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Plate kinematic evolution of the present Arctic region since the Ordovician

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ABSTRACT

The Laurentian, Baltic, and Siberian blocks of the modern circum-Arctic were scattered across a broad area between 10°S and 30°N during the Late Ordovician. Closure of the Iapetus Ocean during the Ordovician and Early Silurian brought Baltica and the Chukotka block in contact with Laurentia, simultaneously producing the Scandian phase of the Caledonian orogeny and creating the supercontinent of Laurussia. The assembly of Laurussia brought the cores of most of the scattered circum-Arctic landmasses into roughly their present-day relative positions. This collisional event also attached Pearya to northern Ellesmere Island, transpressionally sutured Chukotka to the general region of the present-day Canadian Arctic Islands, and attached the Seward Peninsula to Laurentia. Devonian rifting, perhaps driven by a mantle plume, formed the Vilyui basin of eastern Siberia, opened the Oimyakon oceanic basin offshore, and rotated the Siberian block away from North America and toward Baltica.

The major continental blocks that encircle the modern Arctic Ocean have migrated generally northward since the Carboniferous, although some, such as Siberia, have passed over the pole and are now moving southward. During the Jurassic and into the Early Cretaceous, the Chukotka-Barents shelf region passed over a nearly fixed Siberian Traps–Iceland hotspot. Opening of the Amerasia basin of the Arctic Ocean by seafloor spreading may have been initiated as seafloor spreading associated with continued subduction along the northeastern Pacific Rim, but additional stress produced by a hotspot converted what might have been originally orthogonal opening to rotational opening. Volcanism at the margins of the opposing plates of the newly forming Amerasia basin over the site of the fixed Siberian Traps–Iceland hotspot is thought to have created the major high-standing Alpha and Mendeleev submarine ridge system of the northern Amerasia basin. Beginning in the late Paleocene, North

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Figures in this chapter appear in color on the CD-ROM accompanying this volume and on Plate 6A. The CD-ROM also includes an animation of the paleolocations of the arctic continental fragments from 450 Ma to present in 3-m.y. steps.

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Atlantic seafloor spreading split Greenland and the Lomonosov Ridge from Eurasia, creating the Eurasia basin of the Arctic Ocean by slow spreading along the Nansen-Gakkel Ridge that continues to the present day, and produced transtension through parts of far-eastern Siberia.

INTRODUCTION

Regional paleoreconstructions are generally of two distinct types. One type uses computer-generated rotation files to reconstruct digitized plate outlines using the relative motion between the plates, based, where possible, on dated marine magnetic anomalies, relational matching of geological features across boundaries, and estimation of paleopositions based on measured and dated paleomagnetic poles with respect to an assumed north pole where direct determination of paleoposition is not possible. The other type uses pictorial representations of changing plate shapes that do not rigorously control the relative positions of the reconstructed pieces. In this chapter we use the first method and focus on the kinematic evolution of the present Arctic region (Fig. 1). Our database includes the positions of the major continental plates through time, particularly those defined by old cratons, as well as various other plates or blocks that may include, but are not limited to, tectonostratigraphic terranes as defined by Howell et al. (1985). The latter include fault-bounded crustal bodies defined on the basis of stratigraphy and tectonic processes involving dislocations of tens or more kilometers, island arcs, subduction or accretion complexes, and trapped ocean crust. The outlines of the plates are geological boundaries based on published literature supplemented with the inferred position of present-day ocean-continent boundaries. Proxies for the ocean-continent boundaries are determined from satellite-derived gravity signatures, as described in Lawver et al. (1999). For this study we have digitized additional plates, including some of the numerous terranes shown on the terrane map of Northeast Asia (Fig. 2) by Parfenov et al. (1993), and the Lithotectonic Terrane map of Alaska and adjacent parts of Canada (Fig. 3) by Silberling et al. (1994). With the exception of Ellesmere Island, which we have broken into tectonic slivers in order to show deformation during the Eurekan orogeny, the terranes shown in this chapter are rigid representations manipulated as polygons defined by latitude and longitude points rotated through time. In a few cases we show overlapped terranes. Following Silberling et al. (1994), we show the allochthonous Angayucham terrane (see 3a in Fig. 3) of the Ocean composite terrane obducted onto Arctic Alaska during the Jurassic to form the Arctic Alaska composite terrane. In another case, we maintain the outline of the Taimyr block (Fig. 1) through time, but represent temporal deformation and extension of the block by overlapping Taimyr with Baltica or Siberia at different times. In our reconstructions the digitized plates represented by polygons were moved about on the computer screen while maintaining their correct areal extent on an orthographic representation of the globe. When satisfied with the movement of the blocks and terranes through time, we input the poles of rotation determined by the interactive software into a rotational database (from which the figures herein were produced).

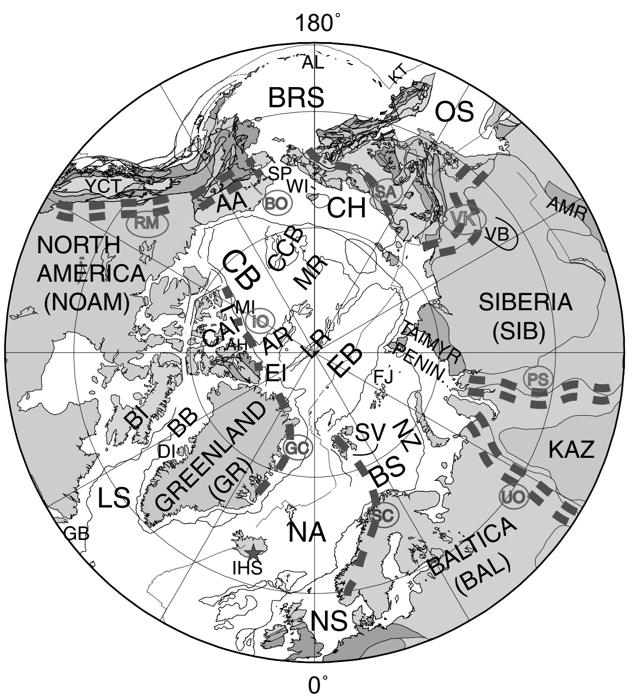

Figure 1. Polar stereographic projection of present Arctic configuration. Each of terrane pieces used in rotational database are shown color coded in Plate 6A-1. As in all figures and plates, major tectonic blocks and terranes are identified using acronyms defined in Table 1. Double-dashed thick black lines are sutures, foreland fold and thrust belts, or zones of major plate collisions. BO represents location of Brookian orogeny. PS represents closure of paleo–Asian Ocean. RM represents Rocky Mountain foreland fold and thrust belt. UO represents closure of Uralian Ocean. Verkhoyansk represents Verkoyansk foreland fold and thrust belt. Single-dashed thick black line represents suture (e.g., SA is South Anyui suture), or represents later-divided parts of Ordovician Scandian orogeny (e.g., GC is Greenland Caledonides and SC is Scandinavian Caledonides).

Relative plate motions for many of the marine terranes and blocks for the past 160 m.y. are now known, based on marine magnetic anomaly patterns (Cande et al., 1989; Royer et al., 1990) and tectonic lineations derived from satellite-gravity data (Sandwell and Smith, 1997). Difficulties are encountered, however, when an absolute framework is sought to describe the motion of continental blocks. Müller et al. (1993) produced a reasonable absolute framework for 130 Ma to the present for most

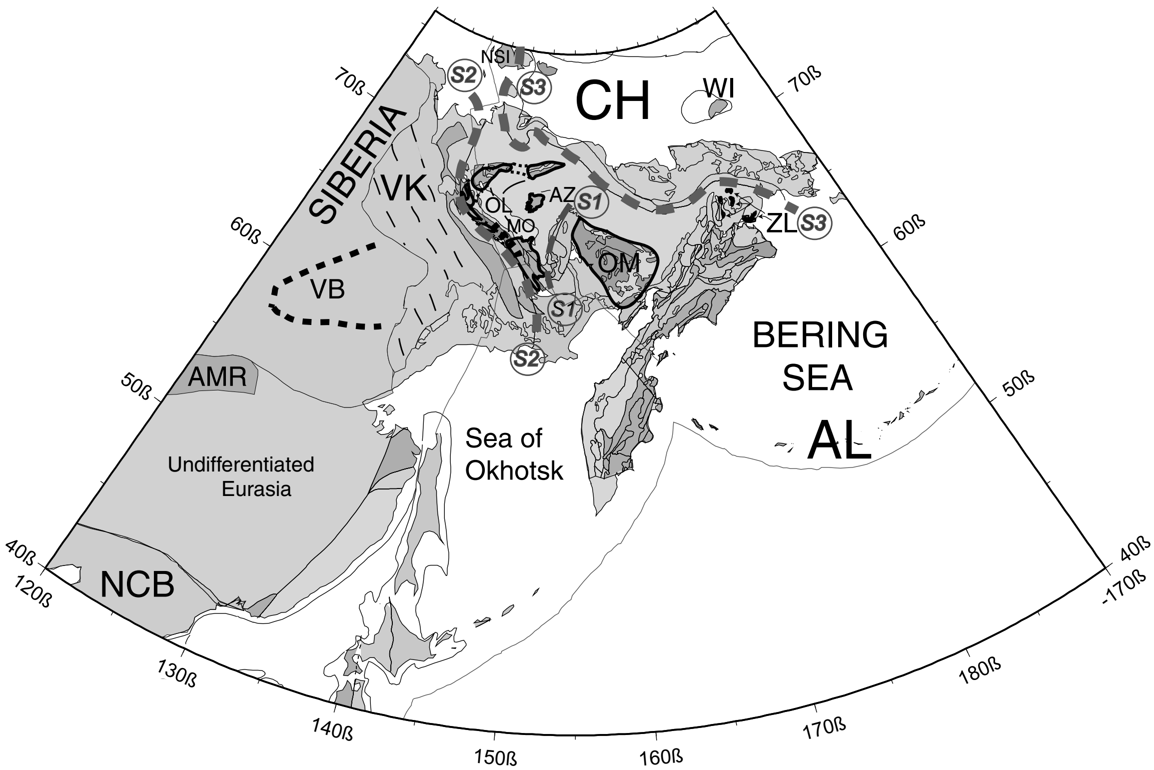

Figure 2. Polar stereographic projection of terranes of northeastern Siberia south to North China block of East Asia. Terranes of Northeast Asia were digitized from map of Parfenov et al. (1993). Abbreviations are as in Table 1. Thick single, dashed lines represent following. S1 is suture between Omolon block with Kolymian loop and Omulevka terranes. S2 is collision of Omulevka terranes and Omolon massif with Siberia resulting in Verkoyansk fold and thrust belt. S3 is South Anyui suture zone, which is one of the collisional zones between the Chukotka block and Siberia. Thick, black dashed line represents outline of Vilyui basin. Thinner dashed lines represent Verkoyansk fold and thrust area.

Indo-Atlantic continental blocks using six hotspots that were assumed to be fixed with respect to each other for the time period considered. The relative motion of the Indo-Atlantic continental blocks as a group was adjusted en masse on the surface of a sphere to best fit the dated tracks of the six hotspots. From this, Müller et al. (1993) produced an absolute framework for a region that extended from North and South America on the west to the eastern margins of Australia and Asia. They were unable, however, to reconcile continental movements with the motion of the Pacific plate because the many subduction zones rimming the Pacific region produce inexact boundary conditions. Combining relative plate motions with paleomagnetic measurements allows some constraints to be imposed on plate motions prior to 130 Ma, but it is impossible to delimit the paleolongitude of continental blocks solely with paleomagnetic data. Consequently, many Paleozoic and Mesozoic plate tectonic reconstructions lack some critical constraints.

Paleomagnetic data are used to approximate the positions of the major continental blocks for times earlier than 130 Ma, and the validity of these positions were corroborated, where possible, with known geologic relations and/or events. The paleomagnetic poles of Van der Voo (1993) for North America are used to tie our hierarchical plate rotation model to the earth in what we refer to as an absolute plate reference frame. Paleomagnetic poles for other continental blocks, such as those of Smethurst et al. (1998) for Siberia, are rotated into reasonable agreement with the North American poles for specific times where appropriate data exist. The Smethurst et al. (1998) poles for Siberia tend to place it a few degrees north of previously published poles, causing our reconstructions to differ from those of Zonenshain et al. (1990) and Golonka (2000). Paleomagnetic poles for other blocks are primarily from Van der Voo (1993) and are rotated into as close agreement as possible with both the North American and Siberian poles. The paleomagnetic pole of Van der Pluijm et al. (1993) is used for Baltica at 450 Ma, but after Baltica collides with North America during the Scandian phase of the Caledonian orogeny its position and consequently that of Eurasia are dependent on the Van der Voo (1993) poles for North America. Nokleberg et al. (1998) compiled a table of paleomagnetic data for northeastern Russia, Alaska, and the Canadian Cordillera that they used to define many of the small terranes of the Arctic. We have not used these data directly in

