & Kiessling, 2002). These maps in full colors are available on the Elsevier homepage.

The maps were constructed using a plate tectonic model, which describes the relative motions between approximately 300 Plate and terranes. This model was constructed using PLATE and PALEOMAP software (Golonka, 2000; Golonka, Ross, & Scotese, 1994; Lawver & Scotese, 1987; Scotese & McKerrow, 1990; Ziegler, Hulver, & Rowley, 1997) which integrate computer graphics and data management technology with a highly structured and quantitative description of tectonic relationships. The heart of this program is the rotation file, which is constantly updated, as new paleomagnetic data become available. Hot-spot volcanics serve as reference points for the calculation of paleolongitudes (Golonka & Bocharova, 2000; Morgan,

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[*] Corresponding author. Fax: +48-12-633-2270.
E-mail address: golonka@geos.ing.uj.edu.pl (J. Golonka).

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1971). Magnetic data have been used to define paleolatitudinal position of continents and rotation of Plate (Bachtadse, Torsvik, Tait, & Soffel, 1995; Bazhenov, Alexutin, Bondarenko, & Sokolov, 1999; Besse & Courtillot, 1991; Didienko et al., 1993; Harbert, 1990, 1991; Irving, 1979; Kent & Van der Voo, 1990; Levashova, Bazhenov, & Shapiro, 1997; Lewandowski, 1993, 1997, 1998; Pechersky, Levashova, Shapiro, Bazhenov, & Sharonova, 1997; Torsvik & Anderson, 2002; Torsvik et al., 1996, 1995, 2001; Van der Voo, 1988, 1993; Xu, Harbert, Dril, & Kravchinsky, 1997).The maps were constructed using a plate tectonic model, which describes the relative motions between approximately 300 Plate and terranes. Because of the journal's figures size and scale, numerous small Plate were concatenated to produce large blocks like Kazakhstan, Siberia or Verkhoyansk. For example, Kazakhstan plate was constructed by transforming elements of Kipchak arc (Golonka, 2000) prior to its appearance in the presented set of maps. This model was constructed using PLATE and PALEOMAP software (Golonka & Gahagan, 1997; Golonka et al., 1994; Lawver & Gahagan, 1993; Lawver & Scotese, 1987; Scotese, 1991; Scotese & McKerrow, 1990; Ziegler et al., 1997) which integrate computer graphics and data management technology with a highly structured and quantitative description of tectonic relationships. Ophiolites and deep-water sediments mark paleooceans, which were subducted and included into foldbelts.

Information from several general and regional geological, geophysical, tectonic and paleogeographic papers were filtered and utilized (Bjornseth et al., 1997; Bogatski et al., 1996; Bogdanov et al., 1998; Doré, 1991; Doré, Lundin, Birkeland, Eliassen, & Jensen, 1997; Drachev, Savostin,

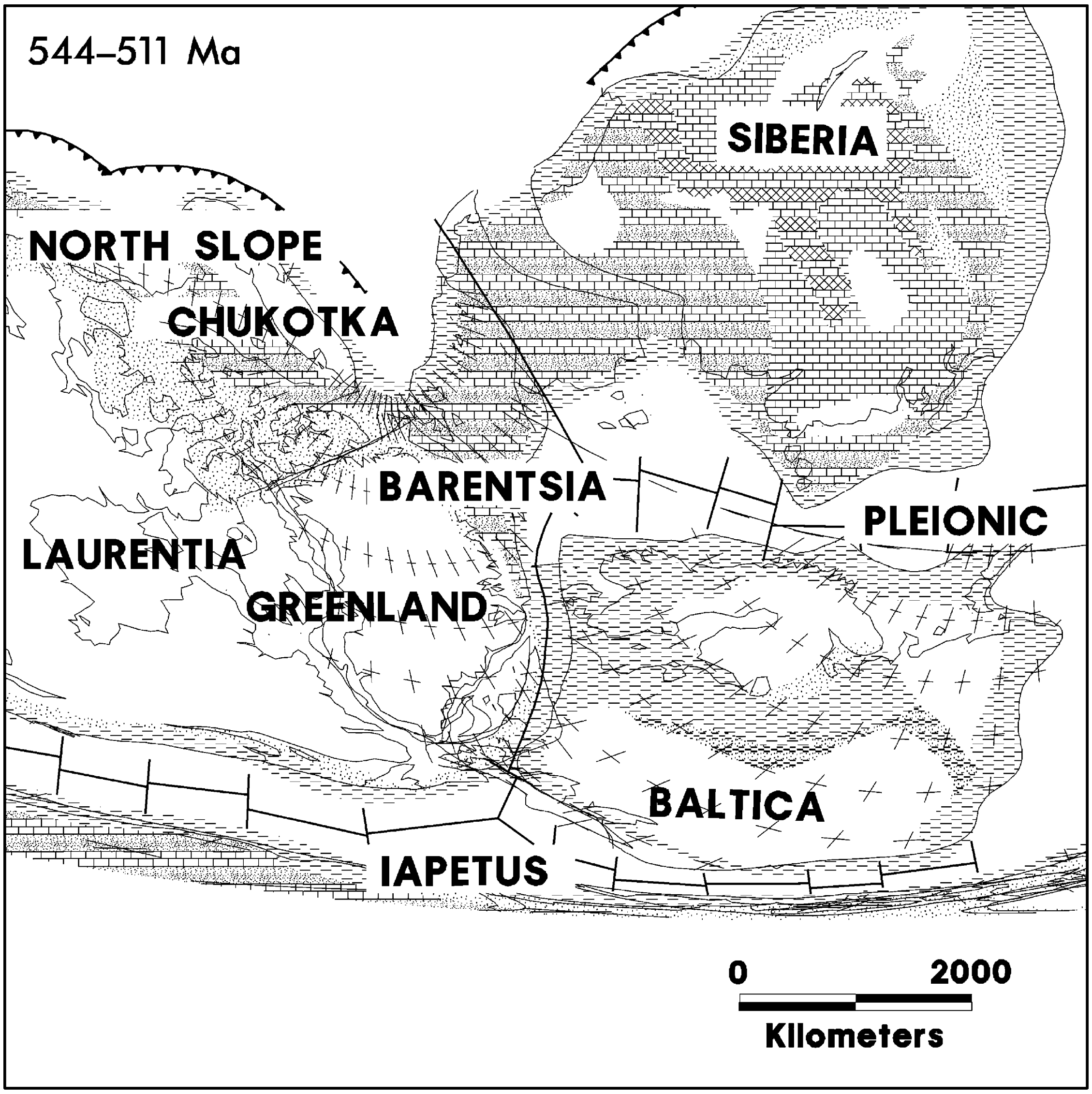

Fig. 1. Paleoenvironment and lithofacies of the major Arctic Plate during Sauk I–Nemakit/Daldynian–Toyonian (Early Cambrian) 544–511 Ma. Mollweide projection.

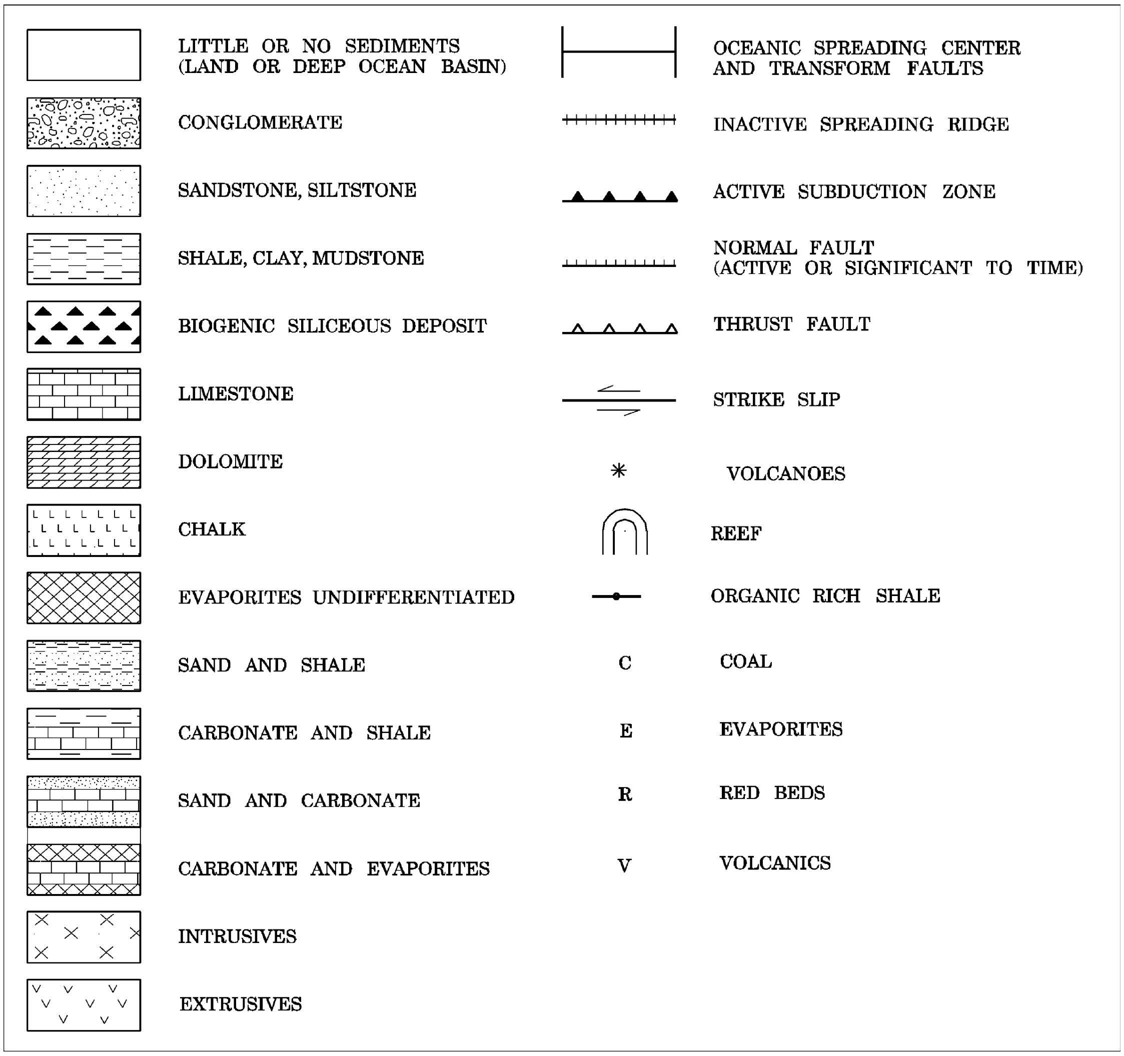

Fig. 1 (*continued*)

Groshev, & Bruni, 1998; Embry, 1989, 1991; Franke, Kruger, & Klinge, 2000; Golonka et al., 1996, 1994, 1999; Golonka & Scotese, 1995; Grantz et al., 1998, 1990; Green, Kaplan, & Vierbuchen, 1984; Gustavsen, Dypvik, & Solheim, 1997; Hansen & Dusel-Bacon, 1998; Inger, Scott, & Golionko, 1999; Jackson & Gunnarsson, 1990; Japsen & Chalmers, 2000; Johnsson, 2000; Khanchuk & Ivanov, 1999; Khudoley et al., 2001; Khudoley & Guriev, 1994; Kiessling, Flügel, & Golonka, 1999; Lane, 1997, 1998; Lane & Dietrich, 1995; Lawver & Gahagan, 1993; Lawver, Müller, Srivastava, & Roest, 1990; Layer et al., 2001; Leith et al., 1993; Lyberis & Manby, 1999; Mackey, Fujita, & Ruff, 1998; Natalin, Amato, Toro, & Wright, 1999; Nikishin et al., 1996; Oxman et al., 1995; Parfenov, 1994, 1997; Parfenov, Natapov, Sokolov, & Tsukanov, 1993; Parrish, Droser, & Bottjer, 2001; Puchkov, 1991; 1996, 1997; Rønnevik et al., 1982; Ronov, Khain, & Balukhovski, 1989; Ronov, Khain, & Seslavinski, 1984; Sakaulina et al., 2000; Scotese & McKerrow, 1990; Sekretov, 2002; Sengör & Natalin, 1996; Sloss, Dapples, & Krumbein, 1960; Smethurst, 2000; Stephenson & Smolyaninova, 1999; Vinogradov, 1968a,b,c; Vinogradov & Drachev, 2000; Whittaker, Hamann, & Pulvertaft, 1997; Williams, Dehler, Grant, & Oakey, 1999; Worrall, 1991; Worrall, Kruglyak, Kunst, & Kuznetsov, 1996; Ziegler, 1982; 1988, 1989, 1990; Ziegler et al., 1997; Zonenshain, Kuzmin, & Natapov, 1990; Zonenshain & Natapov, 1990). We have also utilized the unpublished maps and databases from the PALEOMAP group (University of Texas at Arlington), PLATE (University of Texas at Austin), University of Chicago, Institute of Tectonics of Lithospheric Plate in Moscow, Robertson Research in Llandudno, Wales, and the Cambridge Arctic Shelf Programme. The plate and terrane separation was based on the PALEOMAP system (Scotese & Langford, 1995), with later modifications (Golonka, 2000, 2002). The data from the numerous regional papers were used to verify author's geotectonic concepts, especially timing and mode of rifting, separation of plates and other terranes, or collisions and terrane suturing. The author's unpublished observations have also been utilized. The calculated paleolatitudes and paleolongitudes were used to generate computer maps in the Microstation design format using the equal area Molweide projection for Paleozoic and stereographic polar for Mesozoic and Cenozoic maps.

2. Map discussion: paleogeography, geodynamic evolution and basin development

2.1. Sauk (Early Cambrian–Middle Ordovician, 544–464 Ma): Iapetus and Rheic oceans

2.1.1. Geodynamic evolution

The supercontinent Gondwana and three major continental Plate—Baltica (NE Europe), Laurentia (N. America) and Siberia were distinguished at the beginning of Phanerozoic (Golonka, 2000, 2002; Scotese & McKerrow, 1990; Fig. 1). Baltica consisted of a major part of northern Europe; it was bounded on the west by the Iapetus suture, on the east by the Ural suture, on the south by the Variscan/Hercynian suture, and on the southwest by a suture located close, but not quite along the Teisseyre–Tornquist line. The Laurentian continent included major parts of North America, northwest Ireland, Scotland, Greenland, and Chukotka peninsula. The Early Paleozoic margin of Laurentia can be recognized in the Appalachians. The paleocontinent of Siberia was bounded on the west by the Urals and the Irtysh foldbelts, in the south by the Amurian (Mongolian) terranes and ophiolitic belts and on the northeast by the Verkhoyansk fold belt. These three major plates contained most of the terranes, which are presently located with the Arctic Ocean and along its margins. They were located south of Equator during early Phanerozoic.

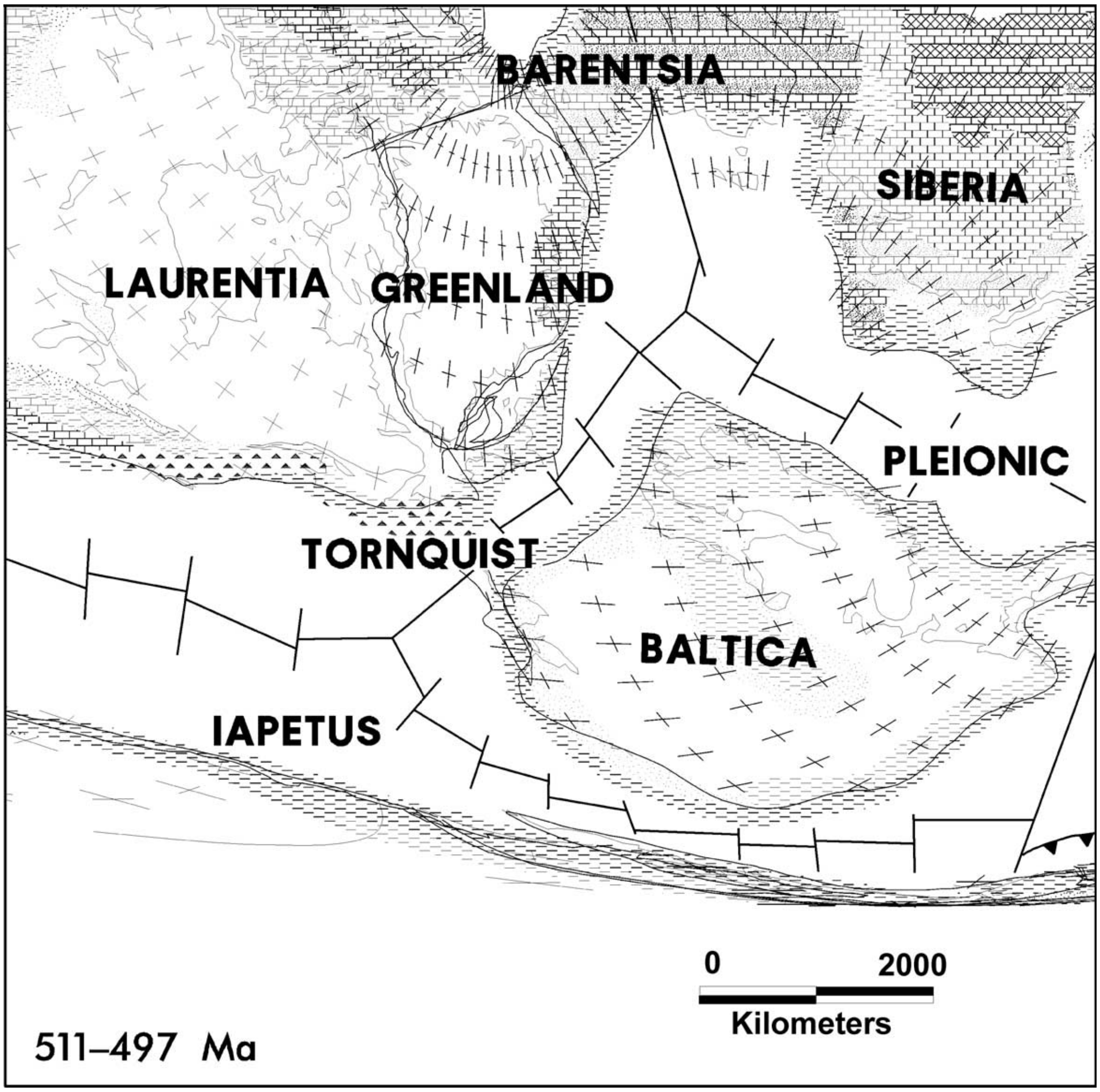

Fig. 2. Paleoenvironment and lithofacies of the major Arctic plates during Sauk II–Middle Cambrian (Middle Cambrian–Dresbachian) 511–497 Ma. Mollweide projection. For explanation see keys in Fig. 1.

The Baltica might have collided with the Cadomian part of Gondwana during Vendian causing deformation in the Timan area and proto-Uralian area. The Pechora–Timan belt and fragments of Ural, Novaya Zemlya and Taimyr (Olovyanishnikov, Siedlecka, & Roberts, 1997; Puchkov, 1997; Roberts et al., 1997; Vernikhovsky, 1997, 1998) are equivalent of the Cadomian belt (Golonka, 2000, 2002). The connection between Siberia, the Verkhoyansk (Kolyma–Okhotsk) terranes (northeastern Russia) and Barentsia (Svalbard and adjacent part of the Barents Sea) remain very speculative. The relative positions of Laurentia, Baltica and Siberia are also somewhat uncertain.

Laurentia and Baltica drifted apart from Gondwana during the Late Vendian time (Torsvik et al., 1996). Their breakup led to the formations of new oceans—Iapetus Ocean between Baltica and Laurentia and between Laurentia and Gondwana, Tornquist Sea between Baltica and Avalonia (part of Gondwana), Pleionic Ocean between Siberia and Baltica. The Paleoasiatic Ocean between Siberia and Gondwana (Chinese Plate) also existed at that time. The position of Baltica in relation with Gondwana's Cadomian terranes agrees roughly with Puchkov's (1997) analysis, suggesting Vendian rifting, following the Cadomian–Timanian orogeny.

The Iapetus Ocean continued to widen with Baltica and Laurentia rapidly drifting northward to low latitudes during Cambrian and Early Ordovician (Figs. 2 and 3). Early Ordovician was the time of maximum dispersion of continents of the Paleozoic. The Iapetus–Tornquist Sea oceanic system also widened significantly (Torsvik et al., 1995, 1996). The estimated width of the ocean between

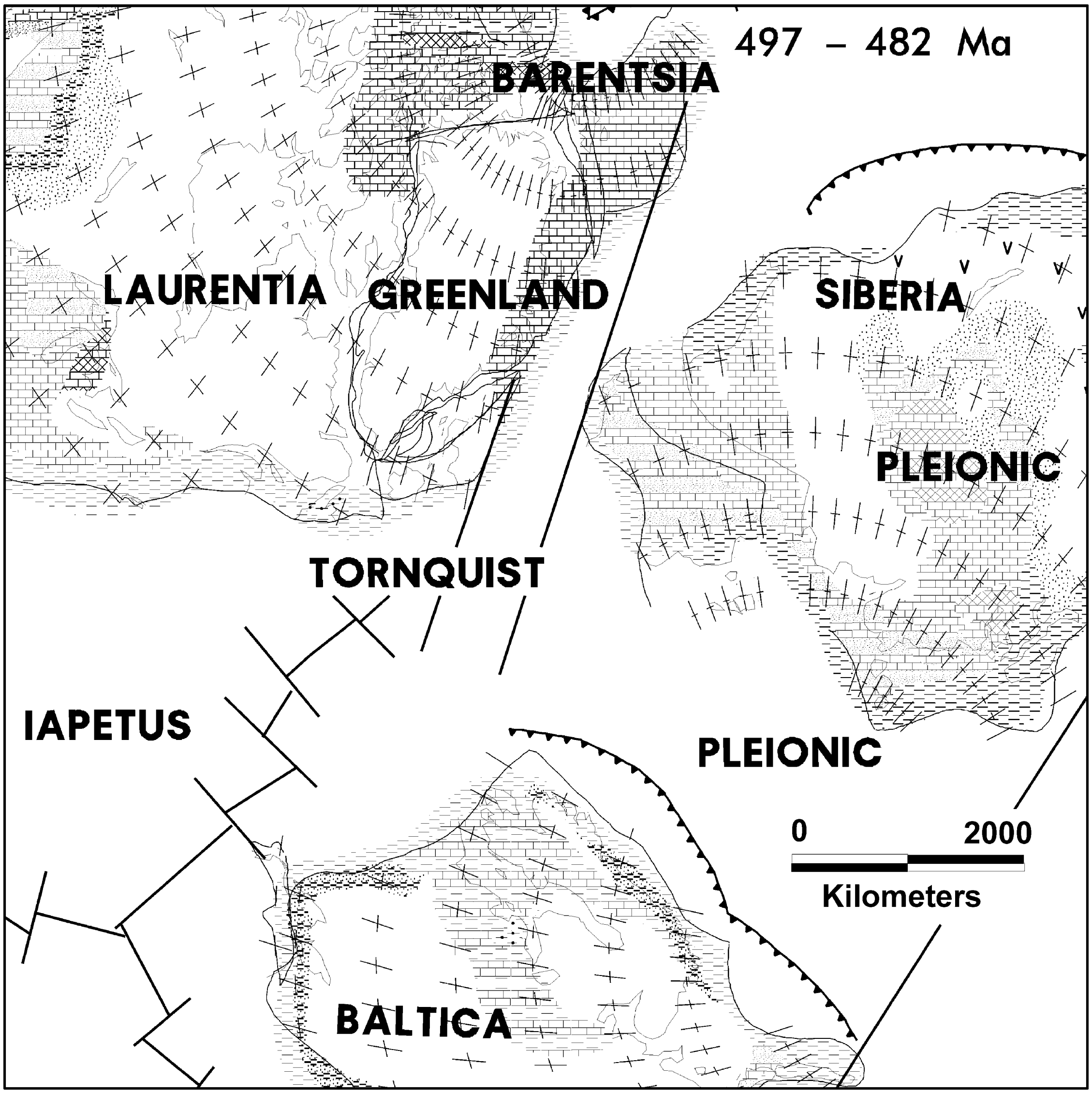

Fig. 3. Paleoenvironment and lithofacies of the major Arctic plates during Sauk III–Tremadocian (Franconian–Tremadocian) 497–482 Ma. Mollweide projection. For explanation see keys in Fig. 1.

Baltica and Laurentia depends upon the latitudinal position of Laurentia. Rifting of arcs (Oliverian/Midland Valley terrane), off the eastern coast of Laurentia, occurred during the Late Cambrian to earliest Ordovician time (McKerrow, Dewey, Scotese, 1991). Arc-continent collisions occurred along the margins of the Iapetus–Tornquist–Pleionic oceanic system in Baltica and in Avalonia causing the Penobscottian, Grampian, Finnmarkian, and Athollian Orogenies (Neuman and Max, 1989; Ziegler, 1990). The deformation events in Baltica might have been related to the transformation of a passive margin into a convergent one, due to the development of a subduction zone.

Major plate reorganization occurred at the end of the Sauk, late Early to Early Middle Ordovician (Fig. 4). The Iapetus Ocean and the Tornquist Sea had begun to narrow. According to Torsvik et al. (1996), Baltica rotated significantly during the Ordovician with the distance between Avalonia and Laurentia being reduced from 5000 to 3000 km by the Llanvirnian. Arcs were present in the east of Laurentia and in Avalonia. Avalonia drifted away from Gondwana toward Baltica. Between Gondwana, Baltica, Avalonia, and Laurentia, a large longitudinal oceanic unit known as the Rheic Ocean (McKerrow et al., 1991) was formed. Rifting events occurred along the Northern Urals and Pay Khoy belts on the eastern margin of Baltica (Nikishin et al., 1996), perhaps following the orogenic events mentioned above. The relationship between the different parts of the Rheic Ocean connections with Paleoasian and Phoibic Ocean as well as the relationship between Laurentia and Siberia, including the mapped strike-slip remains uncertain.

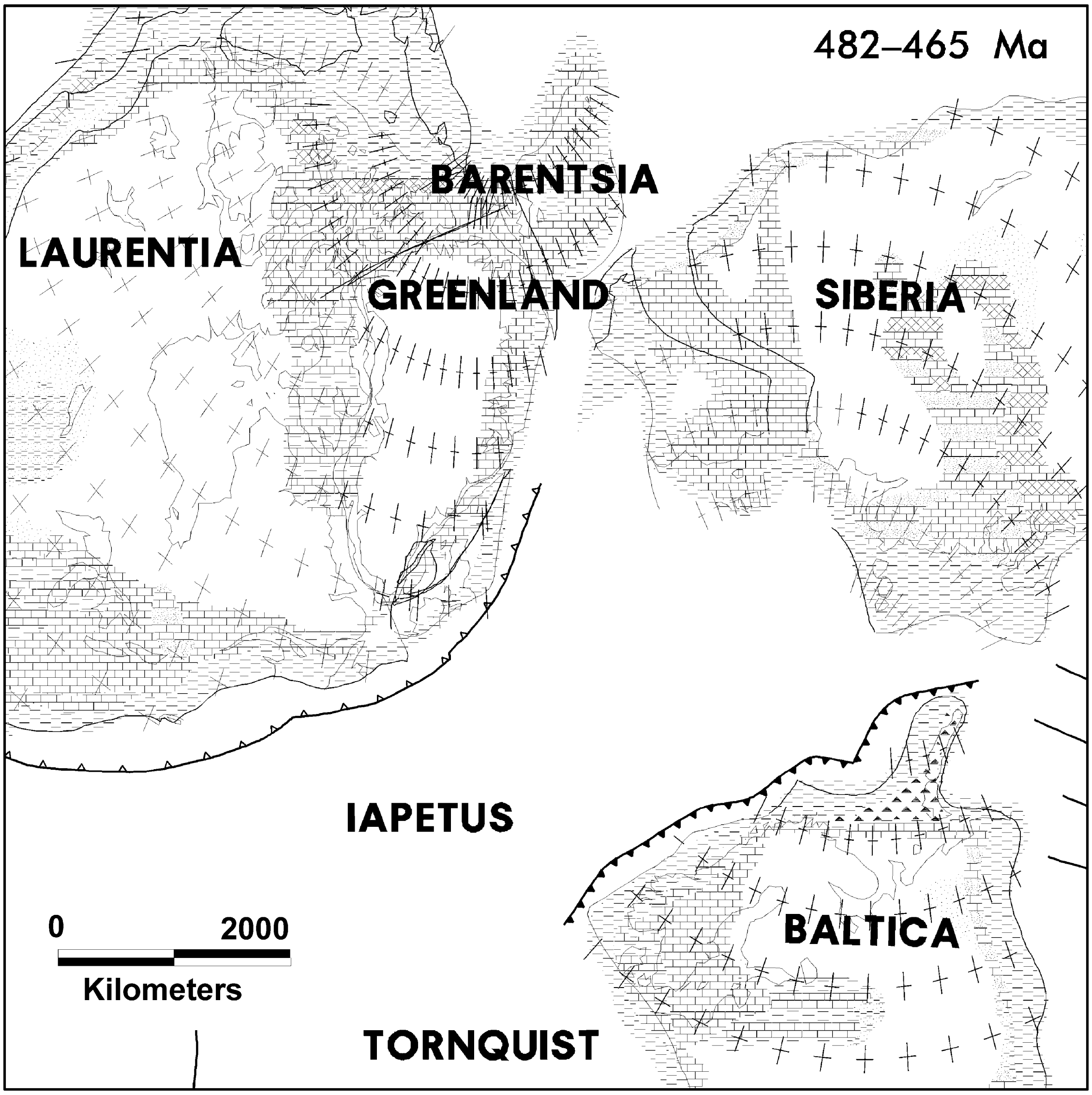

Fig. 4. Paleoenvironment and lithofacies of the major Arctic plates during Sauk IV–'Arenigian' (upper Lower Ordovician) 482–465 Ma. Mollweide projection. For explanation see keys in Fig. 1.

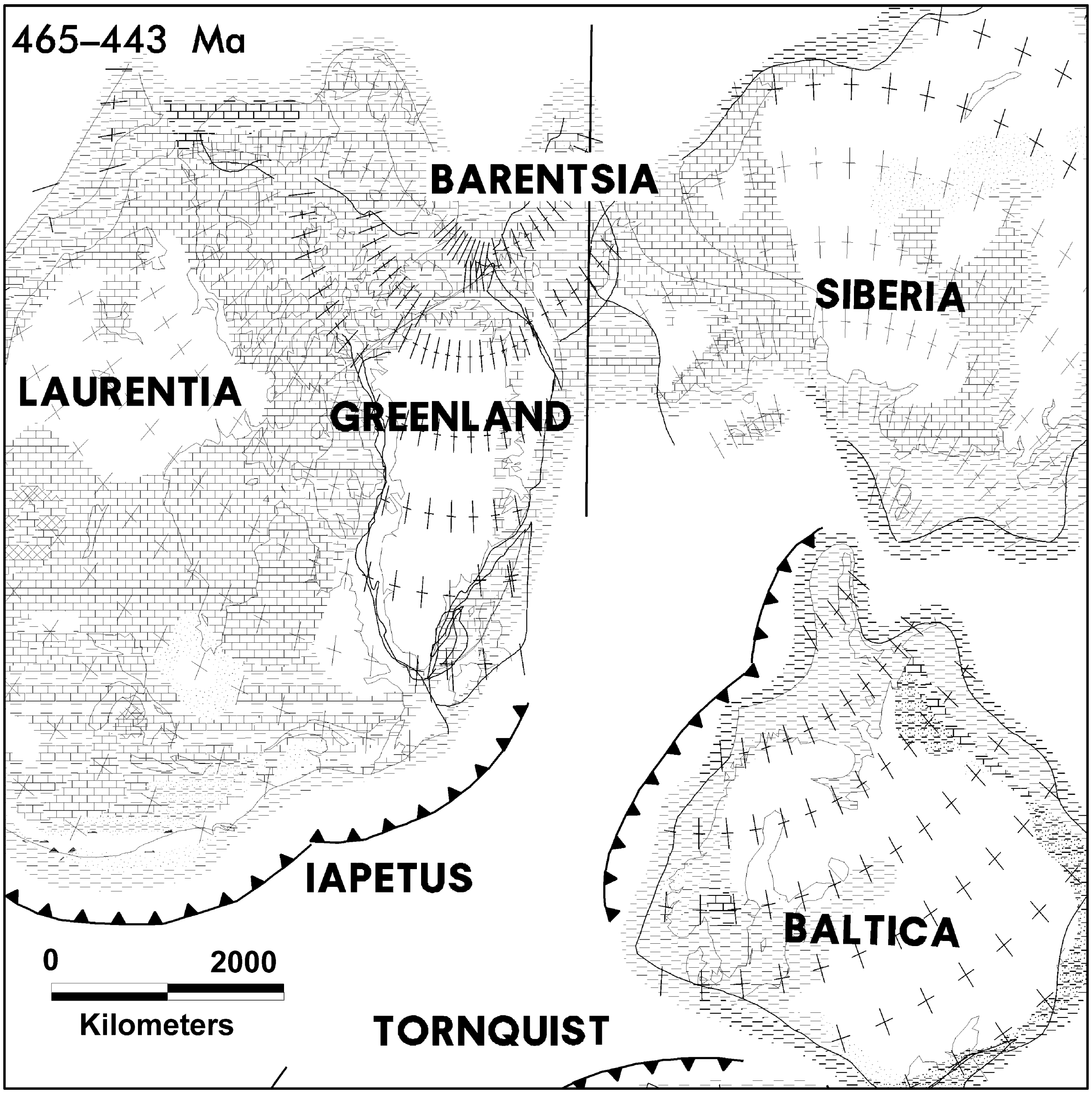

Fig. 5. Paleoenvironment and lithofacies of the major Arctic plates during Tippecanoe I–Caradocian (Middle Ordovician–Caradocian) 465–443 Ma. Mollweide projection. For explanation see keys in Fig. 1.

2.1.2. Lithofacies and basins

Sauk was a time of mature drifting of Laurentia, Siberia and Baltica, following breakup of Precambrian Pangea. Global sea level rise and flooding of passive continental margins was associated with this drifting. Warm, humid climatic conditions, limited continental aridity, and no known continental glaciation exemplified the transition to greenhouse conditions.

The beginning of Sauk is marked by rapid development of the carbonate platform in the epicontinental sea on Siberia (Puchkov, 1996). Siberia was nearly completely submerged and received continent-wide carbonate sedimentation. The carbonate deposits changed into evaporites toward the center of the craton.

Most continents have had wide passive margins that were dominated by fine-grained clastics with coarse-grained clastics restricted to shoreline positions. Sedimentary basins in North America were located only in the marginal zones of the Iapetus Ocean. Subsidence as well as mafic volcanism was typical for the Peri-Appalachian zone. The basalts and rhyolites were associated with rifting at the early stage and with the extension associated with a continuing opening of the Iapetus Ocean. The sedimentary complexes are represented mainly by coarse clastics, sandstones and shales (Ronov et al., 1984). Subsidence and transgressions occurred on the major part of the North American craton during the Sauk supersequence. The size of marine

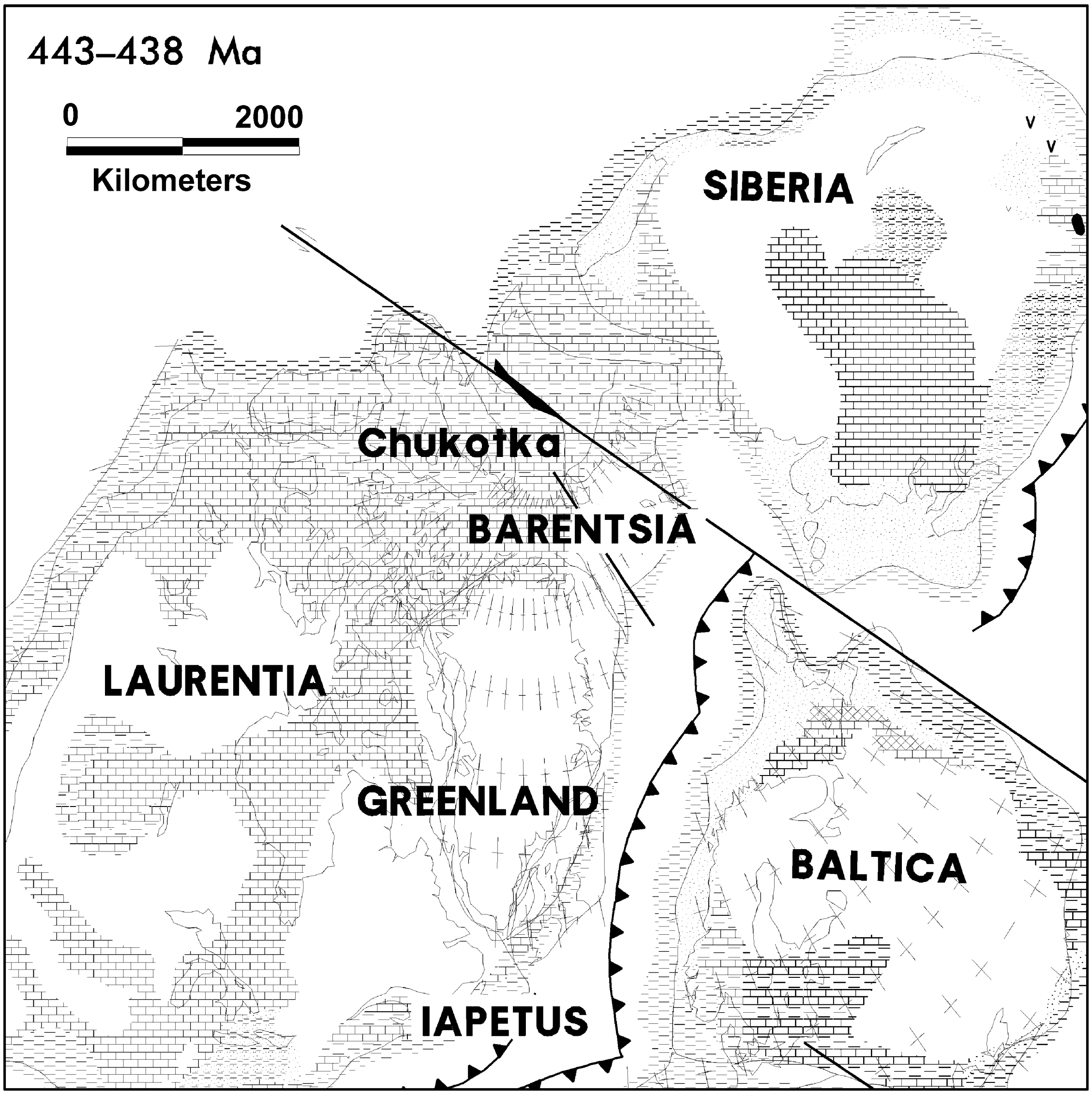

Fig. 6. Paleoenvironment and lithofacies of the major Arctic plates during Tippecanoe II–Llandoverian (Llandoverian) 443–428 Ma. Mollweide projection. For explanation see keys in Fig. 1. Black spots–ophiolites according to Oxman et al. (1995).

basins increased. By Late Cambrian almost one third of the craton was covered by marine sedimentary basins. A stable tectonic regime and a hot climate resulted in the deposition of limestone and dolomite (Fig. 3), particularly in the southern part of the mid-North American continent, on the Barentsia plate, and on the eastern Greenland shelf (Chafetz, 1980; McKerrow et al., 1991; Mellen, 1977; Stewart & Pool, 1974). Mixed carbonate/clastic sediments were deposited on Baltica in Poland and Scandinavia (McKerrow et al., 1991; Ronov et al., 1984).