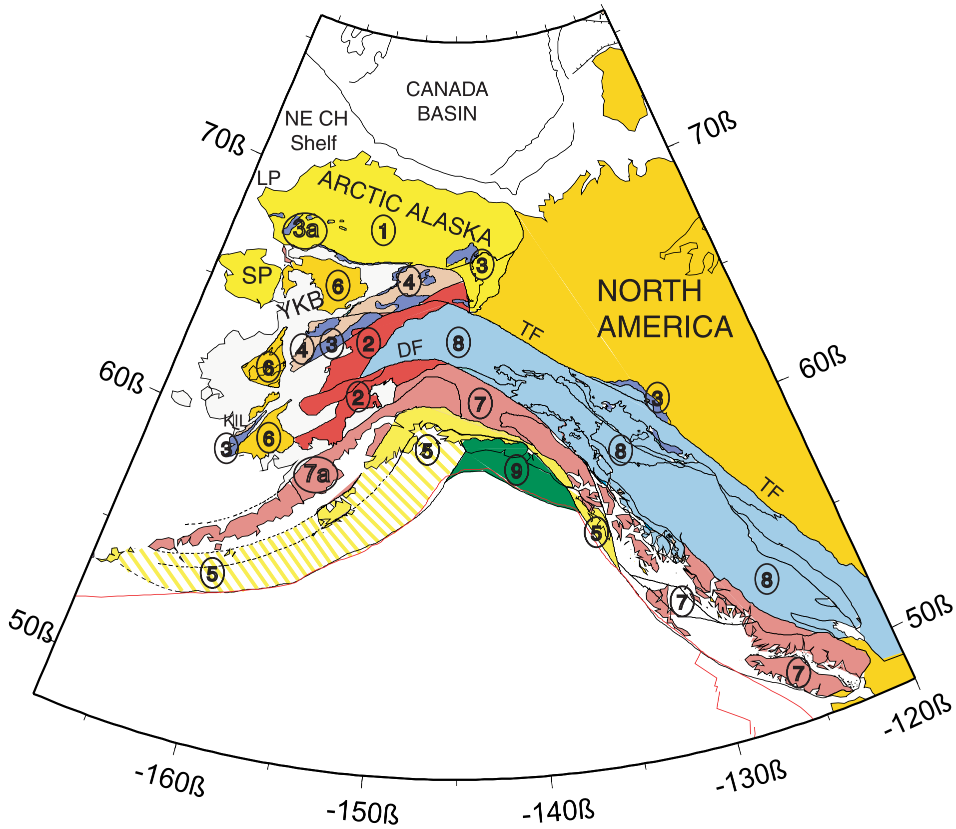

Figure 3. Polar stereographic projection of terranes of Alaska taken from Silberling et al. (1994) lithoterrane map of Alaska and adjacent Canada. Alaskan composite terranes are as identified by number in Table 2. DF is Denali fault; NE CH is Northeast Chukchi; TF is Tintina fault. Stripped part of terrane 5, Southern Margin terrane, represents continental margin where definitive data do not exist. See Table 1 for abbreviations.

this study but tried to make the motion of our small-terrane pieces consistent with the relationships that Nokleberg et al. (1998) showed in their reconstructions.

Relative motion between North America and Eurasia in the Late Cretaceous and Cenozoic is based on identified marine magnetic anomalies of Late Cretaceous to Paleogene age in the Labrador Sea (Srivastava et al., 1992) and of Cenozoic age in the Norwegian-Greenland Sea (Talwani and Eldholm, 1977). The absolute motion of Baltica (as part of Eurasia) is therefore determined directly for the Late Cretaceous and Cenozoic without dependence on paleomagnetic data from Baltica. Avoiding continental overlap is required, but published paleolongitudinal conjectures are not. For times prior to 130 Ma, the positions of tectonic blocks without paleomagnetic data are determined by geologic relations between known blocks, general faunal realms, or other evidence. For times when paleomagnetic data are needed but lacking and other data are ambiguous, motions of the continental blocks are assumed to be simple extrapolations between times for which there are data. If simple extrapolation caused overlap of continental blocks, then the most plausible adjustment was used, and then checked both forward and backward in time.

Our kinematic model for the evolution of the Arctic region relies on a number of recent models as well as the many references mentioned throughout this text. In particular, we use the model of Parfenov (1997) for the motion and relations of many of the large and small terranes of northeastern Eurasia. We use Golonka (2000) for the late Paleozoic motions of some of the major plates that are not easily defined with the paleomagnetic data mentioned earlier. We do not, however, agree with Golonka's placement of Siberia against Barentsia, which he showed as a separate plate. Instead, guided by the paleomagnetic data of Smethurst et al. (1998), we include Barentsia as part of Baltica in the Middle to Late Ordovician. Nokleberg et al. (1998) provided a comprehensive summary of the northeastern Siberian terranes and many of the Alaskan and northwestern North American terranes, but used the cartoon method to produce the time slices they showed. In general, we adopt the designations of Plafker and Berg (1994a) for terranes and seas and try to incorporate the movement they show for Alaskan terranes. Our model does not show paleoseafloor spreading centers because the available evidence does not provide information as to their actual location or paleo-orientation. It is difficult to determine the temporal extent and paleopositions of subduction zones because subduction of young oceanic crust (younger than 25 Ma) may not leave a magmatic signature (DeLong et al., 1978) and because initial subduction may occur for a considerable period of time before a magmatic arc develops behind it. Consequently, lack of evidence for a paleosubduction zone does not necessarily mean that subduction was not occurring, and furthermore, a magmatic arc may continue to be active after the related subduction has stopped.

Acronyms designate continents and fragments of continents, tectonostratigraphic terranes, and ancient oceans and seas in the figures (listed in Table 1), and we follow the time scale of Gradstein and Ogg (1996) throughout. A synopsis of the composite tectonostratigraphic terranes for northeastern Siberia mentioned in this chapter is presented in Table 2 and shown in Figure 2 and a synopsis for Alaska is presented in Table 3 and shown in Figure 3.

TECTONIC EVENTS IN THE FUTURE ARCTIC BEFORE THE ASSEMBLY OF PANGEA (PRE–LATE PENNSYLVANIAN)

Our reconstructions of the paleogeography of the Arctic begin with the Ordovician locations of the modern circum-Arctic landmasses, which are reconstructed in Plate 6B-1 with respect to the Ordovician paleomagnetic pole for North America from Van der Voo (1993). The landmasses are scattered between 10°S and 30°N, with North America rotated ~90° clockwise from its present orientation and straddling the equator. Siberia, based on paleomagnetic poles at 452 Ma (Rodionov, 1966) and 449 Ma (Torsvik et al., 1995), and Baltica were in the temperate zone. Arctic Alaska, at ~30°N, is attached to North America while other coeval Arctic blocks, such as Chukotka, the Omolon block, the northern Taimyr Peninsula, and fragments of far eastern Siberia such as the Omulevka block are shown in plausible, but not tightly delimited positions based on geological relations. The shape of Baltica, shown with Novaya Zemlya and the northern continental fragment of the Taimyr Severna Zemlya block attached, is taken from Nikishin et al. (1996). The southern margin of the Taimyr Peninsula and the Omulevka block remain in relative proximity to each other from our first reconstruction at

TABLE 1. ACRONYMS USED IN FIGURES AND IN TEXT

Acronyn	Name	Acronym	Name
AA	Arctic Alaska	NA	North Atlantic
AB	Amerasia Basin	NCB	North China Block
ACT	Arctic Composite Terrane	NE	Northeastern Chukchi Sea shelf
AFR	Africa	NG	Nansen-Gakkel Ridge
AH	Axel Heiberg Island	NOAM	North America
AL	Aleutian Island Arc	NS	Nares Strait
AMR	Amuria	NZ	Novaya Zemlyna
AR	Alpha Ridge	OB	Oimyakon Basin
AS	Angayucham Sea	OCT	Oceanic Composite Terrane
AZ	Alezaya Arc	OL	Omulevka Block
BAL	Baltica	OM	Omolon Massif
BB	Baffin Bay	OS	Sea of Okhotsk
BI	Baffin Island	P-AV	Peri-Avalonian Block
BRS	Bering Sea	P-LR	Peri-Laurentian Block
BS	Barents Shelf	PAO	PaleoAsian Ocean
CAI	Canadian Arctic Islands	PB	Porcupine Basin
CB	Canada Basin	PD	Piedmont Terrane (SE NOAM)
CCT	Central Composite Terrane	PY	Pearya
CCB	Chukchi Continental Borderland	RT	Ruby Terrane
CCS	Cache Creek Sea	SAB	South Anyui Basin
CH	Chukotka	SAM	South America
DI	Disko Island, West Greenland	SCB	South China Block
EB	Eurasian Basin	SCT	Southern Composite Terrane
EI	Ellesmere Island	SHS	Siberian Traps hot-spot
EURA	Eurasia	SIB	Siberia
FJ	Franz Josef Islands	SP	Seward Peninsula
GB	Grand Banks	ST	Stikine Terrane
GR	Greenland	SV	Svalbard
IB	Iberia	TP	Taimyr Peninsula
IHS	Iceland hot-spot	UO	Uralian Ocean
KA	Koyukuk arc	UY	Uyandina arc
KAZ	Kazakhstan	VB	Vilyui Basin
KT	Kuril Trench	VK	Verkhoyansk Block
LP	Lisburne Peninsula	WCT	Wrangellia Composite Terrane
LR	Lomonosov Ridge	WI	Wrangell Island
LS	Labrador Sea	YCT	Yukon Composite Terrane
MI	Melville Island	YT	Yakutat Terrane
MOS	Mongol-Okhotsk Sea	ZL	Zolotogorskiy terrane
MR	Mendeleev Ridge		

TABLE 2. SELECTED LITHOTECTONIC BLOCKS AND TERRANES OF EURASIA*

Abbreviation	Name	Explanation
AMR	Amuria block	Includes Argun and Gonzha cratonal terranes of Nokleberg et al. (1998). They describe them as having rifted from the southern margin of Siberia during the Late Proterozoic.
AZ	Alazeya Arc terrane	An intensely deformed tectonic melange with a thick sequence of Carboniferous to Lower Jurassic littoral-marine and shallow-marine tuff. The terrane was the product of an elongate subduction zone where subduction ended in the Early to Middle Jurassic with accretion to the Kolyma-Omolon superterrane (Nokleberg et al., 1998).
CH	Chukotka block	Passive continental-margin terrane of a long-lived Late proterozoic, Paleozoic and early Mesozoic, Atlantic-type (Nokleberg et al., 1998). The Late Proterozoic continental-margin arc activity seen in Arctic Alaska is not seen in Chukotka.
NCB	North China Block	Craton that may have rifted from the Gondwanide or Rodinian margin during Late Proterozoic.
OL	Omulevka Block	Passive continental margin terrane with oldest unit containing presumed Late Precambrian Marble, schist, and metavolcanic rocks overlain by Middle and Upper Cambrian fossils, schist, metarhyolite, and quartzite. Upper sequences contain Ordovician through Triassic fossiliferous carbonate rocks, siltstone, mudstone, marl, and some Devonian volcanic rocks (Nokleberg et al., 1998). Assumed to have derived from the Siberian craton called the North Asian Craton by Nokleberg et al. (1998).
OM	Omolon Massif	According to Nokleberg et al. (1998), it consists of poorly exposed Archean to Early Proterozoic crystalline basement overlain by Proterozic conglomerate, sandstone, and siltstone and Vendian dolomite. These are overlain by rift-related Cambrian units and widespread sills and stocks of Middle Cambrian layered gabbro. Lower and Middle Ordovician shallow-marine units are unconformably overlain by by Middle and Upper Devonian calc-alkalic lava, rhyloite tuff, trachyte, trachyandesite, granitc plutonic rocks, and basalt, the latter possibly related to formation of the Vilyui Basin and opening of the Omyikon Basin.
SIB	Siberia Cratonic Block	Called the North Asian Craton by Nokleberg et al. (1994), it consists of Archean and Early Proterozoic metamorphic basement, and Late Proterozic, Paleozoic, and Mesozoic sedimentary cover. Paleomagnetic data indicate the craton formed from accretion of major Archean and Proterozoic fragments between about 850 and 650 Ma (Gusev et al., 1985).
TP	Taimyr Peninsula	It consists of a collage of Late Proterozoic through Mesozoic terranes and overlap assemblages according to Nokleberg et al. (1998). It is divided into three distinct parts by Vernikovsky (1997): the northern part is considered part of the Kara continental margin as part of Baltica; the Central Taimyr Neoproterozoic accretionary belt including 850 Ma granites to Vendian to Early Carboniferous sedimentary cover; and the South Taimyr Paleozoic-Mesozoic fold belt, part of the passive margin of the Siberian continent.
VB	Vilyui Basin	The eastern Siberian Craton was uplifted in the Early Devonian with extensive basic dike swarms and kimberlite bodies up to 700 km long and 150 km wide emplaced along the north-west and south margins of the Vilyui Basin (Parfenov, 1997). As the Vilyui Basin formed, the Omulevka block and the Omolon Massif were rifted from the eastern edge of the Siberian Craton.
VK	Verkoyansk Block	The Verkhoyansk fold and thrust belt contains a number of passive continental margin terranes enclosed in a collage of accreted oceanic and island arc terranes (Nokleberg et al., 1998). We refer to these terranes collectively as the Verkoyansk Block and show it diagramatically with some pieces being rifted from Siberia including the OL and OM blocks with the opening of the Oimyakon Basin and some remaining along the passive margin of Siberia and then reaccreted as the Oimyakon Basin closed in the Mesozoic.
ZL	Zolotogorskiy terrane	According to Nokleberg et al. (1998) it is divided into three units with the oldest being Devonian(?) schist, sparse marble, and metavolcanic. The middle unit consists of Carboniferous and Permian sandstone and siltstones that contain corals, brachyopods, bryozoa, and crinoids. The third layer consists of Upper Jurassic to Lower Cretaceous conglomerate intruded by Early Cretaceous granite and overlain by the Okhotsk-Chukotka volcanic-plutonic belt.

*From Golonka (2000), Parfenov (1997), and Nokleberg et al. (1998).

450 Ma (Plate 6B-1) until they assume their present respective positions during the Permian (Plate 6B-7), in accordance with Zonenshain et al. (1990).