Carbonate and evaporite sedimentation continued on the Siberian craton during the entire Sauk supersequence (Puchkov, 1996; Ronov et al., 1984). It is possible, that a connection existed between Laurentian and Siberian carbonate platforms, through the Barentsia and Verkhoyansk terranes.

2.2. Tippecanoe (Middle Ordovician–Early Devonian, 464–409 Ma): closing of the Iapetus Ocean

2.2.1. Geodynamic evolution

During the Ordovician, Baltica moved northwestward, relative to Laurentia, and the Iapetus Ocean narrowed significantly (Fig. 5). The sedimentary rocks were affected by thrusting. Isotopic age data indicate an early Silurian age for the onset of the Scandian Orogeny marked by the collision between Baltica and Laurentia Orogeny (Soper, Strachan, Holdsworth, Gayer, & Greiling, 1992). In the Late Llandoverian (Fig. 6), west-verging nappes were emplaced in northeast Greenland. After the first phase of the Scandian Orogeny, the southern part of the Iapetus Ocean still remained open between Avalonia and Laurentia. During the Late Silurian, the collision between Baltica and Greenland continued (Fig. 7). This main phase of the Scandian

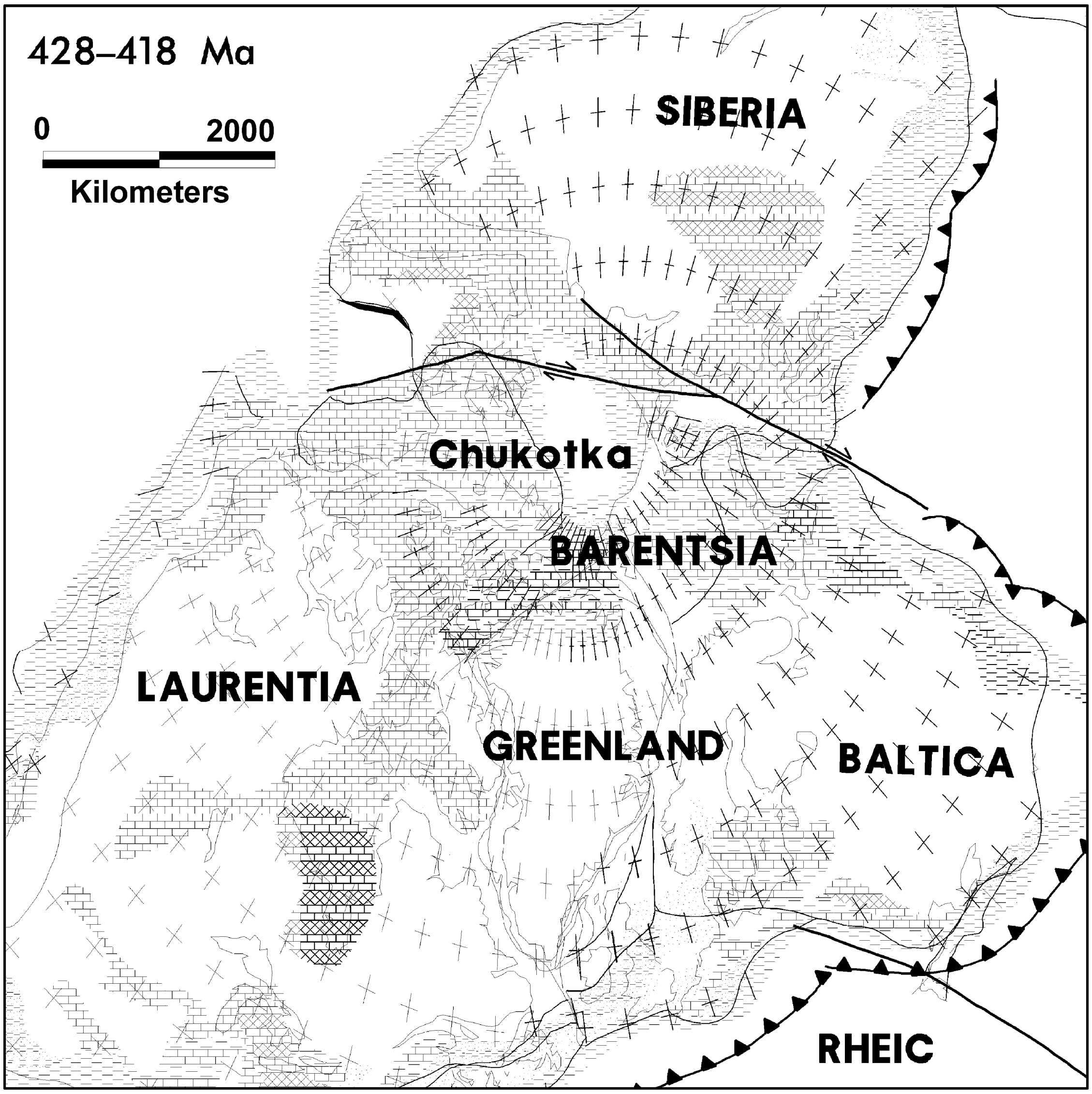

Fig. 7. Paleoenvironment and lithofacies of the major Arctic plates during Tippecanoe III–Wenlockian (Wenlockian–Early Pridolian) Tentative age range 428–418 Ma. Mollweide projection. For explanation see keys in Fig. 1. Black spots–ophiolites according to Oxman et al. (1995).

Orogeny is marked by nappes in Norway and Greenland. Laurentian crust was thrust over Baltica, causing large crustal thickening in the Caledonian belt (Dewey, Ryan, & Andersen, 1993; Torsvik et al., 1996). According to Soper et al. (1992), the East Greenland and Scandinavian Caledonides display similar age and kinematic patterns, indicating a change of convergence vector between Baltica and Greenland from sinistrally oblique to nearly orthogonal. During the Mid-Silurian, western Avalonia docked sinistrally with Newfoundland and eastern Avalonia rotated toward Scotland (Soper et al., 1992). After the complete closure of the Iapetus Ocean, the continents of Baltica, Avalonia, and Laurentia formed the continent of Laurussia (Ziegler, 1989). An extensional regime began to be established in the eastern part of Laurussia, which led to the Devonian development of numerous rifts and back-arc basins in this area (Nikishin et al., 1996).

The Franklinian Orogeny, in the northwestern Canada (Plafker & Berg, 1994), could be a result of collision of the Verkhoyanskian part of Siberia with the North Slope-Chukotkan part of Laurentia (Figs. 5–7). According to Okulitch (1998), the suturing in the Canadian Islands occurred during Ordovician–Silurian time. Zonenshain et al. (1990) postulate the existence of an Arktida continent, which collided with Laurentia (Natalin et al., 1999; Nikishin et al., 1996; Sengör & Natalin, 1996). Paleomagnetic data (Smethurst, Khramov, & Torsvik, 1998) support the latitudinal position of Siberia. A connection of Siberia and Laurentia, through the Verkhoyansk–North Slope-Chukotka terranes, is quite possible and logical. The Barentsia

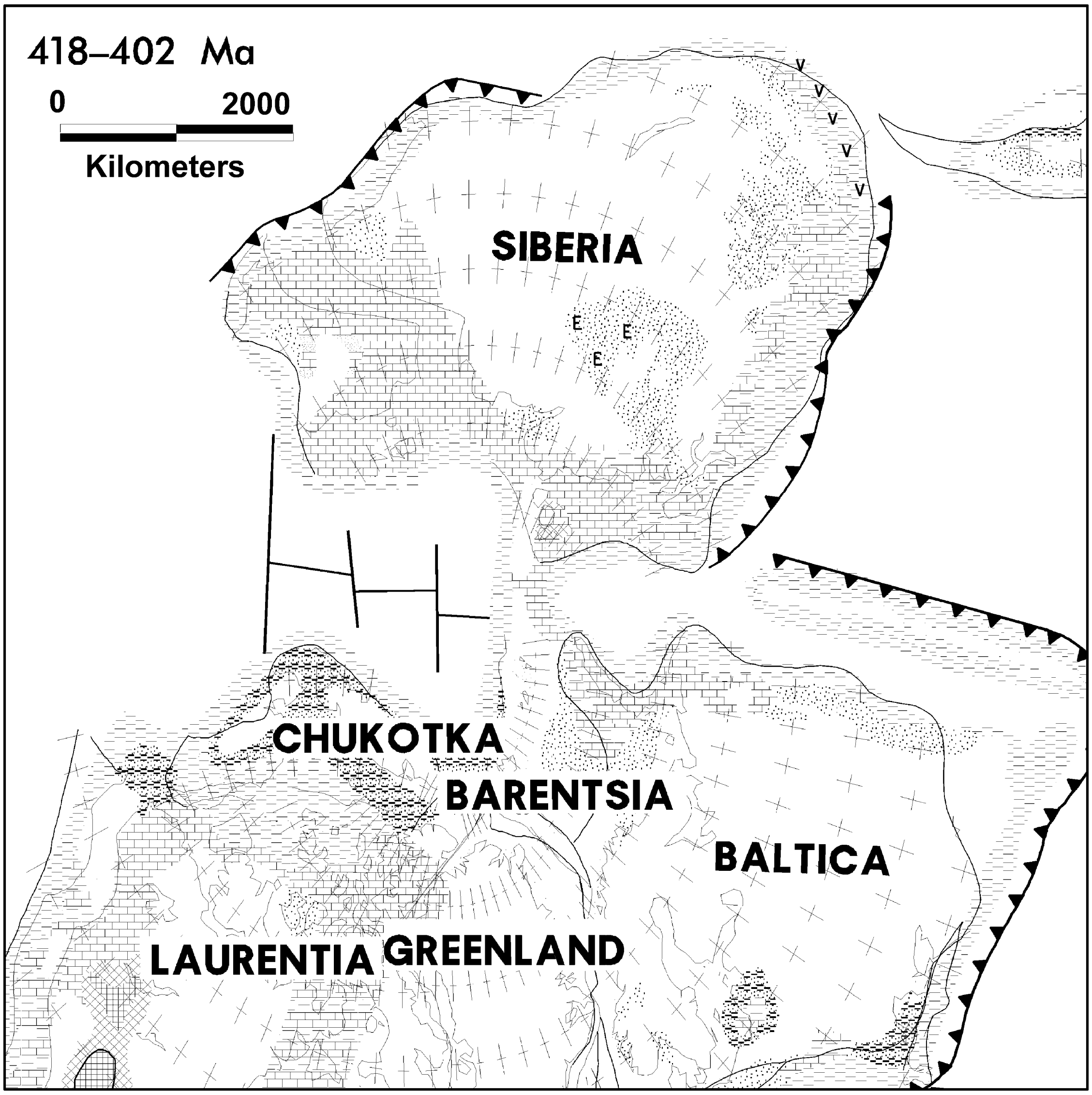

Fig. 8. Paleoenvironment and lithofacies of the major Arctic plates during Tippecanoe IV–Lochkovian (Middle Pridolian–Middle Pragian) 418–402 Ma. Mollweide projection. For explanation see keys in Fig. 1.

microcontinent, including Svalbard, collided with northern Baltica (Ohta, Krasilscikov, & Tebenkov, 1996; Smith, 2000). Thus, the supercontinent Laurasia I was formed. This continent was rimmed by the subduction zones on the southern and eastern margins. Caledonian structures are present in the mountain belts in East Greenland, Norway, and on Svalbard. Caledonian rocks are also suspected to form the basement of the Greenland continental shelf, Norwegian continental shelf, and northwestern Barents Sea (Bogatski et al., 1996; Johansen et al., 1993; Rønnevik et al., 1982).

During early Devonian a new rifting phase and reactivation of the Cambrian–Ordovician rift system began to develop in the Timan Pechora Basin on Baltica (Nikishin et al., 1996). The extensional phase began in the development of the Scandinavian Caledonides (Milnes et al., 1997; Rey, Burg, & Casey, 1997; Schlindwein & Jokat, 2000). The clockwise rotation of Siberia caused rifting between the Chukotka-North Slope and the Verkhoyansk terranes (Parfenov, 1997). Synchronous extension and collision events are typical for the West Laurentian (Cordillera) margin.

2.2.2. Lithofacies and basins

Tippecanoe was a time of maximum first-order sea-level highstand and continental submergence for the Paleozoic. Prolific marine source rock deposition occured, especially during the Early Silurian and Middle Ordovician, in association with a global oceanic anoxic events (OAE). During late-Middle to Late Ordovician, total size of marine basins in North America increased due to transgression southeast and north of Canada. Most

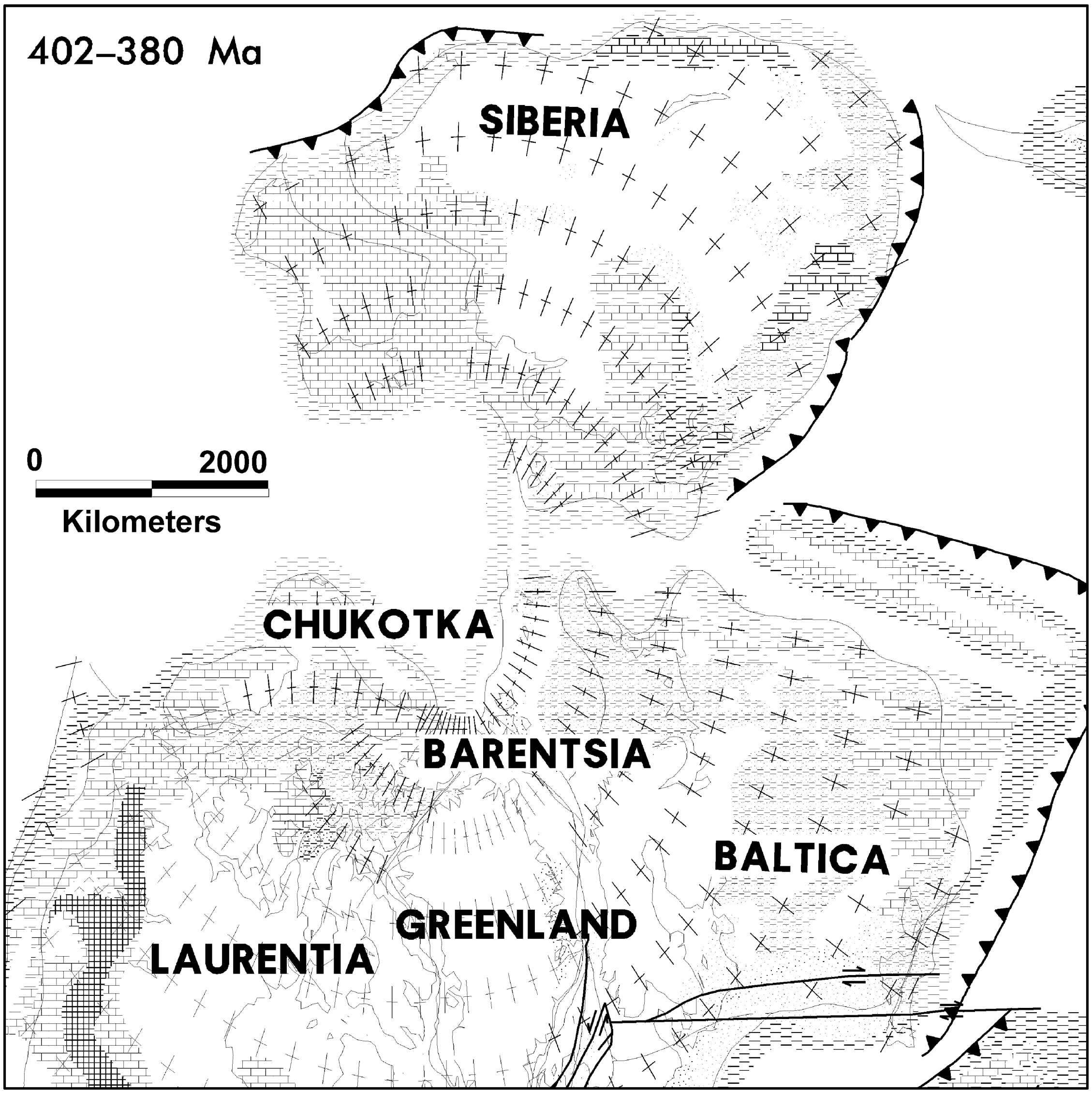

Fig. 9. Paleoenvironment and lithofacies of the major Arctic plates during Kaskaskia I–Emsian (upper Pragian–Eifelian) 402–380 Ma. Mollweide projection. For explanation see keys in Fig. 1.

of the Laurentia plate was submerged at this time, with carbonates dominant in the United States and Canada (Ross, 1976; Fig. 5). Interior basins had restricted circulation and accumulated marine source rocks. Carbonates also dominated in the proto-Arctic area, on Barentsia, and Eastern Greenland (Johansen et al., 1993; McGill, 1974; Surlyk, Hurst, & Bjerreskov, 1980). Carbonate and carbonate–terrigenous facies occurred in the eastern part of Baltica (Nikishin et al., 1996).

After the Late Ordovician transgression, a maximum of the Paleozoic, a regression developed in the Early Silurian in Laurentia and the total size of marine basins was reduced (Figs. 6 and 7). A large land area formed, especially in the mid-continental region. This feature plus a warm climate resulted in the dominant accumulation of carbonates and evaporites. The basins in East Greenland and adjacent part of Baltica were closed, due to the ongoing Caledonian Orogeny. Carbonates covered the Baltic Sea area on Baltica (McKerrow et al., 1991). Shallow-water carbonate muds were deposited in Southern Scandinavia and adjacent parts of Poland (McKerrow et al., 1991; Ronov et al., 1984). The large carbonate platform developed in the proto-Arctic area (Figs. 7 and 8).

Fine-grained clastics accumulated on wide continental margins, particularly along the northern margin of Gondwana. Abundant deeper-water marine shales occurred on wide continental shelves with coarse-clastics at retreating shoreline positions. Well-developed, transgressive, second-cycle sandstones were commonly overlain by black shale. Convergent margins of the Iapetus Ocean between Laurentia and Baltica are characterized by deltaic and submarine-fan depositional systems. Continental deposition

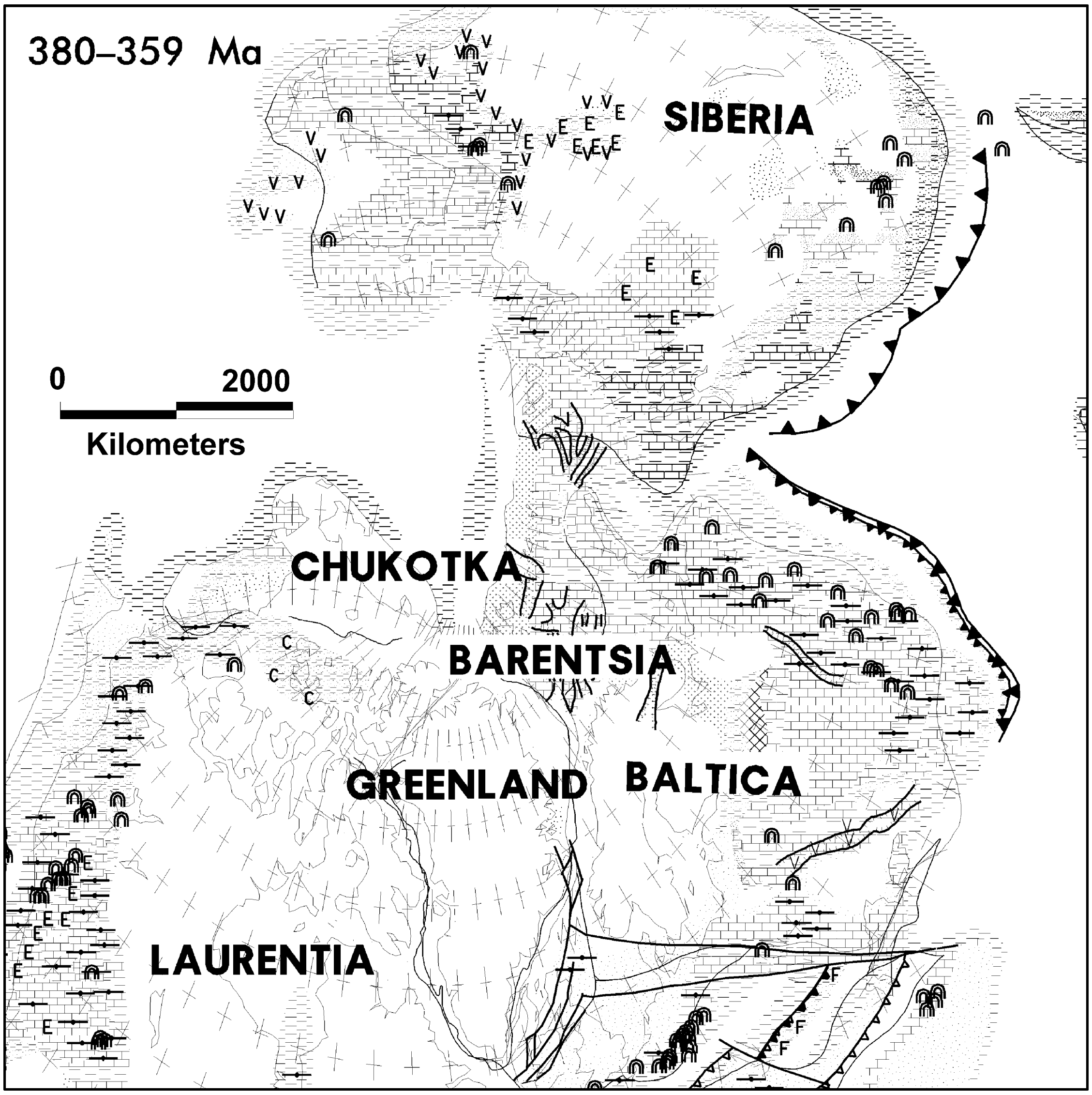

Fig. 10. Paleoenvironment and lithofacies of the major Arctic plates during Kaskaskia II–Frasnian (Givetian–lower Famennian) 380–359 Ma. Mollweide projection. For explanation see keys in Fig. 1.

occured in narrow linear troughs in back-arc and foreland basin settings in Laurentia and Baltica.

2.3. Kaskaskia (Early Devonian–Late Carboniferous, 409–323 Ma): closing of the Rheic Ocean

2.3.1. Geodynamic evolution

According to Milnes et al. (1997), final stage of contraction of the Caledonides in Norway took place during Early Devonian, between 410 and 395 Ma (Fig. 9). At the end of this phase, the strain field in the upper crust changed from contraction to extension.

Siberia passed over a hot-spot. Rifting and fracturing of the Siberian platform was associated with hot-spot activity, expressed by the intrusions of kimberlites. The Vilyuy Trough formed at that time. Kazakhstan began to converge with Siberia, consuming the Paleoasian Ocean floor (Zonenshain et al., 1990). Our reconstruction shows separation of Siberia, together with the Verkhoyansk (Kolyma–Okhotsk) terranes, from Laurentia, following the Franklinian–Innuitian Orogeny (Eide and Torsvik, 1996; Golonka and Scotese, 1995; Sengör and Natalin, 1996; Ziegler, 1989). It is also possible that Verkhoyansk stayed together with Laurentia (Cecile, Khudoley, Kos'ko, & Lane, 1998), while Siberia drifted away, rotating clockwise toward Kazakhstan (Parfenov, 1997).

During Late Devonian (Fig. 10), Laurussia was rotating clockwise (Torsvik et al., 1996) at a somewhat faster rate. The first contact between Laurussia and the central European promontory of Gondwana occurred in the Tornquist-Teisseyre zone. This contact marks the onset of Hercynian Orogeny. The Antler Orogeny occurred in

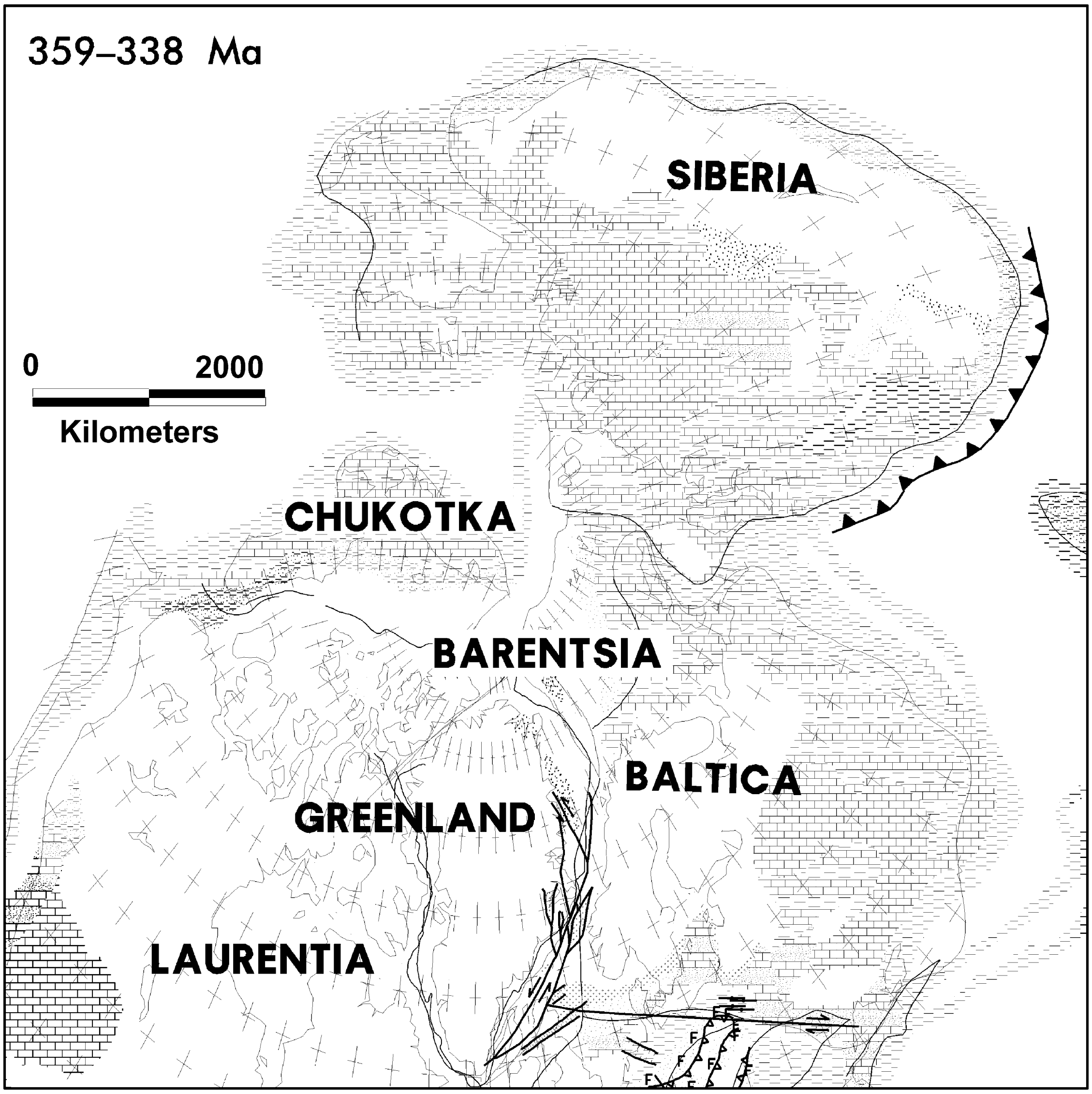

Fig. 11. Paleoenvironment and lithofacies of the major Arctic plates during Kaskaskia III–Tournaisian (upper Famennian–Lower Visean) 359–338 Ma. Mollweide projection. For explanation see keys in Fig. 1.

western Laurussia. Evidence for the Antler Orogeny is primarily derived from Nevada and California, where, during the Late Devonian to Early Carboniferous time (Fig. 11), the contents of the Antler basin were deformed and thrust to the east. Sporadic evidence supporting compressional nature of the Antler Orogeny exists in the rocks of British Columbia, Yukon Territory and Alaska (Oldow, Lallemant, & Leeman, 1989). This Orogeny was perhaps a result of the collision of the eastward advancing island arc with the western margin of North America (Hamilton, 1989). As a result of the Antler Orogeny, an eastward dipping subduction developed along the newly formed margin. The back-arc extensional environment developed in the Canadian Rockies accompanied by basalt flows and alkaline intrusions (Gabrielse & Yorath, 1991).

Development of major rift systems took place throughout Baltica and Siberia. The Dnepr–Donetsk–Pripyat system went through the main phase of rifting on Baltica (Nikishin et al., 1996). Rifting activity resumed along the eastern margin of Baltica, in the Barents Sea, Kola, Timan, Vyatka and Soligalich areas. All the above rifts were back-arc extensions, associated with subduction zone dipping towards Baltica. Rifting occurred between the Siberian plate and the Verkhoyansk (Kolyma–Okhotsk) terranes (Khudoley & Guriev, 1994; Parfenov, 1997). It is possible that the Barents Sea and Verkhoyansk rifts were connected.

During Early Carboniferous (Fig. 12), the Antler Orogeny was concluded in western North America (Hamilton, 1989; Oldow et al., 1989). Siberia rotated clockwise (Smethurst et al., 1998). Kazakhstan continued to converge with Siberia. Only a narrow strait remained from the former Paleoasian Ocean (Bush and Filippova, 1998; Zonenshain et al., 1990).

Fig. 12. Paleoenvironment and lithofacies of the major Arctic plates during Kaskaskia IV–Visean/Serpukhovian (Middle Visean–Serpukhovian) 338–323 Ma. Mollweide projection. For explanation see keys in Fig. 1.

The Verkhoyansk (Kolyma–Okhotsk–Chersky) terranes had broken off Siberia (Khudoley & Guriev, 1994; Zonenshain et al., 1990). Perhaps Siberia rotated clockwise, drifting towards the Kazakhstan plate (Smethurst et al., 1998), while the Verkhoyansk terranes stayed in place. Grabens formed between Greenland and Norway (Stemmerik, Vigran, & Piasecki, 1991).

Rifting was initiated between Laurentia and Baltica along the old Caledonian suture (Stemmerik et al., 1991; Ziegler, 1988). The opening of the Sverdrup Basin, in northern Canada was also initiated (Trettin, 1989). A passive margin developed along the newly opened oceanic basin between Siberia and the Verkhoyansk terranes (Khudoley & Guriev, 1994). An active margin could have existed southeast of Verhoyansk expressed by Middle to Late Devonian rhyolite, andesite, thrachyrhyolite and thrachyandesite and Late Silurian alkaline intrusions (Lychagin, 1983; Parfenov, 1992, 1994).

2.3.2. Lithofacies and basins

Following the consolidation of the Caledonides, from the Middle Devonian to the Late Carboniferous, the East Greenland and Norwegian margins and the western Barents Sea were affected by major sinistral strike/slip or transform movement and transpressional deformation, which formed intramontane basins filled with clastics (e.g. Old Red Sandstone). Up to 8 km of sediments of that were deposited on Svalbard and more than 7 km of continental clastics and volcanic rocks accumulated in a system of left-lateral, strike-slip faults in the East Greenland area. In the northern part of the Devonian basin system, sedimentation was influenced by several periods of compression phases that ended with pre-Tournaisian folding and thrusting. Abundant red beds, molasse, and continental evaporites were deposited in basins in the rain shadow of the north–south oriented Laurussian orogenic belt. Laurussian shelves exhibit both sandstone and shale, with sandstones being most abundant in interior seaways proximal to mountain belts. Deep-sea fans occurred basinward of the narrow collisional margins of southern Laurussia and marginal to the exotic terranes within the Uralian Ocean. Fluvial/deltaic sediments were located at the seaward terminations of Orogenic belts in northern Laurussia and East Siberia. Lacustrine sediments were localized in pull-apart basins within the central Laurussian mountain belt.

The area of carbonate sedimentation was decreasing during Early Devonian on the Laurussian continent (Ronov et al., 1984). The relatively narrow seaway between Northern Canada and the mid-continent area in North America was covered with mixed carbonate–clastic sediment. Carbonates were also deposited along the western margin of Laurussia. On the Siberian continent, carbonates occurred in the North (in present day coordinates) and in the Verkhoyansk area (Vinogradov, 1968a). In the southwestern part of Laurussia, in the peri-Caspian and peri-Ural area, mixed carbonate–clastic facies occurred. The carbonate platform increased in the northern and eastern part of Siberia and adjacent Verkhoyansk terranes (Vinogradov, 1968a). Limestones, dolomites and mixed clastic-carbonate facies were present in the central European terranes (Ziegler, 1989).