Arctic Alaska is shown closed against the Canadian Arctic Islands in Plate 6B-1, a position it occupied prior to its counter-clockwise rotation away from the Canadian Arctic Islands in late Mesozoic time (Carey, 1958; Rickwood, 1970; Tailleur, 1969, 1973). We follow Plafker and Berg (1994a) in showing the Yukon composite terrane to be south of its present position, along the western margin of Laurentia from the Ordovician to the Late Devonian. The Late Proterozoic rocks of the Yukon, Arctic Alaska, and Central composite terranes, which include the cores of the Nixon Fork terrane and the Ruby Mountains terrane, were interpreted by Plafker and Berg (1994a) to have been formed mainly in the Cordilleran miogeosyncline, although some of the terranes of the Arctic Alaska and Central compos-

TABLE 3. COMPOSITE LITHOTECTONIC TERRANES OF ALASKA*

Abbreviation	Name	Explanation
ACT (1)	Arctic composite terrane	Arctic Alaska, Porcupine, and Seward Peninsula terranes and probably part of St. Lawrence Island. Arctic Alaska terrane consists of the North Slope, Endicott, Delong Mountains, Coldfoot, and Hammond subterranes. The Arctic composite terrane constitutes the Alaska segment of the Arctic Alaska-Chukotka microplate, which was separated from the North American craton by rotational rifting in the Early Cretaceous.
CCT (2)	Central composite terrane	Several small northeast-southwest–trending terranes of central Alaska consisting of fragments of miogeoclinal sedimentary sequences, and of ultramafic and deep marine bedded rocks of the Livengood terrane. Includes the moderate-sized Nixon Fork, Dillinger, Minchumina, and Mystic terranes and the small Wickersham, Baldry, Minook, and White Mountains terranes.
KIL	Kilbuck terrane and Idono Complex	Small slivers of Early Proterozoic gneiss and schist of upper amphibolite to granulite facies in southwestern Alaska.
NOAM	Authochthonous North America	North American craton and Cordilleran miogeocline.
OCT (3)	Oceanic composite terrane	Devonian to Early Jurassic oceanic basalt, volcanogenic, and oceanic sedimentary rocks and minor ultramafic rocks of the Angayucham, Tozitna, Innoko, Goodnews, (3a) = Misheguk Mountain, and probably Seventymile terranes in north-central Alaska.
RT (4)	Ruby terrane	Structurally complex and metamorphosed continental margin sedimentary rocks and basalt with mid-Paleozoic and mid-Cretaceous plutonic rocks in north-central Alaska. Probably originally continuous with the Arctic Alaska and Yukon composite terranes.
SCT (5)	Southern Margin composite terrane	Complexly deformed accretionary prism of Upper Triassic to Paleogene continental terrace sedimentary and oceanic sedimentary and volcanic rocks of the Chugach, Ghost Rocks, and Prince William terranes. Local Early Jurassic and mid-Cretaceous blueschist metamorphism.
TCT (6)	Togiak-Koyukuk composite terrane	Late Triassic to Early Cretaceous intraoceanic volcanic arc rocks and their intrusive equivalents of the Togiak, Koyukuk, Nyac, and Innoko terranes and older Triassic and Paleozoic oceanic sedimentary and ophiolite assemblages.
WCT (7)	Wrangellia composite terrane	Late Proterozoic (?) to Early Jurassic volcanic arc and associated syn- and post-arc plutonic rocks, oceanic plateau (?) volcanic rocks, and post-arc sedimentary assemblages of the Wrangellia, (7a) = Peninsular, Alexander, and northern part of the Taku terrane; Late Jurassic to mid-Cretaceous magmatic arc, and flysch deposits of the Gravina-Nutzotin belt.
YCT (8)	Yukon composite terrane	Crystalline rocks of the Yukon-Tanana, Tracy Arm, and Taku terranes and the overlying arc-related rocks of the Stikine terrane in east-central and southeastern Alaska. The crystalline rocks were derived from the western margin of the North American craton.
YT (9)	Yakutat terrane	Allochthonous fragment of the continental terrace of the Pacific coast of North America emplaced by 600 km of post-Oligocene right-slip on the Queen Charlotte–Fairweather fault system and associated underthrusting of the Southern margin composite terrane.

*From Plafker and Berg, 1994.

ite terranes may originally have been part of Chukotka or possibly Siberia (Dumoulin et al., this volume; Blodgett et al., this volume).

The southern Wrangellia composite terrane (7 in Fig. 3; WCT in Plate 6B) contains Early Ordovician to Late Devonian magmatic rocks. It is assumed to have been within 15° of latitude of its present position with respect to the North American craton during those times (Plafker and Berg, 1994a). We place the Wrangellia composite terrane near Siberia in Plate 6B-1, whereas Nokleberg et al. (1998) suggested that it might have been derived from the Barents Sea region, which would be difficult given the plate geometries we show in Plate 6B-1. Plafker and Berg (1994a) rejected the Southern Hemisphere location of Wrangellia suggested by Gehrels and Saleeby (1987) because Devonian invertebrate fossils from the Alexander terrane of the Wrangellia composite terrane have North American affinities (Savage, 1988). The weight of the evidence (Blodgett et al., this volume) indicates that the Middle Cambrian to Lower Devonian invertebrate faunas of the Alexander terrane of the Wrangellia composite terrane, the Nixon Fork and Livengood terranes of the Central composite terrane, and the York and Coldfoot-Hammond subterranes of the Arctic Alaska composite terrane have faunal affinities with Siberia. Moreover, the Cambrian or Ordovician through Carboniferous invertebrate faunas of these terranes are dissimilar to those of North America, including Arctic Canada. Hahn and Hahn (1993) and John Carter (1999, personal commun.) also indicated that at least some elements of the Carboniferous brachiopod faunas of southeastern Alaska have Eurasian, rather than North American affinities. The Alexander, Nixon Fork, Livengood, Coldfoot-Hammond, and York terranes therefore appear to have been in the Northern Hemisphere, and close to or part of Siberia, from at least the Ordovician to the Carboniferous. Many of the Late Triassic faunas found in the Central and Wrangellia composite terranes, however, have tropical paleogeographic aspects and are unlike coeval faunas in northwestern North America (R. Blodgett, 1999, personal commun.). According to Blodgett, little is known about the travels of these terranes between their probable location on the periphery of Siberia in the Devonian to Carboniferous and their amalgamation with southern and central Alaska during the Late Jurassic and Early Cretaceous. Our placement of the Wrangellia composite terrane in Plate 6B-1 (450 Ma) near Siberia is based solely on the faunal data. There is no control on its subsequent migration to its speculative position in the eastern Pacific off North America during the Middle Devonian (Plate 6B-3). Subcomponents of the Wrangellia composite terrane may have drifted into the tropics or been amalgamated with tropical components, before it joined with North America during the Jurassic.

Closure of the Iapetus Ocean and assembly of Laurussia: The Scandian phase of the Caledonian orogeny

The first major event in the long process by which the scattered Arctic landmasses were assembled into the continental framework of the modern Arctic was the Scandian phase of the Caledonian orogeny, when Baltica collided with North America in the region of Greenland during the late Early Silurian (Wenlock) to late Early Devonian (?Emsian). Baltica, Pearya, and possibly Chukotka were added to Laurentia to form Laurussia (Fig. 4 and Plate 6B-2). Closure of the Iapetus Ocean assembled the principal continental components of the modern Arctic (Siberia, Chukotka, Baltica, Greenland, the Canadian Arctic Islands, and Arctic Alaska) between the equator and lat 30°N.

McKerrow et al. (2000) redefined the classic Caledonian orogeny of northwestern Europe to include all the phases from Late Cambrian to Late Devonian age associated with the closure of those parts of the Iapetus Ocean situated between Laurentia to the northwest and Baltica and Avalonia to the southeast and east. Whereas McKerrow et al. (2000, p. 1151) stated "The term 'Caledonian orogeny' should be restricted to tectonic events within, and on the borders of, the Iapetus Ocean," Figure 4 indicates that the Iapetus Ocean extended as far as the margins of Arctic Alaska. The Scandian phase of the orogeny resulted from the continent-continent collision of Baltica with the eastern Greenland section of Laurentia (Stephens and Gee, 1985) during Wenlock to Emsian (?) time (Silurian to Early Devonian). More recent work seems to place the Scandian phase of the Caledonian orogeny for Svalbard in the Silurian, based on Ar/Ar dates (Gee et al., 1994), and closure of Baltica with Greenland appears to have been completed in the Silurian according to MacNiocall et al. (1997). Ziegler (1988, 1989) proposed that the Scandinavian Caledonides have a northward trend in the southwestern Barents Sea (BS in Fig. 1) and link up with the Innuitian orogen (Fig. 1) through the Svalbard Caledonides. Gudlaugsson et al. (1998) preferred the model of Doré (1991), which has the main arm of the Caledonides extending northeast across the Barents Sea as a direct continuation of the structural axis of the Scandinavian–East Greenland Caledonides. In their model, a separate north-oriented arm underlies the northwestern Barents Sea and western Svalbard (SV in Fig. 1). It is this western arm that links the Caledonides of northwestern Europe with the Innuitian orogen of northwestern North America, as Ziegler (1988, 1989) suggested, and associated the Scandian phase of the Caledonian orogeny with the major mid-Paleozoic tectonic events of Laurentia. The geometry of the colliding plates (Figs. 4 and 5) suggests that the earliest part of the Innuitian orogeny of northern Greenland and northern North America and the Scandian phase of the Caledonian orogeny of northwest Europe are the same event. This is expressed in both the early Paleozoic rocks of northwestern Europe (Roberts and Sturt, 1980) and the pre–late Visean (pre–middle Mississippian) rocks of Greenland and northern North America (Trettin, 1991a).

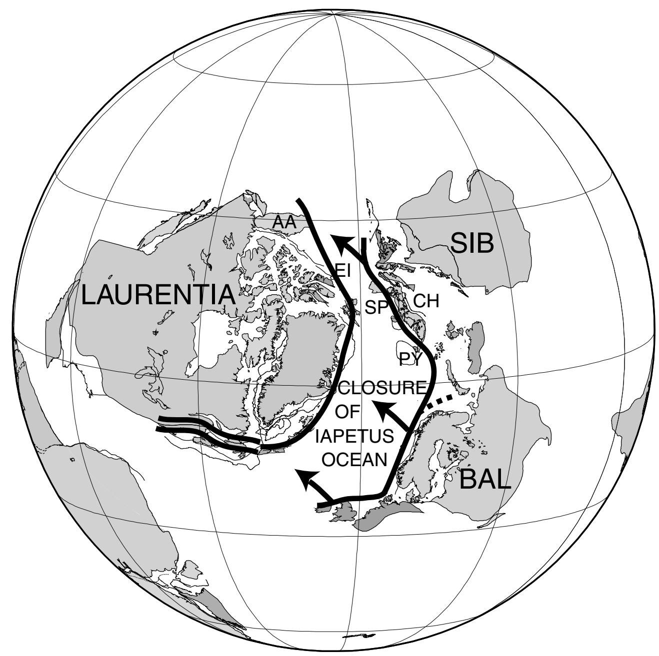

Figure 4. Major Late Ordovician to Early Silurian tectonic events that affected structurally imprinted future Arctic plates. Closure of Iapetus Ocean produced Caledonian deformation along Greenland and Scandinavia, as indicated by single thick lines off eastern Greenland, Canadian Arctic Islands, Chukotka, and western Baltica (BAL). Branching dashed thick line is Caledonian deformation traced into Barents Sea region (Gudlaugsson et al., 1998). Based on deformational events on Wrangell Island (Kos'ko et al., 1993), we have placed Chukotka block (CH) on incoming Baltica plate along with Pearya terrane (PY), which accreted to Ellesmere Island (EI) and parts of Seward Peninsula (SP), which accrete to Arctic Alaska (AA). SIB is Siberia. Single-headed arrows indicate general plate motion directions but are not constrained. Double thick lines indicate collision of peri-Avalon block with Laurentia prior to Late Ordovician.

Caledonian deformation of northern Greenland

Higgins et al. (1991) suggested that the most precise time record of the closing of the Iapetus Ocean is provided by a west-

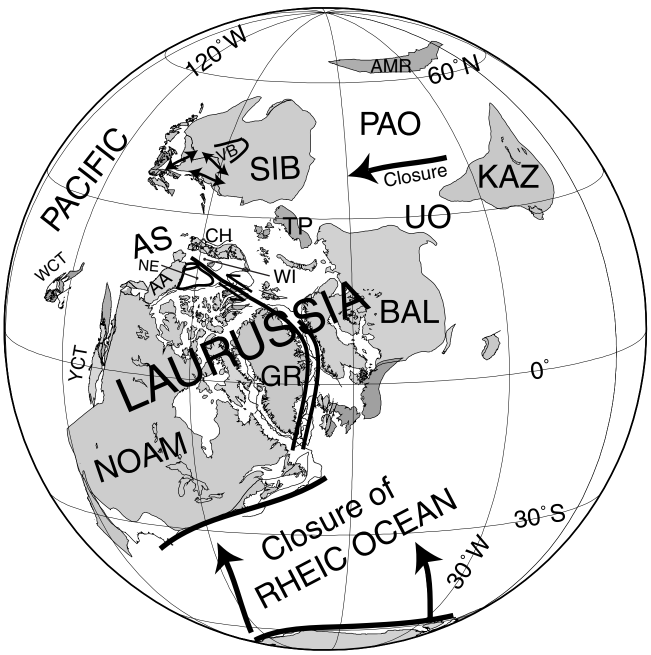

Figure 5. Major Middle to Late Devonian tectonic events that structurally imprinted the future Arctic plates. To southeast of Laurussia, Rheic Ocean was closing during Middle to Late Devonian. NE shows northeast Chukchi Sea shelf region with double line approximating position of the present-day Herald arch. Late Devonian to Carboniferous Ellesmerian orogeny resulted from either collision of some plate, perhaps Siberia (SIB) with northern margin of Laurussia or flat-slab subduction along that margin. Verkoyansk region of present-day eastern Siberian craton was rifted at this time, perhaps by mantle plume in Vilyui basin region. We infer that the mantle plume may have also opened the Oimyakon basin (OB) to west and imparted eastward motion to Siberia. Double-headed arrows indicate active or assumed active seafloor spreading. Single-headed arrows indicate general plate motion directions but are not well defined. See Table 1 for abbreviations.

ward-prograding, chert-pebble conglomerate in the Franklinian basin in northern Greenland. Higgins et al. (1991) thought that these mid-Wenlock (late Early Silurian) deposits had their source in upthrust Ordovician chert sequences exposed to erosion in the rising Caledonian mountain belt to the east. These relationships suggest that the Scandian phase of the Caledonian orogeny began in the Early Silurian prior to mid-Wenlock time, or before 425 Ma. The final Paleozoic orogenic episode in the Franklinian basin according to Surlyk and Hurst (1984) was north-south folding during the Late Devonian–Early Mississippian Ellesmerian orogeny (Trettin, 1991b), which corresponds to the Late Devonian Svalbardian phase of the Caledonian orogeny as defined by Roberts and Sturt (1980).