Middle and Late Devonian was a period of major reef development (Fig. 10). Carbonate-buildup trends occurred along the continental shelves. Many of these

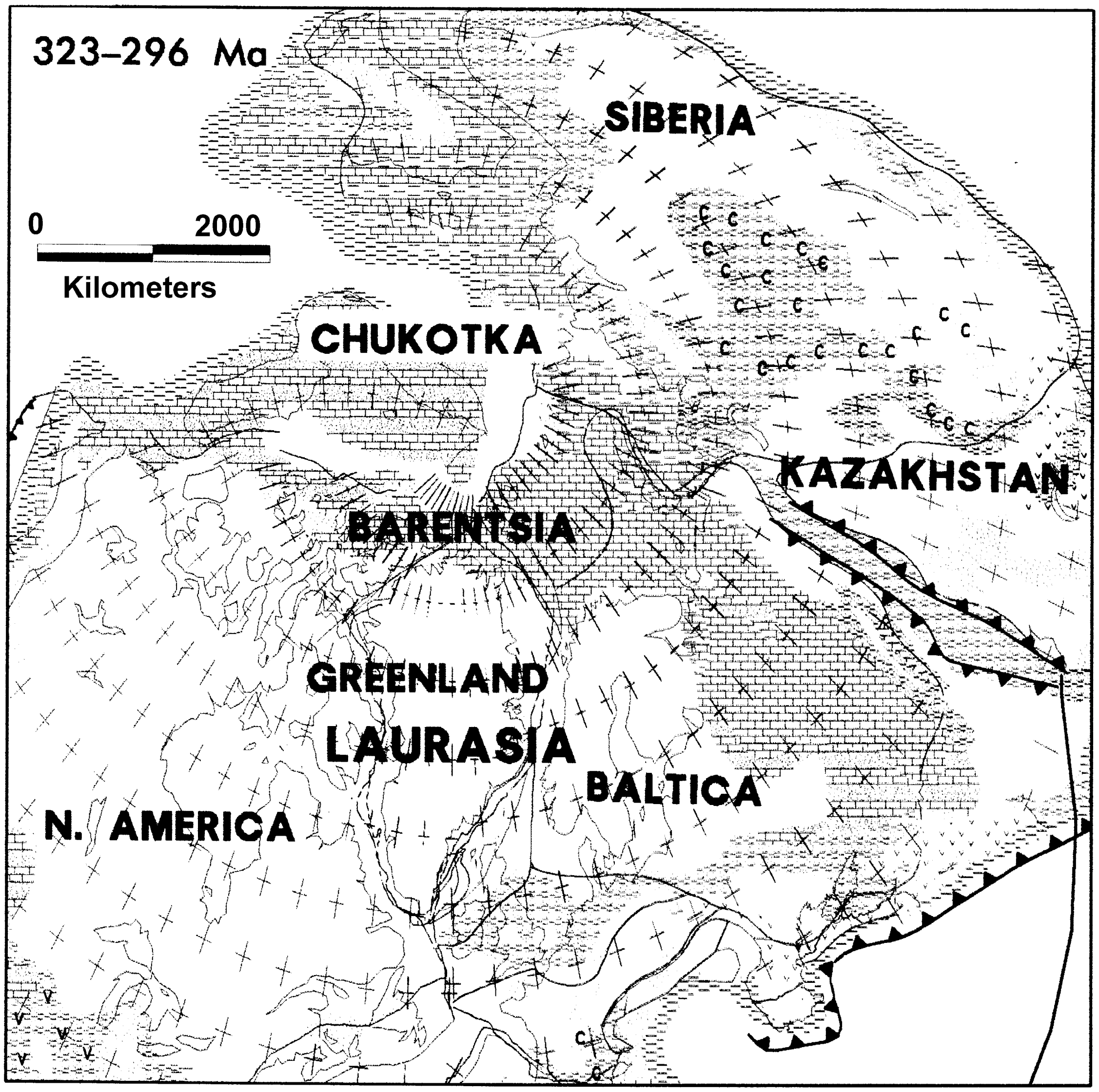

Fig. 13. Paleoenvironment and lithofacies of the major Arctic plates during Lower Absaroka I–Moscovian/Kasimovian (Bashkirian–Kasimovian) 323–296 Ma. Mollweide projection. For explanation see keys in Fig. 1.

carbonate-rimmed shelves provided raised rims for intrashelf basins. Abundant back-stepping reefal margins occurred due to second-order sea-level rise or accelerated subsidence. Devonian buildups were prominent along the margins of the North Caspian Basin, the eastern margin of the Volga-Urals Platform, and within the Timan-Pechora region (Nikishin et al., 1996). Carbonates also occurred in the northern part of Siberia and the Verkhoyansk terranes (Puchkov, 1996; Ronov et al., 1984). The carbonate buildups existed in proximity to Organic-rich deposition, during the time of anoxia. Late Devonian organic-rich marine black shale, potential source rocks, were best developed in large, low-latitude, restricted, intrashelf basins and interior seaways coincident with a global OAE. Oil-prone marine sources in Baltica and Laurentia have contributed substantial reserves. Self-contained Late Devonian carbonate hydrocarbon systems often consist of backstepping coral-stromatoporoid reefs and associated platform grainstones that are overlain by and interbedded with marine source rocks. Overlaying shaly carbonates or evaporites acts as seals for these reservoir rocks.

The emergence of continents and increased input of clastics in during Early Carboniferous decreased the areas of carbonate deposition. Carbonates were replaced by clastics and mixed carbonate facies in the eastern part of Laurussia (Nikishin et al., 1996). Clastic deposition dominated the Early Carboniferous period. Increased deltaic deposition occurred in Orogenic belts and rift grabens. Abundant, deep-water turbidite/flysch deposition occurred in foreland basins associated with the Hercynian collision (Eastern USA and Europe). Worldwide tectonism and plate convergence, associated with the formation of Pangea, increased erosional gradients and enhanced deltaic and flysch deposition. Major deltaic systems developed adjacent to

Fig. 14. Paleoenvironment and lithofacies of the major Arctic plates during Lower Absaroka II/III–Asselian–Artinskian (Gzhelian–Asselian) 296–269 Ma. Mollweide projection. For explanation see keys in Fig. 1.

Fig. 15. Paleoenvironment and lithofacies of the major Arctic plates during Lower Absaroka IV–Guadalupian (Roadian–Changhsingian) 269–251 Ma. Mollweide projection. For explanation see keys in Fig. 1.

the central Laurussian mountain belt. Extensive flysch deposits accumulated adjacent to the Hercynian foldbelt. Mixed carbonate–clastic and carbonate sedimentation existed on relatively broad shelf-seas (Ronov et al., 1984). Carbonate facies still prevailed in the westernmost part of Laurussia. Carbonate buildups were composed of muddy, non-framework algal and skeletal components. The glacioeustatic sea-level fluctuations subjected carbonates to episodes of erosion and karstification.

2.4. Absaroka (Late Carboniferous–Middle Jurassic, 323–177 Ma): Pangea, Anui–Anvil ocean

2.4.1. Geodynamic evolution

The collision between the Kazakhstan plate and Laurussia began in the Late Carboniferous (Puchkov, 1991; 1997) in southern and central Urals, later progressing into the northern parts (Fig. 13). The onset of the Ural suture marked the formation of the supercontinent Pangea (Wegener, 1912). Siberia also began to collide with the Kara Sea plate in the Taimyr area (Vernikhovsky, 1997).

Rifting continued along the old Caledonian suture, between Scandinavia and Greenland in Laurussia (Ziegler, 1988). During Late Carboniferous–Early Permian (Figs. 13 and 14), opening of the proto-North Atlantic was initiated between East Greenland and Baltica (Stemmerik, 2000).

During Permian and Earliest Triassic time (Figs. 15 and 16), Laurussia collided with Siberia to form the continent of Laurasia which became a part of the Pangean supercontinent. The result of this collision was Uralian orogeny which affected Novaya Zemlya and adjacent areas (Puchkov, 1997). The East Barents basin

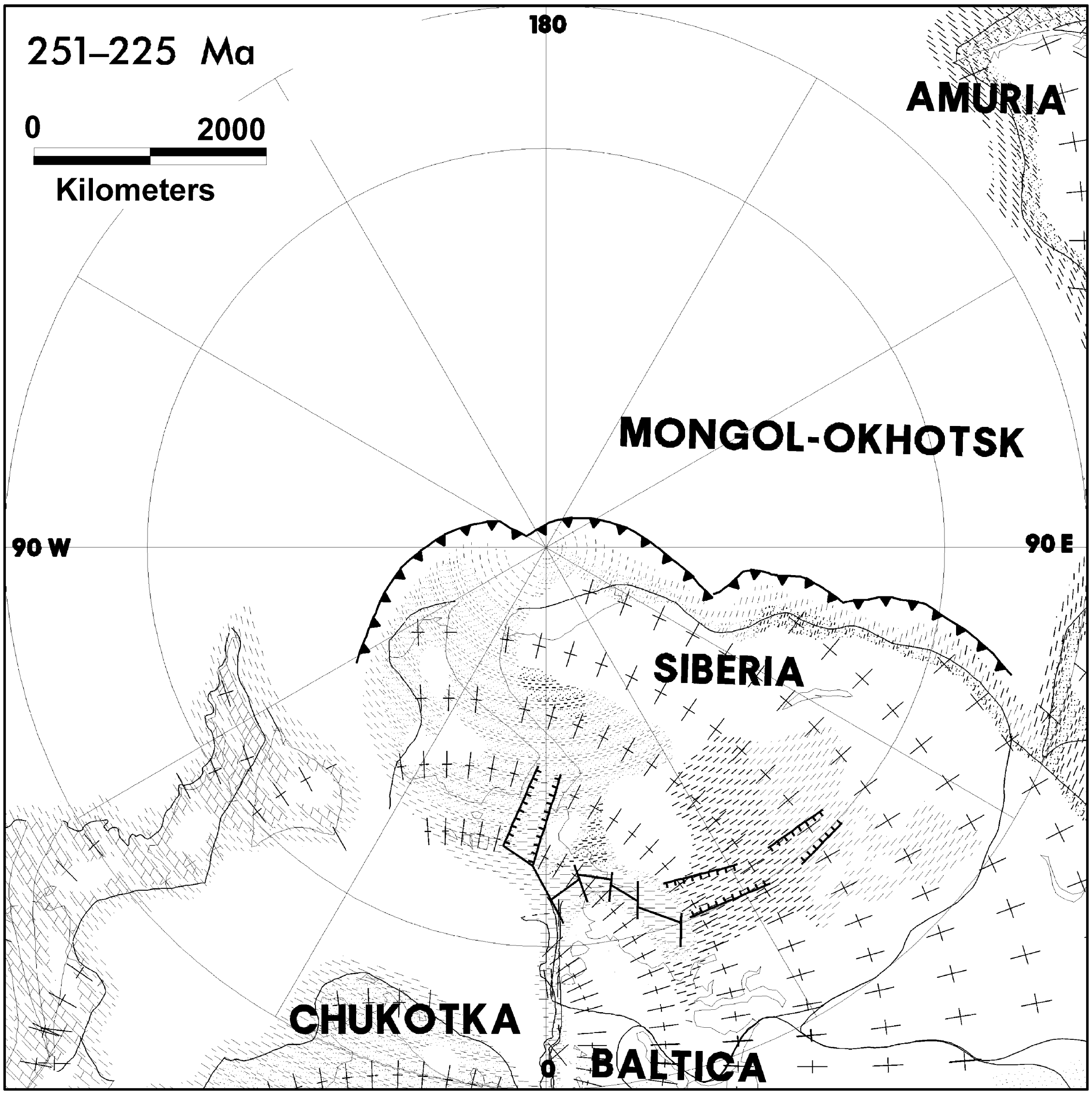

Fig. 16. Paleoenvironment and lithofacies of the circum-Arctic area during Upper Absaroka I–Ladinian (Induan–lower Carnian) 251–225 Ma. Stereographic polar projection. For explanation see keys in Fig. 1.

developed at this time as a foredeep system (Bogatski et al., 1996; Johansen at al., 1993; Rønnevik et al., 1982). The last collisional events of the Uralian Orogeny took place during the Triassic and Early Jurassic time, in the Pay-Khoy-Novaya Zemlya area (Nikishin et al., 1996; Puchkov, 1991, 1997; Zonenshain et al., 1990). The conclusion of the Uralian orogeny was accompanied by uplift of the adjacent areas of Eastern Europe and Western Siberia. The Late Carboniferous–Triassic collision between Siberia and the Kara Sea platform (may be part of Laurussia) in the Taimyr Peninsula was perhaps an extension of the Uralian collision (Gee, Scott, Torsvik, & Vernikhovsky, 1998; Inger et al., 1999; Nikishin et al., 1996; Ziegler, 1989). According to Torsvik and Anderson (2002) Taimyr deformation happened most probably during Late Triassic.

According to Beauchamp (1997), stress-release events of very large magnitude happened around the Permian–Triassic boundary. They were probably associated with plate reorganization like shifts from convergent to divergent plate tectonics. Crustal snap-back with uplift and inversion was followed by collapse of the crust. These stress release events were evidently visible in the Canadian Arctic. Rifting in Siberia was perhaps caused by pulling effect of the subduction zone, which existed along the margin of Mongol–Okhotsk Ocean dipping cratonwards towards East Siberia. The rift zone between the Taimyr and Siberia was an extension of the South Anui–Anvil Ocean, which existed between the Chukotka-North Slope of Alaska and Verkhoyansk terranes (Sengör & Natalin, 1996; Zonenshain et al., 1990).

The episode of very strong, hot-spot related, flood basalt eruptions in the Western Siberian basin (Zonenshain et al.,

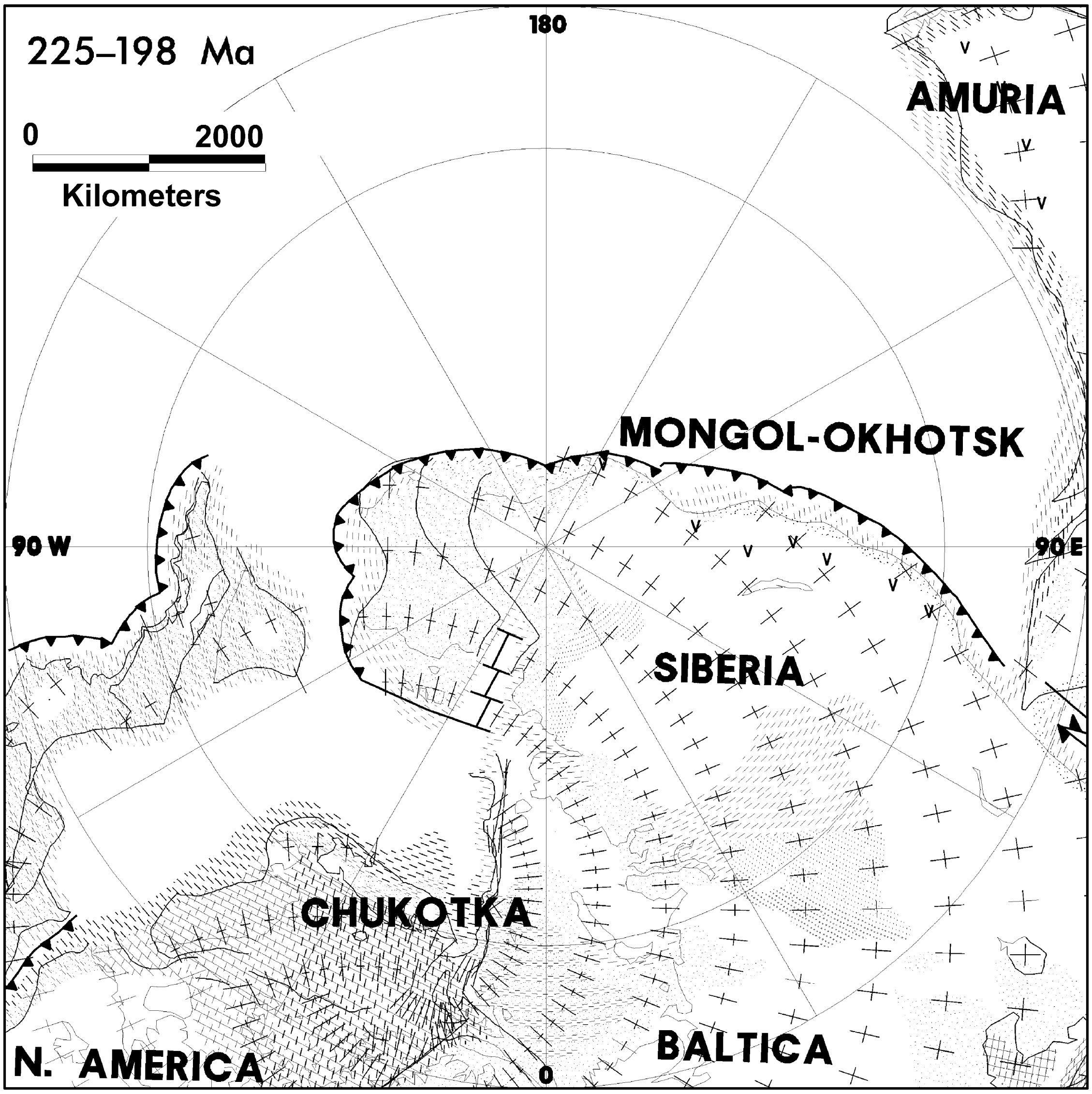

Fig. 17. Paleoenvironment and lithofacies of the circum-Arctic area during Upper Absaroka II–Norian (Upper Carnian–Middle Hettangian) 225–198 Ma. Stereographic polar projection. For explanation see keys in Fig. 1.

1990) began towards the end of the Late Permian, within an extremely short period from 255 to 245 Ma. During 10 million years 1,200,000 km^3 of basalts were extruded. According to Sharma (1997), the bulk of the Siberian lavas erupted within one million years at 250 Ma.

Rifting and breakup of Pangea, initiated during the Early Triassic, continued and intensified at the beginning of the Norian time slice (Golonka, 2000; 2002; Golonka & Ford, 2000; Withjack, Schlische, & Olsen, 1998). The separation of North America and Gondwana, which was initiated by the Triassic stretching and rifting phase, continued during the Early-Middle Jurassic (Fig. 18). According to Withjack et al. (1998) the transition from rifting to drifting was diachronous. In maritime Canada, the drift–rift transition occurred at about 185 Ma. The episode of rifting affected the area between Norway and Greenland throughout Triassic and into the Jurassic time.

2.4.2. Lithofacies and basins

Sea level fluctuations during Late Carboniferous resulted in the large areas with marginal marine/paralic sedimentation and cyclothem deposition, especially in the Appalachians–Variscan forelands in North America, Europe, as well as in western Siberia (Fig. 13). Major coal deposits occurred in eastern Laurussia, Europe, and North America (Ronov et al., 1984).

Carbonates dominated by muddy facies and algal/Palaeoaplysina buildups occurred at low to mid-latitudes during Early Permian time (Beauchamp, 1995; Golonka & Ford, 2000; Kiessling et al., 1999) (Fig. 14). Evaporite facies are present in the Volga-Ural–Caspian Area, central Europe, western North America and Sverdrup basin in Arctic (Golonka & Ford, 2000). Orogenic uplift along Pangean margins created internal drainage and stimulated deposition of continental sediments, red beds, evaporites, and eolian sandstones (Ronov et al., 1984; Ziegler, 1989).

The Uralian orogeny during Late Permian (Fig. 15) resulted in a rapid subsidence phase and formation of foreland basins filled by clastic sediments mainly of fine-grained molasse type in the eastern part of the Volga-Ural, Timan-Pechora basin on the Eastern European Platform, as well as in the eastern Barents sea area (Golonka & Ford, 2000; Johansen et al., 1993; Nikishin et al., 1996; Puchkov, 1991). In the western Barents, carbonates and cyclic spiculitic sediments prevailed (Golonka & Ford, 2000; Stemmerik, 2000). Carbonate, mixed carbonate silici-clastics and siliceous deposits dominated in the Arctic area north of Canada (Beauchamp, 1995; Ronov et al., 1984). Carbonate deposits with reefs and with evaporites and phosphorites were dominant in the western United States (Wardlaw, Snyder, Spinosa, & Abd Gallegos, 1995). The sedimentological conditions in these deposits changed significantly while the area drifted northward (Walker, Golonka, Reid, & Reid, 1995).

Throughout Triassic and Early Jurassic (Figs. 16 and 17) a stable marine shelf existed on the northern Laurasian passive margin. The shelf deposition changed into slope and basin deposits along the northern Verkhoyansk area as indicated by deep-water gravity mass-flow sediments (Egorov, 1992). Although some continental rifting occurred (as part of the rift-phase breakup of Pangea from the Newark and central Europe rift systems through the North Atlantic to the Barents shelf and Arctic Alaska), sedimentation was primarily controlled throughout this time period by eustatic sea level changes. Deposits were dominated by organic-rich, transgressive marine shales. Shoreface to offshore bar

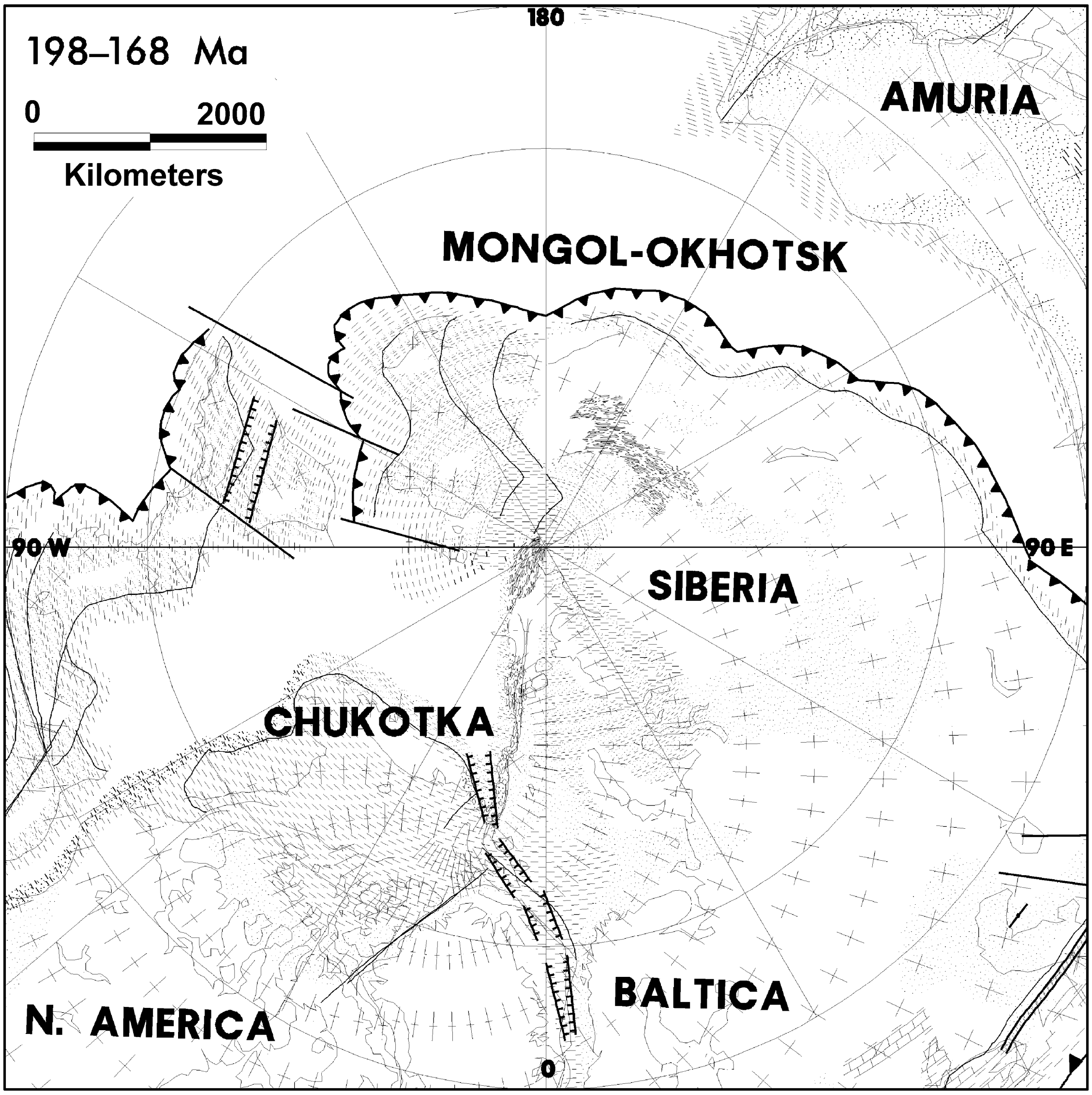

Fig. 18. Paleoenvironment and lithofacies of the circum-Arctic area during Upper Absaroka III–Pliensbachian (upper Hettangian–lower Aalenian) 198–178 Ma. Stereographic polar projection. For explanation see keys in Fig. 1.

sandstones occured in this passive margin sequence during regressive sea level fluctuations. These sandstones thin basinward and become very discontinuous (present-day southward), however, a few of these intervals represent important reservoir units in this region.

A varied and low sea-level caused the formation of restricted and marginal marine basins filled with evaporites and mixed evaporite–carbonate–clastic facies. Large evaporate pans existed in Central and Western Europe (Kiersnowski, Paul, Peryt, & Smith, 1995; Ziegler, 1982, 1989) and on the Eastern European Platform (Nikishin et al., 1996; Ronov et al., 1984). Restriction was caused by the narrowing of the seaway to the Arctic area (Stemmerik, 2000). Changing sea-level caused the cyclic deposition of the clastic–carbonates–evaporite sequences. Four of such large cyclothems are distinguished within the European Zechstein sediments. Low sea level, aridity and rifting resulted in the widespread continental clastic deposits with red beds and evaporites during Early Triassic (Golonka & Ford, 2000; Ronov et al., 1984; Ziegler, 1982; 1989). Rift basins developed in central and northern Atlantic region. Marginal marine environment with clastic deposition existed in the seaway between Europe and Greenland (Stemmerik, 2000). Triassic restricted-marine shelf basins (e.g. Alaska, Sverdrup, and Barents Sea) contain black shales that have source rock potential (Leith et al., 1993; Parrish et al., 2001).

Continental clastic deposition continued during Early Jurassic (Fig. 18). Sediment color changed from red to more grays due to increased wetness. Fine-grained clastics occurred in shallow seaways. Locally coal-bearing alluvial/fluvial depositional systems formed (Golonka & Ford,

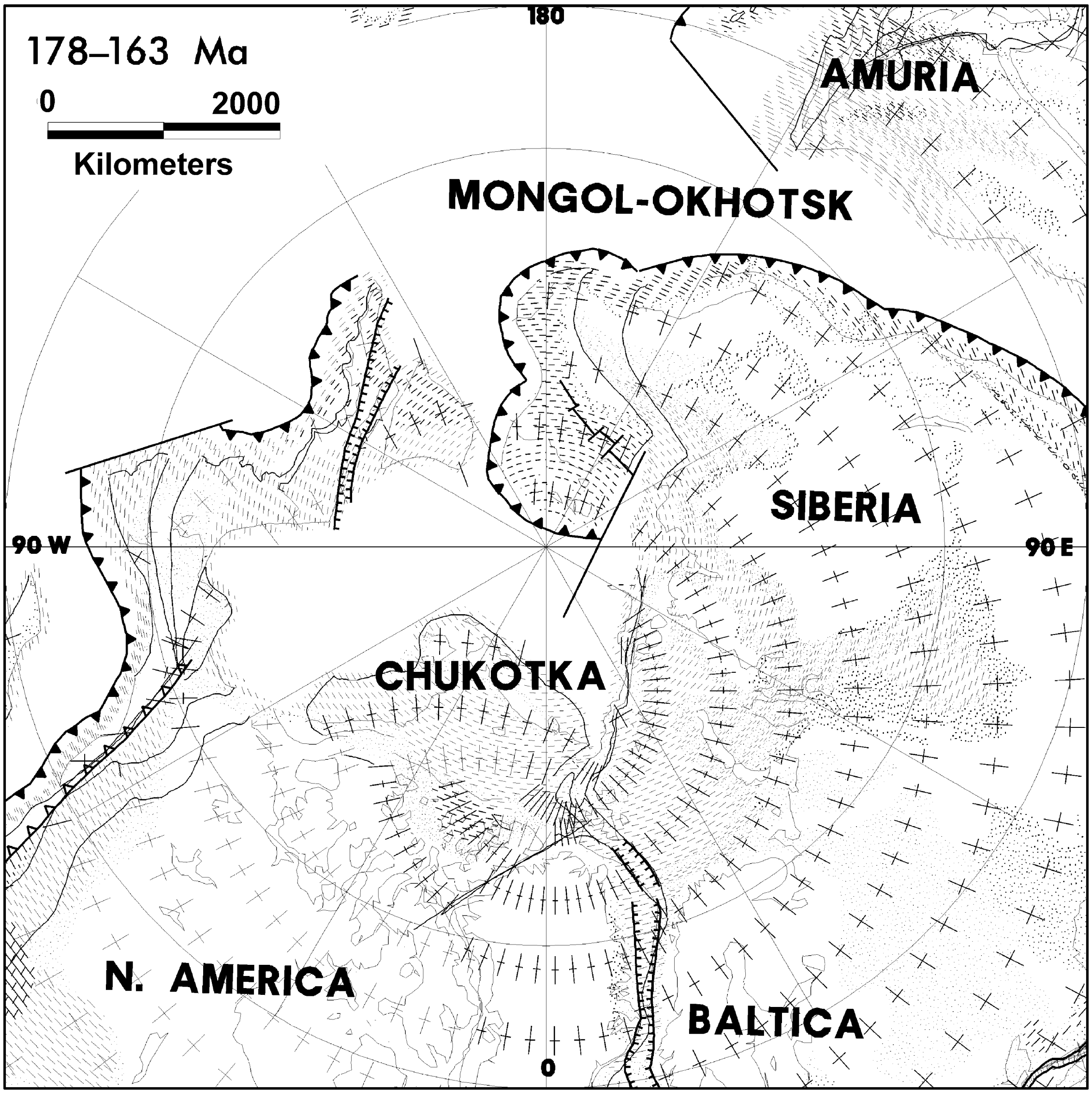

Fig. 19. Paleoenvironment and lithofacies of the circum-Arctic area during Lower Zuni I–Bajocian/Bathonian (Aalenian–Middle Bathonian) 178–163 Ma. Stereographic polar projection. For explanation see keys in Fig. 1.

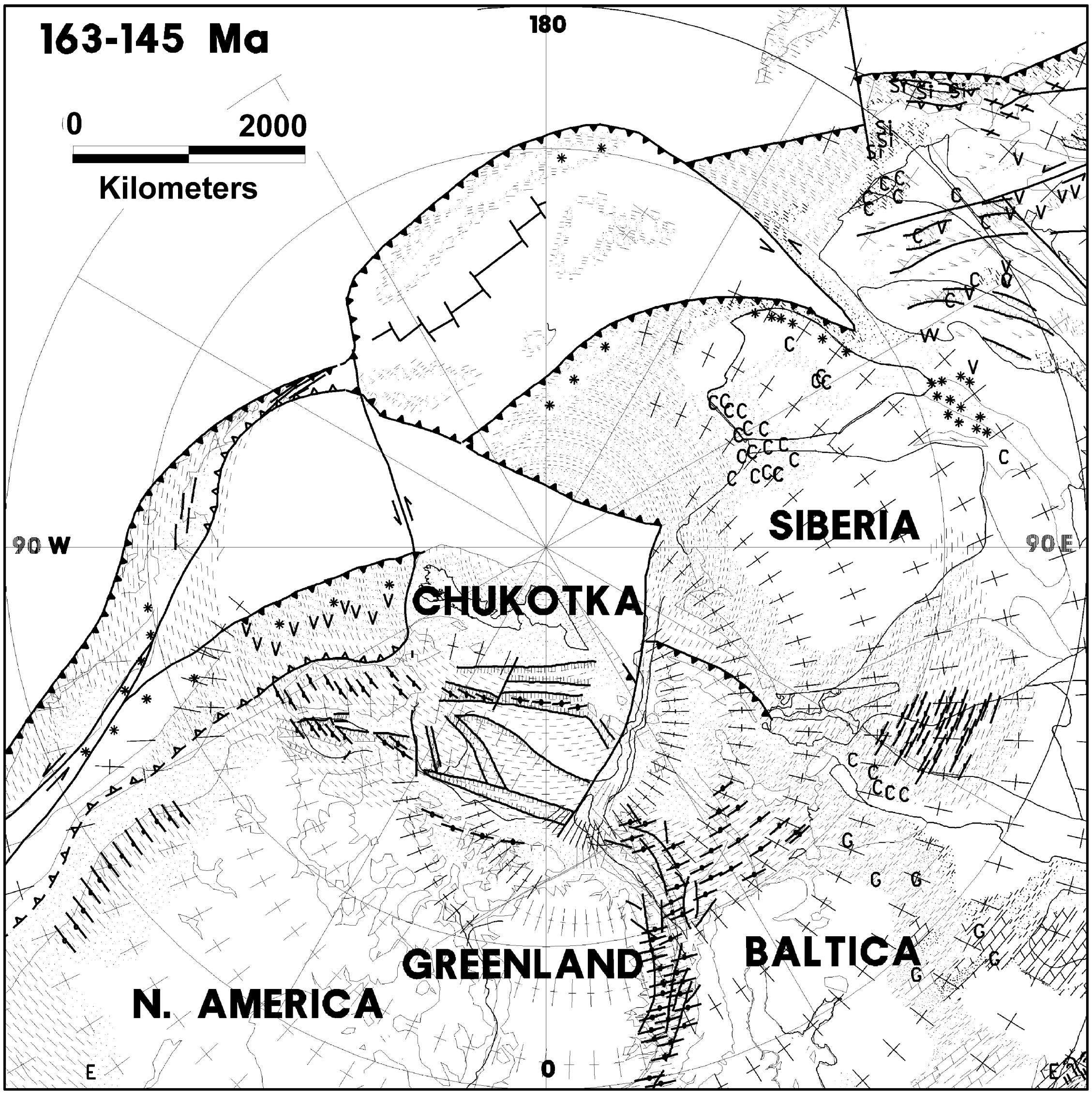

Fig. 20. Paleoenvironment and lithofacies of the circum-Arctic area during Paleoenvironment and lithofacies of the circum-Arctic area during Lower Zuni II–Kimmeridgian (Upper Bathonian–Middle Tithonian) 163–145 Ma. Stereographic polar projection. For explanation see keys in Fig. 1.

2000). Oil-prone, marine source rocks are present in restricted, silled basins of northwest and central Europe, the West Siberian Basin and on North Slope of Alaska (Kingak/Otuk Shale).

2.5. Zuni (Middle Jurassic–Early Paleogene, 177–58 Ma): disassembly of Pangea, opening of Canadian and Makarov basins

2.5.1. Geodynamic evolution

Rifting continued in the North Sea and the future northern Atlantic area in the Middle-Late Jurassic time (Doré, 1991; Ziegler, 1988; Figs.19 and 20). The Jurassic rift pattern is a part of the global Pangea breakup system. This Pangean system included seafloor spreading axes, rifts, and transform faults. These elements connected the Gulf of Mexico, central Atlantic, Ligurian Ocean, Polish–Danish rift, Lower Saxony, North Sea, Mid-Norway, East Greenland–Barents Sea, and Canadian Basin areas (Golonka, 2000). Rifting in the Arctic region was caused by the pulling effect of the Anui–Anvil Ocean subduction zones, as well as mantle upwelling expressed by the hot-spot volcanics of the Chukchi Borderland. Other Jurassic hot-spot volcanics are known from the North Sea area. The North Sea hot-spot can be traced to the present day Rhine Graben, while the Chukchi Borderland hot-spot volcanics may be related to present day Iceland. The Iceland hot-spot has a long track which can be traced to Greenland in the Paleocene, to Baffin Bay in the Late Cretaceous, to the Alpha Ridge in the Early Cretaceous, to the Chukchi Borderland in the Middle-Late Jurassic, to the Yenisey–Khatanga Trough in the Late

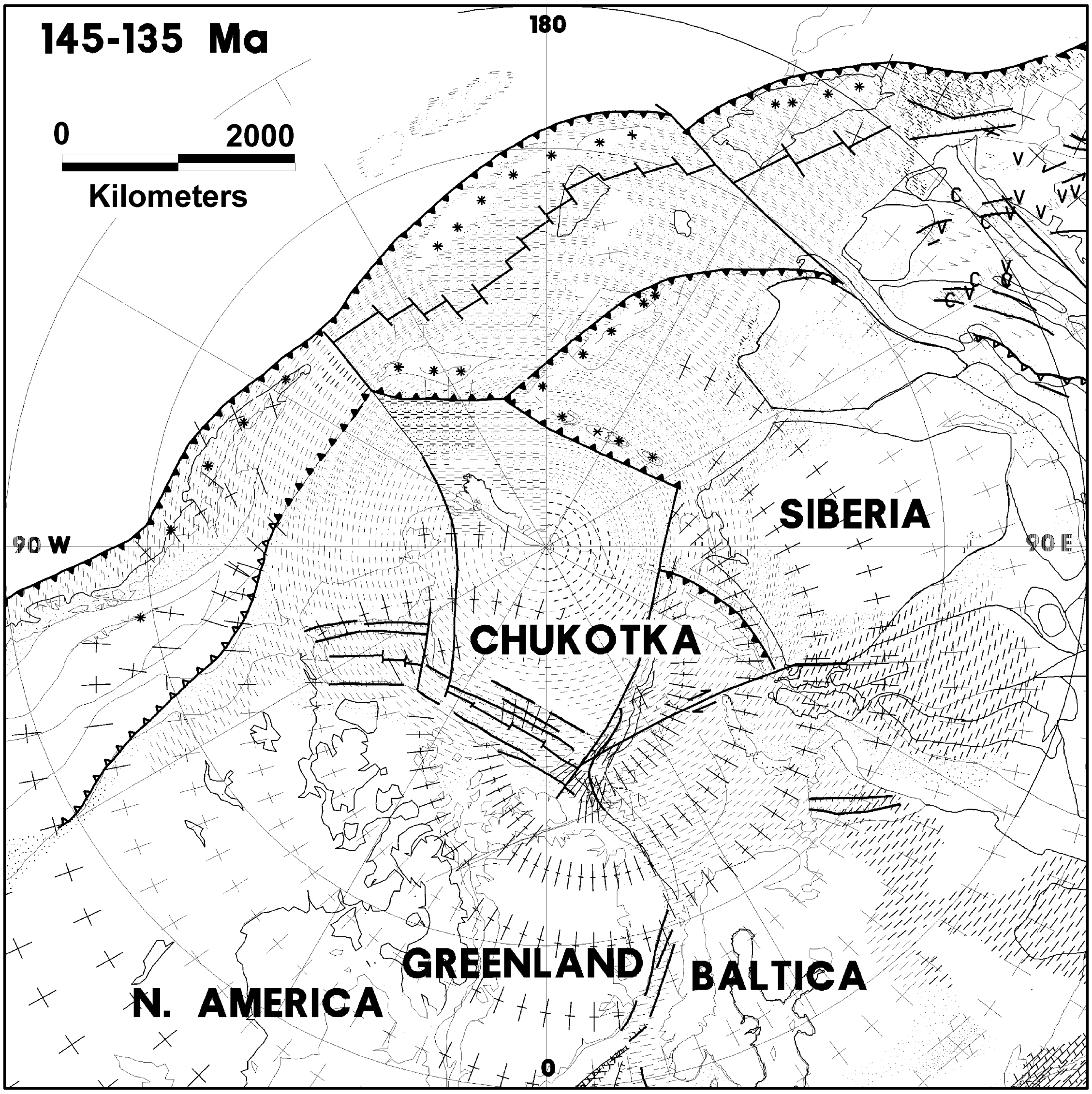

Fig. 21. Lower Zuni III–Berriasian (upper Tithonian–lower Valanginian) 145–135 Ma. Stereographic polar projection. For explanation see keys in Fig. 1.