Emplacement of Pearya

Several tectonic events in northwestern North America can be related to the Scandian phase of the Caledonian orogeny. Perhaps the best documented is the suturing of the Pearya terrane (PY in Plate 6B-1) to the Clements Markham arc of northern Ellesmere Island (Trettin, 1991a; Klaper, 1992) by sinistral transpression as Baltica collided obliquely with Greenland and North America. According to Trettin (1991a), the Pearya terrane was part of the European Caledonides until at least late Middle Ordovician time. It was then emplaced by sinistral transpression upon the Franklinian mobile belt in northern Ellesmere Island beginning in the late Early Silurian. Emplacement was dated by the age of the first Pearya terrane-derived sediment in the Franklinian mobile belt; Trettin (1991c) tentatively assigned a Late Silurian age to the entire emplacement event, while Klaper and Ohta (1993) concluded that the emplacement event predates the Late Silurian.

Emplacement of Chukotka

A key element in reconstructions of the western Arctic is the origin and accretionary history of the Chukotka block (CH) (Plates 6B-1 and 6B-2), which consists of the western part of the modern Chukchi shelf, Wrangell Island (Kos'ko et al., 1993) (WI, Fig. 1), the East Siberian shelf to the west of Wrangell Island (in modern coordinates), and adjacent northeastern Russia. Basement exposures in the center of Wrangell Island consist of Late Proterozoic felsic to intermediate volcanic and volcaniclastic rocks and phyllitic schist and slate intruded by plutonic rocks (Kos'ko et al., 1993). The volcanic rocks yield a U-Pb crystallization age from zircons of 633 +21/−12 Ma; a porphyritic granite sill yields a zircon age of 699 ± 2 Ma; and a leucogranite had an imprecise age of 0.7 Ga (Cecile et al., 1991). These ages and rock types are distinct from the Late Proterozoic equivalents found on the Canadian Arctic Islands and suggest that Chukotka with Wrangell Island and the Canadian Arctic Islands were not one unit during the Late Proterozoic (Cecile et al., 1991). These dates from Wrangell Island are broadly similar, however, to metamorphic ages from the western part of the southern Brooks Range of northern Alaska and to northern Chukotka (Cecile et al., 1991). The rocks underlying the schist belt of the western southern Brooks Range are metasedimentary and metavolcanic rocks intruded by 705 Ma (Hub Mountain) and 750 Ma (Mount Angayukaqsraq) plutonic rocks (Karl et al., 1989; Karl and Aleinikof, 1990). Two similar dates, 681 ± 3 Ma and 676 ± 15 Ma from granitic orthogneiss bodies on the Seward Peninsula, were reported by Patrick and McClelland (1995). The similarities between the Late Proterozoic intrusions on Wrangell Island, the western southern Brooks Range sequence, and the Seward Peninsula suggest that they may have been part of the same block during the Late Proterozoic. If these correlations are valid, the suture between Chukotka and Arctic Alaska is south and west of the present-day location of the Lisburne Peninsula, but north of the Seward Peninsula and the Hub Mountain and Mount Angayukaqsraq areas of the southwestern Brooks Range, which appear to be parts of the ancestral Chukotka. Seward Peninsula is therefore shown separated from Arctic Alaska in Figure 4 (also on Plate 6B-1), but transferred along with the western part of the southern Brooks Range to Arctic Alaska in Plate 6B-2. From west of the Lisburne Peninsula the suture probably trended north or northwest (in modern coordinates) between the Herald arch and Wrangell Island on the southwest and west and a thick section of gently dipping strata that underlies the northeast Chukchi Sea on the east (see Grantz et al., 1987, and Fig. 11, 1990). These gently dipping strata are inferred to include unmetamorphosed, or only mildly metamorphosed Late Proterozoic rocks at mid-crustal depths, and to be part of the ancestral Arctic Alaska.

Kos'ko et al. (1993) and Natal'in et al. (1999) provided insight into the age of suturing of Chukotka to Arctic Alaska. Kos'ko et al. (1993) concluded that deformation and uplift of the upper Proterozoic rocks of Wrangell Island, some western parts of the southern Brooks Range, and possibly the New Siberian Islands and adjacent areas of northeastern Russia occurred between the latest Proterozoic and the Early Silurian. Although they related this deformation to the Middle Ordovician M'Clintock orogeny of northern Ellesmere Island (Trettin, 1987), two of the three dates that they cited for the Wrangell Island deformation are Early Silurian (430 and 432 Ma, Kos'ko et al., 1993). This suggests that the Wrangell Islands and, by extrapolation, possibly all of Chukotka were emplaced against North America during an Early Silurian collision (cf. Plates 6B-1 and 6B-2). This collision was only slightly earlier than the tentatively dated emplacement of the Pearya terrane onto the Franklinian mobile belt in the late Early Silurian to Early Devonian (Trettin, 1991a, 1991c), and broadly correlative with the Scandian phase of the Caledonian orogeny.

Caledonian deformation in Arctic Alaska

The Scandian phase of the Caledonian orogeny may also be represented by the regional deformation within Arctic Alaska. Here a strongly deformed and indurated sequence of marine argillite with interbeds of fine-grained graywacke, quartzose sandstone, carbonate, and chert containing Early Silurian graptolites and Ordovician and Silurian chitinozoans (Carter and Laufield, 1975) in the subsurface of the North Slope subterrane of Arctic Alaska are overlain by steeply dipping, but unmetamorphosed nonmarine clastic sediment containing Middle (perhaps Lower) Devonian plant remains (Collins, 1958). The Middle (Lower?) Devonian nonmarine redbeds are truncated by the same regional unconformity that overlies the Ordovician and Early Silurian argillite and sandstone sequence of Arctic Alaska, but lack the penetrative deformation of the older beds. This suggests that the Middle (Lower?) Devonian redbeds postdate the main deformation of the argillite and sandstone sequence (Moore et al., 1994) and that an orogenic event of Late Silurian and/or Early Devonian age consolidated and penetratively deformed the Ordovician and Silurian argillite and sandstone sequence and elevated it above sea level. The regional unconformity is between moderately deformed argillite and graywacke containing Middle Ordovician graptolites and Early Silurian conodonts and mildly deformed Lower Mississippian nonmarine beds of the Kapaloak Formation (Endicott Group) on the Lisburne Peninsula (Grantz et al., 1983; Moore et al., 1994, this volume). Similarly, complexly deformed chert and phyllite of Cambrian to Ordovician age in the eastern Brooks Range are overlain unconformably by mildly deformed shallow-marine beds with Middle Devonian (Eifelian) invertebrates (Anderson et al., 1994). These deformation events are all attributed to the Scandian phase of the Caledonian orogeny, which was defined as late Early Silurian to Early Devonian by McKerrow et al. (2000).

The presence of Cambrian to Devonian marine conodont and megafossil assemblages of Siberian affinity or a mixture of Siberian and North American taxa (see especially Dumoulin et al., this volume; Blodgett et al., this volume) in several terranes in central and northern Alaska appear to be explained by (1) the relative proximity of Chukotka and other continental fragments to Laurentia (Plate 6B-1) during the Ordovician and perhaps the Cambrian, and (2) the suturing of Chukotka and other continental fragments with Laurentia in the Scandian phase of the Caledonian orogeny (Figs. 4 and 5). Our reconstructions suggest that the Late Silurian to possibly Early Devonian regional deformation observed in the North Slope subterrane of Arctic Alaska is a product of the left-lateral transpression that closed this part of the Iapetus Ocean between 450 and 420 Ma (cf. Plates 6B-1 and 6B-2) and should be assigned to the Scandian phase of the Caledonian orogeny. This event antedated the classic Ellesmerian orogeny, dated by Trettin (1991b) as latest Devonian to earliest Mississippian, by ~50 m.y.

Motion of pre-Pangean Siberia

Paleomagnetic data (Smethurst et al, 1998) suggest that during the Late Silurian (420 Ma, Plate 6B-2), Siberia was situated between 25°N and 50°N, <10° north of our reconstructed position of Chukotka. The locations of Chukotka and Verkhoyansk with respect to Siberia are best approximations from Parfenov (1997) and Golonka (2000). Although there are reasonable paleomagnetic data to locate Siberia at 450 Ma (Smethurst et al., 1998), its locations with respect to North America in Plates 6B-2 and 6B-3 are based on extrapolation between paleomagnetic poles at 435 Ma (Smethurst et al., 1998; Rodionov et al., 1982) and 380 Ma (Kamysheva, 1973). The available paleomagnetic data are insufficient to determine how far Siberia was separated from northern Laurussia during the critical time (Early Silurian) when the Pearya terrane and possibly Chukotka were accreted to North America. Kolesov and Stone (this volume) use the apparent polar wander (APW) path for Siberia of Didenko and Pechersky (1993). This APW path, which is undocumented, shows Siberia farther south during the Silurian than shown by Smethurst et al. (1998), and produces an unacceptable overlap between Siberia and the Taimyr Peninsula.

Comparison of the 420 Ma reconstruction (Plate 6B-2) with the 450 Ma reconstruction (Plate 6B-1) shows that Siberia was moving northwestward as the Iapetus Ocean closed. Golonka

(2000) showed a strike-slip fault operative between Siberia and Laurentia as the Iapetus Ocean was undergoing final closure during the Early Silurian (443–428 Ma, ca. 435 Ma). In our reconstructions, this hypothesized left-lateral fault (Fig. 5) is placed between Chukotka and North America from Svalbard to Arctic Alaska, indicating that there was transpression with oblique collision between Baltica and Greenland during the Early Silurian. Because we have no contemporary geological data on the location of Siberia with respect to Chukotka or North America, and the paleomagnetic data do not delimit Siberia for the critical Late Silurian period, we cannot determine whether Siberia was involved in the Scandian phase of the Caledonian orogeny.

Bennett-Barrovia block

Şengör and Natal'in (1996) combined the Bennett massif, defined as the Precambrian basement under the East Siberian and Chukchi Seas, with the idea of Barrovia land (Tailleur, 1973) to describe a Bennett-Barrovia block. Natal'in et al. (1999) showed their Bennett-Barrovia block as roughly equivalent to offshore Chukotka from west of the New Siberian Islands to the northern margin of the Seward Peninsula, the Hammond terrane of the southern Brooks Range, and the northeastern part of the Chukchi shelf. Tailleur (1973) defined Barrovia as the provenance for the old Arctic Alaska sedimentary basin (Tailleur and Brosgé, 1970) and showed it as encompassing the entire present northern Alaska margin, not just the area to the west of Point Barrow, as Natal'in et al. (1999) showed it in their Figure 7. We place the boundary between the Chukotka block and Laurentia during the Scandian phase of the Caledonian orogeny on the west side of the gently deformed lower Paleozoic and Precambrian strata that underlie the northeastern Chukchi shelf (Grantz et al., 1990), which we consider to be part of Arctic Alaska. Figure 5 shows that the area in question (labeled NE) would be difficult to emplace without producing significant deformation in the pre-Silurian strata of the northeast Chukchi shelf. We therefore place the Chukotka–Arctic Alaska boundary along the southwestern edge of the Herald thrust and the western side of the northeast Chukchi shelf, rather than in the eastern Chukchi Sea on a path that is parallel to the northeast-trending coast of Alaska northeast of the Lisburne Peninsula, as shown by Natl'in et al (1999). We thus consider the northeast Chukchi shelf (NE) as shown in Figure 5 to be part of North America in the Late Ordovician, rather than part of the Bennett-Barrovia block of Natal'in et al. (1999).

Natal'in et al. (1999) proposed that their Bennett-Barrovia block collided with North America during the Late Silurian to Early Devonian, but they assigned the collision to the Ellesmerian orogeny. However, Lerand (1973), who defined the orogeny, and Trettin (1991a, 1991b) and Embry (1991), who summarized the early Paleozoic and Devonian geology of the Canadian Arctic Islands, dated the Ellesmerian orogeny as Late Devonian to Early Mississippian. The age of the collision of Bennett-Barrovia with North America proposed by Natal'in et al. (1999) corresponds, however, to the Scandian stage of the Caledonian orogeny and the age tentatively proposed by Trettin (1991a, 1991c) for the emplacement of Pearya onto the Franklinian mobile belt. We therefore consider the collision of Chukotka with North America to be more or less coeval with the collision of Baltica with northern North America and that the suture, which is west of both the Lisburne Peninsula and the northeast Chukchi shelf, formed during the Scandian phase (late Early Silurian to Early Devonian) of the Caledonian orogeny.

ARCTIC DURING THE ASSEMBLY OF PANGEA (DEVONIAN AND EARLY MISSISSIPPIAN)

During Middle to Late Devonian time (Fig. 5) the Rheic Ocean closed, culminating in the collision of Gondwana with Laurussia and the formation of Pangea (Fig. 6). Two major events affected the position and configuration of the future Arctic continental landmasses during the Devonian. These events were formation of the open-sided Vilyui basin on the Siberian craton and the Late Devonian to Mississippian Ellesmerian orogeny.

Figure 6. Major Carboniferous tectonic events that structurally imprinted future Arctic plates. The Rheic Ocean had closed by mid-Carboniferous time and the Appalachian orogeny (AP) continued with right-lateral deformation along a wide region. To the northwest, the Cache Creek Sea (CCS) was opening, rifting Yukon composite terrane (YCT) from its position along Laurussia. Paleo-Asian (PAO) and Uralian Oceans (UO) were closing as the Kazahkstan block (KAZ) converged with Siberia (SIB) and Baltica (BAL). Ocean crust was being subducted under Siberia (Vernikovsky, 1997) as it moved toward Taimyr Peninsula (TP). Double-ended arrows indicate assumed seafloor spreading. Single-headed arrows indicate general plate motion directions but are not well defined. See Table 1 for abbreviations.

Motion of Siberia and the position of continental fragments later accreted to Siberia

During the Devonian (Plates 6B-3 and 6B-4) a large embayment in the Pacific margin resulted from the motion of Siberia with respect to Chukotka and Arctic Alaska, and was called the Angayucham Ocean by Nokleberg et al. (1998). The 330 Ma reconstruction (Plate 6B-5) differs from those of Nokleberg et al. (1998) and Parfenov (1997) in that we place Siberia farther east relative to Arctic Alaska than is shown in their reconstructions. Our reconstructions are based on overlapping the paleomagnetic 95% confidence ellipses for Siberia (Smethurst et al., 1998) with those of North America (Van der Voo, 1993), combined with reasonable assumptions concerning placement of Siberia with respect to Baltica. In addition to the Angayucham Sea (Fig. 6) between Siberia and Chukotka, there was a narrow sea (Vernikovsky, 1997) between Siberia and the northern Taimyr Peninsula margin of Laurussia. The eastward motion of Siberia in an absolute framework starting in Late Devonian (cf. Plates 6B-4 and 6B-5) suggests that the opening of the Oimyakon basin and the narrow sea between Siberia and Taimyr Peninsula may have been contemporaneous, and possibly related.

Devonian dike swarms traceable for 700 km along the northwest and south edges of the major Vilyui sedimentary basin (Vilyui basin, Fig. 5 and Plate 6B-5) on Siberia date the age of the initial formation of the Vilyui basin (Parfenov, 1997). The ocean crust of the Oimyakon basin (Plate 6B-5) may also have been initiated by this eruptive episode because Middle to Late Devonian volcanic rocks are found in both the Omulevka and the Omolon blocks (Nokleberg et al., 1998), which were separated from Siberia by opening of the Oimyakon Sea. Khramov (1984, 1986) presented paleomagnetic data for the Omulevka block that suggest it was part of the Siberian platform during the Ordovician and Silurian. A prime candidate for the cause of the Middle Devonian rift event is the impact of a mantle plume under Siberia. We suggest that the Vilyui basin represents the failed arm of one of Burke and Dewey's (1973) plume-generated triple junctions, and that the Oimyakon basin represents the successful arms. Based on the paleomagnetic data of Smethurst et al. (1998), Siberia moved northwestward with respect to Laurussia during Ordovician to Early Devonian time (Plates 6B-1 to 6B-3), but by Late Devonian time (Plate 6B-4) Siberia had apparently changed direction to move northeast while undergoing significant clockwise rotation (Plate 6B-5). Such a reversal of plate motion and rotation is consistent with interaction with a Middle Devonian mantle plume.

Şengör and Natal'in (1996) suggested that the Vilyui rift opened during the Late Devonian (360 Ma). Following Parfenov (1997), we show a widening basin (Fig. 5) between Siberia and the Omulevka and Omolon blocks. There are no geological data for the position of the Omulevka or Omolon blocks during the Carboniferous and Permian, and consequently the width of the intervening sea, the Oimyakon basin, is not known. Although Parfenov (1991) cited paleomagnetic data that place the Omulevka block 20°–30° south of Siberia during the Middle Devonian to Mississippian, close scrutiny of Parfenov's (1991) Figure 14 suggests that the Omulevka block was then 10°–18° north of, rather than south of, Siberia. Kolesov and Stone (this volume) have new paleomagnetic data for the Omulevka block during the Late Devonian that agree with the interpretation shown in Figure 5. They also compiled available data for the Omulevka block with respect to Siberia for younger times through the Late Cretaceous that place the Omulevka block as much as 25° or more south of Siberia during the Triassic. The plate motions implied by the values listed in Kolesov and Stone (this volume) range up to 100 mm/yr, and the locations of Siberia are as much as 15° north of where Smethurst et al. (1998) showed it for the Triassic. We resolve the uncertainty by simply placing the Omulevka block ~1000 km west of Siberia at 300 Ma (Plate 6B-6) until we begin to close the Oimyakon basin in the Middle Jurassic (Plates 6B-11 and 6B-12). Parfenov (1997) and Golonka (2000) both suggested that the Oimyakon basin started to close ca. 250 Ma with the caveat that it may have remained open until the Valanginian or Hauterivian (ca. 130 Ma). Blodgett (1998) suggested a Siberian affinity for late Early Devonian fossils from the Nixon Fork subterrane of central Alaska (see Central composite terrane in Table 2), which indicates that terranes that eventually accreted to North America, as well as terranes like the Omulevka and Omolon blocks that later rejoined Siberia, were rifted from Siberia during the Devonian.

Ellesmerian orogeny

According to Trettin (1991b, 1991c), a tectonic event of uncertain origin produced the Ellesmerian orogeny in the Franklinian mobile belt of the northern and central Canadian Arctic Islands and northern Greenland, and he suggested convergence of an unidentified plate with the northern margin of Laurussia as the most probable cause. Klaper (1992) attributed the extensive compressional deformation found on Ellesmere Island to this orogeny, and the cause to be collision of a continental Siberian plate with the northern margin of Laurussia during the Middle and Late Devonian (Plates 6B-3 to 6B-5). Trettin (1991a, 1991b) tentatively placed the Ellesmerian orogeny at the end of a sequence of orogenic events that range in age from middle Givetian or possibly Eifelian (Middle Devonian) to the Tournaisian (Early Mississippian), and indicated that the age of the orogeny sensu stricto (Trettin, 1991b) is latest Devonian (Famennian) to Early Mississippian (Tournaisian). This event roughly correlates with the Svalbardian or Acadian phase of the Caledonian orogeny.

Our reconstructions for the Middle Devonian to Late Mississippian (Plates 6B-3 to 6B-5) do not make a definitive case for a collision between Siberia and Laurussia that would correlate with the Svalbardian phase of the Caledonian orogeny. Plate 6B-4 shows a possible interaction of Siberia with the Taimyr Peninsula, but it is unlikely that that alone would have led to an Ellesmerian orogeny along the Canadian Arctic Islands as far west as Melville Island (MI on Plate 6B-4). Zonenshain et al. (1990), however, provided support for the origin of the Ellesmerian orogeny in a Svalbardian phase collision between northern Laurussia and a continental mass to the north, but as in the Canadian Arctic Islands, identification of the causative agent remains uncertain. They suggested that the North Taimyr–Severnaya Zemlya continental fragment, which was between Siberia and Baltica, collided with northern Laurussia near the end of the Devonian to the beginning of the Carboniferous (360 Ma, Plate 6B-4), but Nikishin et al. (1996) showed little or no movement between Severnaya Zemlya, Taimyr, and Baltica after the Late Cambrian, and showed Baltica as part of Laurussia during the Late Devonian and Early Mississippian.

The Ellesmerian orogeny consists mainly of faulting in northern Ellesmere Island and thin-skinned folding above the base of Ordovician evaporites from southern Ellesmere Island on the northeast to Melville Island and adjacent islands on the southwest (Trettin, 1991a). The orogeny appears to be absent from the eastern Brooks Range, because Early Devonian (Eifelian) to Cretaceous strata there lack compressive deformation (Anderson et al., 1994). Evidence for Ellesmerian deformation on the North Slope of Alaska may be preserved, however, in the Topagoruk test well, ~90 km south-southeast of Point Barrow. Collins (1958) reported unmetamorphosed medium gray chert conglomerate and dark gray carbonaceous lutite at the bottom of the well that dip 30°–65° and contain Middle (Early?) Devonian plant debris. These beds are overlain unconformably by red to gray lutite and sandstone with some red chert conglomerate that dip 8° or less. The redbeds could not be dated, but are overlain abruptly by light gray sandstone- and siltstone-bearing marine fossils of Permian age. The steep dips in the Middle (Early?) Devonian nonmarine beds may represent the Late Devonian or Early Mississippian Ellesmerian orogeny.

The areas of known or inferred Ellesmerian deformation are 1000 km or more from the presumed suture between Siberia with North Taimyr–Severnaya Zemlya, or with Chukotka as they existed during the Middle to Early Mississippian (Plates 6B-4 to 6B-5). If collision and convergence at this suture generated the stress that created the Ellesmerian orogeny, it was a far-field effect that was transmitted across Chukotka and left little deformation in the early Paleozoic and Precambrian strata that underlie the northeast Chukchi shelf. It would also imply that the early Paleozoic crust beneath the Franklinian mobile belt and the Arctic Alaska sedimentary basin of northern Alaska were mechanically more susceptible to compression than the crust that underlies the northeast Chukchi Sea and Chukotka. Dalziel et al. (2000) explained similar far-field effects in the Gondwanide fold belt, where orogenic deformation occurs 1500 km behind an active subduction zone, by flat-slab subduction. Sanford et al. (1985) suggested that compressional stresses at cratonal margins might reactivate fault-bounded basement segments far into craton interiors. Another explanation for the Ellesmerian orogeny may be reactivation of convergence, and subsequent redevelopment of subduction or compression along the suture between Chukotka and the northern margin of Laurussia, along which the Iapetus Ocean closed during the earlier Scandian phase of the Caledonian orogeny. The Ellesmerian orogeny, which roughly correlates with the Svalbardian phase (Roberts and Sturt, 1980) or Acadian phase (McKerrow et al., 2000) of the Caledonian orogeny. Deep seismic reflection profiling across the Canadian Arctic Islands may be needed to definitively determine the tectonic associations of the Ellesmerian orogeny.

Subduction and rifting along the western margin of Laurussia (North America)

According to Howell et al. (1985), the western margin of North America underwent a late Precambrian regional rifting event that produced a passive margin that received shelf and slope sediment through much of the Paleozoic. Oceanic island arcs and backarc basins of Cambrian to Late Devonian age that were unrelated to North America, but were eventually accreted to it during the Mesozoic (Howell et al., 1987), were oceanward of this margin. These arcs and backarc basins were accreted to the western and Arctic margins of North America from at least northern California (Rubin et al., 1991) to western Arctic Alaska (Plafker and Berg, 1994a). Plafker and Berg (1994a) noted dates for magmatism related to these arcs that range from 350 to 370 Ma for their Yukon composite terrane to 365 to 410 Ma for the Coldfoot terrane of Arctic Alaska in the southern Brooks Range. There is also evidence for a primitive Devonian arc on the outboard Alexander terrane of the Wrangellia composite terrane (Table 1). During the Late Devonian, an elongate sliver of continental rock with strong lithologic affinities to western North America drifted away from the continent and left an ocean basin between the sliver and North America (Plates 6B-5 to 6B-7). This sliver, consisting mainly of crystalline rocks, was named Stikinia by Tempelman-Kluit (1979) and the Yukon-Tanana terrane by Mortensen (1992). The crystalline rocks are overlain depositionally by Upper Triassic to Middle Jurassic marine clastic and volcanic and carbonate arc rocks and intruded by comagmatic igneous rocks of the Stikine terrane. Together the Yukon-Tanana and Stikine terranes form the Yukon composite terrane of Plafker and Berg (1994a). The ocean basin that formed between the Yukon composite terrane and North America was named the Anvil Ocean by Templemen-Kluit (1979), but was referred to as the Cache Creek Sea by Monger and Berg (1987) and Plafker and Berg (1994a). The latter indicated that the Cache Creek Sea is of at least Early Mississippian to Middle (?) Jurassic age and formed behind a Late Devonian to Early Mississippian magmatic belt. Nokleberg et al. (1998) adopted the interpretation of Mihalynuk et al. (1994) and used the term Cache Creek Ocean for oceanic crust outboard of the Yukon composite terrane, crust which in reality is simply part of the ancestral Pacific Ocean, as shown in Nokleberg et al. (1998, Fig. 8). They also used the term Slide Mountain Ocean for the region that Plafker and Berg (1994a) referred to as the Cache Creek

Sea. We restrict our use of the term "ocean" to its modern usage and use "sea" for marginal oceanic basins that may or may not have been fully open to the Pacific Ocean, much like the present-day Japan Sea or the Sea of Okhotsk. In general, we adopt the place-name usage of Plafker and Berg (1994a, 1994b) herein.

Mortensen (1992) suggested that the magmatic arc along the outboard margin of the Yukon composite terrane was associated with continentward subduction from the Late Devonian to the Early Mississippian, but that its polarity had reversed by mid-Permian time. This agrees well with Tempelman-Kluit's (1979) timing of rifting of his Anvil Ocean, which he believed to have been initiated as a backarc basin in response to Late Devonian continentward subduction outboard of the Yukon composite terrane. The existence of evidence for a mid-Permian reversal of subduction direction suggests that the Cache Creek Sea was sufficiently wide, and subduction sufficiently long lived, to generate a westward-subducted slab that imprinted the geologic record of the Yukon composite terrane. Gordey et al. (1987) suggested that by mid-Mississippian time the Cache Creek Sea had become sufficiently deep and wide that clastic sediment from the rifted sliver (Yukon composite terrane) could no longer reach the margin of the North American craton. While many authors (as summarized in Plafker and Berg, 1994a) indicate the width of the Cache Creek Sea as unknown, it is commonly suggested, on the basis of sedimentation patterns, that it may have been thousands of kilometers wide. We show a width of 1000–1200 km for the Cache Creek Sea based on a rough analogy with the Cenozoic South China Sea, where the Palawan, Reed Bank, and other blocks were rifted from the South China block margin and transported ~1200 km southward from the Eocene until spreading stopped in the Miocene (Lee and Lawver, 1995).