Triassic, and to West Siberia in the Early Triassic (Golonka & Bocharova, 2000).

The North Sea–North Atlantic Jurassic rifting did not develop into sea-floor spreading. During the Early Cretaceous, the central Atlantic spreading center propagated into the area between Iberia and Newfoundland (Figs. 21 and 22). The Ligurian Ocean–North Sea rift system was replaced by the eastern Mediterranean, Bay of Biscay–Labrador Sea rift system (Golonka, 2000; 2002). This tectonic event induced a lowstand in relative sea level that affected the entire North Atlantic and Arctic region. Repeated faulting during the Early Cretaceous, combined with sea level fluctuations, resulted in several regional hiatuses/unconformities across the region.

The Verkhoyansk (Kolyma–Okhotsk–Cherski) superterrane was accreted with the North Asian craton during Early Cretaceous (Parfenov, 1992, 1997; Parfenov et al., 1993). According to Zonenshain et al. (1990), this accretion was caused by the nearly simultaneous convergence of continental and different exotic terranes with each other and with the Verkhoyansk fan along the Siberian margin. According to Parfenov (1992), the time of accretion was from the latest Jurassic to the Late Neocomian (pre-Albian). South Anui Ocean was closed between 130 and 120 Ma. Translational movement took place in East Asia (Cox, Debiche, & Engebretson, 1989; Sengör & Natalin, 1996; Zonenshain et al., 1990).

North Alaska terranes collided with southern Alaska (Grantz, Johnson, & Sweeney, 1990; Oldow et al., 1989). At the same time, the Chukotkan plate collided with the Verkhoyansk (Kolyma–Okhotsk) superterrane, which was at this time already a part of Siberia (Fig. 23). The Albian to

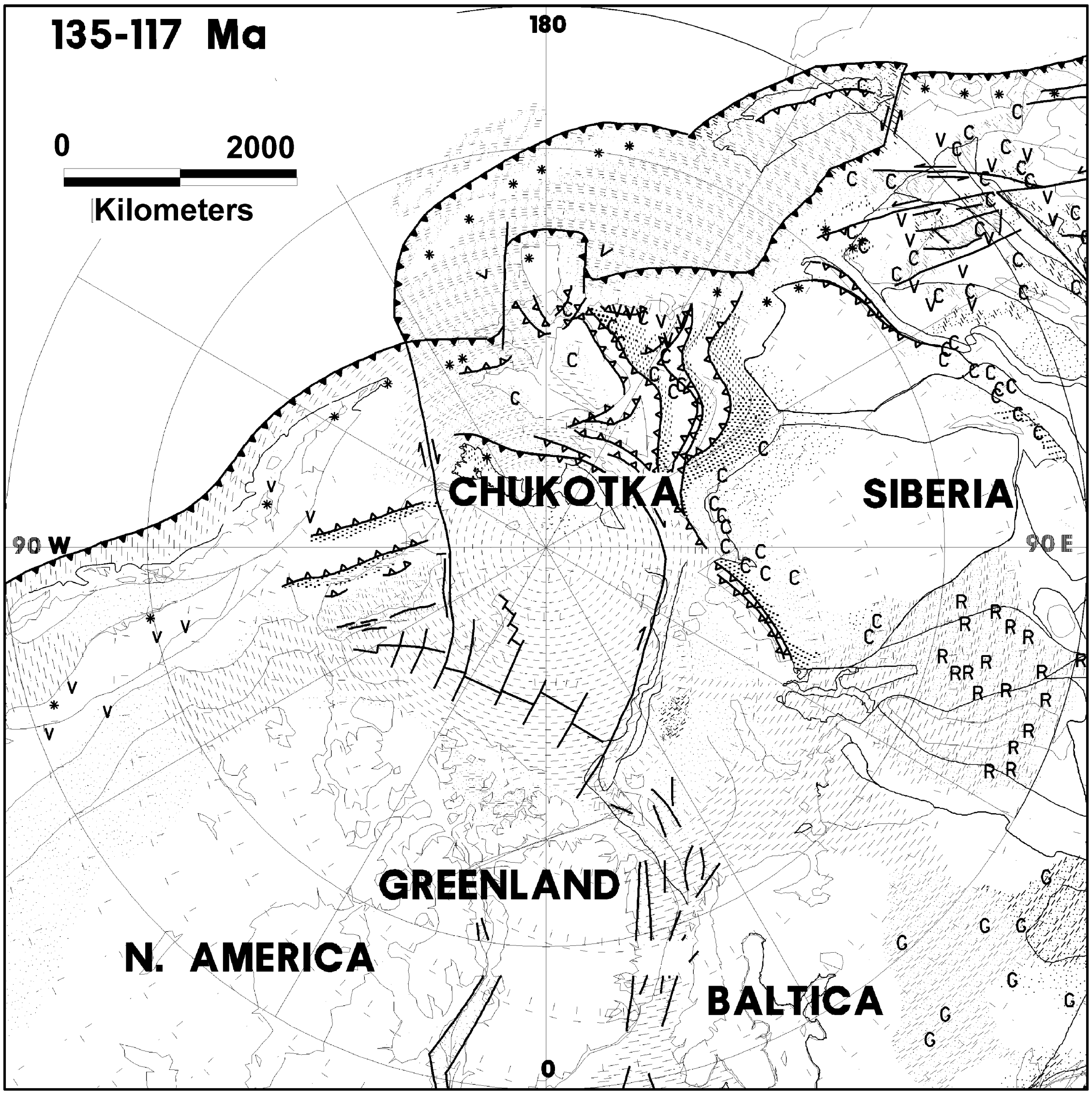

Fig. 22. Paleoenvironment and lithofacies of the circum-Arctic area during Upper Zuni I–Barremian (upper Valanginian–lower Aptian) 135–117 Ma. Stereographic polar projection. For explanation see keys in Fig. 1.

Late Cretaceous Okhotsk–Chukotka volcanic–plutonic belt marked the position of the active Asian margin at this time (Bocharova, Golonka, & Meisling, 1995).

During the Late Jurassic (Fig. 20), terranes colliding along the western margin of North America and closing of the Anvil Ocean initiate the first thrusting episode of the Brooks allochthon in northern Alaska (Moore, Walalce, Bird, Mull, & Dillon, 1994). Olistostromes of the Okpikruak Fm. record the first evidence of collisional foredeep deposition in the Colville Trough at this time. The compressional force was translated along a megaregional shear, which separated the Anvil and Anui Oceans. This shear may correlate to a fault zone, which includes the Northwind lineament. Brooks thrusting did not continue west of this zone. From Late Jurassic time onwards, this boundary can be used to subdivide the part of the province north of the oceanic Canadian Basin into western (Chukchi plate) and eastern (North Alaska plate) subprovinces.

A major plate tectonic reorganization of the circum-Arctic area occurred during the Late Cretaceous (Figs. 24 and 25). A subduction zone and convergent margin developed in the Albian along the southeastern margin of the Canadian Basin (Golonka, 2000). Rifting in the Makarov Basin was followed by Late Cretaceous sea-floor spreading. The Svalbard and northern Barents Sea area were uplifted, and affected by compressional tectonics and volcanism (Gustavsen et al., 1997). The Vøring Basin area began to be affected by intense rifting during Late Cretaceous time.

The location of Iceland between the Baffin Island and Greenland, approximately during the time span between 100 and 70 Ma (Lawver and Müller, 1994), resulted in

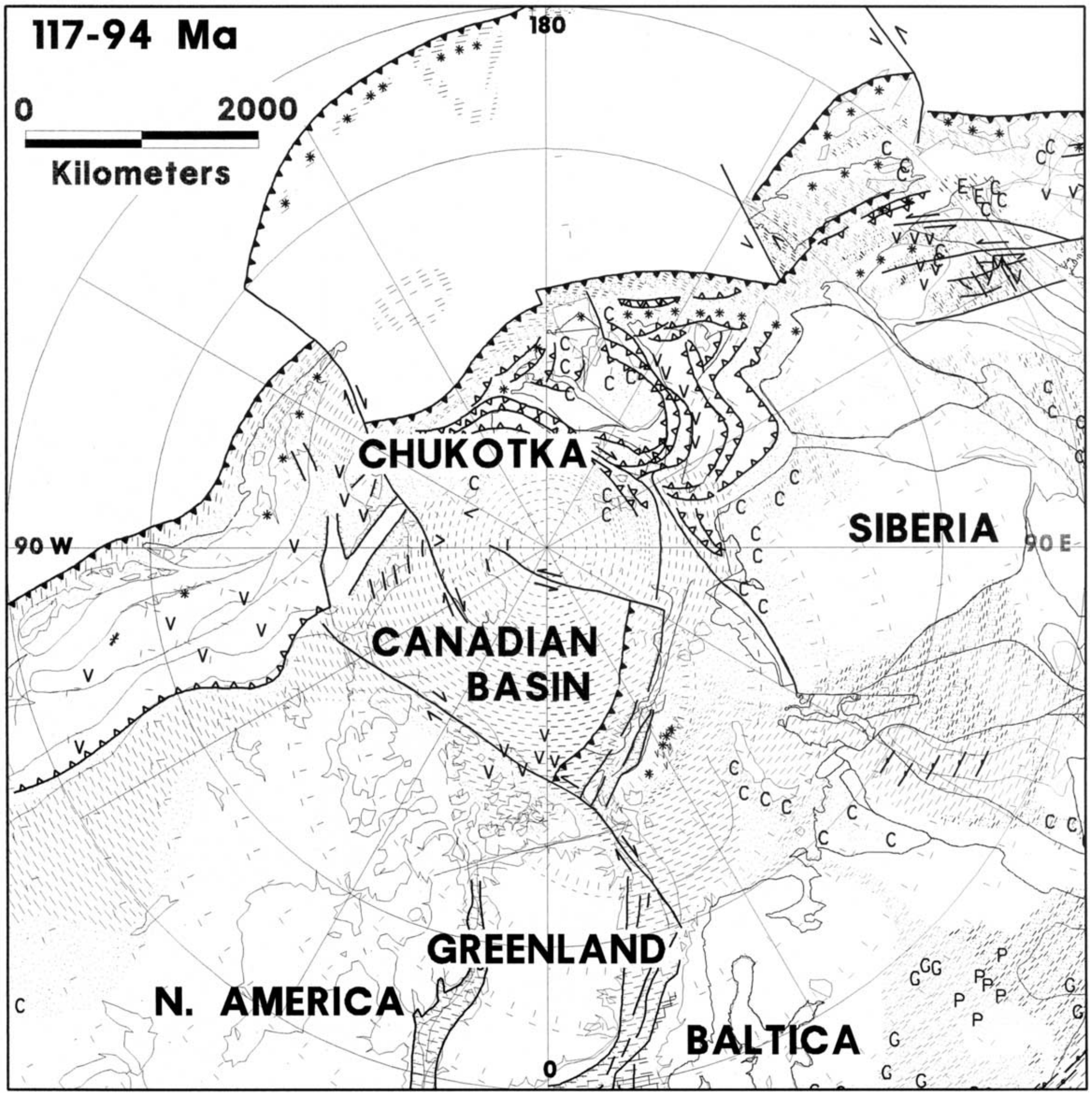

Fig. 23. Paleoenvironment and lithofacies of the circum-Arctic area during Upper Zuni II–Albian (Upper Aptian–Middle Cenomanian) 117–94 Ma. Stereographic polar projection. For explanation see keys in Fig. 1.

the spreading of the Labrador Sea, rifting in the Baffin Bay and emplacement of volcanics on the western coast of Greenland (Gill, Holm, & Nielsen, 1992; Gill, Pedersen, & Larsen, 1995; Holm, Hald, & Nielsen, 1992; Larsen, Pedersen, Pedersen, & Piasecki, 1992). Spreading in the Makarov Basin was perhaps also related to the opening of the Labrador Sea. The Makarov spreading affected rifting in on the Eurasian continent, in the Zyrianka Basin (Bocharova et al., 1995).

The northeast active margin of the Pacific and Eurasia was defined by the Okhotsk–Chukotka volcanic belts (Parfenov, 1992; Parfenov et al., 1993). Small Plate and volcanic arcs like Koni-Murgal, Koryak and Khatyrka (Zonenshain et al., 1990) were moving towards the Eurasian margins. By the end of the supersequence, the Izanagi plate was subducted and terranes accreted to Eurasia. The Kula plate appeared at the northeastern margin of Asia. The renewed compression in the Verkhoyansk fold-and-thrust belt was associated with the terrane collision. Further south, the Sikhote Alin terrane collided with the Asian margin. The collision resulted in intense folding and thrusting, followed by sinistral strike-slip faulting (Zonenshain et al., 1990).

The Brooks–Herald fold-and-thrust belt developed in the northern part of Alaska and on the Eurasian shelf, north of Chukotka (Grantz et al., 1990; Moore et al., 1994). According to Parfenov (1992), in Late Cretaceous to Paleocene time, the active margin of the Pacific was displaced 300 km east, towards the Pacific Ocean. A subduction zone developed along the Kamchatka–Koryak volcanic belt.

The western North American Cordillera continued to compress during the Cretaceous and Cenozoic (Fig. 25), until the Eocene. This compression resulted in thrusting and margin-parallel, transcurrent faulting (Oldow et al., 1989).

Fig. 24. Paleoenvironment and lithofacies of the circum-Arctic area during Upper Zuni III–Turonian (upper Cenomanian–lower Campanian.Tentative age range 94–81 Ma. Stereographic polar projection. For explanation see keys in Fig. 1.

The Atlantic passive margins were uplifted (Wernicke & Tilke, 1989). The widespread inversion in the North Sea and in central Europe could have been a result of the stress induced by the movement of Europe and ridge push from the Bay of Biscay spreading (Golonka & Bocharova, 2000). The Eurekan Orogeny in the Arctic (Okulitch, Harrison, & Mayr, 1998) was also a related event.

2.5.2. Lithofacies and basins

The main Late Jurassic rift system included the area between Norway and Greenland and the western margin of the Barents Sea up to Central Spitzbergen Basin (Doré, 1991; Golonka, 2000; Ziegler, 1988). The processes of subduction pull and mantle upwelling, produced a system of narrow marine troughs and exposed rift-shoulder uplifts developed parallel to the Laurasian margin. These rift depressions subsequently developed into the Sverdrup Basin, the East Siberian Sea Basin, and the North Chukchi Basin. A possibility exists that the Colville Trough is also floored by an extension of the East Siberian Sea–Chukchi Sea failed rift system. The central rift developed into the Canadian oceanic basin, with sea floor spreading possibly concluded between 140 ma (M15) and 133 ma (mid-Hauterivian unconformity).

Late Jurassic deposition was dominated by shales and bituminous black shales in contrast to Early and Middle Jurassic coarse clastic deposition (Ettensohn, 1994; Ulmishek and Klemme, 1990). In the Barents Sea, these organic-rich shales were deposited during a period of restricted sea-water circulation which enhanced preservation of organic matter. Climate modeling for Late Jurassic indicates the existence of strong all-season circular upwelling, which would have contributed to increased biologic productivity. Similar conditions existed in the North Sea

Fig. 25. Paleoenvironment and lithofacies of the circum-Arctic area during Upper Zuni IV–Campanian (Middle Campanian–Danian/Selandian) 81–58 Ma. Stereographic polar projection. For explanation see keys in Fig. 1.

area, West Siberia, and other circum-Arctic regions like Svalbard, the Sverdrup Basin, Beaufort–Mackenzie area, Alaska North Slope, and Chukchi-East Siberian Basins (Dypvik, 1985; Ettensohn, 1994; Leith et al., 1993). The West Siberian Basin formed a large southward-enclosed marine embayment where the large area was covered by Late Jurassic–Early Cretaceous source rocks. In northern Alaska deposition of organic-rich Kingak Shale occurred throughout the Jurassic and the earliest Cretaceous (Leith et al., 1993).

The North Sea–North Atlantic Jurassic rifting did not develop into sea-floor spreading. During the Early Cretaceous, the central Atlantic spreading center propagated into the area between Iberia and Newfoundland. The Ligurian Ocean–North Sea rift system was replaced by the Eastern Mediterranean, Bay of Biscay–Labrador Sea rift system. This tectonic event induced a lowstand in relative sea level that affected the entire North Atlantic and Arctic region. Repeated faulting during the Early Cretaceous, combined with sea level fluctuations, resulted in several regional hiatuses/unconformities across the region. The ‘Late Cimmerian’ unconformity at the transition from Late Jurassic to Early Cretaceous time is recognized in most basins in the North Atlantic and Arctic areas. Other prominent unconformities are seen in the Berriasian–Hauterivian and Aptian. The predominant sediment type during the Early Cretaceous was fine-grained, shallow and deep-water clastics. Coarse-grained clastics and marginal marine sediments were deposited in the marginal parts of the mega-province and during periods immediately following the unconformities. Deep-water fine-grained clastics probably dominated sedimentation in the southern part of the Barents Sea, and in the Mid-Norway and East Greenland areas (Gustavsen et al., 1997; Johansen et al., 1993; Stemmerik, 2000).

Fig. 26. Paleoenvironment and lithofacies of the circum-Arctic area during Lower Tejas I–Ypresian (Thanetian–Ypresian) 58–49 Ma. Stereographic polar projection. For explanation see keys in Fig. 1.

The Late Cretaceous was characterized by a major marine transgression and a hot, wet climate. Deep-water fine-grained clastics probably dominated sedimentation in the Vøring and Møre Basins, but the possibility for localized sand deposition is good (Bjornseth et al., 1997). There is also the possibility for the occurrence of organic-rich dark shales, especially during the Turonian OAE although there are no proven Late Cretaceous source rocks. No Upper Cretaceous sediments have been found in Svalbard. Substantial deposition persisted in the Viluy, Khatanga and West Siberian Basins. (Green et al., 1984)

A major reorganization of the circum-Arctic area, which occurred during the Late Cretaceous, caused the uplift of the Svalbard and northern Barents Sea areas (Bogatski et al., 1996; Rønnevik et al., 1982; Skagen, 1993). Compressional tectonics and volcanism is associated with the uplift. Erosion was widespread on the lands bordering the Arctic Ocean. Paleocene deposition continued in the West Siberian, Viluy and Chukotka basins (Green et al., 1984).

2.6. Tejas (Early Paleogene–Neogene, 58–2 Ma): opening of northern-Atlantic and Eurasian basin

2.6.1. Geodynamic evolution

At the end of Cretaceous and in the Early Paleogene, a strong volcanic event resulted in nearly 1000 m of plateau basalts in the onshore East Greenland area (Holm et al., 1992; Eldholm, Skogseid, Sundvor, & Myhre, 1990; Planke, Skogseid, & Eldholm, 1991; Skogseid, Pedersen, Eldholm, & Larsen, 1992). At the same time, dolerite sills and thin dikes were emplaced within the post-Devonian section

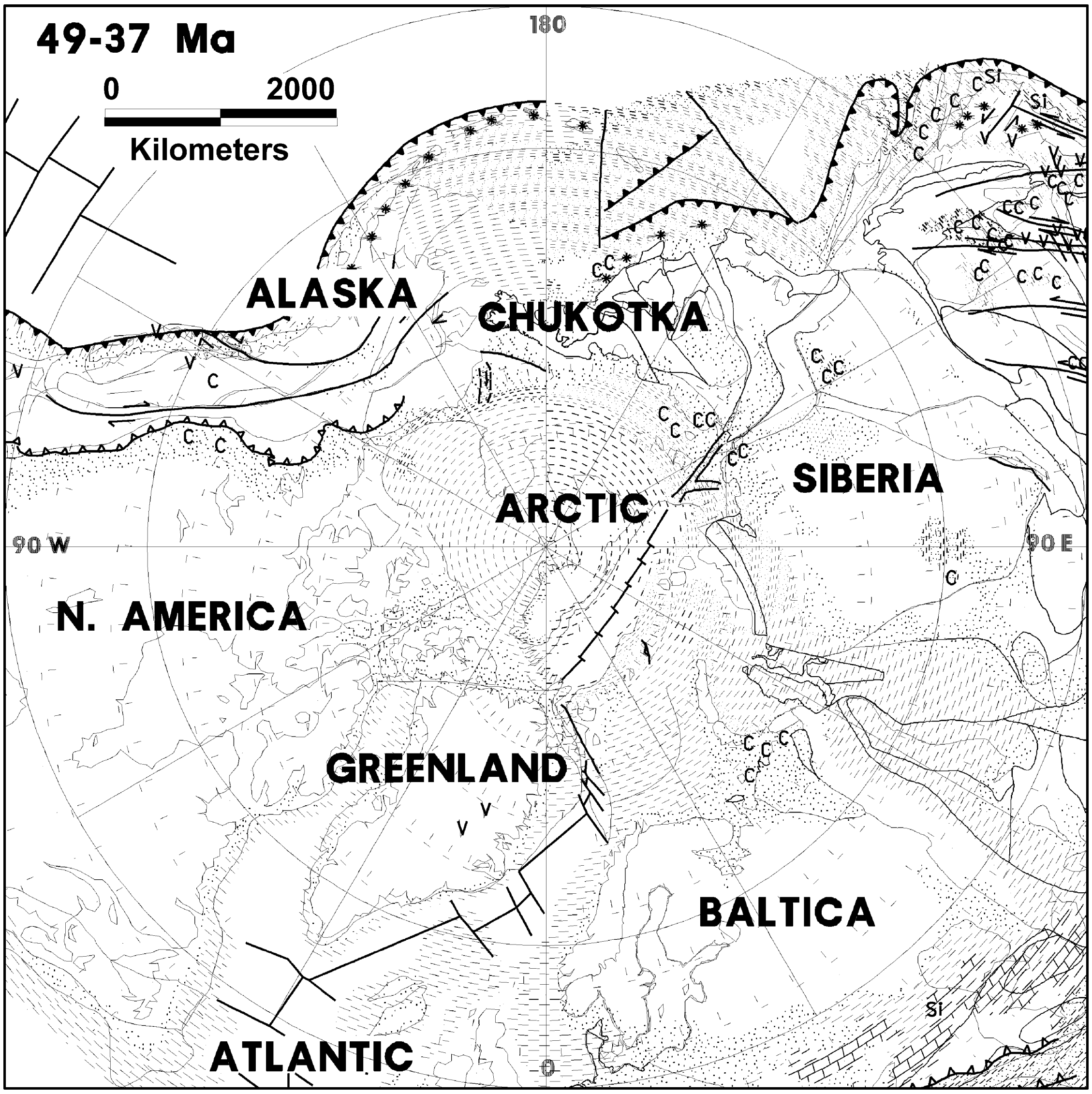

Fig. 27. Paleoenvironment and lithofacies of the circum-Arctic area during Lower Tejas II–Lutetian (Lutetian–Bartonian). Tentative age range 49–37 Ma. Stereographic polar projection. For explanation see keys in Fig. 1.

throughout the region. Seaward dipping basalts are also present in the East Greenland continental margin area. They can be correlated to basalts along the Vøring Basin Escarpment, and the western Barents Sea margin. This period of volcanism was caused by crustal separation in the initial phase of drifting and by the inception of seafloor spreading (Fig. 26).

The Laramide Orogeny and foreland basin development took place in western North America (Oldow et al., 1989). The Alaskan terranes continued their accretion process. The Eurekan orogeny, primarily a response to sea-floor spreading in the Labrador Sea and Baffin Bay, affected much of the Arctic, from the Late Paleocene to the Eocene (Golonka, 2000, 2002; Okulitch et al., 1998; Figs. 26 and 27) A compressive foldbelt had been developed in West Spitzbergen, and North Greenland. Compression also affected the Canadian Arctic, mainly Ellesmere Island and the adjacent areas. The Late Cretaceous–Tertiary deformation of Svalbard created the West Svalbard Orogenic belt, as Greenland slid by Svalbard during the opening of the North Atlantic–Arctic basins. The Beaufort foldbelt formed during Eocene and Late Miocene deformations (Lane & Dietrich, 1995).

The Central Spitzbergen Basin area developed as a foreland at this time. The West Svalbard Orogenic belts are considered by Lyberis and Manby (1999) as strike-slip or transpressive orogen resulting from the continental collision and lateral escape. En-echelon folds, flower structures, and local extensional features were interpreted as evidence for transpressive deformation. The compressional aspects of the orogenic belt have also been emphasized (Golonka, 2000, 2002). Greenland and Svalbard finally rifted apart in the Early Oligocene (Fig. 28), transforming the previously sheared margin into a passive margin.

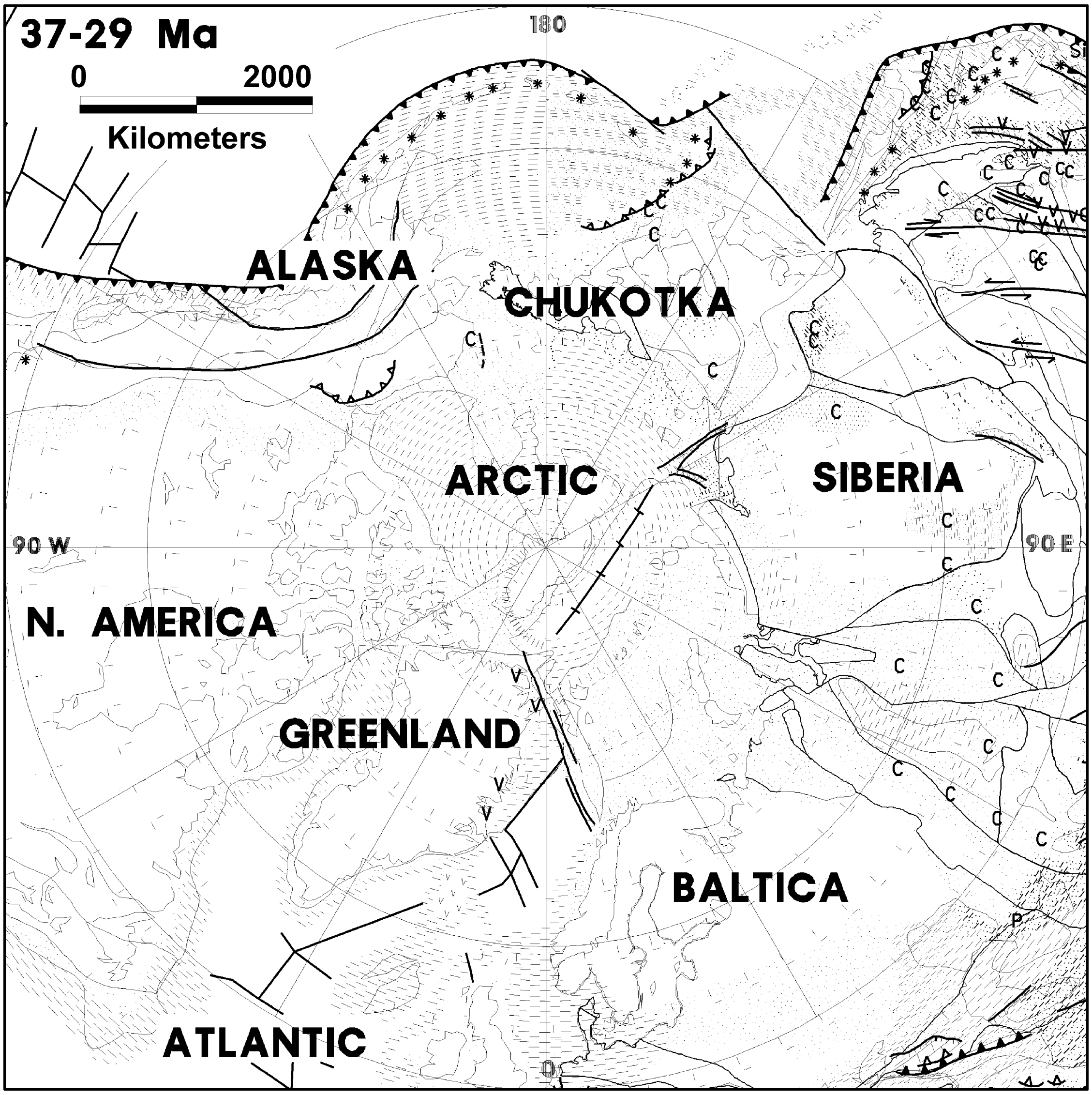

Fig. 28. Paleoenvironment and lithofacies of the circum-Arctic area during Lower Tejas III–Rupelian (Priabonian–Rupelian) 37–29 Ma. Stereographic polar projection. For explanation see keys in Fig. 1.

The breakup of North America, Greenland and Eurasia occurred during the Tejas I time (Fig. 26). The Northern Atlantic and the Norwegian-Greenland Sea basins opened, during the early Eocene (Lawver & Gahagan, 1993; Ziegler, 1988) (Fig. 27). This opening was initiated at the Paleocene/Eocene transition and was accompanied by extensive volcanism along the plate boundaries (Eldholm et al., 1990; Planke et al., 1991; Skogseid et al., 1992). At the same time, oceanic spreading was still active west of Greenland. The opening of the Arctic Ocean (Eurasian Basin) was initiated, in the Late Paleocene (Kristoffersen, 1990). Back-arc extension, behind the Aleutian arc, formed the Bering Sea between Chukotka and Alaska (Worrall, 1991). According to Oldow et al. (1989), fragments of the Cretaceous Kula plate were trapped within the Bering Sea.

During Eocene time, sea-floor spreading finally shifted from western to eastern Greenland and the North Atlantic. According to White (1992), shortly after the Iceland plume was reactivated, the extension between Greenland and the northwestern European margin continued until it developed into a full oceanic spreading center. The voluminous volcanic complexes, containing wedges of seaward-dipping reflectors, were deposited in the vicinity of the continental-oceanic transition (Coffin & Eldholm, 1994; Planke et al., 1991; Skogseid et al., 1992). Continuation of seafloor spreading in the North Atlantic resulted in opening of the Eurasian Basin in the Arctic (Zonenshain et al., 1990). This basin was separated from the Canadian basin by the Lomonosov Ridge.

Spreading continued in the Bering Sea (Oldow et al., 1989; Worrall, 1991; Zonenshain et al., 1990). The Farallon plate, in the Pacific Ocean, began to fragment when the northern part broke off forming the Vancouver plate (Winterer, Atwater, & Decker, 1990).

Fig. 29. Paleoenvironment and lithofacies of the circum-Arctic area during Upper Tejas I–Aquitanian (Chattian–Aquitanian) 29–20 Ma. Stereographic polar projection. For explanation see keys in Fig. 1.

Neogene was a time of mature seafloor spreading globally, with local rifting events (Figs. 29–31). Spreading in the North Atlantic and Arctic Eurasian Basin continued, and Iceland formed as a volcanic platform astride the North Atlantic spreading ridge (Lawver & Müller, 1994). Strike-slip motion was initiated between Greenland and Svalbard. Extension occurred in the western part of the Sea of Okhotsk and in the Tatar Strait, between Sakhalin and the eastern margin of Russia (Bocharova et al., 1995; Zonenshain et al., 1990).

2.6.2. Lithofacies and basins

The breakup history of the Greenland–Norwegian Sea and the subsequent sea-floor spreading of the North Atlantic significantly influenced the Cenozoic geologic evolution. South of the Greenland–Senja Fracture Zone, spreading was initiated prior to Anomaly 24 (Early Eocene).

Later the pattern was changed and at Anomaly 21 (Middle Eocene) spreading extended as far north as the southern limit of the Hornsund Fault Zone. Spreading was initiated north of 74°N at Anomaly 13 time (Early Oligocene).

Following the Late Cretaceous–Paleogene volcanism, the onshore areas of East Greenland were strongly uplifted and eroded during the Tertiary. The central and eastern parts of the Barents Sea were also uplifted during Paleogene–Neogene time. As a result of this uplift, erosion has removed most of the Cenozoic sedimentary record (Bogatski et al., 1996; Rønnevik et al., 1982; Skagen, 1993). At the same time,

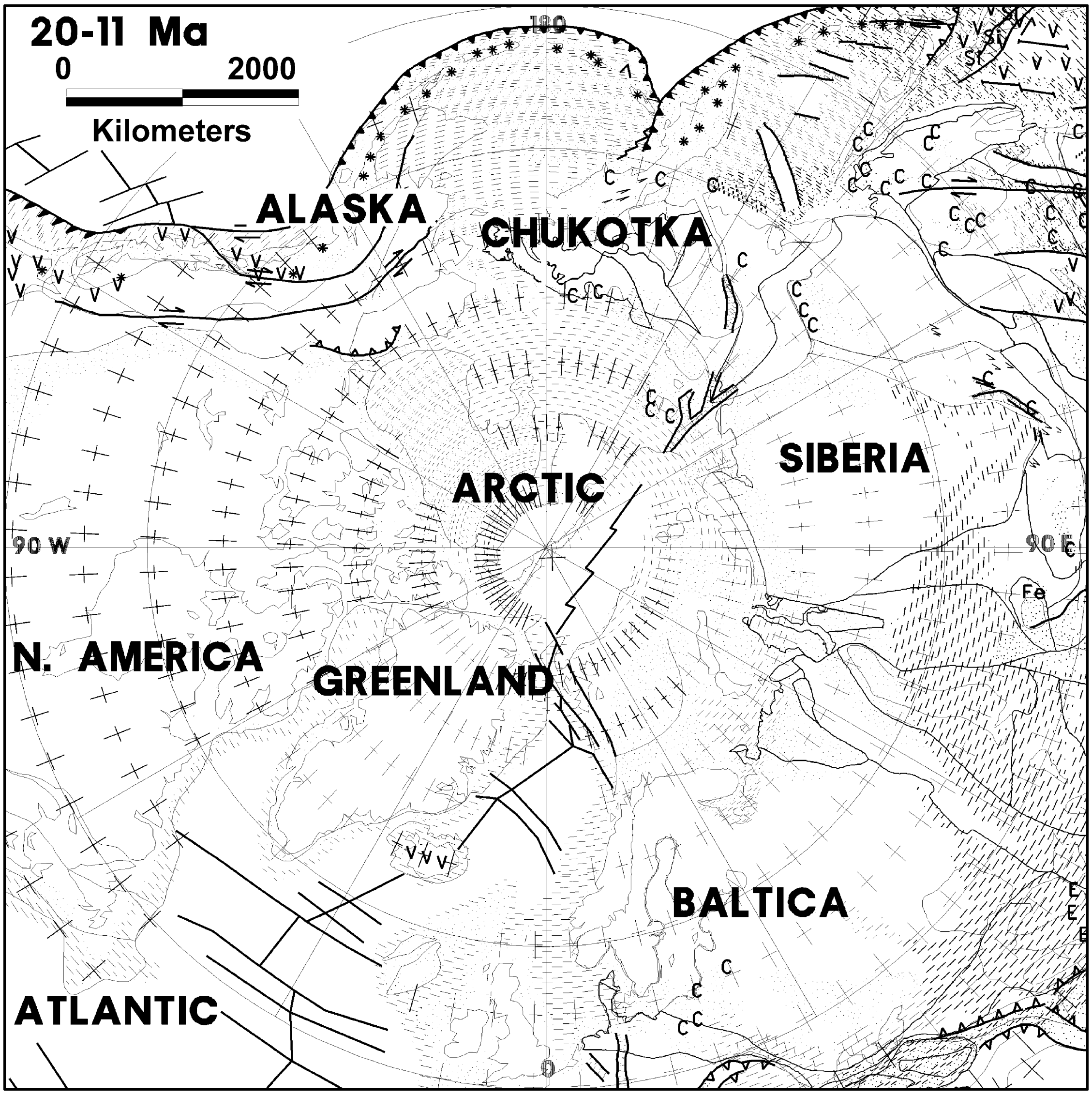

Fig. 30. Paleoenvironment and lithofacies of the circum-Arctic area during Upper Tejas II–Serravallian (Burdigalian–Serravallian) 20–11 Ma. Stereographic polar projection. For explanation see keys in Fig. 1.

the Atlantic passive margin developed in the outer shelf areas of the East Greenland province, in the Vøring Basin, and along the western margin of the Barents Sea (Bogatski et al., 1996; Doré, 1991; Eldholm et al., 1990; Johansen et al., 1993; Rønnevik et al., 1982). Passive margin subsidence resulted in deeper marine conditions. Large volumes of sediments were deposited in the southwestern part of the Barents Sea during Eocene time and during Pliocene-Pleistocene time. During Neogene time, major uplift of the Norwegian mainland occurred. A thick, basinward-thickening wedge of Plio–Pleistocene fine-grained clastic sedimentation resulted from this uplift. A thick wedge of the fine-grained sediments can also be expected in the eastern part of the East Greenland shelf.

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Fig. 31. Paleoenvironment and lithofacies of the circum-Arctic area during Upper Tejas III–Messinian (Tortonian–Gelasian) 11–2 Ma. Stereographic polar projection. For explanation see keys in Fig. 1.

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