TECTONIC ACTIVITY IN THE ARCTIC DURING THE TIME OF PANGEA (LATE PENNSYLVANIAN TO MIDDLE JURASSIC)

Pennsylvanian

The mid-Paleozoic Rheic Ocean (Plates 6B-2 to 6B-4) was essentially closed by 300 Ma (Fig. 6 and Plate 6B-6) as North America sutured to Africa and the Piedmont block (the present southeastern United States) during the Alleghenian orogen (Hatcher et al., 1990). The resultant supercontinent, Pangea, lasted for at least 100 m.y. By Carboniferous time (Fig. 6) the Cache Creek Sea between the Yukon composite terrane and North America had begun to open. Only the rapidly narrowing paleo–Asian Ocean separated Siberia from the Kazakhstan block (Golonka, 2000). The open sea between the northern Taimyr block and Siberia (Fig. 6) closed when the northern part of the Taimyr Peninsula, as part of the Kara continental block of Pangea, sutured to Siberia (Plate 6B-6) starting ca. 300 Ma, according to Vernikovsky (1997). During the Carboniferous (Fig. 6) Eurasia coalesced with closure of the Uralian Ocean between Baltica and Kazakhstan and the paleo–Asian Ocean between Kazakhstan and Siberia (Golonka, 2000). Vernikovsky (1997) illustrated the collision of the northern Taimyr Peninsula block with the Pangean margin through subduction beneath Siberia. Such Siberian-directed subduction would also explain the westward motion of Kazakhstan and closure of the paleo–Asian Ocean (cf. Figs. 6 and 7). The presence of as much as 4 km of eastward-wedging middle Carboniferous through Triassic sediment in the Vilyui basin of eastern Siberia (Parfenov, 1997) implies that the eastern end of the basin was still open at that time, and that the Omulevka block did not rejoin Siberia until sometime after the Triassic.

Triassic to Early Jurassic

By Triassic time (Fig. 7) the Cache Creek Sea was closing and northern Eurasia was largely assembled by the suturing of Siberia, Kazakhstan, and Baltica following closure of the Ural and paleo–Asian Oceans. Through time the nucleus of the future circum-Arctic landmasses generally moved northward; a major acceleration took place when the Central Atlantic opened dur-

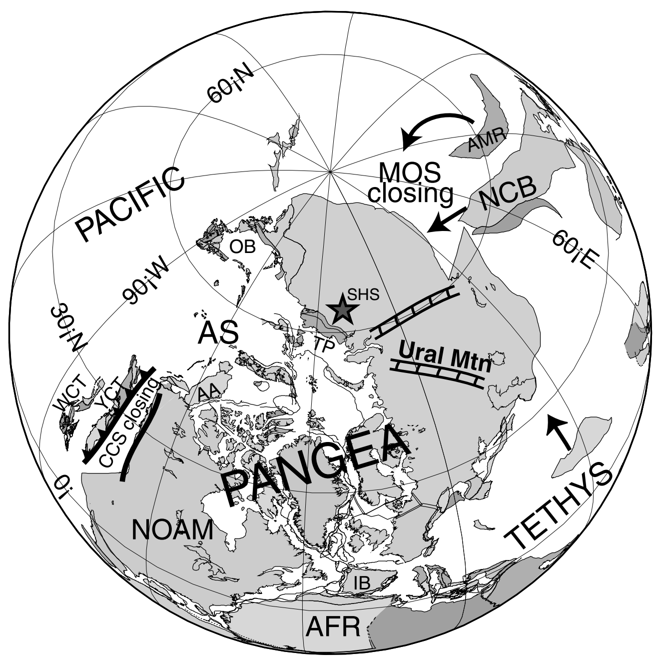

Figure 7. Major Triassic tectonic events that structurally imprinted the Arctic plates. Large star (SHS) indicates location of eruption of Siberian Traps. Yukon composite terrane was undergoing westward-directed subduction as Cache Creek Sea closed. Mongol-Okhotsk Sea was closing as Amuria and North China blocks approached Pangea. Double-ended arrows indicate active or assumed active seafloor spreading. Single-headed arrows indicate general plate motion directions, but are not well defined. Ladder structures indicate recently closed Uralian and paleo–Asian Oceans (see Fig. 6). See Table 1 for abbreviations.

ing the Early to Middle Jurassic (Klitgord and Schouten, 1986). Eruption of the Siberian Traps at the Permian-Triassic boundary ca. 248 Ma (Renne et al., 1995) was the major tectonic event in the future Arctic region between the Early Permian and the Middle Triassic (Plates 6B-7 and 6B-8). The work of Nie et al. (1990), using biomes to delineate the Late Permian paleogeography of the northern continental plates, placed the point of eruption of the 248 Ma Siberian Traps close to the current latitude of the Iceland hotspot. Siberia in a paleomagnetically acceptable latitudinal position has been shifted longitudinally with the rest of Pangea such that a fixed location of the present-day Iceland hotspot (taken to be ~65°N, 17°W; Lawver and Müller, 1994) coincides with the initial eruption point of the Siberian Traps. Although many people do not believe that hotspots are fixed (Norton, 1995, 2000), we believe that the Indo-Atlantic hotspots can be assumed to have been relatively fixed for the past 250 m.y. The voluminous magmatism of the North Atlantic igneous province (ca. 55 Ma, White and McKenzie, 1989) can be explained by the lateral flow model of Sleep (1997), wherein plume material flowed to the thinner part of the lithosphere as the keel of Greenland passed overhead.

Lawver and Müller (1994) traced the track of a fixed Iceland hotspot in the absolute reference frame of Müller et al. (1993) from its present location to northern Ellesmere Island at 130 Ma (see Plate 6B-12 at 120 Ma). As delimited by the paleomagnetic data of Van der Voo (1993) and Smethurst et al. (1998), the extension back in time of the absolute reference frame of Müller et al. (1993) produces a Triassic to Early Jurassic track for a Siberian Traps hotspot that agrees with the early age relationship for the emplacement of the Siberian Traps as determined by Basu et al. (1995). They found slightly younger magma to the east and north of the initial point of eruption (see Plate 6B-9) for a possible 210 Ma position of the hotspot. The location of the fixed Iceland hotspot at 150 Ma (Plate 6B-11) is only a few hundred kilometers from Kong Karls Land, Svalbard, where Bailey and Rasmussen (1997) postulated a Siberian Traps–Iceland hotspot may have produced the Late Jurassic (Early Kimmeridgian) basalts they studied there.

BREAKUP OF PANGEA AND ITS IMPACT ON THE ARCTIC (MIDDLE JURASSIC TO PRESENT)

Rapid northwestward motion of North America (Fig. 8), beginning with the opening of the Central Atlantic in the Jurassic (Klitgord and Schouten, 1986), appears to have strongly affected the western margin of North America, Arctic Alaska, and Chukotka. Considered broadly, Mesozoic and younger Alaska is the product of dextral strike-slip displacement and tectonic convergence between the oceanic plates of the northeastern Pacific Ocean and northwestern North America as North America moved northwestward in an absolute framework. Arctic Alaska became the Arctic Alaska composite terrane when the upper part of the Oceanic composite terrane was obducted onto it from the south during the Late Jurassic (Plates 6B-9 and 6B-10). The Ocean composite terrane includes pieces of the ultramafic Misheguk Mountain allochthonous terrane (3a in Fig. 3) that were emplaced upon oceanic rocks of the Ocean composite terrane by convergence within the Angayucham Sea during the Middle Jurassic (Wirth, 1991; Wirth and Bird, 1992), and an attenuated degree of convergence between the Pacific and the Arctic Alaska composite terrane continues to the present. A comprehensive summary of the geology and tectonic development of Alaska during this time was given in Plafker and Berg (1994b).

Accretion of Alaska by orthogonal convergence between the Farallon and North American plates (Jurassic to mid–Early Cretaceous)

From Aalenian (ca. 190 Ma) or earlier to the mid-Cretaceous, northeastward convergence between the Pacific Ocean and North America uniformly stressed the western continental

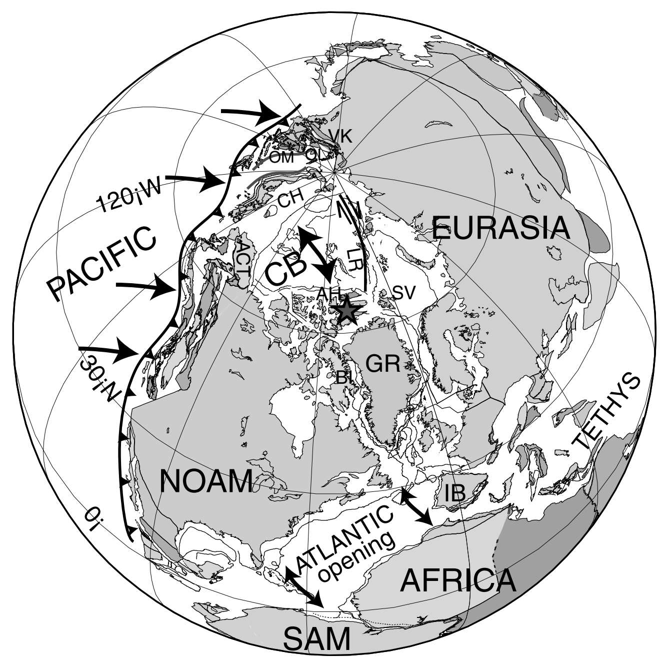

Figure 8. Major mid-Cretaceous tectonic events that structurally imprinted the Arctic plates. Opening of Central Atlantic produced significant northwest motion of North America, Greenland, and Eurasia. Continentward subduction was active along most of Pacific margin of North America and future Arctic region. During Late Jurassic into Early Cretaceous, Canada basin opened about a point south of Mackenzie Delta, rotating Arctic Alaska composite terrane and Chukotka away from Canadian Arctic Islands. A right-lateral strike-slip fault operated along Lomonosov Ridge margin of Eurasia. Siberian Traps–Iceland hotspot is shown under Ellesmere Island and is assumed to have been responsible for Early Cretaceous flood basalts found on Axel Heiberg Island. Double-ended arrows indicate active or assumed active seafloor spreading. Single-headed arrows indicate general plate motion directions but are not well defined. See Table 1 for abbreviations.

margin of North America (Fig. 8) as far north as south-central Alaska, and probably to or beyond the present western end of the Arctic Alaska composite terrane. This convergence closed the Cache Creek Sea off the future coast of British Columbia and southeastern Alaska between 240 and 180 Ma (Late Triassic to earliest Middle Jurassic); sutured the Yukon composite terrane against North America, mainly during the Early Jurassic; and sutured the Wrangell composite terrane against the Yukon composite terrane during the Early Cretaceous (Plates 6B-12 and 6B-13). Closure of the Cache Creek Sea, accommodated by subduction toward the Pacific (McClelland et al., 1992) beneath the Yukon composite terrane (Plates 6B-9 and 6B-10), produced both the Late Triassic to Early Jurassic Quesnellia arc and the Late Triassic to Middle Jurassic Stikine arc (Plafker and Berg, 1994a). Closure of the Cache Creek Sea ca. 175 Ma was roughly coeval with the initiation of seafloor spreading in the Central Atlantic (Klitgord and Schouten, 1986) and the initial breakup of Pangea. Opening of the Central Atlantic and the subsequent northwestward motion of North America may thus have had a substantial far-field effect on the tectonics of the Pacific margin from California to Alaska, and possibly as far as Amuria in northeastern Eurasia (Fig. 8).

Continued north-directed convergence during the Early Cretaceous successively thrust more distal oceanic allochthons upon more proximal continental margin allochthons of the Arctic Alaska composite terrane to largely complete the structural stacking of the Brooks Range orogen by late Early Cretaceous (Albian) time, although Late Cretaceous and/or Paleogene convergence on low-angle thrust faults also took place (Moore et al., 1994). Mid–Early Cretaceous convergence between the Pacific basin and North America also sutured a series of ensimatic islands arcs formed in the Pacific Ocean to western Alaska (Fig. 8 and Plates 6B-11 to 6B-13). The first of these to dock was the Early Cretaceous Koyukuk arc (KA, Plate 6B-10). The Koyukuk arc was sutured to the Angayucham terrane of the Ocean composite terrane, which had been obducted onto the southern margin of the Arctic Alaska composite terrane during the Late Jurassic and early Early Cretaceous (Plates 6B-11 to 6B-14). Later arrivals include the Jurassic and Early Cretaceous Togiak and Nyac arc terranes (Box and Patton, 1989). These terranes are listed separately in Table 1 but are incorporated in the Koyukuk terrane in Plates 6B-10 and 6B-11.

Opening of the Amerasia basin

The Amerasia basin of the Arctic Ocean opened when the Arctic Alaska composite terrane and Chukotka rotated counterclockwise away from the Canadian Arctic Islands in early Early Cretaceous time about a pole of rotation at or south of the present Mackenzie Delta. This rotation was first hypothesized by Carey (1958) and elaborated on by Rickwood (1970), Tailleur (1969, 1973), and many others. Although alternative kinematic schemes have been suggested (see summary by Lawver and Scotese, 1990), congruent lines of evidence now indicate that the basin formed by some variant of rotational rifting. The evidence includes (1) matching bathymetry across the Canada basin (the southern section of the Amerasia basin) (Carey, 1958); (2) facies trends in the Mississippian to Triassic strata of northern Alaska that indicate that these beds had sources north of Alaska, probably in the Canadian Arctic Islands (Rickwood, 1970, and many later workers); (3) matching stratigraphy and structural features across the Canada basin (Grantz et al., 1979, 1998; Embry, 1990; Embry et al., 1994); (4) a fan of lineated seafloor magnetic anomalies in the Canada basin that converge toward the Mackenzie Delta (Taylor et al., 1981; Brozena et al., 1998); (5) a narrow, linear negative-gravity anomaly in the satellite-derived gravity data of Laxon and McAdoo (1994) that is along the axis of symmetry of the magnetic anomalies and closely resembles the gravity anomalies seen at other abandoned seafloor-spreading centers; and (6) well-developed rift shoulders and rift margin grabens that contain Jurassic and Cretaceous marine sediment parallel to both the Canadian (Miall, 1979; Dixon, 1982; Harrison et al., 1999) and Alaskan (Grantz and May, 1982) margins of the Amerasia basin. A paleomagnetic estimate of the degree of rotation (~66°) was obtained by Halgedahl and Jarrard (1987) on samples from test wells on the rift shoulder of the Canada basin in northern Alaska. The satellite altimetry data of Laxon and McAdoo (1998) and aerogeophysical work (Brozena et al., 1998) suggest that opening of the basin was a multistage process that can be generalized as rotation about a pole south of the Mackenzie Delta. Brozena et al. (1998) speculated that opening started with an orthogonal phase that was followed by rotation, while Lane (1997) argued for strictly orthogonal opening without rotation.

Similar timing of the extensional events that opened the Amerasia basin and the convergence at the North Pacific Rim that created the main features of the Brooks Range orogen suggested to Tailleur (1969) that these processes were tectonically linked. Work by Harris (1989), Wirth (1991), and Wirth and Bird (1992) indicated that the initial convergence that created the Brooks Range allochthons may have been as young as 171–163 Ma (mid–Middle Jurassic) when 187–184 Ma (late Early Jurassic [Toarcian]) ophiolitic ultramafic rocks of the future Misheguk Mountain terrane (Patton et al., 1994) of the southwestern Brooks Range were thrust over an accretionary prism consisting of Upper Devonian to Lower Jurassic oceanic rocks of the future Angayucham terrane, also part of the Oceanic composite terrane. Stacking of the multiple nappes that characterize the Brooks Range orogen was initiated by the north-directed emplacement of the Angayucham terrane upon the continental rocks of the Arctic Alaska composite terrane during the Late Jurassic (?) and early Early Cretaceous. This event is recorded by the abrupt deposition of the south-sourced, synorogenic, flyschoid Okpikruak Formation, of this age, upon north-sourced stable outer shelf sedimentary deposits of the Arctic Alaska composite terrane exposed in Brooks Range allochthons (Crane, 1987; Mayfield et al., 1988; Moore et al., 1994; Mull et al., 1982). A southern source for the Okpikruak Formation is demonstrated by the clasts and olistostromes of Angayucham terrane lithologies that it contains. The oldest strata in the northern foothills of the central and western Brooks Range that have not undergone large-scale tectonic (thrust) transport are those of the Albian age Fortress Mountain Formation (Mayfield et al., 1988), indicating that the convergence that created the Brookian orogeny was largely completed by Albian time. The convergence that created the Brookian orogeny therefore ranges from at least the Middle Jurassic to post-Neocomian but pre-Albian (i.e., Barremian or Aptian) Early Cretaceous.

Initiation of the rift stage of the extension that created the Amerasia basin is recorded by the oldest deposits in rift margin grabens that formed on the rift shoulders of the Amerasia basin. The Dinkum and related grabens on the Alaskan rift shoulder (Grantz and May, 1982; Hubbard et al., 1987) contain clastic deposits that, at their base, are of Hettangian? or Sinemurian age (Mickey et al., this volume), confirming that extension began early in the Early Jurassic. The rift shoulder along the Canadian Arctic Islands margin of the Amerasia basin contains grabens with strata as old as late Toarcian (Harrison et al., 1999), and the initial age of margin-parallel faults in the southwestern Arctic Islands and Mackenzie Delta region indicate that continental rifting there began in early Middle Jurassic (Aalenian) time (Embry and Dixon, 1994). In the Canada basin, as in many areas where seafloor spreading initially occurs within a continent, rapid sedimentation covered the spreading center and greatly subdued or precluded formation of coherent marine magnetic anomalies (Lawver and Hawkins, 1978). Lineated, but currently uncorrelated seafloor magnetic anomalies in the Canada basin extend to the gravity anomaly taken to mark its extinct spreading axis (Brozena et al., 1998; Grantz et al., 1998), indicating that the seafloor spreading in the basin was completed by the onset of the Cretaceous normal magnetic superchron, near the beginning of Aptian time (ca. 120 Ma). The age of the extension that created the basin was thus no earlier than early Early Jurassic, and not later than earliest Aptian. This is similar to the Middle Jurassic (but possibly older) to Barremian or Aptian range of the principal convergence in the Brookian orogeny.

The similarity in age of extension in the Amerasia basin and the main convergence that produced the Brookian orogeny in northern Alaska, and the compatible trends of their extension and convergence axes, suggest a kinematic link between these adjacent tectonic provinces. Both the extension and convergence axes are, moreover, similar in trend to the east- to northeast-trending convergence velocity vectors between the Farallon plate and North America from prior to 175 Ma to after 125 Ma (Engebretson et al., 1985), which encompasses the span of time during which the Amerasia basin opened. It is not clear, however, what specific process may have linked Farallon–North America and Brooks Range convergence with Amerasia basin spreading. Trench rollback related to subduction of the lower crust of the Angayucham Sea and the southern fringes of Arctic Alaska beneath Arctic Alaska (Grantz et al., 1991; Miller and Hudson, 1991), in a manner broadly analogous to that proposed by Rubin et al. (1995) for crustal extension in north-central Alaska and northeasternmost Russia during the mid-Cretaceous, may provide a viable mechanism, but many uncertainties remain. For example, the main (Middle Jurassic to Early Cretaceous) phase of the Brookian orogeny, which correlates with extension in the Amerasia basin, can only be traced as far west as Wrangell Island (Kos'ko et al., 1993), and its possible continuation northwest beneath the East Siberian Sea to the northwest corner of the Amerasia basin is conjectural. In addition, a large transform fault along the Amerasia side of Lomonosov Ridge, which is required for the rotational opening of the Amerasia basin, has yet to be conclusively demonstrated.

We propose that rifting in the Amerasia basin was triggered when the northern part of a zone of crustal weakness drifted over a hotspot, perhaps the remnant of the mantle plume that created the Siberian Traps at 248 Ma (Renne, 1995). The opening of the Amerasia basin may have been initially orthogonal followed by rotation. Brozena et al. (1998) and Grantz et al. (1998) suggested that the boundary between the irregular magnetic anomalies along the margins of the Amerasia basin and the well-ordered northwest-fanning magnetic lineations in the center of the basin (Taylor et al., 1981) may mark a transition from orthogonal to rotational rifting; however, the age of the transition is not known. We speculate that the rift initially propagated south-southeastward through the early Paleozoic Franklinian deep-water basin, which now underlies the Arctic continental margin of the Canadian Arctic Islands (Trettin et al., 1991) and the Arctic coastal plain of northern Alaska (Moore et al., 1994). It is thought that this deep-water basin contained the zone of crustal weakness along which the axial rift of the Amerasia basin formed. Passage of the rift from the relatively thin Precambrian crust presumed to underlie the Franklinian deep-water basin to the thick Precambrian crust of the cratonic Mackenzie platform is thought to have blocked further propagation to the south-southeast. The marked increase in thickness of Precambrian crust in the vicinity of the Mackenzie Delta coincides with the region where the structural effects associated with the rifting die out toward the pole of rotation in the lower Mackenzie River Valley.

Opening of the Amerasia basin and the kinematically linked closure of the South Anyui basin, the last remnant of the Angayucham Sea, resulted in the collision of Chukotka with some part of Siberia. This collision, which closed the basin and created the South Anyui suture zone, has been dated as pre-Albian (112 Ma) (Parfenov et al., 1995; Parfenov, 1997; Sokolov et al., this volume). This age is compatible with the presence of well-developed lineated magnetic anomalies at the extinct spreading axis of the Canada basin, which had to have formed prior to the start of the Cretaceous normal magnetic superchron (chron 34n; Gradstein et al., 1994) in earliest Aptian time (ca. 120 Ma), because the lineated magnetic anomaly over the abandoned spreading center is reversed. As can be seen in Plate 6B-12, there is a substantial gap between the South Anyui suture zone, which forms the western margin of Chukotka in this figure, and the Omolon block. Whether this gap should be between Chukotka and the Omolon block or between the Omolon block and Siberia is uncertain. Parfenov (1997) has deformation in the Verkoyansk fold and thrust belt continuing until Albian to Campanian time, but he showed the South Anyui basin closed by 110 Ma. The gap shown in our Plates 6B-12 through 6B-15 in this area should not be interpreted to indicate the presence there of an open sea with oceanic crust. Rather, it indicates that a global reconstruction of this region implies that substantial compression occurred in this region into the Cenozoic, particularly as the Eurasian basin opened.

Accretion of Alaska by orthogonal convergence between the Farallon and North American plates: Middle to Late Cretaceous

During the mid-Cretaceous a strong component of dextral strike-slip displacement developed between the Pacific Ocean basin and northwestern North America. This component initiated the northwestward migration of coastal terranes along the western margin of North America and contributed to a 135° clockwise rotation of the Ruby Mountains terrane with respect to the continental margin (Tailleur, 1980; Plafker and Berg, 1994a) (e.g., cf. Plates 6B-11 and 6B-12 to 6B-14). During the Late Cretaceous, northward-dipping subduction continued beneath much of the Pacific margin of Alaska and Siberia (Miller and Hudson, 1991). Between 110 Ma and 80 Ma, a significant magmatic belt and associated thermal metamorphism overprinted a broad east-west–trending belt across north-central Alaska (Miller, 1994), adjacent parts of Canada (Armstrong, 1988), and the Russian far east (Parfenov and Natal'in, 1986). In southern Alaska, the final suturing of the Wrangell composite terrane to North America occurred after the Cenomanian (91 Ma) with closure of the last remnant of the intervening ocean basin (Plates 6B-11 to 6B-13). Cole et al. (1999) also attributed the north-directed shortening in the Cantwell basin between 70 and 60 Ma to final suturing of the Wrangellia composite terrane to southern Alaska.

Accretion and formation of northeastern Eurasia by convergence and collision during the Mesozoic

Through the early Middle Jurassic (Plate 6B-10) the Siberian craton was the northeastern margin of Eurasia. Beginning ca. 150 Ma, as recorded by deformation in the Verkhoyansk fold and thrust belts (Parfenov, 1997), the Omulevka and Omolon blocks began to collide with Siberia (Fig. 8 and Plate 6B-11), initiating closure of the Oimyakon basin and moving the continental margin outboard of the Omulevka and Omolon blocks. Deformation along the collision zone at the platform margin continued, however, until 80 Ma (early Late Cretaceous). Both Parfenov (1997) and Nokleberg et al. (1998) showed the development of a seafloor-spreading center in a "South Anyui basin" during the Early and Middle Jurassic. Parfenov (1997) placed the spreading center between the Koyukuk arc and Eurasia and connected it to a spreading center between the Alazeya arc and North America, whereas Nokleberg et al. (1998) placed it behind opposite outward-facing arcs, the Koyukuk arc off North America and the Uyandina arc off Eurasia. This Mesozoic seafloor-spreading center may be the equivalent of backarc basin extension behind a major subduction zone along the Pacific margin (Bonderenko and Didenko, 1997) outboard of both the arc shown in Plate 6B-11 and the Omolon block. The Verkoyansk orogen (Parfenov et al., 1995) records many complex tectonic events involving closure of a number of marginal basins (Plates 6B-10 to 6B-12). During the Late Jurassic, the Mongol-Okhotsk Sea closed and major blocks accreted to the southern margin of Siberia, including Amuria and the North China and South China blocks (Parfenov, 1997; Nokleberg et al., 1998), completing the assembly of eastern Eurasia (Plates 6B-10 to 6B-11).

Rotational opening of the Amerasia basin was probably stopped by collision of Chukotka with Eurasia at the South Anyui suture zone (Parfenov et al., 1995; Parfenov, 1997; Sokolov et al., this volume). Parfenov (1997) showed a complete assembly of far eastern Siberia as early as the Albian (ca. 110 Ma). Our rigid plate model, however, suggests that closure between Chukotka and the remainder of far eastern Siberia may not have been completed until sometime in the Cenozoic (cf. Plates 6B-14 and 6B-15). Our model requires some deformation in far eastern Siberia after closure of the South Anyui basin, but whether the deformation was elimination of oceanic crust or convergence and thickening of continental crust is not known. Studies of the present plate boundary between Eurasia and North America (Fujita and Cook, 1990) indicate a series of transtensional structures from the Laptev Sea margin near the New Siberian Islands to the Mona rift at ~65°N, 146°E (Fig. 2). While our model is not definitive, it suggests there may have been as much as 300 km of closure somewhere within far eastern Siberia between the time of collision at the South Anyui suture zone ca. 120 Ma and the present. The only other possibility would be an as-yet unrecognized, but significant plate boundary between Eurasia and North America where the required Late Cretaceous and Cenozoic motion could have been accommodated.

Accretion of Alaska by oblique and normal convergence between the Kula plate and North America during the Late Cretaceous and Paleogene

Formation of the Kula-Pacific spreading center in the northeastern Pacific Ocean ca. 85 Ma (Woods and Davies, 1982) rotated the convergence velocity vectors between the Kula plate and northwestern North America from northeast to north and increased their velocity from 80–100 to 150–200 km/m.y. These changes strengthened the dextral strike-slip component of the motion between the Kula and Farallon plates and the western margin of North America. They also created a complex system of dextral strike-slip faults of large horizontal displacement within and along the continental margin of western North America as far north as south-central Alaska (St. Amand, 1957; Grantz, 1966; Plafker and Berg, 1994a). These faults include the Queen Charlotte, Fairweather, and Denali fault systems of coastal British Columbia; southeast Alaska and interior central Alaska; and the Tintina fault within the Cordillera of western Canada and central Alaska. Displacement on the Tintina fault system was mainly during the Late Cretaceous and early Tertiary, but there may have been Late Jurassic or older offsets (Gabrielse, 1985). The Denali system has been active from the Late (mainly latest) Cretaceous to the Holocene, and the Queen Charlotte–Fairweather system has had mainly late Cenozoic displacement. In south-central and western Alaska, the Kula–North America convergence was in general normal to the continental margin and produced the accretionary prisms of the Chugach and Prince William terranes of the Southern Margin composite terrane, and parts of the Yakutat terrane (see Table 3; Fig. 8 and Plate 6B-14). Far-field effects of the Kula–North American convergence appear to have created duplexes within the allochthons of the central Brooks Range and low-angle thrust faults and foreland folds within the northern foothills of the Brooks Range and the continental shelf and slope of the eastern Beaufort Sea (Grantz et al., 1991; Moore et al., 1994). Geologic and paleomagnetic data (Grantz, 1966; Globerman, 1985; Plafker and Berg, 1994a) support a counterclockwise bending of southwestern Alaska of 45°–60° between ca. 65 and 50 Ma.

The predominant building blocks of which southeast, central, and southwestern Alaska and adjacent parts of British Columbia were assembled are slivers sliced off coastal western North America by dextral strike slip along the Tintina, Denali, Fairweather, and Queen Charlotte fault systems and their predecessors. These fault-bounded slivers became tectonostratigraphic terranes as a result of the tens or hundreds of kilometers of northwest and westward tectonic transport that carried them to their present locations in central and southwestern Alaska (Plates 6B-12 to 6B-16). These predominantly continental terranes are generally outboard (south) of the ensimatic island-arc terranes (Koyukuk, Togiak, and Nyac; see Togiak composite terrane in Table 2) that were accreted to western Alaska between the Jurassic and late Early Cretaceous.

A major jump in the location of the Kula–North American plate convergence from the foot of the continental slope in the Bering Sea (the Beringian margin) to the modern Aleutian arc occurred during the early Eocene. Scholl et al. (1986, 1987) reported that the Aleutian arc formed ca. 50–55 Ma, which is also about the time that the Mid-Atlantic Ridge split the outer Barents Sea shelf from Eurasia to create the Lomonosov Ridge and the Eurasia basin of the Arctic Ocean (Karasik, 1973; Vogt et al., 1979). Subduction at the Aleutian arc consumed the Kula-Pacific spreading center ca. 42 Ma (middle Eocene) (Lonsdale, 1988), ending the strong north-directed convergence (150–200 km/m.y. according to Engebretson et al., 1985) between the Pacific basin and southern Alaska. Thereafter, convergence vectors between the Pacific plate and North America had northwesterly azimuths and velocities of ~60–80 km/m.y. (Engebretson et al., 1985, Fig. 8). These vectors were parallel to the western margin of North America as far west as 140°W, and the motion continued to drive displacement along the major, seismogenic Queen Charlotte, Denali, and Fairweather dextral strike-slip fault systems of coastal northwestern North America and interior Alaska. West of 145°W, where the continental margin changes trend from northwest to southwest, the same convergence vectors are orthogonal to the continental margin and drove subduction at the Aleutian Trench. West of 180°W, the arcuate trend of the Aleutian arc and trench progressively bring the convergence velocity vectors and the trench into near parallelism, producing a transition from a fully convergent margin off south-central Alaska to a predominantly dextral strike-slip boundary along the south margin of the western Aleutian Islands. West of the Aleutian Trench, the Pacific plate converges orthogonally with eastern Eurasia along the generally northeast-trending Kuril Trench (Fig. 9) outboard of the Kamchatka Peninsula and the Sea of Okhotsk. Predecessors of this conver-

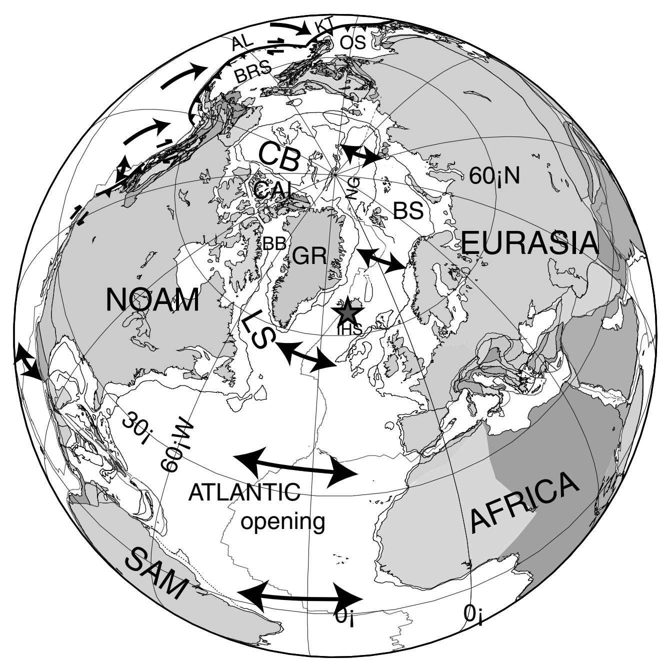

Figure 9. Major Cenozoic tectonic events that affected the Arctic region shown on present-day configuration. Late Cretaceous seafloor spreading in Labrador Sea and Baffin Bay split Greenland from North America. Cenozoic seafloor spreading began east of Greenland between Rockall Plateau–Hatton Bank and eastern Greenland. This seafloor spreading rifted Lomonosov Ridge from Barents Sea shelf margin. Double-ended arrows indicate active or assumed active seafloor spreading. Bering Sea region behind Aleutian Trench underwent “extrusion” as result of collision and oroclinal bending of Alaska. Right-lateral strike-slip arrows indicate direction of motion along faults along western margin of North America as well as along western end of Aleutian Island arc. Single-headed arrows indicate general plate motion directions but are not well defined. Subduction continues to the west of the Aleutian Trench at the Kurile Trench.

gence may have active when the South Anyui basin closed between 150 and 120 Ma (cf. Plates 6B-11 and 6B-12) and later produced a series of volcanic arcs that accreted to Siberia, starting with the Olyutorka-Kamchatka arc during the Maastrichtian (ca. 70 Ma) (Parfenov, 1994). The lesser Kuril and Kronotsky arcs appear to have been accreted in the Early Eocene (Parfenov, 1994), although Nokleberg et al. (1998) show them as having accreted during the Miocene.

Track of the Iceland hotspot from the Arctic to the Atlantic

According to Lawver and Müller (1994), a fixed present-day Iceland hotspot would have underlain northern Ellesmere Island ca. 130 Ma. The Alpha Ridge (AR in Fig. 1), which Vogt et al. (1979) suggested was a hotspot track, intersects the North American continental margin in the area where Lawver and Müller (1994) showed the fixed Iceland hotspot at the time of the opening of the Amerasia basin. A series of flood basalts recorded in the Canadian Arctic Islands include massive outpourings on Axel Heiberg and Ellesmere Islands during the late Albian (Embry, 1991). Embry (1991) reported early Aptian volcanic flows occur on northern Ellesmere Island, and Tarduno et al. (1998) dated part of the basalts of the Strand Fjord formation on Axel Heiberg Island as 95.3 ± 0.2 Ma (Cenomanian). As the North Atlantic and the Labrador Sea opened, the northeastern margin of the North American continent and Greenland drifted over the fixed hotspot. Uplift of the eastern margin of Baffin Island and flood basalts at Cape Dyer (Clarke and Upton, 1971) on the southern end of Baffin Island are also attributed to passage over the Siberian Traps–Iceland hotspot (Lawver and Müller, 1994). The Disko Island flood basalt along western Greenland (Gill et al., 1992) traces the track of the hotspot during the Paleocene. The hotspot uplifted the eastern margin of central Greenland ca. 40 Ma (Larson, 1990) and generated the alkalic basalts of Iceland and its surrounding platform from 25 Ma to the present.

Propagation of Central Atlantic seafloor spreading into the Arctic region and creation (opening) of the Eurasia basin

During the Late Cretaceous, Central Atlantic seafloor spreading propagated into the Labrador Sea and Baffin Bay (Roest and Srivastava, 1989; Srivastava and Roest, 1999). The pole of motion between North America and Eurasia for the period between the late Albian, by which time most authors would agree that the Amerasia basin had opened, and ca. 58 Ma in the late Paleocene, when the Eurasia basin (Fig. 9) began to open (Kristoffersen, 1990), was located near 68°N, 150°E (Srivastava and Roest, 1989). Such a pole, originally located south of far eastern Siberia, implies continued extension, albeit at a fairly slow rate, from the pole of rotation in far eastern Siberia toward the Baffin Bay region from the late Albian to the late Paleocene. We propose that some of this extension may be represented by the dispersed Late Cretaceous to early Tertiary extension seen in seismic reflection profiles from the Chukchi borderland of the Amerasia basin (Plate 6B-13) (Grantz et al., 1993) and locally within the broad Siberian margin (Drachev et al., 1998).

The major Cenozoic event in the Arctic was the initiation of opening of the Eurasia basin by extension of North Atlantic seafloor spreading (Talwani and Eldholm, 1977) into the Arctic between Greenland and Svalbard (site of the future Fram Strait) by splitting the 50–100-km-wide Lomonosov Ridge from the outer Barents Sea shelf ca. 58 Ma. We suggest that the initial position of the rift ~50–100 km inboard of the ocean-continental boundary of the early Paleocene Barents shelf was a consequence of two factors: the general parallelism of the North Atlantic spreading axis with the shelf margin, and the relative strength of the adjacent oceanic and continental lithospheres (Brace and Kohlsted, 1980). On reaching the Arctic near the continental margin, the Mid-Atlantic Ridge propagated through the weaker continental lithosphere of the outer Barents Sea shelf in preference to the more competent oceanic lithosphere beneath the adjacent Amerasia basin (Fig. 9 and Plates 6B-15 and 6B-16). Opening of the Eurasia basin accelerated the southward motion of Alaska and the westward translation of Arctic Canada while western Eurasia continues to move slightly northward.

SUMMARY AND CONCLUSIONS

The geologic framework of the present-day Arctic region is the product of a relatively small number of first-order plate tectonic events that operated through most of the Phanerozoic.

Eurasia, Pangea, and the major landmasses of the present-day Arctic region were largely assembled by plate migration and collision beginning with closure of the eastern part of the Iapetus Ocean during the Silurian to create Laurussia. Subsequent closure of the Rheic and paleo–Tethys Oceans in the Late Pennsylvanian united Laurussia with Gondwana and created Pangea, bringing most of the present Arctic landmasses into proximity.

Closure of the Iapetus Ocean during the Middle to Late Silurian involved the collision of Baltica, Pearya, and Chukotka with Laurentia and brought Caledonian deformation to Arctic North America. The Scandian phase of the Caledonian orogeny included left-lateral transpression between the Canadian Arctic Islands region and Chukotka, now part of northeastern Siberia.

A Devonian rifting event was possibly caused by a hotspot that produced the Vilyui basin on the Siberian craton. This event rifted a number of blocks from the Siberian margin, opened the Oimyakon Sea, and changed the absolute motion of Siberia from northwestward to northeastward.

We lack definitive evidence for the root cause of the later and distinct Ellesmerian orogeny of northwestern North America. It may have been a far-field effect of a collision of an unknown continental fragment with northern Laurussia during the Late Devonian to Early Mississippian; flat-slab subduction beneath the northern margin of Laurussia, similar to the subduction that caused the Mesozoic Gondwanide fold belt; or thin-skinned convergence generated by reactivation of the suture between Chukotka and Laurussia at which the Iapetus Ocean was closed during the Scandian phase of the Caledonian orogeny.

Emplacement of the Siberian Traps in northern Russia southeast of the modern Kara Sea ca. 250 Ma (Late Permian) was possibly the initial manifestation of the present-day Iceland hotspot, now located at ~65°N, 17°W. Migration of the newly amalgamated Arctic landmasses across this hotspot left a broken trail of igneous provinces and extensional features that include the extensive Siberian Traps, the Alpha and possibly the Mendeleev Ridges of the Amerasia basin, the Kap Washington volcanics of northern Greenland, flood basalts on Axel Heiberg and Ellesmere Islands in the Canadian Arctic Islands, Disko Island on West Greenland, and the volcanic accumulations on the present Iceland platform.

Tensional stresses created in the Arctic landmasses as they drifted across the Siberian Traps–Iceland hotspot, in conjunction with the distal effects of subduction of the Pacific plate beneath Arctic Alaska at the Pacific Rim, are thought to have triggered the rotational rifting that opened the Amerasia basin of the Arctic Ocean during early Early Cretaceous. The rift apparently propagated south-southeast along a zone of weakness within the early Paleozoic Franklinian deep-water basin until it encountered the Mackenzie platform of the Canadian shield in the vicinity of the Mackenzie Delta, which localized the pole of rotation in the lower Mackenzie River Valley.

Convergence of the oceanic plates of the Pacific Ocean with Alaska and northeastern Russia from the Jurassic onward amalgamated the allochthonous lithotectonic terrane fields of western Canada, southern and central Alaska, and Russia west of the Siberian shield and created the broad array of continental fragments, accretionary prisms of both continental margin and oceanic sediments, volcanic arcs, and ophiolites with sporadic blueschist metamorphism that characterize the continents that border the northern rim of the Pacific Ocean.

Slow but progressive migration of the future Arctic landmasses carried them from low latitudes in the Late Silurian to their present polar position by Late Cretaceous time.

Extension of seafloor spreading from the North Atlantic split the Lomonosov Ridge from the outer Barents Shelf beginning ca. 58 Ma, and created the slow-spreading Eurasia basin of the Arctic Ocean as well as transtensional rifts in far eastern Siberia and possibly in the Chukchi continental borderland.

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